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Highways in the River Environment:

Roads, Rivers, and Floodplains

Second Edition

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16. Abstract

This manual provides information for understanding, assessing, and addressing interactions between river functions and transportation infrastructure. The manual adopts a holistic approach by illustrating not only the effects of rivers on roads and bridges, but also the effects of roads and bridges on rivers and their floodplains. Recognizing these mutual impacts and interactions, this manual provides planners, engineers, geologists, environmental specialists, and other transportation professionals with the tools to create reliable, resilient, and sustainable transportation facilities because their design and implementation recognizes the important functions and values of rivers and their floodplains.

The manual describes the river and floodplain functions of conveyance and storage, river evolution, habitat, and connectivity. It provides an overview of Federal policy pertaining to highways in the river environment and describes the overall processes for planning, design, construction, and maintenance of transportation infrastructure. The manual provides information and tools in hydrology and hydraulics, fluvial geomorphology, and sediment transport modeling. Recognizing the importance of biological contributions to river forms and functions, the manual integrates biology into its presentation of biogeomorphological concepts and tools. Finally, the manual provides information about other important, sometimes regional, topics relevant to design of resilient bridges and roads in the riverine environment, including coincident flows at confluences, ice, wood in rivers, human-generated debris, water quality, invasive species, beaver activity, mud and debris flows, alluvial fans, tidally influenced and tidally dominated rivers and streams, and inspection and monitoring.

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Figure 8.18 in this manual (entitled “Potential road alignments on a fan”) is adapted from Figure 872.7 (entitled “Alternative Highway Locations Across Debris Cone”) in the 7th Edition Highway Design Manual (HDM) from the California Department of Transportation (Caltrans). This figure is used by permission from Caltrans, which intended it for use by, and to inform and guide, its officers and employees on bank protection and erosion control at desert wash locations. Its use in this manual does not constitute a standard, specification, or policy. The figure provides examples of generalized alignments for crossing an alluvial fan but is not a substitute for engineering knowledge or experience or sound engineering judgment.

This second edition of HEC-16 significantly expands on the scope and detail of the first HEC-16 “Addendum to Highways in the River Environment/Hydraulic and Environmental Design Considerations” (1980).

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Glossary

Abrasion:	Removal of streambank material resulting from entrained sediment, ice, wood, or debris rubbing against the bank.
Adaptive Management:	A structured, iterative process of robust decision making used in situations with great uncertainty. The aim is to reduce risk by system monitoring and project adjustments over time.
Aggradation:	Deposition of sediments by a river.
Alluvial Channel:	Channel wholly in alluvium; no bedrock is exposed in channel at low flow or likely to be exposed by erosion.
Alluvial Fan:	A fan-shaped deposit of material at the place where a stream issues from a narrow valley of high slope onto a plain or broad valley of low slope. An alluvial cone is made up of the finer materials suspended in flow while a debris cone is a mixture of all sizes and kinds of materials.
Alluvial Stream:	A stream that has formed its channel in cohesive or noncohesive materials that have been and can be transported by the stream.
Alluvium:	Unconsolidated material deposited by a stream in a channel, floodplain, alluvial fan, or delta.
Alternating Bars:	Elongated deposits found alternately near the right and left banks of a channel.
Anabranch:	Individual channel of an anabranched stream.
Anabranched Stream:	A stream where large islands or, more rarely, large bars divide flow at normal and lower stages. Individual islands or bars are wider than about three times the water width. Compared to braided streams, channels are more widely and distinctly separated.
Anadromous:	Fish that migrate upstream from the sea to spawn.
Anastomosed:	See anabranched stream.
Anastomosing Stream:	An anabranched stream.
Angle of Repose:	The maximum angle (as measured from the horizontal) at which a pile of gravel or sand (noncohesive) particles can stand.
Annual Exceedance Probability:	The probability that the magnitude of an event (for example annual maximum flood peak) will be equaled or exceeded in a single year.
Annual Flood:	The maximum flow in one year (may be an average daily value or instantaneous peak value).
Anthropogenic Litter (AL):	Litter and trash resulting from human activity.

Aquifer:	An underground layer of water-bearing permeable rock, rock fractures, or unconsolidated materials.
Armor Layer:	Surface layer of large particles (relative to those below) formed naturally (by selective entrainment of relatively finer particles) or formed artificially by placement of large rocks to resist erosion.
Armoring:	A natural process whereby an erosion-resistant layer of relatively large particles is formed on a streambed due to the removal of finer particles by streamflow. Also, the placement of a coarse material covering to resist erosion.
Average Velocity:	Velocity at a given channel cross-section determined by dividing discharge by cross-sectional area.
Avulsion:	A sudden change in the channel course that usually occurs when a stream breaks through its banks; usually associated with a flood or other catastrophic event.
Backfill:	The material used to refill a ditch or other excavation, or the process of doing so.
Backslope:	Area on the landward side of a natural levee where elevations decrease gradually with distance from the channel.
Backswamp:	Marshes and wetlands at the intersection of the backslope with the phreatic surface of the alluvial aquifer.
Backwater:	An increase in water surface elevation relative to the elevation that would normally occur under unrestricted channel and floodplain conditions. It is often induced by a bridge or other structure that obstructs or constricts the free flow of water in a channel.
Backwater Area:	The low-lying lands adjacent to a stream that may become flooded due to backwater.
Bank:	The rising ground bordering the riverbed along one or both edges of the channel.
Bank, left or right:	The side of a channel as viewed in a downstream direction.
Bankfull:	Water level in a stream corresponding to where water is flowing within the banks just before it spills out into the floodplain.
Bankfull Discharge:	Discharge that, on the average, fills a channel to the point of overflowing.
Bank Protection:	Engineering works for the purpose of protecting streambanks from erosion.
Bank Revetment:	Erosion-resistant materials placed directly on a streambank to protect the bank from erosion.
Bar:	An elongated deposit of alluvium within a channel, not permanently vegetated.

Base Flood:	A flow event with a one percent annual exceedance probability.
Base Floodplain:	The floodplain associated with the Base Flood.
Bathymetry:	The underwater depth of the bed of the channel, lake, ocean, or other body of water.
Bay:	Body of water connected to the ocean with an inlet.
Bed:	The bottom of a channel bounded by banks.
Bedform:	A recognizable relief feature on the bed of a channel, such as a ripple, dune, plane bed, antidune, or bar. Bedforms are a consequence of the interaction between hydraulic forces (boundary shear stress) and the bed sediment.
Bed Layer:	A flow layer, multiple grain diameters thick (usually two), immediately above the bed and associated with bed load sediment transport.
Bed Load:	Sediment that is transported in a stream by rolling, sliding, or skipping along the bed or close to it; considered to be within the bed layer (contact load).
Bed Load Discharge (bed load):	The quantity of bed load passing a cross-section of a stream in a unit of time.
Bed Material:	Material found in and on the bed of a stream (may be transported as bed load or in suspension).
Bed Material Discharge:	The part of the total sediment discharge that is composed of grain sizes found in the bed.
Bedrock:	Rock exposed at the surface of the earth or overlain by soils and unconsolidated material.
Bed Sediment Discharge:	The part of the total sediment discharge that is composed of grain sizes found in the bed.
Bed Shear (tractive force):	The force per unit area exerted by a fluid flowing past the channel bed, bank, or other boundary.
Bed Slope:	The inclination of the channel bottom.
Bed Sorting:	A method of accounting for the exchange of sediment between bed layers and flowing water.
Biogeomorphology:	The study of how biological processes interact with geomorphic processes to create, modify, destroy, and recycle landforms and entire landscapes.
Boulder:	A rock fragment whose diameter is greater than 250 mm.
Braid:	A subordinate channel of a braided stream.
Braided Stream:	A stream where small mid-channel bars or small islands divide the flow at normal and lower stages. The individual width of bars and islands is less than about three times water width. A braided stream has the aspect of a single large channel containing subordinate channels.

Bridge Opening:	The cross-sectional area beneath a bridge that is available for conveyance of water.
Bulking:	Increasing the water discharge to account for high concentrations of sediment in the flow.
Bulking Factor:	The ratio of the sediment and water volumes to the water volume.
Capacity Supply Ratio:	The ratio of the total bed material load transported by the historic sequence of flows in the design reach compared to that in the sediment supply reach immediately upstream.
Cascade:	Very steep stream reach with channel slopes in the range of 10 percent to 30 percent, typically considered a transport reach.
Catchment (area):	See drainage basin.
Causeway:	Rock or earth embankment carrying a roadway across water.
Caving:	The collapse of the upper bank caused by undermining the lower bank materials due to the action of flowing water.
Channel:	The bed and banks that confine the surface flow of a stream.
Channel Classification:	Classifying a stream according to a set of observations or typical characteristics (e.g., straight, meandering, braided).
Channel Diversion:	The removal of flows by natural or artificial means from a natural length of channel.
Channel Migration Zone:	A zone determined based on geomorphic analyses that identifies the areas of past, present, and potential future planforms. This zone identifies areas where a channel is likely to move, either gradually or rapidly.
Channel Pattern:	The aspect of a stream channel in plan view, with reference to the degree of sinuosity, braiding, and anabranching.
Channel Process:	Behavior of a channel with respect to shifting, erosion and sedimentation.
Channelization:	Straightening or deepening of a natural channel by artificial cutoffs, grading, flow-control measures, or diversion of flow into an engineered channel.
Choking (of flow):	Excessive constriction of flow which may cause severe backwater effects.
Clay (mineral):	A particle whose diameter is in the range of 0.00024 to 0.004 mm.
Clay Plug:	A cutoff meander bend filled with fine grained cohesive sediments.
Clear-Water Scour:	Scour when there is no movement of the bed material upstream of the bridge crossing at the flow causing bridge scour.

Climate Change:	Climate change refers to any significant change in the measures of climate lasting for an extended period. Climate change includes major variations in temperature, precipitation, or wind patterns, among other environmental conditions, that occur over several decades or longer. Changes in climate may manifest as a rise in sea level, as well as increases in the frequencies and magnitudes of extreme weather events now and in the future. (FHWA Order 5520)
Cobble:	A fragment of rock whose diameter is in the range of 64 to 250 mm.
Cohesive Streambed:	Cohesive bed material can include caliche, hardpan, loess, highly compact and dense clays, and in the broader sense, erodible rock.
Coincident Flow:	The combination of peak flows or flow hydrographs at a confluence.
Colluvium:	Sediments accumulated at the base of hillslopes.
Concentration (sediment):	The ratio of sediment to the water and sediment mixture expressed volumetrically, by weight, or in milligrams per liter.
Confluence:	The junction of two or more streams.
Constriction:	A natural or artificial control section, such as a bridge crossing, channel reach, or dam, with limited flow capacity in which the upstream water surface elevation is related to discharge.
Contact Load:	Sediment particles that roll or slide along in almost continuous contact with the streambed (bed load).
Contraction:	The effect of channel or bridge constriction on flow streamlines.
Contraction Scour:	In a natural channel or at a bridge crossing, the removal of material from the bed and banks across all or most of the channel width. This component of scour results from a contraction of the flow area at the bridge which causes an increase in velocity and shear stress on the bed at the bridge.
Countermeasure:	A measure intended to prevent, delay, or reduce the severity of hydraulic problems.
Critical Shear Stress:	The minimum amount of boundary shear stress capable of initiating sediment or soil particle motion (i.e., the point of incipient motion).
Crossing:	The relatively short and shallow reach of a stream between bends; also, crossover or riffle.
Cross-Section:	A transect normal to the downstream direction in a channel or floodplain.
Current:	Water flowing through a channel.
Current Meter:	An instrument used to measure flow velocity.
Cut Bank:	The concave bank of a meandering stream.

Cutoff:	(1) A direct channel, either natural or artificial, connecting two points on a stream, thereby shortening the original length of the channel and increasing its slope; (2) A natural or artificial channel which develops across the neck of a meander loop (neck cutoff) or across a point bar (chute cutoff).
Cutoff Wall:	A wall, usually of sheet piling or concrete, that extends down to scour-resistant material or below the expected scour depth.
Daily Discharge:	Discharge averaged over one day (24 hours).
Debris:	Floating or submerged material, such as logs, other vegetation, and trash, transported by a stream.
Debris Flow:	Fluid flow controlled primarily by the composition of the sediment/debris mixture. Debris flow contains approximately 40 to 50 percent sediment by volume.
Degradation (bed):	A general and progressive (long-term) lowering of the channel bed due to erosion, over a relatively long channel length.
Delta:	A landform that is created from the deposition of sediment that is carried by a river as the flow leaves the mouth of the river and enters slower moving or stagnant water.
Deposition:	The geological process of adding sediments, soil, rocks, and silts to landform or landmass. Deposition in rivers is typically found when the sediment transport capacity decreases and the suspended material can longer be carried by the river.
Depth of Scour:	The vertical distance a streambed is lowered by scour below a reference elevation.
Design Flow (design flood):	The discharge that is selected as the basis for the design or evaluation of a hydraulic structure.
Discharge:	Volume of water passing through a channel in a given period.
Dominant Discharge:	(1) The discharge of water which is of sufficient magnitude and frequency to have a dominating effect in determining the characteristics and size of the stream course, channel, and bed; (2) That discharge which determines the principal dimensions and characteristics of a natural channel.
Dominant Wave Period:	Wave period of the highest energy waves.
Drainage Basin:	An area confined by drainage divides, often having only one outlet for discharge (catchment, watershed).
Drift:	Alternative term for vegetative debris.
Dry Bulk Density:	Density of a sediment deposit (mass per unit volume), including sediment and voids.
Dynamic Breakup:	Spring breakup of cover ice that is produced during increasing discharge where ice has maintained strength.

Dynamic Equilibrium:	A state of balance between continuing processes. A channel is in dynamic equilibrium when it adjusts to varying flow, sediment, and biological inputs without a trend toward a substantially different condition.
Ecological Zone:	A landscape unit that unites certain interrelated animal and plant communities
Eddy Current:	A vortex-type motion of a fluid flowing contrary to the main current, such as the circular water movement that occurs when the main flow becomes separated from the bank.
Effective Discharge:	The discharge that transports the largest fraction of the load of sediment of the bed material over a period of years.
Element:	The three- or more-sided polygon that is the computational unit in two- and three-dimensional hydraulic and sediment transport models.
Encroachment:	Human activity, occupation, or construction within the river or its floodplain including highway fill, new construction, substantial improvements, and other transportation development.
Endangered species:	The Endangered Species Act (ESA) defines an endangered species as "any species which is in danger of extinction throughout all or a significant portion of its range" with exceptions as noted in the ESA. [16 U.S.C. § 1532(6)].
Entrain, entrainment:	Incorporation of sediment from the bed and banks into the water flow.
Entrenched Stream:	Stream incised into bedrock or consolidated deposits.
Ephemeral Stream:	A stream or reach of stream that does not flow continuously throughout the year.
Equilibrium Slope:	Channel slope at which sediment supply and transport capacity are balanced or when alluvial particles on the channel bed cease motion when there is no sediment supply.
Erosion:	Displacement of sediment/soil particles due to water, ice, or wind action.
Estuary:	(1) The region near a river mouth where fresh river water mixes with saltwater and which receives both fluvial and littoral sediment influx. (2) The part of a river that is affected by tides.
Evolution (planform):	A gradual change in the planform of a river.
Fall Velocity:	Velocity at which a sediment particle falls through a column of still water.
Fill Slope:	Side or end slope of an earth-fill embankment. Where a fill-slope forms the streamward face of a spill-through abutment, it is regarded as part of the abutment.

Fine Sediment Load:	That part of total sediment load that is composed of particle sizes finer than those represented in the bed (wash load). Typically, fine-sediment load is finer than 0.062 mm for sand-bed channels. Silts, clays, and sand could be considered wash load in coarse gravel and cobble-bed channels.
Flashy Stream:	Stream characterized by rapidly rising and falling hydrograph stages. Typically associated with mountain streams or highly urbanized catchments.
Flocculation:	Aggregation and settling of very fine sediment as small clumps due to chemical and biological processes in estuaries.
Flood-Frequency Curve:	A graph indicating the probability of occurrence that the annual flood discharge equals or exceeds a given magnitude, or the recurrence interval corresponding to a given magnitude.
Floodplain:	Nearly flat, alluvial lowland bordering a stream that is subject to frequent inundation by floods.
Floodway:	See regulatory floodway.
Flow-Control Structure:	A structure located either within or outside a channel that acts as a countermeasure for controlling the direction, depth, or magnitude of flow.
Flow Duration Curve:	A plot showing the percentage of time that a certain flow in the river is equaled or exceeded.
Flow Habit:	The general characteristics of river flow: ephemeral, perennial, or flashy.
Flow Resistance:	The boundary impediment to flowing water depending on several factors, including boundary roughness, vegetation, irregularities, etc.
Flow Separation:	The detachment of a boundary layer from a surface into eddies or circulation. This occurs when a fluid passes a solid, such as on the downstream side of obstructions including bridge piers, vegetation, and large rocks.
Flow Slide:	Saturated soil materials that behave more like a liquid than a solid. A flow slide on a channel bank can result in a bank failure.
Fluvial Geomorphology:	The science dealing with the morphology (form) and dynamics of streams and rivers.
Fluvial Performance Standard:	State or local standards that reduce negative effects on the environment, minimize maintenance needs, and promote conditions for river functions to continue unimpeded within the channel-floodplain corridor around and through a river crossing.

Fluvial System:	The natural river system consisting of (1) the drainage basin, watershed, or sediment source area; (2) tributary and mainstem river channels or sediment transfer zone; and (3) alluvial fans, valley fills, and deltas, or the sediment deposition zone.
Freeboard:	The vertical clearance of the lowest structural member of the bridge superstructure above the water surface elevation of the overtopping flood. Also, the vertical distance above a design stage that is allowed for waves, surges, drift, and other factors.
Froude Number:	A dimensionless number that represents the ratio of inertial to gravitational forces in open channel flow.
Geomorphology:	That science that deals with the form of the Earth, the general configuration of its surface, and the changes that take place due to erosion and deposition.
Graded Stream:	A geomorphic term for streams that have apparently achieved a state of equilibrium between the rate of sediment transport and the rate of sediment supply throughout long reaches.
Gravel:	A rock fragment whose diameter ranges from 2 to 64 mm.
Gravelometer:	Metal plate with openings of sizes ranging from 2 mm to 180 mm used to measure the median grain size of cobbles and gravels.
Groundwater:	Water found below the ground surface in the void spaces in soils and geologic strata; water in an aquifer.
Habitat:	The natural environment of an animal, plant, or other organism.
Headcutting:	Channel degradation associated with abrupt changes in the bed elevation (headcut) that generally migrates in an upstream direction.
Headwater:	The source of a stream, generally at the upstream end of a catchment or watershed.
Helical Flow:	Three-dimensional movement of water particles along a spiral path in the general direction of flow. These secondary-type currents are of most significance as flow passes through a bend; their net effect is to remove soil particles from the cut bank and deposit this material on a point bar.
Hiding, Hiding Function:	Also, Einstein’s hiding factor. In a stream with a wide range of bed material sizes, smaller particles are “hidden” by larger ones, reducing their mobility, while larger sizes are more exposed, making them more easily moved in the presence of smaller particles.
Histogram:	Bar graph used to represent the distribution of data grouped into classes or intervals.
Hydraulics:	The applied science of the behavior and flow of liquids, especially in pipes, channels, structures, and the ground.

Hydraulic Geometry:	General term applied to alluvial channels to denote relationships between discharge and channel dimensions, hydraulics, and sediment load.
Hydraulic Model:	A small-scale physical or numerical representation of a flow situation.
Hydraulic Performance Standard:	Criteria used to determine bridge and culvert dimensions for design flows. These standards can include minimum freeboard and maximum backwater.
Hydraulic Radius:	The cross-sectional area of a stream divided by its wetted perimeter.
Hydraulic Structures:	The facilities used to impound, accommodate, convey, or control the flow of water, such as dams, weirs, intakes, culverts, channels, and bridges.
Hydro-regime:	Inundation length and timing.
Hydrograph:	The graph of stage or discharge over time.
Hydrology:	The science concerned with the occurrence, distribution, and circulation of water on the earth.
Hydrologic Floodplain:	Region of subsurface connectivity that allows water to freely move between flow in the channel and subsurface flow in the alluvial aquifer underlying the channel.
Hydromodification:	Human alteration of the natural flow of water through a landscape.
Hydrophytic:	A plant that grows either partly or totally submerged in water and can grow in waterlogged soil.
Hyperconcentrated Flow:	Water and sediment mixtures with high sediment concentrations where fluid densities and viscosities are affected by the sediment but where hydraulic models can generally produce acceptable results. Hyperconcentrated flow contains approximately 20 to 40 percent sediment by volume.
Hyporheic:	An area or ecosystem that is beneath or alongside the bed of a river or stream that is saturated with water.
Ice Breakup:	Spring conditions when river ice cover breaks up producing ice blocks and floes. See “thermal” and “dynamic” breakup.
Ice Floe:	A large flat free-moving ice mass.
Ice Jam:	Ice blocking or constricting flow in a river during spring ice cover breakup.
Ice Run:	Downstream drift of individual or jumbled pieces of ice.
Imbricated:	In reference to stream bed sediment particles, having an overlapping or shingled pattern.
Impervious:	Not allowing fluid to pass through, such as some pavements and concrete.

Incised Reach:	A stretch of stream with an incised channel that only rarely overflows its banks.
Incised Stream:	A stream which has deepened its channel through the bed of the valley floor, so that the floodplain is a terrace.
Ineffective Flow:	An area of flow where water is not being conveyed in a downstream direction (e.g., eddies and ponded areas above or below an embankment).
Infiltration:	The process of water on top of the ground entering the soil.
Interception:	The process of interrupting the movement of water in the hydrologic cycle; raindrops adhering to leaves and canopy.
Invasive Species:	Non-native species that cause damage to the natural environment or harm to human health or economy.
Invert:	The lowest point in the channel cross-section or at flow control devices such as weirs, culverts, or dams.
Island:	An area, emergent at normal stage, that divides the flow of a stream. Islands often originate by establishment of vegetation on a bar, by channel avulsion, or at the junction of a minor tributary with a larger stream.
Joint Probability:	The probability of occurrence of two events. The events may be independent or may be correlated.
Knickpoint:	Headcut in noncohesive alluvial material.
Landslide:	Mass wasting with sediment concentrations generally greater than 50 percent by volume.
Lateral Encroachment:	Encroachments into the channel from the sides such as a bridge embankment, often abrupt but does not persist in the downstream direction.
Lateral Erosion:	Erosion in which the removal of material is extended horizontally as contrasted with degradation and scour in a vertical direction.
Levee:	An embankment, generally landward of the bank, that confines flow during high-water periods, thus preventing overflow into lowlands. Levees can be constructed or natural. See natural levees.
Littoral:	Of or pertaining to a shore, especially of the sea.
Live-bed Scour:	Scour when the bed material in the channel upstream of the bridge is moving at the flow causing bridge scour.
Load (or sediment load):	Amount of sediment being moved by a stream.
Local Scour:	Removal of material from around piers, abutments, spurs, and embankments caused by an acceleration of flow and resulting vortices induced by obstructions to the flow.
Longitudinal Encroachment:	Channel and floodplain encroachments that persist in a long-stream manner, such as roadway embankments or levees.

Longitudinal Profile:	The profile of a stream or channel drawn along the length of its centerline. In drawing the profile, elevations of the water surface or the thalweg are plotted against distance as measured from the mouth or from an arbitrary initial point.
Mass Wasting:	Downhill movement of soil and rock due to gravity, such as a landslide.
Mathematical Model:	A numerical representation of a flow situation using mathematical equations (also computer model).
Meander or Full Meander:	A meander in a river consists of two consecutive loops, one flowing left, followed by one flowing right, or vice-versa.
Meander Amplitude:	The distance between points of maximum curvature of successive meanders of opposite phase in a direction normal to the general course of the meander belt, measured between center lines of channels.
Meander Belt:	The distance between lines drawn tangent to the extreme limits of successive fully developed meanders.
Meander Length:	The distance along a stream between corresponding points of successive meanders.
Meander Loop:	An individual loop of a meandering or sinuous stream lying between inflection points with adjoining loops.
Meander Ratio:	The ratio of meander width to meander length.
Meander Radius of Curvature:	The radius of a circle inscribed on the centerline of a meander loop.
Meander Scrolls:	Low, concentric ridges and swales on a floodplain, marking the successive positions of former meander loops.
Meander Width:	The amplitude of a fully developed meander measured from midstream to midstream.
Meandering Stream:	A stream having a sinuosity greater than some arbitrary value. The term also implies a moderate degree of pattern symmetry, imparted by regularity of size and repetition of meander loops. The channel generally exhibits a characteristic process of bank erosion and point bar deposition associated with systematically shifting meanders.
Median Diameter:	The particle diameter of the 50th percentile point on a size distribution curve such that half of the particles (by weight, number, or volume) are larger, and half are smaller (D_{50}).
Metamorphosis (planform):	An abrupt change in the channel planform characteristics.
Mid-channel Bar:	A bar lacking permanent vegetal cover that divides the flow in a channel at normal stage.
Migration:	Change in position of a channel by lateral erosion of one bank and simultaneous accretion of the opposite bank.
Mud:	A soft, saturated mixture mainly of silt and clay.

Mud Flow:	See hyperconcentrated flow.
Native Species:	Plants and other species that are historically indigenous to a region that have evolved with the climate and region.
Natural Levee:	A low ridge that slopes gently away from the main channel banks that is formed along streambanks during floods by deposition.
Nominal Diameter:	Equivalent diameter of a hypothetical sphere of the same volume as a given sediment particle.
Nonalluvial Channel:	A channel whose boundary is in bedrock or non-erodible material.
Normal Stage:	The water stage prevailing during the greater part of the year.
Open-bottom Culvert:	A culvert on spread or pile-supported footings with natural channel materials as the bottom.
Overbank Flow:	Water movement that overtops the bank either due to stream stage or overland surface water runoff.
Oxbow:	The abandoned former meander loop that remains after a stream cuts a new, shorter channel across the narrow neck of a meander. Often bow-shaped or horseshoe-shaped.
Pavement (Streambank):	Streambank surface covering, usually impermeable, designed to serve as protection against erosion. Common pavements used on streambanks are concrete, compacted asphalt, and soil-cement.
Paving:	Covering of stones on a channel bed or bank (used with reference to natural covering).
Pebble Count:	Method used to determine size distribution of coarse bed materials which are too large to be sieved.
Perennial Stream:	A stream or reach of a stream that flows continuously throughout the year under normal precipitation conditions.
Phreatic:	Of or relating to groundwater, underground water in the zone of saturation (beneath the water table).
Phreatic Line:	The upper boundary of the seepage water surface landward of a streambank.
Pile:	An elongated member, usually made of timber, concrete, or steel, that serves as a structural foundation component of a river-training structure or bridge.
Piping:	Removal of soil material through subsurface flow of seepage water that develops channels or “pipes” within the soil bank or embankment.
Planform:	River characteristics as viewed from above (e.g., on a map or vertical aerial photograph).

Point Bar:	An alluvial deposit of sand or gravel lacking permanent vegetal cover occurring in a channel at the inside of a meander loop, usually somewhat downstream from the apex of the loop.
Rapid Drawdown:	Lowering the water against a bank more quickly than the bank can drain.
Rapid Assessment Method:	Time-efficient approaches often developed by states for evaluating the ecological status of riverine, wetland, and riparian areas. Evaluations include landscape, biotic, and abiotic metrics. Also, in stream or river reconnaissance, time-efficient approaches to making qualitative and quantitative observations of forms, features, processes, and functions in the river environment, especially as they interact with, or pose a risk to highways and transportation infrastructure.
Reach:	For purposes of study, a segment of stream length that is arbitrarily bounded or characterized by a consistent attribute.
Recurrence Interval:	The reciprocal of the annual exceedance probability of a hydrologic event (also return period, exceedance interval).
Reference Reach:	A dynamically stable reach selected as the design template for a design reach.
Regime:	The stability condition of a stream or its channel. A stream is in regime if its channel has reached an equilibrium form consistent with its flow characteristics. Also, the general pattern of variation around a mean condition, as in flow regime, tidal regime, channel regime, sediment regime, etc. (used also to mean a set of physical characteristics of a river).
Regime Change:	A change in channel characteristics resulting from such things as changes in imposed flows, sediment loads, or slope.
Regime Channel:	Alluvial channel that has attained a state of dynamic equilibrium with respect to erosion and deposition.
Regime Formula:	A formula relating stable alluvial channel dimensions or slope to discharge and sediment characteristics.
Regulatory Floodway (Floodway):	23 CFR 650.105(m) defines this term as “the flood-plain area that is reserved in an open manner by Federal, State or local requirements, i.e., unconfined or unobstructed either horizontally or vertically, to provide for the discharge of the base flood so that the cumulative increase in water surface elevation is no more than a designated amount (not to exceed 1 foot as established by … FEMA … for administering the National Flood Insurance Program).”
Rehabilitation:	Making the land (or river) useful again after a disturbance.
Relief Bridge:	An opening in an embankment on a floodplain to permit passage of overbank flow.
Response Reach:	A reach with a net storage of sediment.

Restart File:	A computer file containing the hydraulic and sediment transport results from a previous simulation used as the starting condition for a new simulation.
Restoration:	The process of repairing damage to the diversity and dynamics of ecosystems.
Return Period:	The average length of time between occurrences in which the value of a random variable (e.g., flood magnitude) is equaled or exceeded. The return period is the inverse of the Annual Exceedance Probability.
Revetment:	Rigid or flexible armor placed to inhibit scour and lateral erosion. See bank revetment.
Riffle:	A natural, shallow flow area extending across a streambed in which the surface of flowing water is broken by waves or ripples. Typically, riffles alternate with pools along the length of a stream channel (e.g., in a gravel-bed channel).
Riparian:	Pertaining to anything connected with or adjacent to the banks of a stream (e.g., corridor, vegetation, zone).
Riprap:	Layer or facing of rock, meeting common specifications, placed to armor a structure or embankment from erosion. Riprap has also been applied as wire-enclosed riprap, matrix riprap, and vegetated riprap. Common usage of the term often applies to the rock suitable for such applications.
Risk:	The consequences associated with hazards considering the probabilities of those hazards. More specifically for this document, risks are the consequences associated with the probability of flooding including interactions with encroachments.
Rock:	Geomaterial (material of geologic origin) that is sufficiently large or hard that excavation involves relatively great effort (i.e., drilling, wedging, blasting, or other methods).
Roughness Coefficient:	Numerical measure of the frictional resistance to flow in a channel, as in the Manning or Chezy formulas.
Rubble:	Rough, irregular fragments of materials of random size used to retard erosion. The fragments may consist of broken concrete slabs, masonry, or other suitable refuse.
Runoff:	The portion of a rainfall event discharged from a watershed into the stream network during and immediately following the rainfall of either perennial or intermittent form.
Sack Revetment:	Sacks (e.g., burlap, paper, or nylon) filled with mortar, concrete, sand, stone, or other available material used as protection against erosion.
Saltation:	Sediment movement in turbulent flow where particles briefly lose contact with the bed.
Salinity:	Grams of salt per thousand grams of sea water.

Sand:	A rock fragment (particle) whose diameter is in the range of 0.062 to 2.0 mm.
Scour:	Erosion of streambed or bank material due to flowing water; often considered as being localized. See local scour, contraction scour, and total scour.
Sediment or Fluvial Sediment:	Fragmental material transported, suspended, or deposited by water.
Sediment Concentration:	Weight or volume of sediment relative to the quantity of transporting (or suspending) fluid.
Sediment Discharge:	The quantity of sediment that is carried past any cross-section of a stream in a unit of time. Discharge may be limited to certain sizes of sediment or to a specific part of the cross-section.
Sediment Load:	Amount of sediment being moved by a stream.
Sediment Regime:	The amount, spatial distribution and timing of sediment movement through a river, including the general pattern of variation around a mean condition. Factors controlling sediment regime are grain size, sediment supply, and prevailing flow conditions; it can react in response to any variations in these factors.
Sediment Transport Function:	Relationship, equation, or groups of equations used to estimate the quantity of sediment moved by flowing water.
Sediment Yield:	The total sediment outflow from a watershed or a drainage area at a point of reference and in a specified time. This outflow is equal to the sediment discharge from the drainage area.
Seepage:	The slow movement of water through small cracks and pores of bank material.
Shear Stress:	See unit shear force.
Shoal:	A relatively shallow submerged bank or bar in a body of water.
Significant Wave Height:	The primary measure of energy in a sea state that is calculated as the average height of the one-third highest waves or by energy density spectral analysis methods.
Sill:	(1) A structure built under water, across the deep pools of a stream, with the aim of changing the depth of the stream; (2) A low structure built across an effluent stream, diversion channel, or outlet to reduce or prevent flow until the main stream stage reaches the crest of the structure.
Silt:	A particle whose diameter is in the range of 0.004 to 0.062 mm.
Sink (sediment)	An area, land feature, or water body that accumulates sediment.

Sinuosity:	The ratio between the thalweg length and the valley length of a stream.
Slope (of channel or stream):	Fall per unit length along the channel centerline or thalweg.
Slope Protection:	Any measure such as riprap, paving, vegetation, revetment, brush, or other material intended to protect a slope from erosion, slipping, or caving, or to withstand external hydraulic pressure.
Sloughing:	Sliding or collapse of overlying material; same ultimate effect as caving, but usually occurs when a bank or an underlying stratum is saturated.
Slump:	A sudden slip or collapse of a bank, generally in the vertical direction and confined to a short distance, typically resulting from the substratum being washed out or having become unable to bear the weight above it.
Soil:	Any unconsolidated geomaterial composed of discrete particles with interstitial spaces in between.
Sorting:	Progressive reduction of size or weight of particles of the sediment load carried down a stream.
Source (sediment):	Area or landform that supplies sediment to a river or to a depositional area.
Species of Concern	Also Species of Special Concern. A species that might be considered for concentrated conservation actions by a state.
Specific Gravity:	The ratio of weight (or mass) of a solid particle to the weight (or mass) of the same volume of water at a specific temperature, typically 4 degrees C.
Stage:	Water-surface elevation of a stream with respect to a reference elevation.
Stream Simulation:	A design procedure intended to create conditions within a crossing like those conditions in the natural channel to provide for aquatic organism passage.
Step-pool Reach:	A stream reach with a channel slope in the range of 3-10 percent, typically considered a transport reach in the Montgomery-Buffington stream classification.
Stream:	A body of flowing water that may range in size from a small rill to a large river. The term is sometimes applied to a natural channel or drainage course formed by flowing water whether it is occupied by water or not.
Stream Evolution Model:	Conceptual model describing the sequence of channel changes that occurs when a stream lowers its bed elevation relative to its floodplain sufficiently to trigger bank instability, rapid widening, creation of an inset floodplain, and conversion of the former (higher) floodplain into a terrace.

Stream Power:	The product of discharge, energy slope, and unit-weight of water. Stream power is governed by the rate at which potential energy is supplied to the river as it flows downstream. Some of the stream power is dissipated in overcoming friction and drag at the bed and banks. The remainder is available to do work on the landscape by entraining and transporting sediments, wood, debris, etc.
Streambank Failure:	Collapse of a bank due to an unstable condition such as removal of material at the toe of the bank by scour. Streambank failures can occur as sloughing, slumping, caving, and mass failures.
Streambank Protection:	Any technique used to prevent erosion or failure of a streambank.
Streambed Mining:	Removal of alluvial streambed material (generally sand and gravel) by mechanical or hydraulic methods.
Substrate:	Material underlying that portion of the streambed which is subject to direct action of the flow.
Supply Reach:	Reach of river with a net erosion of sediment from the bed and banks, and overland erosion.
Surface Storage:	The collection of runoff held above ground, such as in ponds, retention swales, and wetlands.
Suspended Sediment Discharge:	The quantity of suspended sediment (that is sediment supported by turbulence in the flow) per unit time that passes through a stream cross-section.
Thalweg:	The line following the lowest elevation of the riverbed.
Thermal Breakup:	Spring breakup of cover ice that is produced during increasing discharge where ice has lost strength due to solar radiation and rising temperatures.
Threatened Species	The Endangered Species Act defines a threatened species as "any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range." [16 U.S.C. § 1532(20)].
Tidal Prism:	The volume of water that flows into an estuarine river during the flood tide. The same volume (plus the contribution from freshwater river flow) flows out during the ebb tide.
Toe of Bank:	That portion of a stream cross-section where the lower bank terminates and the channel bottom or the opposite lower bank begins.
Topography:	The arrangement of the natural and artificial physical features of an area.
Total Scour:	The sum of long-term degradation, contraction scour, and local scour.
Total Sediment Load:	The sum of suspended load and bed load or the sum of bed material load and wash load of a stream (total load).

Transfer Zone:	Reach with sediment inputs and outputs relatively balanced.
Transport Capacity:	The amount of sediment a reach can carry based on velocity, depth, and sediment size.
Transport Reach:	Reach that is carrying as much sediment out of the reach as it is carrying into the reach.
Turbulence:	Motion of fluids in which local velocities and pressures fluctuate irregularly in a random manner, as opposed to laminar flow where all particles of the fluid move in distinct and separate lines.
Unit Discharge:	Discharge per unit width (may be averaged over a cross-section or local at a point).
Unit Shear Force (shear stress):	The force or drag developed at the channel bed by flowing water. For uniform flow, this force is equal to a component of the gravity force acting in a direction parallel to the channel bed on a unit wetted area.
Unsteady Flow:	Flow of variable discharge and velocity through a cross-section with respect to time.
Velocity:	The speed of flow usually expressed as distance per unit time. The average flow velocity is the velocity at a given cross-section determined by dividing discharge by cross-sectional area.
Vertical Abutment:	An abutment, usually with wingwalls, that has no fill slope on its streamward side.
Vertical Contraction Scour:	Scour resulting from flow impinging on bridge superstructure elements (e.g., low chord).
Wash Load:	Suspended material of very small size (generally clays and silts) originating primarily from erosion on the land slopes of the drainage area and present to a negligible degree in the bed itself. Wash load includes larger materials supplied and transported by the channel but not found in appreciable quantities in the bed.
Watershed:	See drainage basin.
Wave period:	The time for two successive wave crests to pass a fixed point.
Winnowing:	The natural process where flowing water removes finer material from a coarser sediment.

Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AdH	Adaptive Hydraulics (modeling system, USACE)
AEP	Annual Exceedance Probability
AOP	Aquatic Organism Passage
BFE	Base Flood Elevation
BIRM	Bridge Inspector’s Reference Manual
BMP	Best Management Practice
CAD	Computer Aided Design
CAP	Community Assistance Program
CDOT	Colorado Department of Transportation
CEQ	Council on Environmental Quality
CFR	Code of Federal Regulations
CGS	California Geological Survey
CLOMR	Conditional Letter of Map Revision
CMZ	Channel Migration Zone
CPU	Central Processing Unit
CRAM	California Rapid Assessment Method
CSR	Capacity Supply Ratio
CVIBI	Colorado Vegetation Index of Biotic Integrity
CWA	Clean Water Act
CWCB	Colorado Water Conservation Board
DB	Design Build
DEM	Digital Elevation Model
DOT	Department of Transportation
ELJ	Engineered Logjam
EO	Executive Order
ERDC	Engineering Research and Development Center (USACE)
ESA	Endangered Species Act
EWN	Engineering with Nature
EWP	Colorado Emergency Watershed Protection Program
FAHP	Federal-Aid Highway Program
FDC	Flow Duration Curve

FEH	Fluvial Erosion Hazard
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FHZ	Fluvial Hazard Zone
FIRM	Flood Insurance Rate Map
FIS	Flood Insurance Study
FISRWG	Federal Interagency Stream Restoration Working Group
FSA	Farm Service Agency
FSSSWG	Forest Service Stream Simulation Working Group
GI	Green Infrastructure
GIS	Geographic Information System
GPS	Global Positioning System
GPU	Graphics Processing Unit
H&H	Hydrology and Hydraulics
HASP	Health and Safety Plan
HDG	Highway Drainage Guidelines
HDS	Hydraulic Design Series
HEC	Hydraulic Engineering Circular
HEC-RAS	Hydrologic Engineering Center - River Analysis System (USACE)
HGM	Hydrogeomorphic Assessment Method
HSPF	Hydrologic Simulation Program Fortran
HWM	High Water Mark
IUCN	International Union for Conservation of Nature
IVM	Integrated Vegetation Management
LCP	Life Cycle Planning
LiDAR	Light Detection and Ranging
MSA	Magnuson Stevens Act
NAIP	National Agricultural Imagery Program
NASEM	National Academies of Sciences, Engineering, and Medicine
NBS	Nature-Based Solutions
NCHRP	National Cooperative Highway Research Program
NED	National Elevation Database
NEH	National Engineering Handbook
NEPA	National Environmental Policy Act

NFIP	National Flood Insurance Program
NHI	National Highway Institute
NISC	National Invasive Species Council
NMFS	National Marine Fisheries Service
NMRAM	New Mexico Rapid Assessment Method
NNBF	Natural and Nature-Based Features
NOAA	National Oceanic and Atmospheric Administration
NOI	Notice of Intent
NPDES	National Pollutant Discharge Elimination System
NRC	National Research Council
NRCS	National Resources Conservation Service
O&M	Operation and Maintenance
ODFW	Oregon Department of Fish and Wildlife
ODOT	Oregon Department of Transportation
OHWM	Ordinary High Water Mark
ORAM	Ohio Rapid Assessment Method
RAM	Rapid Assessment Method
RD	Rural Development
ROW	Right of Way
SCS	Soil Conservation Service (now NRCS)
SEM	Stream Evolution Model
SET	Stream Evolution Triangle
SFHA	Special Flood Hazard Area
SIAM	Sediment Impact Analysis Method
SMA	Shoreline Management Act
SRH2D	Sediment and River Hydraulics – Two-Dimension (USBR)
SWPPP	Storm Water Pollution Prevention Plan
TAM	Transportation Asset Management
TMDL	Total Maximum Daily Load
TTI	Texas Transportation Institute
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USDA	United States Department of Agriculture
USDOT	United States Department of Transportation

USEPA	United States Environmental Protection Agency
USFS	United States Forest Service
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
USLE	Universal Soil Loss Equation
VIC	Variable Infiltration Capacity
WDFW	Washington Department of Fish and Wildlife
WRDA	Water Resources Development Act
WSDOT	Washington Department of Transportation

Chapter 1 - Introduction

1.1 Purpose and Scope

This manual provides technical information for understanding, assessing, and addressing interactions between river functions, processes, and transportation infrastructure. It complements other Federal Highway Administration (FHWA) manuals as a set of references that may inform planning, design, permitting, construction, operation, and maintenance of transportation infrastructure in river environments. This manual is for Federal, State, and local transportation professionals and their consultants.

This and complementary FHWA manuals discussed in this section support planning, implementation, and stewardship of sustainable, resilient, and reliable transportation networks. The FHWA describes sustainability as considering three primary values or principles: social, environmental, and economic (FHWA, 2022a). The goal of sustainability is the satisfaction of basic social and economic needs, both present and future, and the responsible use of natural resources, all while maintaining or improving the well-being of the environment on which life depends. Figure 1.1 illustrates these three values.

Commonly, society views sustainability through a lens of balancing the needs of the environment with the economic needs of roadway and bridge development. This balancing results in the identification of viability as shown in the figure, but this is only part of the picture. Balancing the environment with social values results in what is bearable, or acceptable, by both society and the environment, while balancing the social and economic results in what is equitable. Past Federal transportation investments have too often failed to consider transportation equity for all community members, including traditionally underserved and underrepresented populations (USDOT, 2022). “Underserved populations” include minority and low-income populations but may also include many other demographic categories that face challenges engaging with the transportation process and receiving equitable benefits (See FHWA, 2015c). The U.S. Department of Transportation (USDOT or Department) has committed to pursuing a comprehensive approach to advancing equity for all (USDOT, 2022; see also FHWA 2021; and Executive Order 13985, 86 FR 7009 (2021)). Equity in transportation seeks the consistent and systematic fair, just, and impartial treatment of all individuals, including individuals who belong to traditionally underserved communities or populations (USDOT, 2022).

Sustainability results when all three values (social, environmental, and economic) are in balance. Planners and analysts sometimes refer to these three dimensions – economic, environment, and social – as the “triple bottom line” of sustainability. A sustainable approach to highways means helping decision makers make balanced choices among economic, social, and environmental values that will benefit current and future road users. For FHWA, a sustainable highway project satisfies basic social and economic needs, makes responsible use of natural resources, and maintains or improves the well-being of the environment.

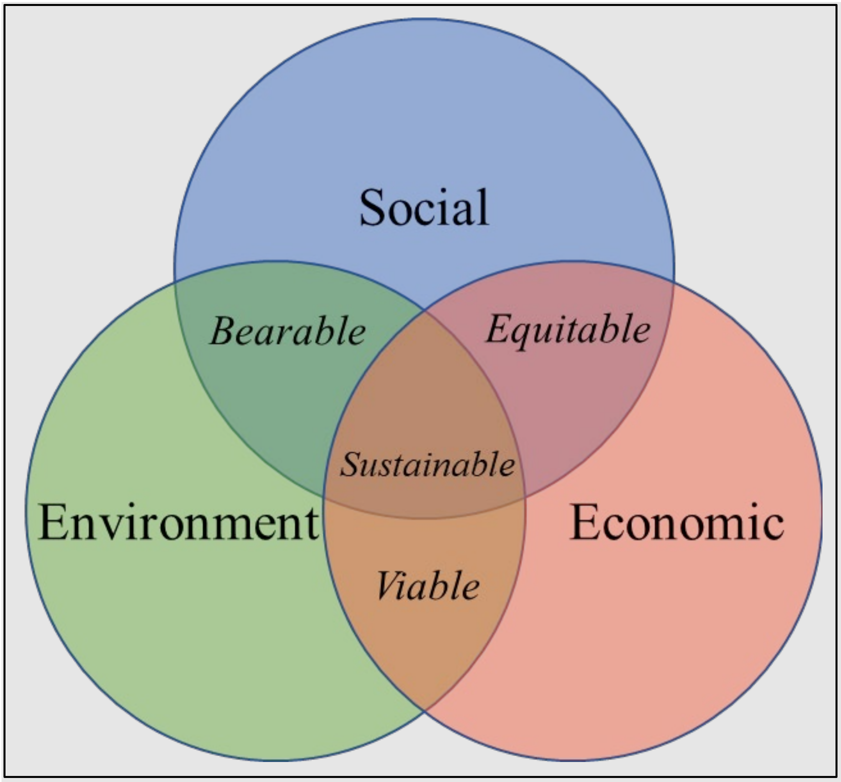

Figure 1.1. Balancing economic, social, and environment aspects for sustainability.

Resilience

With respect to a project, the FHWA defines "resilience" as a project with the ability to anticipate, prepare for, and or adapt to changing conditions and or withstand, respond to, and or recover rapidly from disruptions, including the ability: (A) to resist hazards or withstand impacts from weather events and natural disasters, or reduce the magnitude or duration of impacts of a disruptive weather event or natural disaster on a project; and (B) to have the absorptive capacity, adaptive capacity, and recoverability to decrease project vulnerability to weather events or other natural disasters. 23 U.S.C. § 101(a)(24) (added by Sec. 11103 of the Bipartisan Infrastructure Law (BIL), enacted as the Infrastructure Investment and Jobs Act, Pub. L. 117-58 (Nov. 15, 2021)). See also FHWA Order 5520 (FHWA 2014).

This manual also addresses issues related to hydraulic structures to facilitate more resilient and reliable designs within which potential future river conditions are identified and accommodated. Reliability is tied to resilience because a resilient transportation network is safer and less susceptible to delays and failures.

Resilient and reliable designs are essential to addressing the significant and growing risk presented by climate change. (USDOT, 2021). In the transportation context, this risk is many-faceted, including risks to the safety, effectiveness, equity, and sustainability of the Nation's transportation infrastructure and the communities it serves. The USDOT recognizes that the United States has a "once-in-a-generation" opportunity to address this risk, which is increasing over time (USDOT, 2021; see also Executive Order 14008 on Tackling the Climate Crisis at Home and Abroad, 86 FR 7619 (2021)). Addressing the risk of climate change is also closely interlinked with advancing transportation equity, as discussed above, because of the disproportionate impacts of climate change on vulnerable populations, including older adults, children, low-income communities, and communities of color. The USDOT intends to lead the way in addressing the climate crisis.

The FHWA also encourages the advancement of projects that address climate change and sustainability (FHWA, 2021). To enable this, FHWA encourages recipients to consider climate change and sustainability throughout the planning and project development process, including the extent to which Federal-aid projects align with the President's greenhouse gas reduction, climate resilience, and environmental justice commitments.

The FHWA believes that this manual will be useful for aligning and integrating these concepts and components of sustainability within the context of highways and the riverine environment. Such alignments will consist of both direct and indirect interstices and situations.

As that alignment also includes stream stability, this manual expands on several topics included in Hydrologic Engineering Circular Number 20 (HEC-20) *Stream Stability at Highway Structures* (FHWA 2012a) and provides information on additional topics. Where HEC-20 focuses on physical processes related to stream stability, this manual includes discussion of biological influences on rivers. This manual also includes information on the range of natural functions that rivers provide, including habitat and connectivity functions.

Sediment transport is an area where there has been continued advancements in theory and methods, especially in computer simulations. Transportation hydraulic engineers are increasingly using sediment transport modeling to better inform structure designs. Therefore, this manual includes information and methods for developing models well-suited for addressing transportation needs.

The FHWA supports State and local governments in the design, construction, and maintenance of the Nation's highway system. First published in 1975, the FHWA's *Highways in the River Environment – Hydraulic and Environment Design Considerations* was an early example of this support. HIRE, as it was known, was a foundational reference for roadway and hydraulic structure designs in river environments. In 1990, the FHWA issued an addendum to HIRE; Hydraulic Engineering Circular Number 16 (HEC-16) (FHWA, 1990). A 2001 revision was Hydraulic Design Series Number 6 (HDS 6) *River Engineering for Highway Encroachments – Highways in the River Environment* (FHWA 2001). Advancements in research and technology have rendered some of the content of HDS 6 obsolete. Additionally, as summarized in Table 1.1, the FHWA has more thoroughly presented many of the topics in HDS 6 in other manuals. Therefore, the FHWA has archived HDS 6 as a primary FHWA technical information manual, and this manual replaces much of its content.

Table 1.1. HDS 6 topics and their current FHWA primary resources.

HDS 6 Topic	Current FHWA Primary References
Open channel flow	HDS 7 (FHWA 2012c)
Alluvial channel flow	HEC-20 (FHWA 2012a) and this manual
Sediment transport	HEC-20 and this manual
River form and response	HEC-20 and this manual
River stabilization	HEC-23 (FHWA 2009)
Contraction scour (as a sediment transport process)	HEC-18 (FHWA 2012b)
Debris Control	HEC-9 (FHWA 2005)
Data needs and resources	HEC-20 and this manual

As Table 1.1 demonstrates, this manual shares considerable subject matter with HEC-20 *Stream Stability at Highway Structures* (FHWA 2012a). This HEC-16 manual assumes familiarity with HEC-20 terminology and concepts, though this manual includes some added explanation of terms and concepts for readability. This manual, along with HEC-20, HEC-18 *Evaluating Scour at Bridges* (FHWA 2012b), and HEC-23 *Bridge Scour and Stream Instability Countermeasures* (FHWA 2009a) collectively represent a comprehensive analysis procedure. This procedure guides practitioners in identifying stream stability issues (HEC-20 and this manual), informing hydraulic and scour analyses (HEC-18), and developing suitable scour and stream instability countermeasures when they are appropriate (HEC-23).

Bridges, culverts, and roadways can impact rivers, floodplains, and their habitats. At the same time, channel dynamics—including erosion, sediment deposition, and channel shift— often affect bridges, culverts, and roadways. Therefore, this manual addresses these interactions so that planners and engineers may create highway structures with the goals of providing cost-effective hydraulic performance, limiting environmental impacts, and accounting for potential channel change, where appropriate. Related FHWA manuals support these goals. HDS 7 *Hydraulic Design of Safe Bridges* (FHWA 2012c), HDS 5 *Hydraulic Design of Highway Culverts* (FHWA 2012d), and the *Two-Dimensional Hydraulic Modeling for Highways in the River Environment: Reference Document* (FHWA 2019a) address bridge and culvert hydraulics. These hydraulic analyses incorporate representative design flows, which are the topics of HDS 2 *Highway Hydrology* (FHWA 2002) and HEC-17 *Highways in the River Environment – Floodplains, Extreme Events, Risk, and Resilience* (FHWA 2016). This HEC-16 manual identifies representative hydrology and hydraulics as important factors for geomorphic and sediment transport analyses. This manual addresses impacts on habitats and river connectivity including barriers created by culverts, which is the focus of HEC-26 *Culvert Design for Aquatic Organism Passage* (FHWA 2010a). Transportation facilities in coastal waterways face similar processes and constraints as they do on rivers, but the hydrologic and hydraulic processes differ. HEC-25 *Highways in the Coastal Environment* (FHWA 2020) addresses these coastal topics.

1.2 Organization

This manual is organized into eight chapters and includes a glossary, list of acronyms, reference section, and an appendix. **Chapter 1**, this chapter, discusses the purpose, background, organization, target audience, and units.

Chapter 2 introduces the settings and context of the roads within the river environment in the U.S. transportation system. The system includes culverts and bridges crossing streams and rivers, and road embankments located within floodplains that often connect to culverts and bridges. This portion of the transportation network is in the river environment, which includes surface features (channels, riparian areas, floodplains, and wetlands) and the shallow alluvial aquifer below and connecting the surface features. Chapter 2 provides descriptions of the functions of the individual features and interactions between them. Chapter 2 groups natural river functions into four categories: 1) conveyance and storage, 2) river evolution, 3) habitats, and 4) connectivity. Human functions that frequently impact or alter these natural functions are discussed throughout the chapter. The natural system is the basis for these descriptions. Chapter 2 provides context for weighing a range of potential impacts of human actions and activities on rivers and floodplains, and to inform decisions where the transportation network interacts with the river environment.

Chapter 3 describes Federal policy for highways in the river environment involving two broad arenas: highway engineering and river management. The chapter provides some background on these policy arenas, some relevant FHWA specific statutes and regulations applicable to the river environment, and an overview of other Federal statutes and regulations that may affect highway projects in the river environment.

Chapter 4 describes how transportation planning, design, construction, and maintenance activities benefit from considering the range of river functions. This chapter explores opportunities to consider river form and function during construction and when performing maintenance, because decisions made at any of these stages influence the risks, resilience, and reliability of the infrastructure. Bridges and culverts affect in-channel flows and can substantially impede flood flows.

Transportation projects can impact the environment, so this chapter also discusses aspects of permitting, regulatory compliance, environmental impacts, environmental mitigation, and monitoring, as well as the use of ecologic principles and working with natural processes. In turn, rivers cause many problems for bridges, culverts, and roadways, including channel lowering or filling, and channel shifting. The other side of planning and design is avoiding these problems. Anticipating, accommodating, and avoiding these problems achieves a safer and more resilient transportation system, and lowers future costs for remedial designs, permitting, and maintenance.

Finally, Chapter 4 describes how more sustainable and resilient projects can be developed by considering the effects of climate change and basin modifications on the hydrology, sediment supply, channel evolution, and river ecology.

Chapter 5 provides information on hydrologic and hydraulic (H&H) analyses. Bridge and culvert hydraulic analyses focus on extreme events to design structures that have adequate capacity to pass design flows protective of the public health, safety, and welfare. H&H analyses are not, however, limited to extreme events. Channels and their associated habitats respond to a wide range of flows. This chapter provides information covering the entire range of flows and includes information on methods for evaluating channel-forming flows. This chapter also discusses H&H impacts of bridges and culverts, and hydraulic modeling approaches.

Chapter 6 provides information on identifying dominant processes acting on a channel, the types of data that are beneficial to obtain, and resources for filling data needs. Projected channel change is a major consideration during planning and design activities for transportation facilities in the river environment. Several approaches are discussed for identifying whether the channel is expected to change vertically or laterally over the design life of a structure.

Chapter 7 provides information on sediment transport and methods for simulating vertical and lateral channel changes. This chapter addresses sediment transport modeling insights that help guide planning and design decisions. Hydrologic and hydraulic analyses are nearly always performed, but there may be a need to investigate channel stability questions through more advanced methods. The chapter includes discussion of processes, data needs, and computer modeling alternatives, approaches, and practices.

Chapter 8 is a resource on topics that are more regional or specialized including:

- Coincident flows at confluences and how mainstem-tributary interactions can affect channel forms and processes.
- Ice floes and managing ice-related risks at crossings.
- Wood loading benefits and risks.
- Human-generated debris production, source control, management approaches, and potential benefits.
- Water quality.
- Invasive species impacts, avoiding introduction and spreading, and control.
- Beaver activity influences, impacts, and accommodation.
- Mud and debris flow risks at transportation facilities.
- Alluvial fan processes, analyses, and options for transportation design.
- Tidally influenced streams and fluvial, biological, and sediment transport conditions they present.
- Inspection and monitoring.

1.3 Target Audience

The target audience for this manual is civil engineers, hydraulic engineers, roadway designers, planners, environmental staff, field inspectors, construction supervisors, biologists, fluvial geomorphologists, biogeomorphologists, coastal engineers, and other personnel involved in the analysis, planning, design, and operation of highways in the river environment.

This manual will help those with varied experience in riverine hydrology, hydraulics, and sediment transport to understand and, as appropriate, to apply scientific methods, engineering approaches, and biogeomorphological principles to create resilient transportation infrastructure in the riverine and floodplain environment. For experienced engineers and biogeomorphologists, this manual serves as a reference document for specific highway-oriented assistance and consultation for projects.

Those with an interest in addressing the growing risk presented by climate change to transportation infrastructure may also find this manual helpful. It provides information they may find valuable as they explore ways to implement climate and resilience strategies and to safely reconnect communities by reducing or eliminating transportation barriers to mobility, access, and economic development.

This manual does not attempt to “simplify” complex practices into mechanistic, “one-size-fits-all” approaches. Rather it provides the transportation community with an overview and awareness of good practices. This awareness allows practitioners to seek appropriate technical documentation and expertise for specific projects. Other references, summary manuals, and original sources in these fields are cited for further details.

Within this framework, this manual does not have the force and effect of law and it is not meant to bind the public in any way. The FHWA intends any descriptions of processes and approaches to provide illustrative insights into the underlying scientific and engineering concepts and practices. However, these descriptions do not constitute a standard, specification, or policy.

1.4 Units in this Manual

This manual uses customary (English) units. However, in limited situations both customary units and SI (metric) units are used or only SI units are used because these are the predominant measure used nationwide and globally for such topics. In these situations, the manual provides the rationale for the use of units. Appendix A provides information on units and unit conversions.

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Chapter 2 - River and Floodplain Functions

This chapter expands on the discussion of river features and processes in HEC-20 (FHWA 2012a) to include the wide range of environmental and societal functions that rivers serve. This HEC-16 manual characterizes functions as either natural or a result of human needs and activities (anthropogenic). Human functions for a river may include water supply, waste disposal, transport, hydropower, and recreation, but people also benefit from habitat and other natural functions present in rivers. River corridors accommodate agriculture, development, borrow pits, diversions, levees, transportation infrastructure, and more; each affecting the natural functions. One goal of managing highways in the river environment is to strike a balance by avoiding, or at least substantially reducing, disruption to natural functions while providing for transportation functions.

A river is not just its channel or channels, but includes its riparian areas, wetlands, floodplains, the hyporheic zone, and the alluvial aquifer. Each of these river areas performs a variety of natural and human-centered functions. This chapter groups natural river functions into four categories: 1) conveyance and storage, 2) river evolution, 3) habitats, and 4) connectivity. The chapter contains discussions of human functions that frequently impact or alter these natural functions. Transportation corridors that cross or run along rivers and floodplains are one of many human functions affecting rivers. This chapter provides context for the rest of this document and supports collaboration during transportation project planning, delivery, and operation.

2.1 Conveyance and Storage

This section describes fundamental river functions of conveyance and storage of water, sediment, wood, and debris. Flowing water forms rivers and smaller watercourses conveying and storing water that is supplied by precipitation, but can also include water derived from melting glaciers, groundwater springs and artificial inter-basin diversions. Floodplains convey and temporarily store water during high flow events that exceed channel capacity. Water moving through the river system collects, transports, and deposits sediment, wood, and various types of debris. Although these functions are discussed individually, they continuously interact with each other and with the other categories of functions described throughout this chapter.

2.1.1 River Flow

Streams and rivers, including predominantly “dry” washes and other ephemeral channels, are the largest drainage features as they collect water from smaller surface drainage features and from groundwater in catchments and watersheds. Flow conveyance, the movement or transport of water, is the primary function of rivers. This chapter also discusses secondary functions resulting from flow conveyance. In perennial streams, water is found within the channels most of the time, ranging from low flows supplied entirely from groundwater sources up to bankfull flows. Flooding occurs when runoff from heavy or prolonged rainfall or snowmelt exceeds the channel’s conveyance capacity. Figure 2.1 shows a river at near-bankfull conditions, in this case from snowmelt. The figure also illustrates the channel boundary and a small portion of the floodplain. Water moves between the local alluvial aquifer, or shallow groundwater, and the channel, depending on the relative water surface levels.

The cutaway in Figure 2.2 depicts a river flowing through its floodplain. Floodplains form by long-term sediment accumulation that builds up layers of river sediments (alluvium). Above the surface, the river flows through a channel-wetland complex. Below ground, river water also flows downstream through the shallow “hyporheic alluvial aquifer.” The term aquifer, in this context, captures that river sediments (alluvium) can hold and transmit significant volumes of below-ground water. The hyporheic alluvial aquifer differs from a deep groundwater aquifer, or the aquifer fed mostly by precipitation across the wider watershed. “Hyporheic exchange” is the term that describes water movement between the surface and the hyporheic alluvial aquifer. At any moment and location along its course, flow of the river may be above or below the ground surface with continuous exchange between channels, wetlands, side channels, floodplains, and aquifers. Although exchange of flow between the river surface and groundwater features can be expected at most flows, at flood levels surface water spills out of the channel into the floodplains where it is stored and conveyed downstream. As discharges and water surface levels increase, more surface features are included in the surface water conveyance. Floods may be conveyed primarily in the channel or the main conveyance could be in the floodplains, depending on flood levels and the relative sizes of the channel and floodplain, longitudinal slopes, geometric variability, and flow resistance.

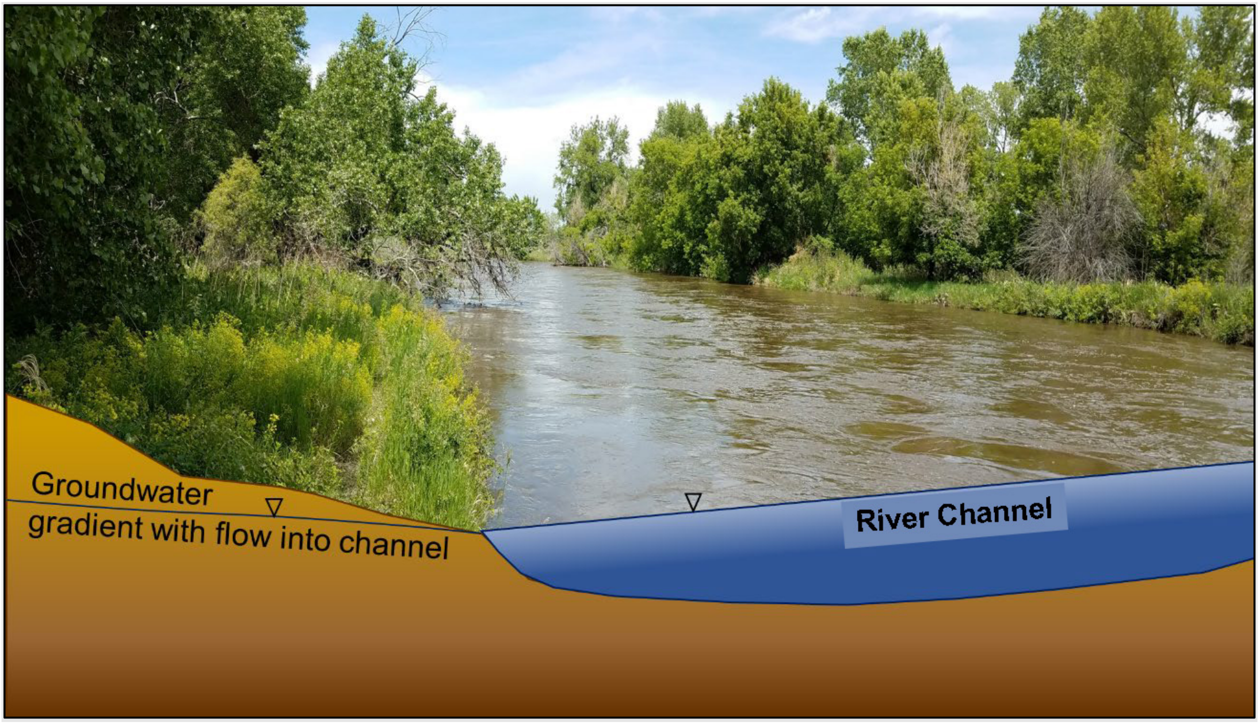


Figure 2.1. River channel and vegetated banks at near-bankfull flow. Image used by permission of Tetra Tech, Inc.

Water depths and velocities often vary across the channel. Within a cross-section, velocity tends to be higher in areas of deeper water, but this is not always the case. Flow separation (circulation and eddies) occurs downstream of obstructions, vegetation, and large wood, or due to abrupt changes in bank alignment. In these localized areas of flow separation, flow depths may be relatively high and velocities low. In meandering channels, the greatest depths occur along the outside bank lines of bends, but depending on discharge and location in the bend, high velocities may occur over the point bar at the inner bank. Therefore, the distribution of velocity within the channel can shift location as flows change.

Floodplains often have variable topography and vegetation. Figure 2.3 shows a floodplain that appears to have little variability in topography. Channel meanders are barely perceptible as the river may have been straightened, the forested area along the channel is irregular, and agricultural practices appear to have created a smooth floodplain making older channel features difficult to identify. Bank erosion changes the channel position laterally within the floodplain. As described in HEC-20 (FHWA 2012a), bank erosion can create a more sinuous, meandering channel path that produces lower channel slopes than the adjacent valley and floodplains. The straight channel shown in the figure likely has a longitudinal slope as high as the valley. As flood flows move down valley there is exchange of water and sediment between the channel and adjacent floodplains as indicated by the sand deposit in the floodplain at the bottom of the 2009 image. In meandering rivers, where the channel slope is lower than the valley slope, exchange of flow and sediment between the channel and floodplains is more vigorous than it would be for a straight channel.

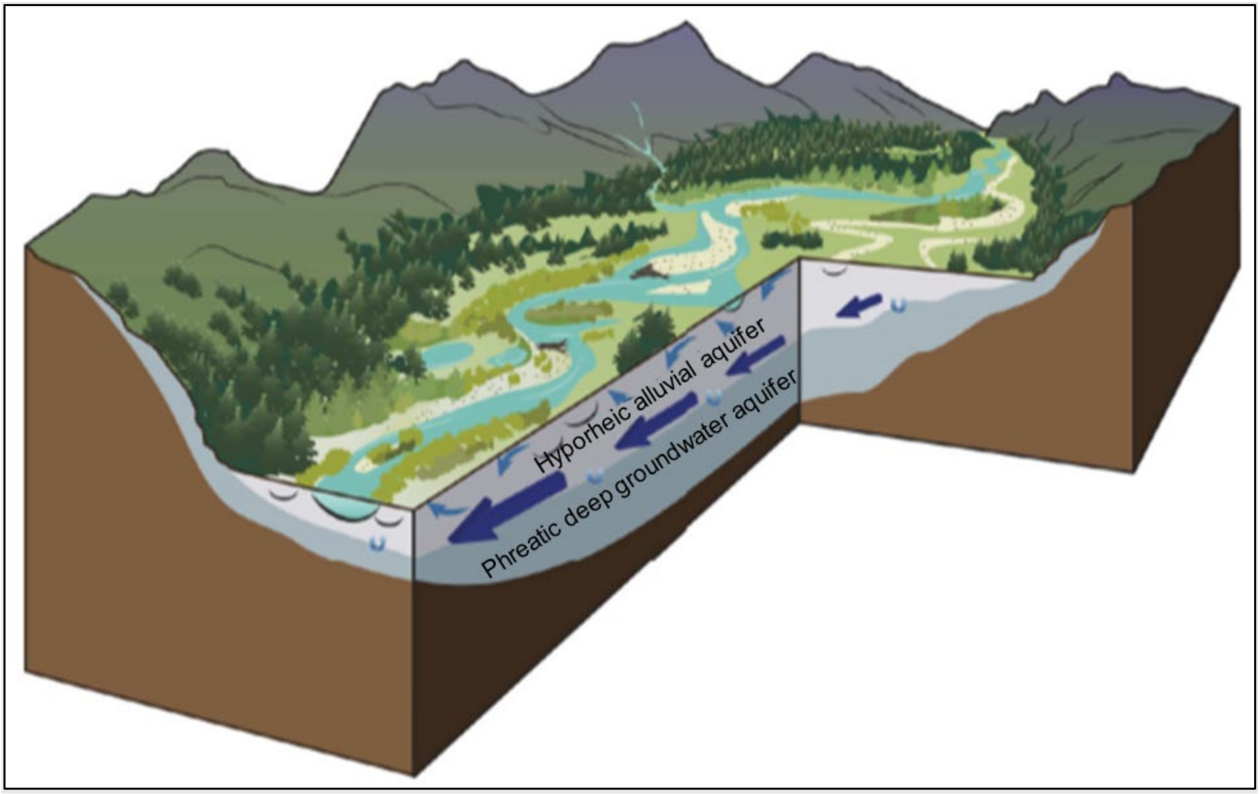


Figure 2.2. Surface and subsurface conveyance, storage, and exchange. Source: Hauer et al. 2016 and used by permission.

River channel widths and depths and floodplain widths generally increase as drainage areas and runoff volumes increase from the headwaters downstream through the basin. The channel width and depth at any location are dependent on the magnitudes and durations of flows, slope, vegetation, sediment supply, bed and bank materials, and geology. Human activities such as floodplain encroachments or changing land use can affect most of these factors. If there are changes to prevailing flow durations and magnitudes over time, channels may respond by widening, deepening, and changing their planform (their overall shape as viewed from above).

Flow resistance within the channel is often depth dependent, with less resistance occurring at higher flow depths. This may also be true for the floodplain, with high flow resistance when floodplain flow is shallow and decreasing flow resistance as the flow paths become more connected and vegetation becomes more submerged. However, flow resistance may increase with depth in wooded floodplains as flow encounters tree limbs and foliage.

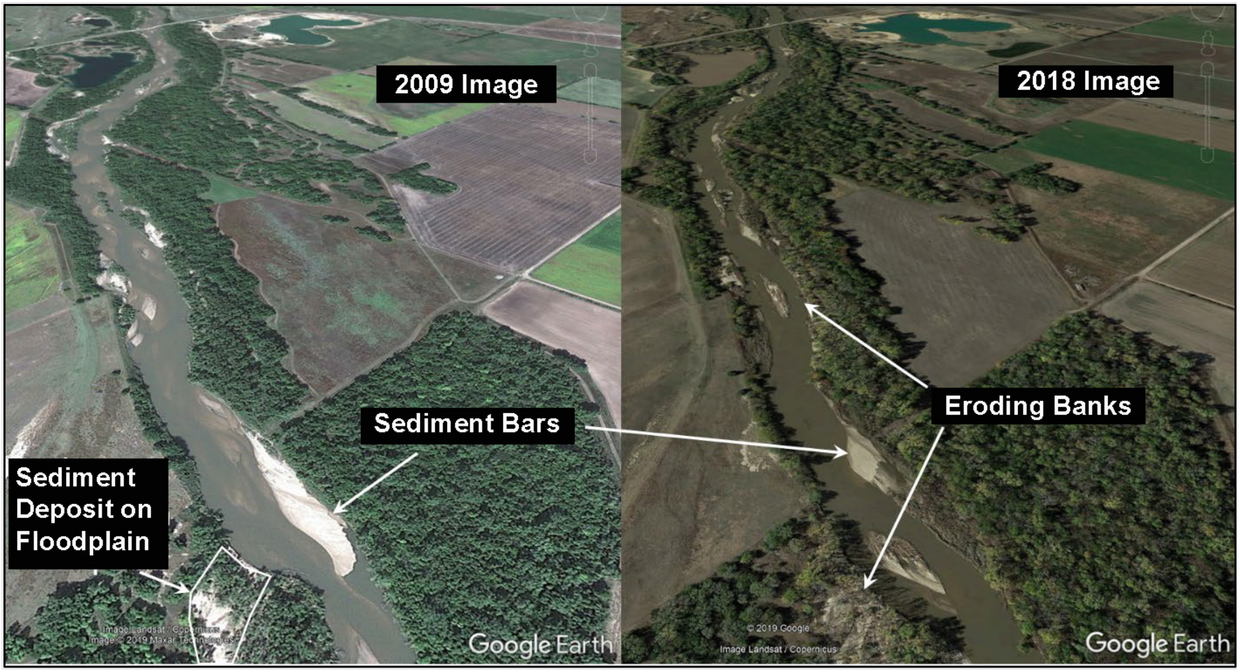


Figure 2.3. Comparison images from 2009 and 2018 of a highly impacted river and floodplain.

2.1.2 Sediment Transport and Storage

Rivers and floodplains also convey and store sediment at widely differing scales, from individual particles to river reaches and throughout entire watersheds. At the particle scale, an individual sediment grain may be at rest with water flowing above it, moving along the bed, or moving in the water column. Particles move between these states; they erode and become mobilized, then they are transported and redeposited. Erosion and deposition change of the geometry along river reaches. Within watersheds there are often areas that are primarily sediment supply zones (or sources), transfer zones, and depositional zones (Figure 2.4), although these processes can occur throughout the channel network and the zones are not always easily identified.

Rivers derive sediment from erosional sources in their headwaters and transport it downstream to depositional areas lower in the watershed, which may include alluvial fans, a larger river, a lake, the ocean, or a closed basin. The processes involved in sediment movement depend not only on hydraulic variables, fluid properties, and sediment particle characteristics, but also on biological factors including aquatic, riparian, and floodplain vegetation; aquatic organisms; and beavers. The movement of sediment through the channel network is not continuous. Sediment is transported and stored intermittently between events in alluvial features including bars, shoals (shallow submerged banks or bars), alluvial fans, deltas, and floodplains. Comparing the aerial photos in Figure 2.3 from 2009 and 2018, the size and location of the bars differ substantially, and the channel bank lines have shifted. It is likely that the volume of sediment within this reach has changed over this period even without a long-term trend of either erosion or sediment storage. The wooded area at the bottom of the 2009 image shows a floodplain sediment deposit from flow leaving the channel at this point.

Erosion of a channel bank may be balanced by deposition on the opposite point bar resulting in a channel that keeps essentially the same dimensions, while shifting to a different location through lateral migration across the floodplain. In this instance, there may be minimal change to channel hydraulic conditions or sediment transport capacity. A sediment imbalance that affects the channel slope or cross-section geometry locally changes channel velocities, depths, and the sediment transport capacity. Because sediment transport capacity is often very sensitive to velocity, relatively small local changes in velocity can quickly produce larger changes to sediment transport capacity causing the channel to accommodate the sediment imbalance.

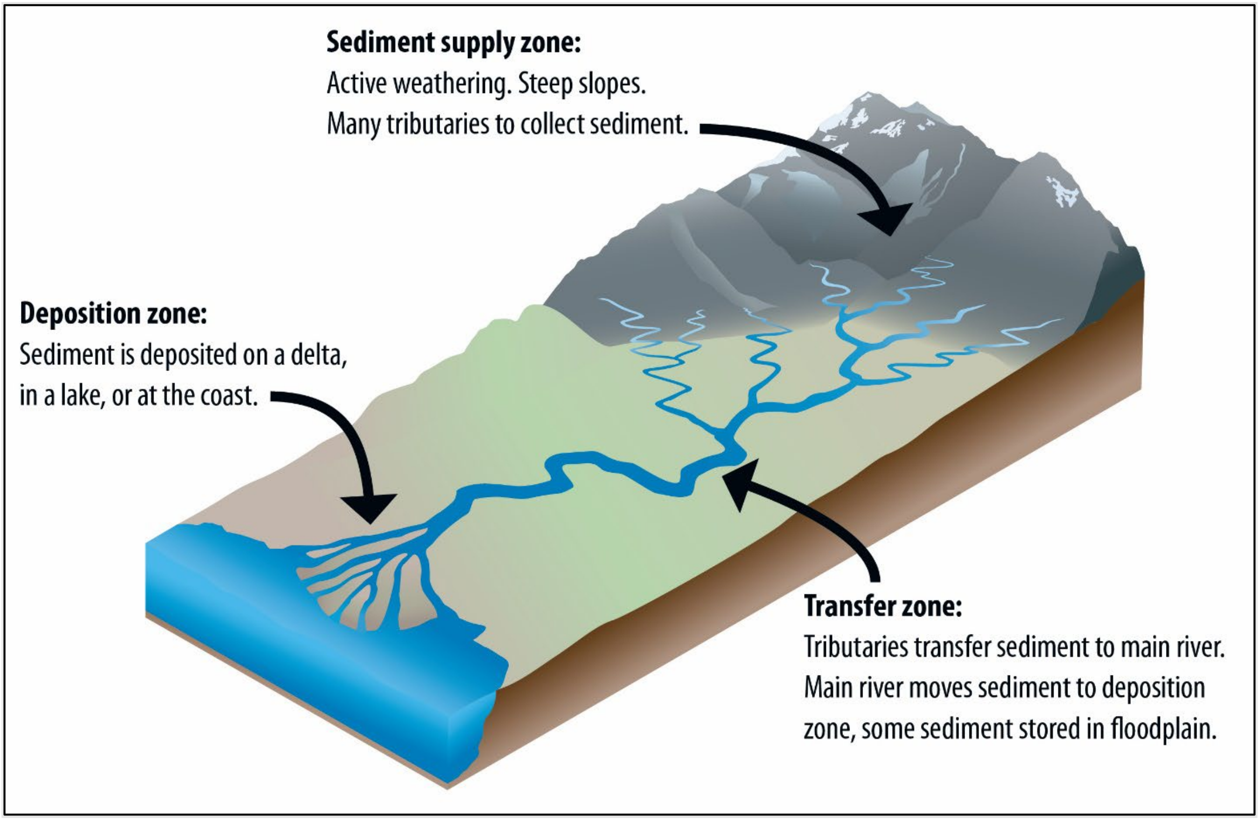


Figure 2.4. The river sediment transfer system. Adapted from Skidmore et al. (2011).

More widespread aggradation (channel bed raising from sediment deposition), degradation (channel bed lowering from erosion), and planform adjustments also change the sediment transport capacity of the reach (see HEC-20, Section 2.4). Aggradation and degradation can change velocity by changing channel gradient (slope), but relatively large amounts of sediment are generally needed to produce a significant channel gradient change. The degree of meandering, or sinuosity, also affects channel gradient by changing the length of the channel. The volume of sediment needed to change channel gradient by altering the sinuosity can be quite small when the channel erodes one bank and sediment accumulates on the opposite bank.

The processes of erosion, transport, and deposition are based on sediment size, density, cohesion, and presence of vegetation. Erosion of a channel bed occurs when the upstream supply of sediment is less than the capacity of the flow to transport sediment. Conversely, deposition occurs when the upstream sediment supply exceeds the transport capacity. This is the sediment continuity concept discussed in HEC-20 Section 2.4. Erosion of exposed land, and especially agricultural areas, produces fine sediments including clays, silts, and sands. Anywhere flow concentrates, there is the potential for erosion.

Bank erosion is also a common source of fine sediment. Figure 2.5 shows a channel bank where the bank toe is gravel and cobble, but the upper bank is predominantly sand and silt. As discussed in HEC-20, Section 2.3.9, bank retreat occurs from a variety of processes including:

- Erosion of the bank toe.
- Granular material cascading down the steepened bank face.
- Geotechnical failure of overly steep, high, or saturated banks, and subsequent entrainment of the failed materials (see sloughing, slumping, and caving in the glossary).

Once silts and clays are entrained into the flow, they are easily transported (wash load), and only deposit in low velocity environments or due to flocculation as fine particles combine to form larger particles. Wash load generally refers to very fine particles that are transported in the water column and are not found in appreciable amounts in the channel bed. For the channel bank in Figure 2.5, eroded silts and sands from the upper bank are easily transported. The silts are not found in the bed, which predominantly consists of sand. In general, silts and clays are more likely to deposit in floodplains, lakes, and estuaries rather than in channel beds.

Figure 2.5. Channel bank with gravel/cobble toe, sand/silt upper bank, and vegetated floodplain surface. Image used by permission of Tetra Tech, Inc.

Although complex physics governs these processes, it is important to recognize that human actions can produce imbalances in sediment transport that result in accelerated amounts of erosion and sediment deposition. These imbalances can be localized, such as that area just upstream or downstream of a culvert but may extend through a large portion of a river, such as downstream of a dam. Local and regional imbalances can easily become problems for many structures within their design lifetimes.

Particle sizes found in appreciable quantities in the channel bed (bed material) originate from the upstream channel network especially from channel beds, but also from bank erosion, hillslopes, and valley sides. Movement of the bed material occurs when hydraulic forces exceed the material resistance. As illustrated in Figure 2.6, an armor layer, composed of coarse particles on the bed overlaying finer particles, is stationary until the fluid lift and drag (hydraulic forces) acting on an individual particle overcome the submerged particle weight and bracing (material resistance forces) from the surrounding particles. Sand particles from upstream sources may be moving over the otherwise stationary coarse surface when the flow velocity is high enough to move the sand, but not high enough to move the coarse material. In this condition, the amount of sand transport is based on sand supply rather than the capacity of the flow to move sand. This is an example of supply-limited sediment transport. As discharge increases, individual coarse particles begin to move, and with enough flow the armor layer is disrupted, the bed is mobilized, and the bed material is transported at rates determined by the flow velocity, depth, shear stress, and turbulence.

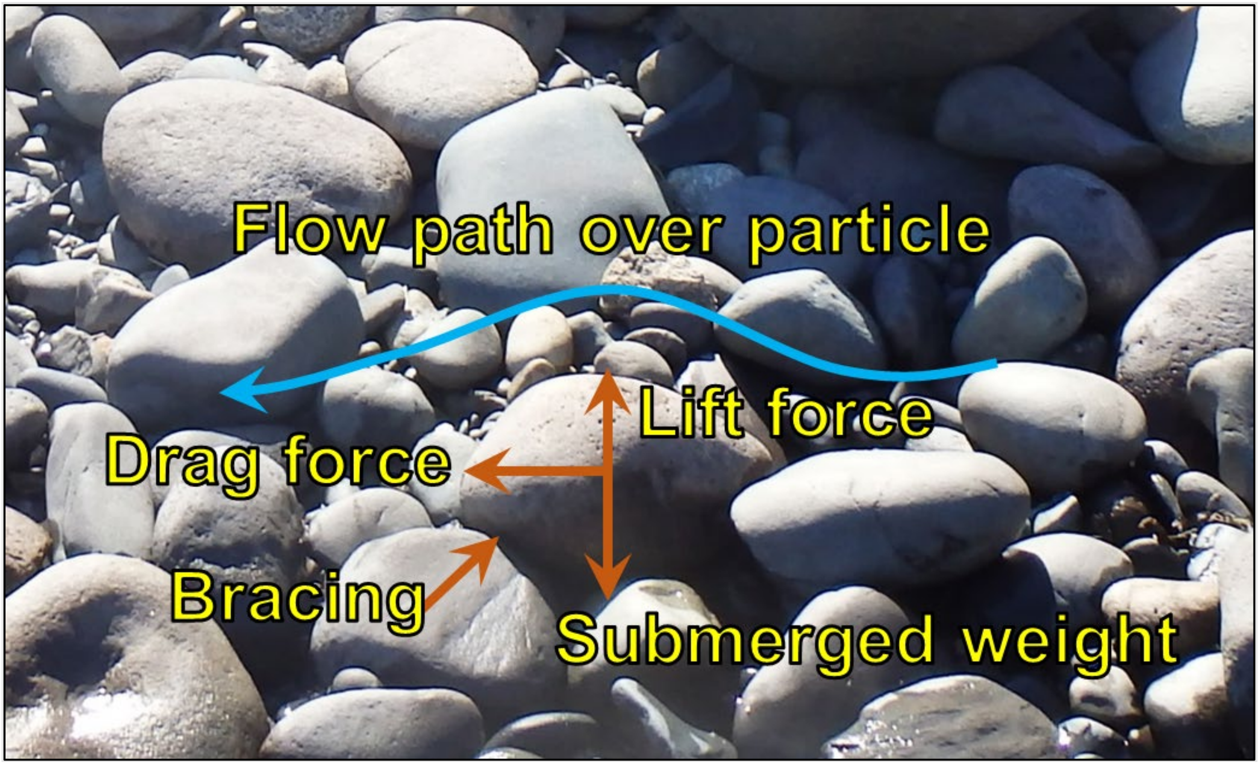


Figure 2.6. Lift and drag forces from flowing water act to move a particle. These forces are resisted by the particle submerged weight and bracing from other particles. Image used by permission of Tetra Tech, Inc.

As flow recedes, the armor layer reforms as coarse material ceases motion and finer material is transported downstream. Channels with predominantly sand beds are nearly always mobile except for very low velocity conditions. HEC-20, (Sections 6.4.2 and 8.2.2) discusses armoring processes. Figure 2.7 shows an undisturbed armor of gravel and cobble with virtually no sand present. At this same location, removing the armor exposes finer-grained (or maybe smaller) material, which contains the gravel and cobble, but also includes a substantial amount of sand.

When eroded, silts and clays are nearly always transported downstream since flow has a high capacity to move these particles. Conversely, sands and gravels are transported based on the hydraulic transport capacity, supply from upstream, and the availability in the bed mixture. Although there are many complexities involved in the processes governing sediment transport, river forms develop over time based on the factors described above. It is important to recognize that problems at transportation and other infrastructure can be prevented or reduced by avoiding large changes in flow and sediment conveyance.

Figure 2.7. Example of armor layer with minimal sand present and substantial sand exposed when the armor is removed. Image used by permission of Tetra Tech, Inc.

2.1.3 Wood Transport

Rivers provide an important function of transporting and distributing wood. The transport of wood along a river is a multi-step, dynamic process. It involves:

- Hydraulic conveyance.
- Random conglomeration and deposition at locations dictated by flow magnitude and duration.
- Temporary to permanent storage along the channel or in overbank areas.
- Ultimate burial or deterioration along the river or discharge to the coast.

In this manual, wood refers to leaves, twigs, branches, trunks, and root masses from trees, shrubs, and other riparian vegetation. It does not refer to wood that has been processed into lumber, which, as a type of debris, is addressed in Section 2.1.4. Nearly all rivers located in wooded riparian areas contain wood and it plays important physical, ecological, and biological functions (USBR and ERDC 2016). Wood transport in rivers plays a critical function in global carbon cycle regulation. In particular, floodplain sediment and coarse wood in rivers provide both carbon storage and substantial carbon export to oceans (Wohl et al. 2012, Rathburn et al. 2017). "Large wood" (tree trunks and root masses) plays a significant role in channel morphology. "Small wood" (leaves, twigs, and branches) from native species provides important smaller-scale habitat structures and nutrients to the river system. Accordingly, fish and other aquatic species are intrinsically adapted to the natural occurrence and distribution of wood from native species.

Wood and associated organic materials enter rivers through multiple processes, including landslides, natural succession, wind-fall, beaver and other animal activity, bank erosion, and channel migration (see Figure 2.8). Wood supplies to rivers can vary from individual trees or parts of trees falling into the river through everyday processes to massive inputs associated with episodic events. Many factors affect the presence, abundance, and characteristics of wood in a river. These influencing factors include: the conditions of associated riparian forests; regional topographic, geologic, and climatic influences; involved tree and other plant species; and both historic and current human activities, such as permitting and construction access and methods.

Figure 2.8. Large wood recruited by trees falling into the East Fork Lewis River, WA. Image used by permission of WEST Consultants, Inc.

Large wood can form flow obstructions when it becomes embedded in the channel. Smaller wood pieces often accumulate on obstructions formed by larger pieces. This can then create logjams capable of redirecting the path of the river or causing the river to divide around them. Small wood pieces also commonly deposit in overbank locations during high flow events.

Available records indicate that, prior to clearing by settlers, instream wood loads were abundant in many regions of North America (Sedell and Luchessa 1981, Whitney 1996, USBR and ERDC 2016). Across most of the continent during this period, the endemic population of North American beavers impacted flows and morphologies of these wood-laden rivers, resulting in rivers capable of supporting habitats and ecosystems far richer and more diverse than those today (Naiman et al. 1988, Goldfarb 2018).

More than a century of human development activities has greatly reduced the abundance of instream wood, not just in North America but globally (Gregory et al. 2003). Among these causes are forestry activities; widespread catchment and floodplain development coupled with destruction of riparian corridors; river channel management actions for purposes of navigation, flood control, and water supply; and active removal of logjams and beaver dams which, in the past, was thought to improve fish passage. Construction of hydraulic structures such as dams, levees, bridges and culverts, and revetments modify the hydrologic and hydraulic characteristics of a river and often create physical barriers that can limit or completely block the transport of wood along a river. The potential impact on wood transport is therefore a key consideration for the planning, design, operation, and maintenance of transportation infrastructure in the river environment.

A variety of research has demonstrated that wood is a fundamental component of healthy river ecology supporting critically interwoven physical, biological, and bio-geochemical functions (Maser and Sedell 1994, Nagayama and Nakamura 2010, Roni et al. 2014, Whiteway et al. 2010, USBR and ERDC 2016). Regional and reach-dependent differences in climate, topography, geology, and type of trees present affect the physical and biological influences of wood for specific ecological functions of a river system. Identification of these factors relies on evaluation of geology, vegetation quality and coverage, climate, hydrology, hydraulics, and transport of sediment and wood through the river system. The presence and distribution of wood along a river also changes over time according to the supply of wood, hydrologic variability, transport through the river system, and decomposition.

Ecological functions of wood in the river environment include:

Providing shade to regulate water temperatures.

Creating hydraulic influence that increases local water elevations, develops pools, and create low velocity habitat.

Providing channel grade control.

Reducing flow velocity and corresponding increase in residence time.

Retaining and storing sediment and flotsam (small wood and organic material).

Retaining nutrients.

Forming side channels.

Increasing floodplain connectivity.

Maintaining biological structure and ecosystem productivity.

Maintaining channel and floodplain physical complexity.

Providing complex cover for aquatic organisms.

Increasing surface water and groundwater exchange.

Improving water quality.

Increasing recharge and aquifer storage.

Creating habitats for fish and macroinvertebrates.

Large wood and other vegetation in and around a channel can influence the hydrology and hydraulics of a river to varying degrees, depending on the number and size of channels as well as flow magnitude. Large wood and herbaceous vegetation present obstructions creating hydraulic resistance to flow, thereby causing energy losses that slow flow velocities, increase flow depths, and generally retard and reduce flood peaks. Reduced energy and flow velocities in turn limit the ability of the river to erode the channel boundary or transport sediment. Given the relative difference in total channel obstructed flow area, large flood events are relatively less affected than more frequently occurring lower flows. It follows that large wood has the greatest influence on smaller watercourses, as in river headwater areas, where the proportional influence of large wood would be the greatest over the largest range of flows. However, in streams with multiple channels and wooded islands/floodplains, the influence of wood in “slowing the flow” can increase with stage (water level) and discharge.

Wood affects channel morphology in a variety of ways. It can alter channel geometry, grade, and complexity by:

- Slowing, accelerating, or redirecting flow.
- Defining channel profile elevations by acting as a local grade control.
- Inducing scour or deposition at the channel bed and banks.
- Reducing in-channel flow capacity.
- Reducing flow velocities on floodplains.
- Increasing flow depth.
- Dictating whether the river has a single-thread or multiple channels.
- Increasing connectivity between the channel and floodplain.

Similarly, obstructions and flatter stream profiles created by wood along the bed of a channel can increase storage of sediment and nutrients and reduce the median grain size of the channel substrate. These effects generally contribute a greater variability of velocities and depths along a channel, the downstream slowing and reduction of flood peaks, and a greater diversity of habitats.

Wood also can pose a variety of risks to transportation infrastructure, especially if that infrastructure was designed with no provision for wood loadings and passage. Potential risks are associated with obstruction and loss of hydraulic conveyance at under-sized hydraulic structures vulnerable to blockage, structure and roadway overtopping and inundation, structural damage or failure from wood impacts, unintentional flow diversions and flooding, and increased constriction/local scour of the channel bed and banks around partially blocked structures. Figure 2.9 illustrates the effect of wood accumulation on bridge stability. Appropriate consideration of wood dynamics in the design and sizing of bridges can be critical for sustainable and resilient infrastructure. According to Cook (2014), floating organic matter (including both anthropogenic debris and naturally generated wood and ice) had contributed to more than five percent of bridge failures in the United States recorded at that time.

Risks related to scour and hydraulic obstructions associated with wood transport are pertinent concerns for the performance of any transportation infrastructure in the river environment. Extensive accumulations of wood at a structure may present tremendously difficult, reoccurring, and expensive removal and disposal costs that are burdensome for operations and maintenance personnel.

Figure 2.9. Effect of wood accumulation against the closely spaced, in-channel piers of a bridge in New York. Source: FHWA.

The obstruction of wood transport by transportation infrastructure creates potentially serious environmental risks including limiting wood supplies to downstream reaches and restricting essential ecological functions associated with wood discussed previously. Recognizing, understanding, and managing wood-related risks is important at all phases of transportation infrastructure project delivery and potentially generates significant savings in infrastructure operating expenses.

Planners and designers can enhance project sustainability when they consider the risk of wood transport relative to the project location early in the project development process. Their activities may include site visits to observe existing conditions, review of maintenance records for similar transportation facilities nearby, and evaluation of potential wood recruitment. Based on these assessments, alternative facility configurations and sizes may be evaluated along with potential environmental impacts and mitigation measures.

During the design phase, practice often determines project specific features and details to accommodate recognized risks of interactions with wood transport. During other phases of highway project delivery, transportation professionals may also promote long-term project function and provide public safety while meeting goals for habitat conservation. For example, establishing, following, monitoring, and adjusting operations and maintenance procedures can help achieve such functions and goals. The FHWA has developed a variety of tools for managing the risks of wood to transportation infrastructure including: 1) methods for assessing drift (large wood and floating debris) accumulation potential (FHWA 2012a), 2) procedures for assessing scour at bridges, including the effects of debris (FHWA 2012b), and 3) design of debris control structures as countermeasures to debris accumulation (FHWA 2005).

2.1.4 Debris Transport

While not always intentional, rivers function as a kind of disposal system for human-derived debris. River flows transport the debris that is moveable downstream, sediments carried by the water abrade the debris, and waters tend to oxidize chemically-susceptible debris. Finally, river flows hide debris that remain through submergence.

Research on the large accumulations of trash in both the Pacific and Atlantic Oceans indicates that river systems are the primary source of marine debris (Hoellein et al. 2014, Law et al. 2010, Moore 2008, Ryan et al. 2009). At the same time, the public has long been concerned about the appearance and public health implications of trash on beaches and impacts on animals ingesting such debris (Thompson et al., 2009) as well as about the impact of litter, particularly plastic deteriorating into microplastics, on water quality and habitat (Schuyler et al. 2014, Choy and Drazen 2013, Phillips et al. 2010, Cole et al. 2011, van Sebile et al. 2012). Accordingly, consideration of the role of transportation infrastructure on the supply of trash to the river environment is a step toward avoiding or mitigating environmental impacts associated with anthropogenic debris similar to that shown in Figure 2.10. This can include trash collection at rest areas, collection of roadside trash, public education on trash impacts on streams, and signage to deter illegal dumping at bridges.

Figure 2.10. Stream-transported trash and debris, consisting of human-generated litter and naturally occurring items, accumulates along riverbanks and at stream crossings. Source: USEPA.

Problems and risks posed by human-derived debris in rivers associated with transportation infrastructure vary from the macro to the micro. At the macro scale, debris can accumulate on transportation infrastructure such as bridges and culverts, obstructing their hydraulic conveyance, potentially causing loss of hydraulic function. Obstructions and loss of hydraulic conveyance can result in structure overtopping, flow diversions, excess hydraulic stresses, exacerbated scour conditions, and overall hydraulic structure failure.

Environmental risks of trash in rivers include despoiled aesthetics of the natural environment; alteration of the natural channel substrate characteristics; and potential resistance to natural channel processes of sediment transport, erosion, and deposition. The extent to which such debris fulfills habitat needs for benthic and aquatic organisms in urban streams lacking natural complexity due to the removal of large wood is a subject of ongoing research. However, trash as habitat is less desirable than naturally developed habitat due to differences in its aesthetics, structure, and nutrient values (Wilson et al. 2020). Therefore, where human-derived debris dominates the available habitat, restoration of natural habitat conditions would be most effective at reestablishing riverine functions. In such environments, control of debris, such as contributions of litter and trash from sources such as highway rest areas, and restoration of diverse and complex habitat by the addition of wood and wood transport would be appropriate. Developing well-vegetated riparian areas helps to buffer rivers from trash, debris, and other pollutants. It may also act to discourage dumping of trash close to the water’s edge.

When planning for or designing modifications to existing or construction of new transportation infrastructure, use of appropriate techniques for the avoidance, control, or mitigation of the addition of anthropogenic debris to the river environment may enhance both the river and roadway environments. General techniques include planning alignments for transportation infrastructure that maximize separation from rivers, designing physical barriers to anthropogenic litter (AL) such as fences or trash racks along routes to the river, maintenance and operations procedures for transportation infrastructure that emphasize good practices to reduce AL, providing opportunities for appropriate waste disposal, installing and maintaining appropriate signage, and enforcing litter prevention and waste disposal laws.

2.2 River Evolution

“*Nobody ever steps in the same river twice….*” **Heraclitus**

This well-known quotation is 100 percent accurate: rivers change constantly, through both time and space as shown in Figure 2.11. The satellite image of the Dnieper River (Ukraine) illustrates that, through history, the course of the river has never been the same twice. Meander bends grow, change shape, and shift. Periodically, bends become so tortuous that they are cut off to create abandoned channels and ox-bow lakes in the floodplain that may persist for centuries. The river evolves continuously through time and space, driven by variations in the flows of water, sediment, and wood from upstream and how these drivers of change interact with the sediments, vegetation, and artificial structures that bound the channel. Such changes are often gradual, and over short distances and time spans, they may be imperceptible. In streams where change is very slow and gradual, it is possible to approximate its form as being “stable” (i.e., steady in time, uniform in space). The approximation of stability is attractive because it greatly simplifies the science needed to support river engineering and management.

Even in streams that appear stable, changes still occur. Such changes are undeniable, and sometimes intolerable if they become drastic and abrupt. For example, people who visit a stream repeatedly over a long period might be surprised to discover one morning that the bend in the river that had been migrating slowly for years has suddenly been abandoned by the flow, which now takes a short-cut through the lower ground at the inner bank (a meander cutoff). Or they might discover one morning that the footpath they have used for years is gone, blanketed by an extensive layer of fresh gravel deposited on the floodplain during a large, over-night flood (overbank deposition).

Figure 2.11. Rivers: always changing (Dnieper River, Ukraine).

Historically, society has expended significant resources attempting to stabilize rivers that change by nature. Not only do these attempts sometimes end in failure, but they also can negatively affect key river functions. This is true whether rates of change are slow and sufficiently incremental to be imperceptible over human timescales, or rapid and large enough to pose significant risks to life and property.

Perceptions of Channel Stability

A person walking a dog along a relatively short reach of stream every morning does not detect any downstream trend in the width of the channel. Yet, in most rivers, if that walk was extended to cover a longer reach, it would become obvious that the channel widens with distance downstream as the drainage area increases. Also, the dog walker fully expects the channel to be in the same place today as it was yesterday, and so it appears until one day it is noticed that the drop-off on the outside of a tight bend in the stream has moved a little closer to the footpath, even though the channel looks the same.

Transportation professionals create more sustainable and resilient highway infrastructure when they recognize river evolution and allow rivers to change gradually through space and time. This is especially relevant today as the FHWA and others seek to ensure the transportation network is resilient and reliable for all users despite the risk associated with a changing climate. (USDOT 2021; FHWA 2021). In addition, this approach not only benefits the transportation infrastructure, but it also can reduce or in some cases reverse the negative impacts to ecological, habitat, and socio-economic functions of the river. Recognizing these other functions offers the opportunity for transportation professionals to collaborate with other stakeholders invested in the river.

The following sections provide a foundation for a collaborative approach for transportation development in the riverine environment with descriptions of tools and concepts related to biogeomorphology, river and floodplain stability, the stream evolution model, and river restoration.

2.2.1 Biogeomorphology

Flowing water, along with glaciers, winds, waves, and landslides, drive land-forming (morphic) processes on earth (geo). Biological (bio) processes affecting the landscape are driven by organisms ranging from the microscopic scale (algae and bacteria), through invertebrates, insects, fish, amphibians, birds, reptiles, rodents, and mammals, to the largest mega-fauna including trees. Biogeomorphology is the study of how biological processes interact with geomorphic processes to create, modify, destroy, and recycle landforms and entire landscapes.

Patagonia Beaver Introduction

In 1946, 20 North American beavers were deliberately introduced into Patagonia. Because of a lack of predation, by 2015 their population had grown to between 98,000 and 165,000. They colonized nearly all freshwater, aquatic, and wetland environments, and their activities have damaged many ecosystems, perhaps irreversibly (Westbrook et al. 2017).

Biogeomorphology is a long-established science. For example, Darwin (1881) recognized that earthworms help turn weathered rock into soil. Lobeck (1939) similarly identified a variety of animals and plants as effective geomorphic agents, including ants, beavers, and trees (both standing and as wood-jams). The field of biogeomorphology has grown significantly in the last two decades, particularly with respect to river forms and processes. Some of the new research confirms the roles of trees and beavers in creating and adaptively maintaining complex river forms and processes over timescales ranging from modern (Pollock et al. 2018), to historic (Polvi and Wohl 2012), and even geologic (Davies and Gibling 2010). The research also reveals a long list of organisms that affect river forms and processes. For example, caddisfly larvae living in the riverbed spin silk nets that bind together gravel particles. In doing so, they can double the stability of the riverbed (Johnson et al. 2009). Cyprinid fish and lamprey have been shown to alter the texture and mobility of fine-grained river sediments (Boeker and Geist 2016; Pledger et al. 2017). In the large Fraser River, salmon have been shown to reshape the bed by creating bedforms called salmon dunes (Hassan et al. 2008). In smaller, mountain streams in British Columbia, Hassan et al. (2008) assess salmon as being responsible for approximately half of the annual bed load yield. (Bed load is sediment that is transported in a stream by rolling, sliding, or skipping along the bed or close to it.) Johnson et al. (2019) conclude that most organisms that live in or near rivers can function as biomorphic agents.

The geomorphic impacts of native organisms on their environments tend to be beneficial to the individuals, their species, and the wider ecology, including processes surrounding plant succession and facilitation (Corenblit et al. 2007). These biologic effects on geomorphology also occur when a non-native organism invades a river *outside* its native range, and the impacts can be devastating. With the broader perspective of biogeomorphology, planners and designers have a tool to develop and maintain transportation infrastructure in a cost-effective and sustainable manner while collaborating with other river stakeholders.

2.2.2 Dynamic Stability

Sediment movement within and through a river segment contributes to river evolution. Rivers acquire sediment in the headwater supply zone, transport it through the transfer zone, and deposit it further downstream, in the depositional zone. While these zones are easy to characterize in theory (see Figure 2.4), they are not always easy to delineate within a particular watershed. Multiple sequences of supply, transfer, and deposition zones exist in most rivers, which complicates clear classification.

Over long periods, the river degrades in the supply zone and aggrades in the depositional zone, with sediment inputs and outputs in the transfer zone being, on average, balanced. Consequently, the river reach linking the supply and deposition zones may not change much, even over relatively long periods. Under this condition of “dynamic equilibrium” the channel in the transfer reach may be classified as being dynamically stable. In 1955, E.W. Lane pictured the relation between water and sediment flows as a pair of scales or balance (Figure 2.12). In Lane’s representation, the capacity of the flow to transport sediment is represented by the product of discharge and slope, a quantity analogous to stream power. This is balanced against the supply of sediment from upstream, which is represented by product of sediment load and sediment size. Biogeomorphology shows that Lane’s balance can be improved by acknowledging the influence of biology (Figure 2.12(b)).

Lane’s balance is never static, even in a stream that is in dynamic equilibrium, but usually its fluctuations are small and quickly reversed. By contrast, transportation projects, other human activities, and natural disturbances can cause a bigger and more protracted imbalance. Figure 2.13 illustrates how the backwater effect can induce aggradation upstream of a culvert crossing. Prior to construction, sediment transport capacity was in balance with sediment supply. Through time, backing up of flow at the culvert reduced the sediment transport capacity of the stream. This occurred because of a reduction of energy slope. Lane’s balance represents this in the lower right side of Figure 2.13 by shifting the bucket left along the arm of the scale. Discharge, upstream sediment supply, and particle size, D_{50}, do not change, so the balance tilts counterclockwise and the pointer indicates that aggradation occurs. Downstream of the culvert the sediment supply is decreased, which is represented in Figure 2.13 by a smaller pile of sediment on the scale pan. The slope, discharge, and particle size, D_{50}, are unchanged, so the balance tilts clockwise, and the pointer indicates degradation. This situation can be avoided by providing sufficient hydraulic capacity such that backwater only occurs during large, rarely occurring floods.

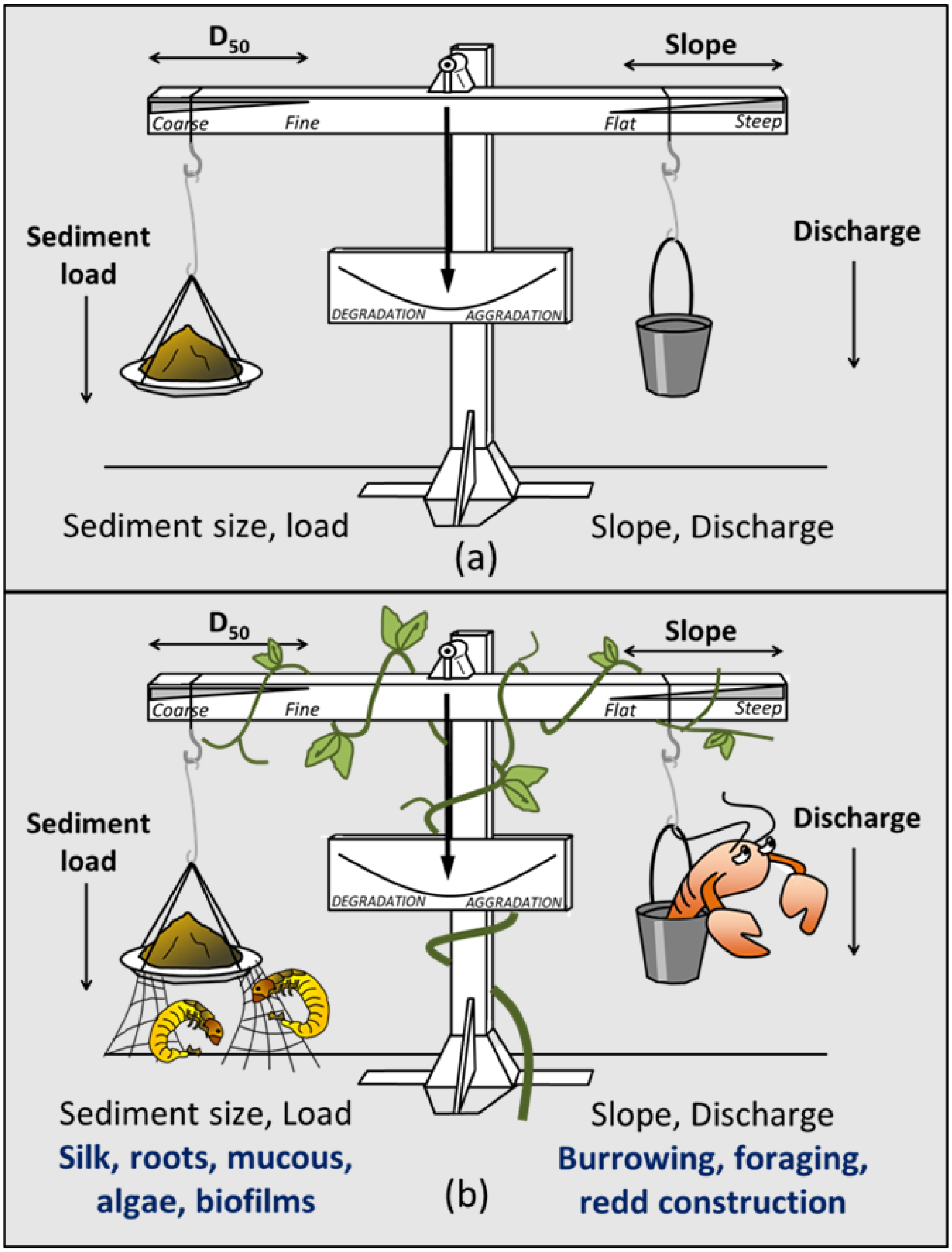


Figure 2.12. (a) Lane's balance in its original form and (b) modified to acknowledge the influences of the river ecosystem on sediment transport and stable channel form. Source: Johnson et al. (2019) after E.W. Lane.

As well as at culverts and bridges, transportation projects involving longitudinal encroachments can cause sediment transport imbalances affecting the channel discharge; channel realignments and bend cutoffs affecting the slope; dredging reducing sediment supply, and channel clearing increasing channel discharge. Transportation infrastructure can also be impacted by sediment imbalances caused by other channel and basin changes including floodplain development, reservoirs, natural bend cutoffs, forest fires, flow diversions including inter-basin diversions, changing land use, and other activities. Channel response to these changing inputs can be rapid or persist over decades, which emphasizes the importance of awareness of activities in the basin and on developing resilient designs.

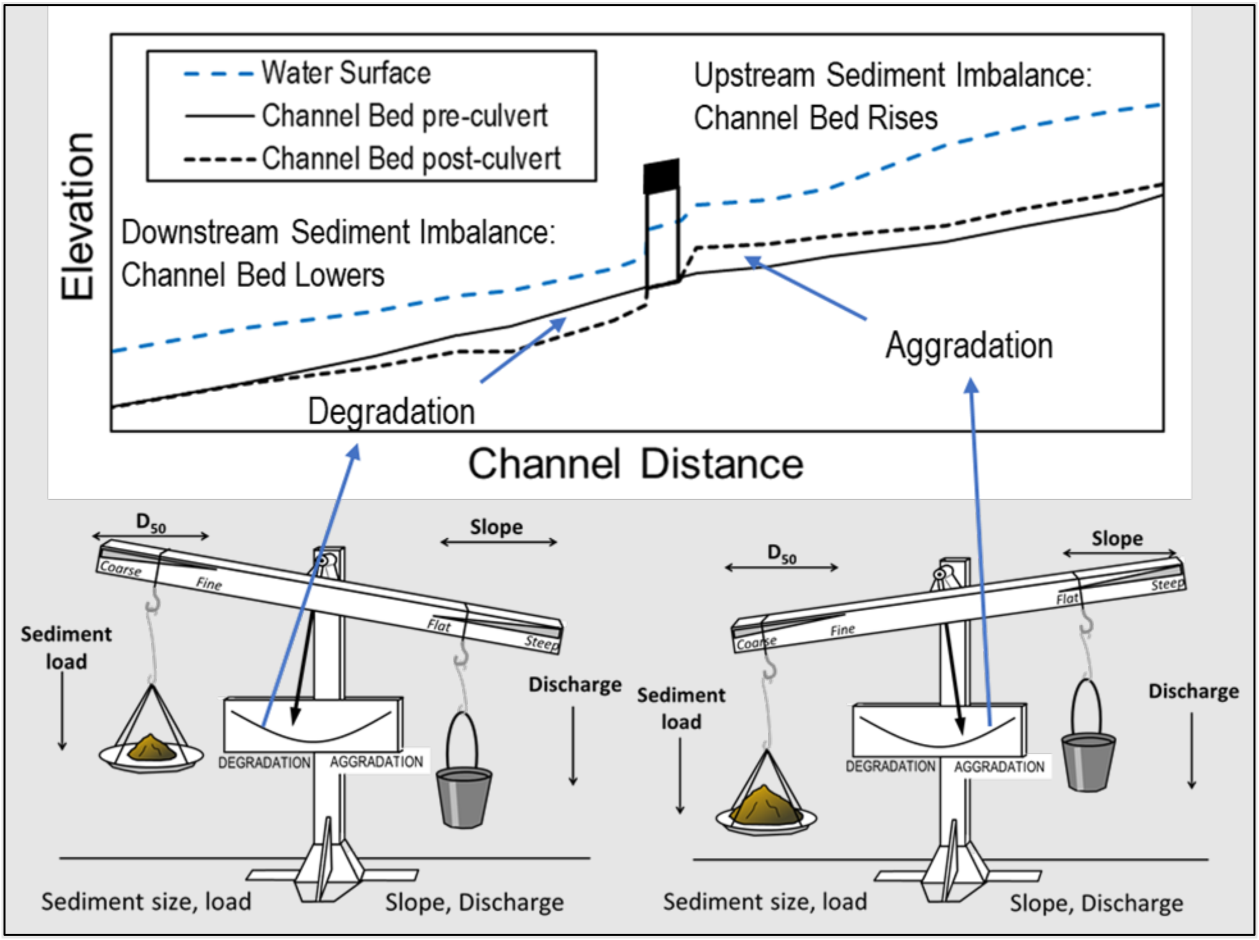


Figure 2.13. Lane's balance illustrating a possible channel response to an undersized culvert.

When the capacity of a stream to transport sediment balances the supply of sediment, the channel changes little through time. However, this stability is dynamic, because the sediment making up the boundaries of the channel is mobile. There are many channel patterns that can be classified as being dynamically stable. For decades, engineers have developed empirical (regime) and theoretical (analytical) equations to provide the basis for designing stable channels (Simons and Şentürk 1976). Figure 2.14 summarizes Schumm's planform classification (Schumm 1981). The figure illustrates that many of the planforms feature multiple channels and flow paths. Planform stability matters because instability can pose risks to roads that encroach into the river or its floodplain.

As with Lane's balance, both stable channel classifications and stable channel design equations have been updated to account for the influence of biogeomorphology. For example, Hey and Thorne (1986) added bank vegetation type (trees, shrubs, grasses, barren) as an additional factor to improve the predictive capacity of hydraulic geometry equations for stable gravel-bed rivers. Castro and Thorne (2019) replotted the dynamically stable planforms in Figure 2.14 in a Stream Evolution Triangle, which treats river forms as being influenced by biology as well as hydrology and geology (Figure 2.15).

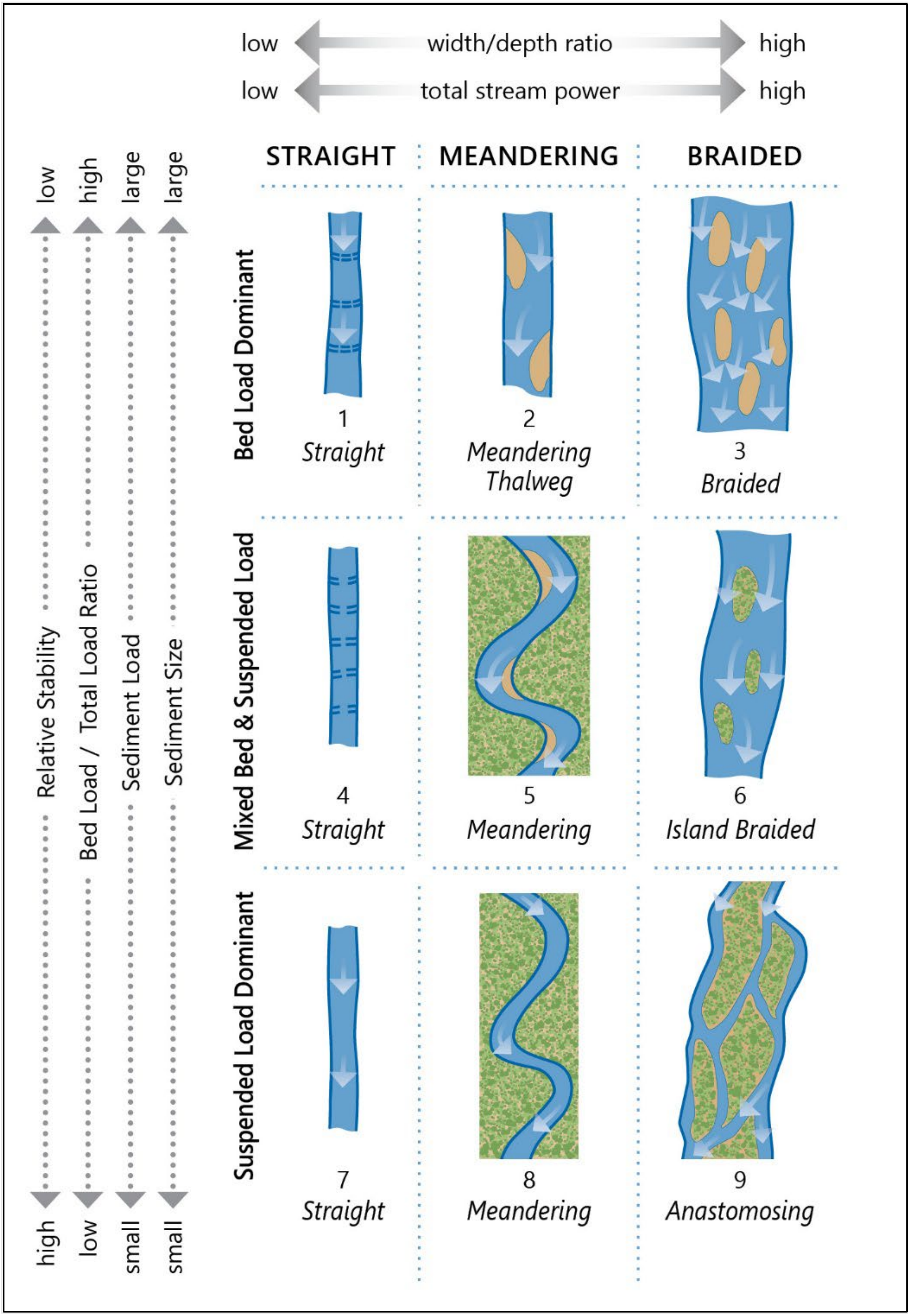


Figure 2.14. Range of stable channel planforms and stream characteristics in planform classification. Adapted from HEC-20.

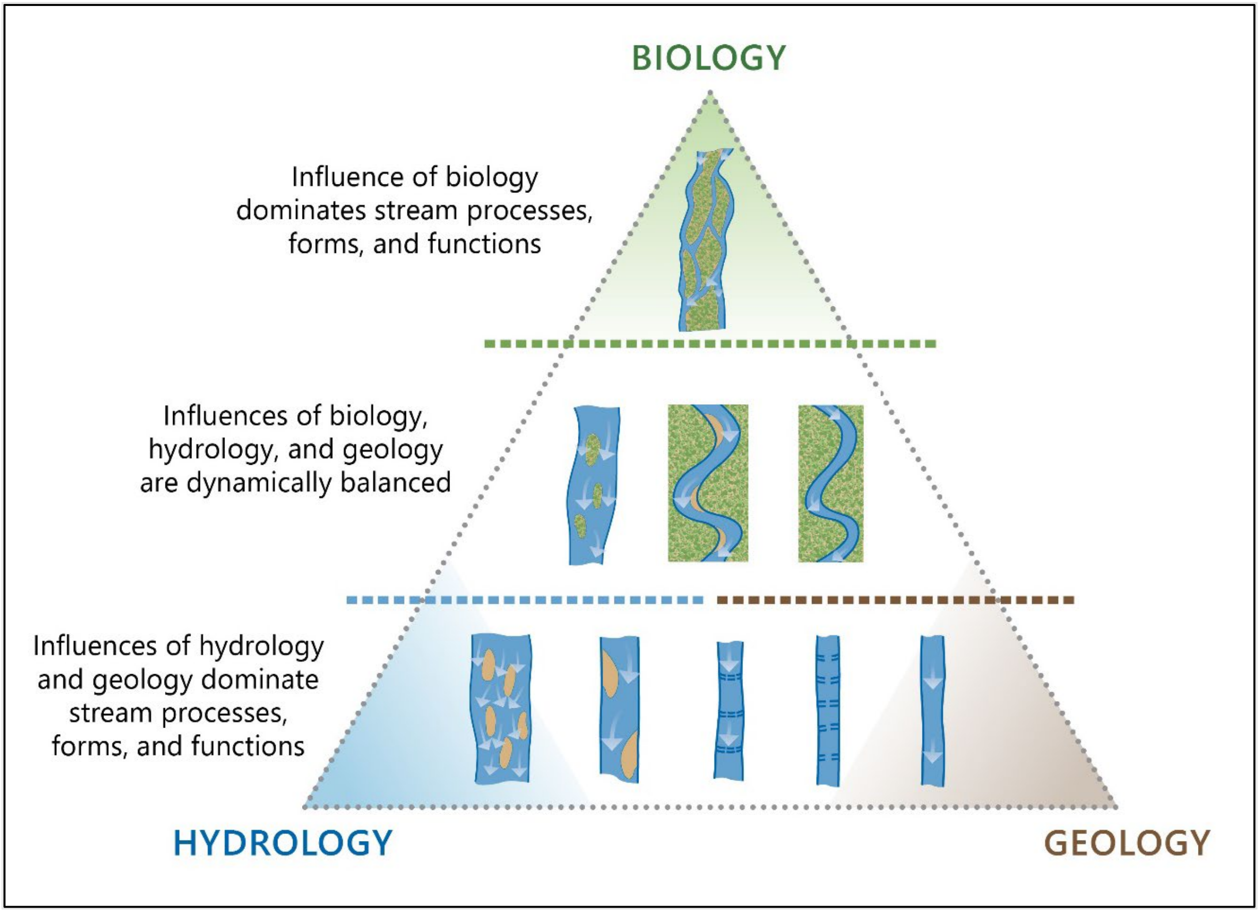


Figure 2.15. The Stream Evolution Triangle represents the relative influences of hydrology, geology, and biology on channel forms and processes. Adapted from Castro and Thorne (2019).

Geomorphic classifications of stable channels explain planforms only in terms of flows and sediment loads. The Stream Evolution Triangle (SET) adds the influence of biology, showing that stable forms are not determined solely by relationships between flow, rock, and sediment, but are also affected by river life. Planforms at the base of the SET show the relative influences of stream power and sediment load without biology – as in Lane’s balance. But as the relative influence of biology grows, flow is slowed, stream power is spread out and sediment becomes less mobile – resulting in meandering, island braiding and, at the apex of the SET, anabranching.

Disturbances responsible for changes in the size, shape, or position of a river come in many forms. Disturbance may result from gradual changes in watershed runoff or sediment yield, which change the river system in ways that persist for decades. Disturbance may also result from a discrete event, like a flood or drought, from which the river recovers in a few years. Following a major disturbance, river depth, width, and planform may change unpredictably for years or decades. This is known as “complex response” (Schumm 1977).

In any reach of a river, changes in channel size, shape, or position that occur in response to minor disturbances are quickly reversed without a noticeable change in physical characteristics. These adjustments take place within the band of dynamic stability shown in Figure 2.16. Planform classes differ in their tolerance to disturbance. Referencing the planform classes in Figure 2.14, response to disturbance is summarized as follows:

- Types 1 - 3 are sensitive to disturbance and are more frequently taken outside their dynamically-stable tolerance band. They have capacity to recover, and likely to follow the evolutionary trend for reach B (Figure 2.16). However, they are vulnerable to following the evolutionary trajectory depicted for reach C, with the form or position of the river being permanently altered following disturbance.
- Types 4 - 6 are naturally resistant to disturbance but are more likely to be taken out of their dynamically-stable band than types 7 through 9. These types of rivers can still recover their pre-disturbance form, as depicted for reach B in Figure 2.16 but this may take longer.
- Types 7 - 9 are naturally resilient to disturbance. They may remain dynamically stable for decades to centuries. These rivers follow the pattern of reach A in Figure 2.16. Only a major disturbance will take this type of river outside of its dynamically stable band and even then, these types of rivers can quickly recover their pre-disturbance form, as depicted for reach B in Figure 2.16.

An artificially stabilized reach may have low capacity to recover from a significant disturbance simply because it cannot go back to the unnatural size, shape, or position imposed on it prior to disturbance. In this case, the future evolutionary trajectory and form of the river is permanently altered, as shown for reach C in Figure 2.16. The pre-disturbance channel form may only be recovered by channel reconstruction or rehabilitation.

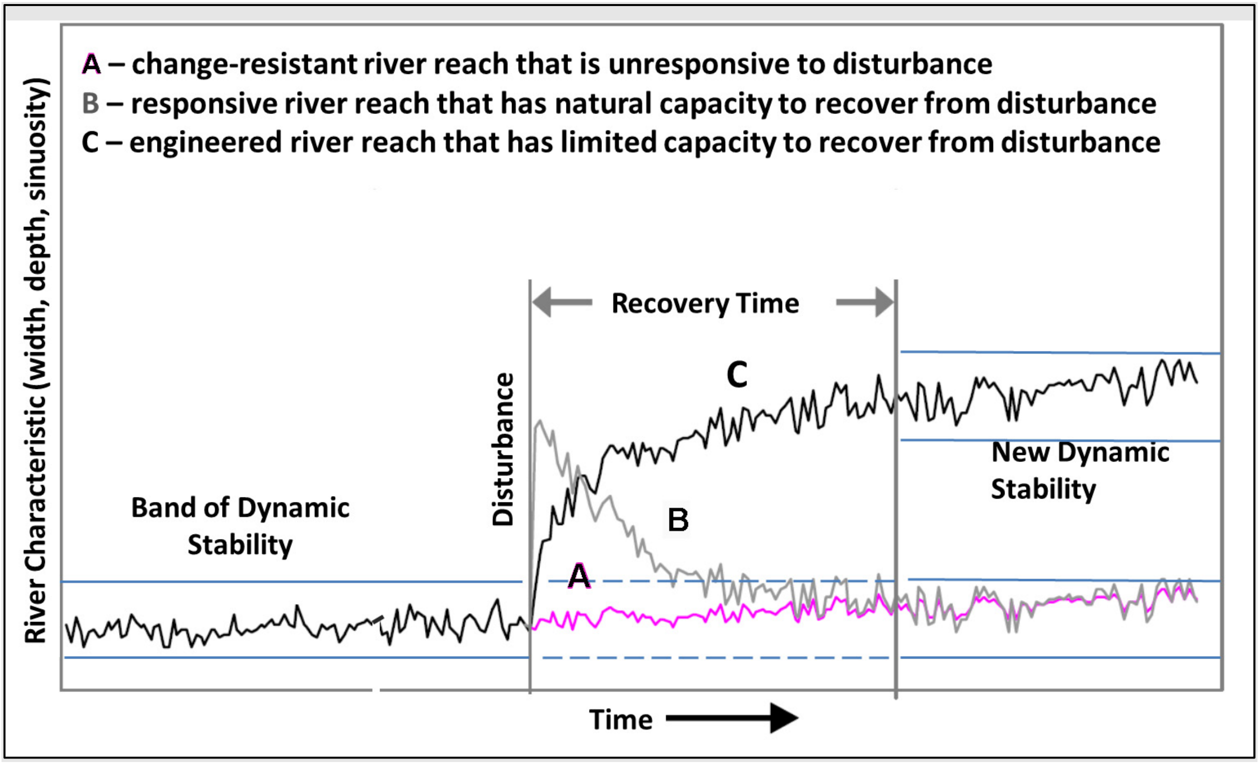
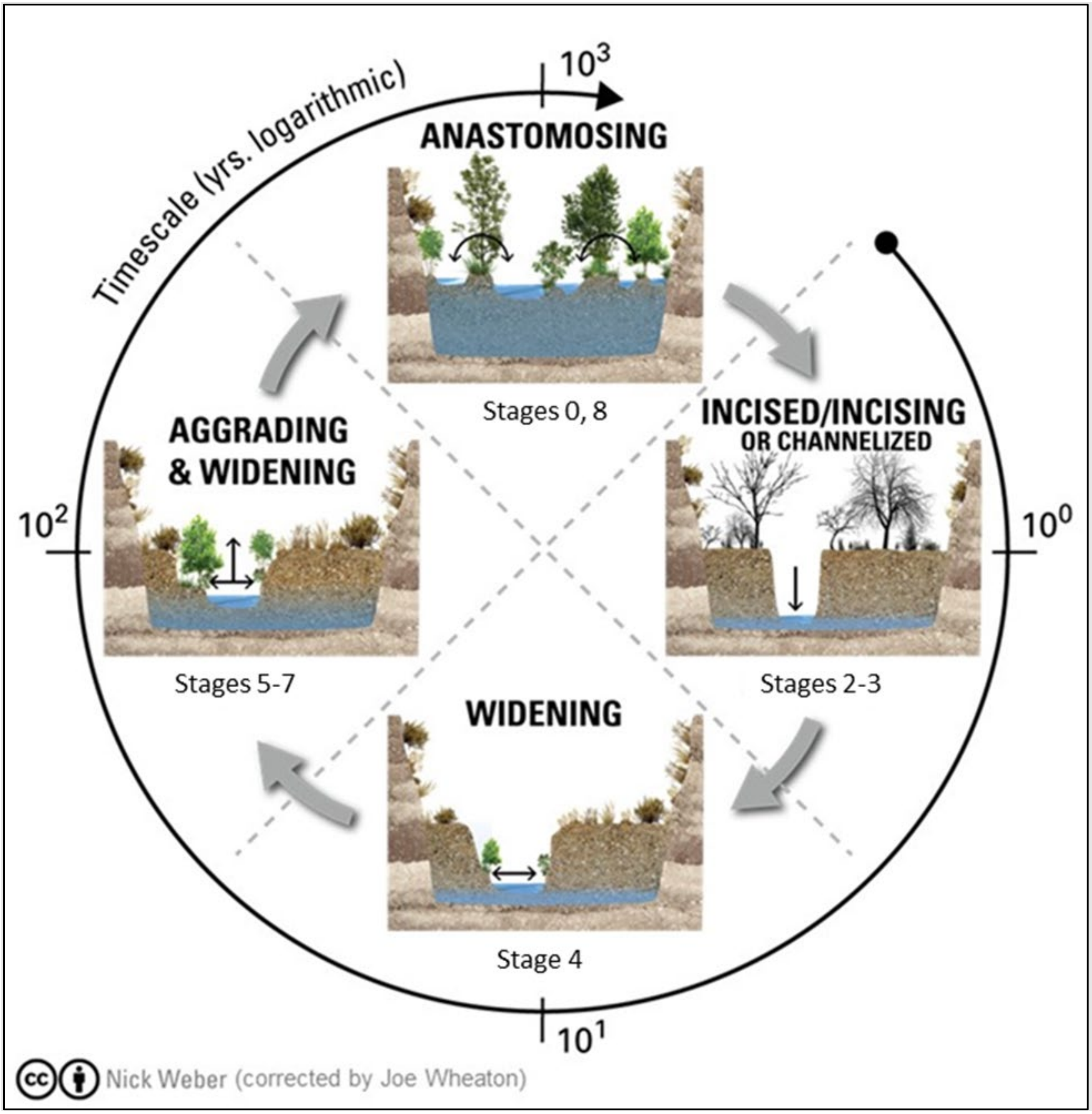


Figure 2.16. Potential river responses to a disturbance.

Sustainable and resilient transportation infrastructure planning and design recognize that the river observed today is the cumulative outcome of all past disturbances, responses, recoveries, and engineering. The river tomorrow will be different based on future disturbances, responses, recoveries, and engineering. “Dynamically stable“ rivers are constantly: 1) responding within their bands of dynamic stability, 2) recovering from a discrete event disturbance, or 3) adjusting to a gradual disturbance.

2.2.3 The Stream Evolution Model

Disturbance may result from transportation-related projects involving channelization, straightening, narrowing at a road crossing, base level lowering, or channel relocation. The adjustments and channel forms resulting from a major disturbance tend to follow particular sequences (Schumm et al. 1984). One sequence is the stream evolution model (SEM), a conceptual model describing what happens when a channel starts to incise (scour) into its floodplain (Cluer and Thorne 2014). In its original form, the SEM is highly detailed, and its basic principles can be illustrated by the simplified version shown in Figure 2.17. The figure is taken from Shahverdian et al. (2019) which was a simplification of Cluer and Thorne (2014).



Nick Weber (corrected by Joe Wheaton)

Figure 2.17. Simple rendition of the Stream Evolution Model.

Stage 0 in the SEM evolution sequence represents the pre-disturbance condition. In both the pre-disturbance and fully-recovered stages, the river is a complex of channels and wetlands – the anastomosed, or anabranched, type 9 planform in Figure 2.14. Stage 1 represents limited and reversible incision so it is not shown in Figure 2.17. Incision into the floodplain (stages 2-3) is followed by widening caused by bank instability (stage 4). During stages 5-7, the bed aggrades and the channel continues to widen. Eventually, the channel recovers either its original pre-disturbance channel/wetland complexity as it progressively reconnects to its floodplain (stage 0) or it creates a new, fully connected floodplain that is inset within the original floodplain. Figure 2.17 indicates that incision happens quickly – in 1 to 10 years – but natural recovery is slow and may take a century or longer.

The SEM accounts for the hydrologic and geomorphic attributes of the river, as well as habitats and ecosystem benefits provided by the river. All of these diminish as the stream degrades and widens, but gradually recover as the river aggrades and reconnects either to its original or new floodplain (Figure 2.18). Each SEM stage shows pie charts related to river attributes and benefits. The pie chart sizes indicate the functionality of the river with respect to these attributes and benefits. The pie pieces represent the degree to which each is either present and functional, or missing and not functional. The incising and widening stages can lose both attributes and benefits that are gradually regained, though unlikely to original levels.

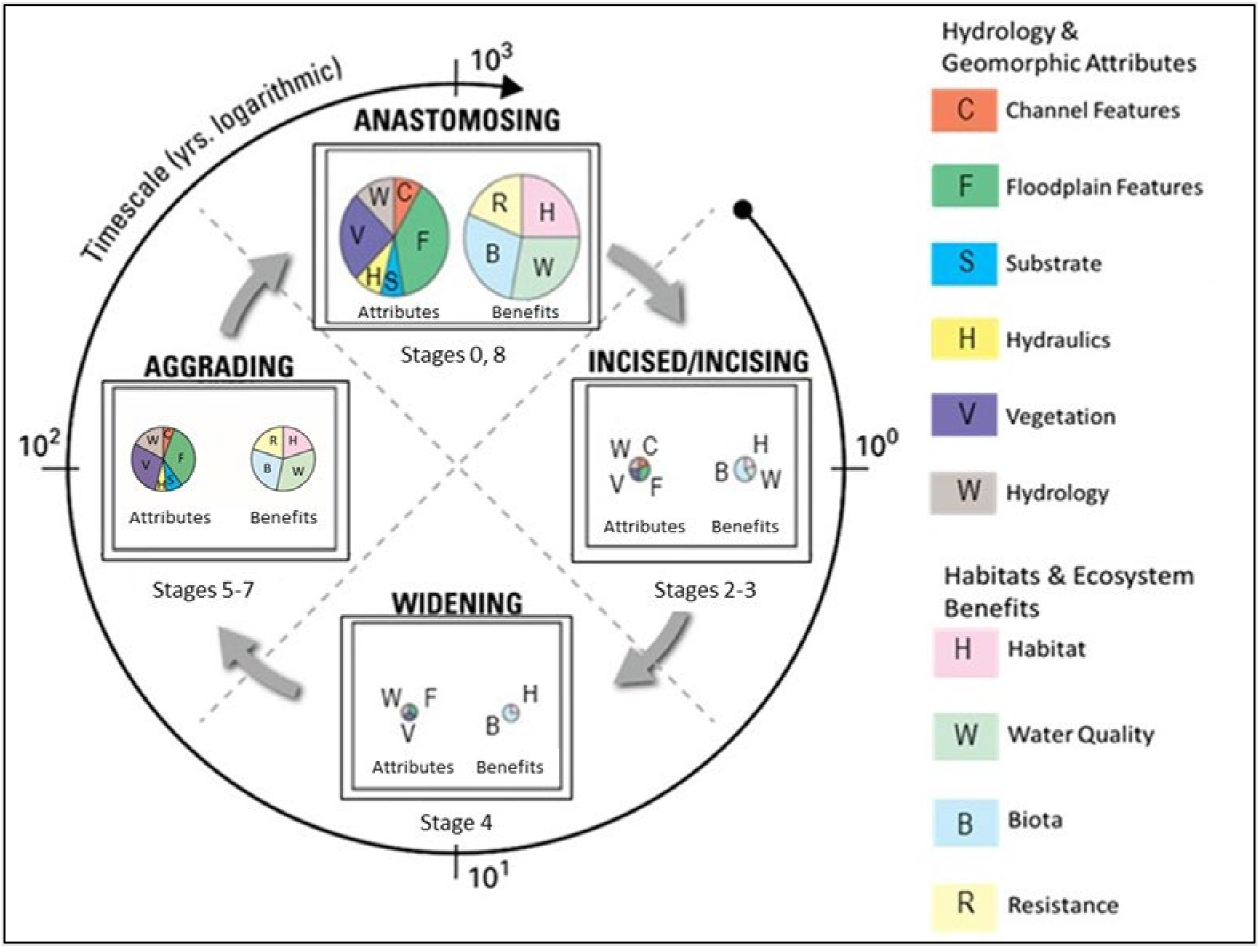


Figure 2.18. Simplified version of the SEM uses pie charts from the original SEM to show how the hydrology and geomorphic attributes and habitat and ecosystem benefits provided by the river first decrease and then recover during incised channel evolution.

2.2.4 River Restoration

During the 21st century, geomorphologists, engineers, and scientists have employed river restoration approaches to accelerate recovery of river forms and functions that have been lost for a variety of reasons. These reasons range from artificial stabilization or channelization of a river reach to large-scale watershed development. Recognizing the inevitability of river evolution and adjustment, sustainable river restoration avoids efforts that attempt to design, maintain, preserve, or repair static-stable river forms. These forms are often not cost-effective and do not allow the river to adapt to and ameliorate changes in, for example, land use or climate.

River restoration rarely involves returning a river to a pre-disturbance state. While this may be possible in wilderness areas, most rivers in need of restoration are in areas with people and infrastructure, including transportation corridors. The landscape contexts for river restoration range from wilderness to fully built-out cities, and restoration projects that consider their landscape context can be more successful. (See Johnson et al. (2019) for a detailed discussion of restoration opportunities based on the types and levels of human activity.) In practice, restored rivers in wildlands look different from restored rivers in croplands or those in urban population centers. These differences are expressed in terms of typical stream attributes including flow regime, stream power, sediments, and connectivity. Although full restoration is rarely feasible, the functionality of any degraded river can be improved, even in the most heavily developed contexts and in places where infrastructure (including roads) encroaches close to the channel.

River restoration in areas with recurring problematic interactions between transportation infrastructure and the river can be effectively planned by considering the relative positions of the river and the road in the context of a Channel Migration Zone (CMZ) (Rapp and Abbe 2003). The CMZ is the area within which the channel is likely to move, either gradually or rapidly. It is determined based on geomorphic analyses that identify areas occupied by past, present, and potential future channel planforms, as illustrated in Figure 2.19. King County, WA (1999) has published detailed information on preparing a CMZ study and map.

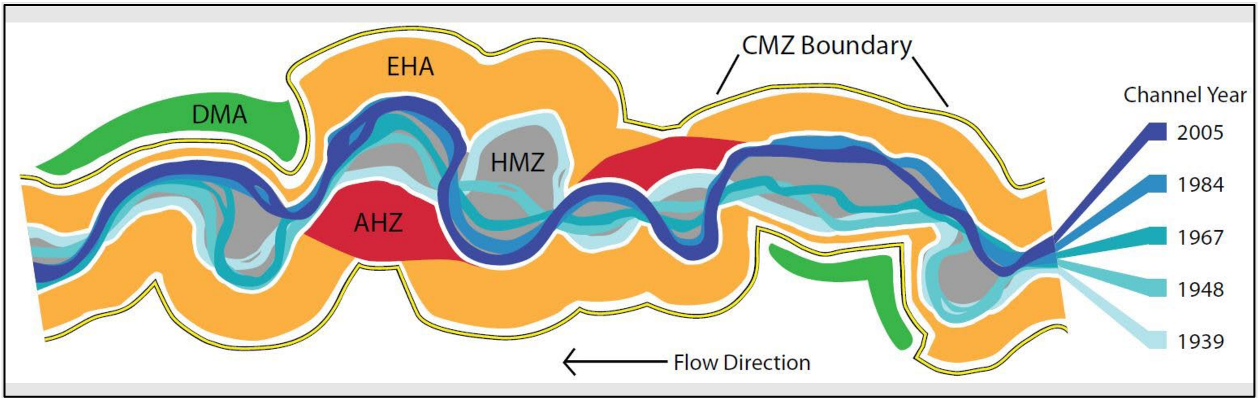


Figure 2.19. CMZ for a reach based on geomorphic information on past, present and potential future river adjustments. The corridor swept by the channel between 1939 and 2005 is the HMZ = Historic Migration Zone. EHA = Erosion Hazard Area, AHZ = Avulsion Hazard Zone, DMA = Disconnected Migration Area. Source: Oregon Department of Geology and Mineral Industries.

When delineating the CMZ to support river restoration, the designers consider pre-existing infrastructure (including highways, road crossings) and development that may limit the space (right-of-way) where the river can be allowed to respond, adjust, and evolve. When planning transportation systems, delineating the CMZ may be beneficial to avoid putting new infrastructure potentially at risk of damage or destruction, whether the location of the channel shifts gradually as part of stream evolution, or changes course abruptly (an avulsion) during a flood. In Figure 2.19, the Historic Migration Zone (HMZ) and Avulsion Hazard Zones (AHZ) pose the greatest risk to infrastructure because these areas have recently been occupied by the channel or are in an area that the channel can abruptly occupy. The Erosion Hazard Area (EHA) designates the area within the CMZ with potential erosion risk. The Disconnected Migration Area (DMA) is an area that is not subject to channel migration in the foreseeable future.

2.3 Habitat

In addition to providing for conveyance of flow, sediment, wood and debris (Section 2.1) and shaping the landscape (Section 2.2), the river and floodplain also function as habitat. Figure 2.20 illustrates a river with an active floodplain supporting a channel-riparian-wetland-floodplain mosaic of habitats. When a river-floodplain system has a strong food web with habitat diversity, there is a home for riverine species that range from microbes, through fish and birds, to top predators, as illustrated in Figure 2.21. The figure also illustrates the role of temperature (T) and nutrients (including nitrogen (N) and phosphorus (P)) in the food web. The functions of riverine, riparian, floodplain, and wetland habitats are described in the following sections.

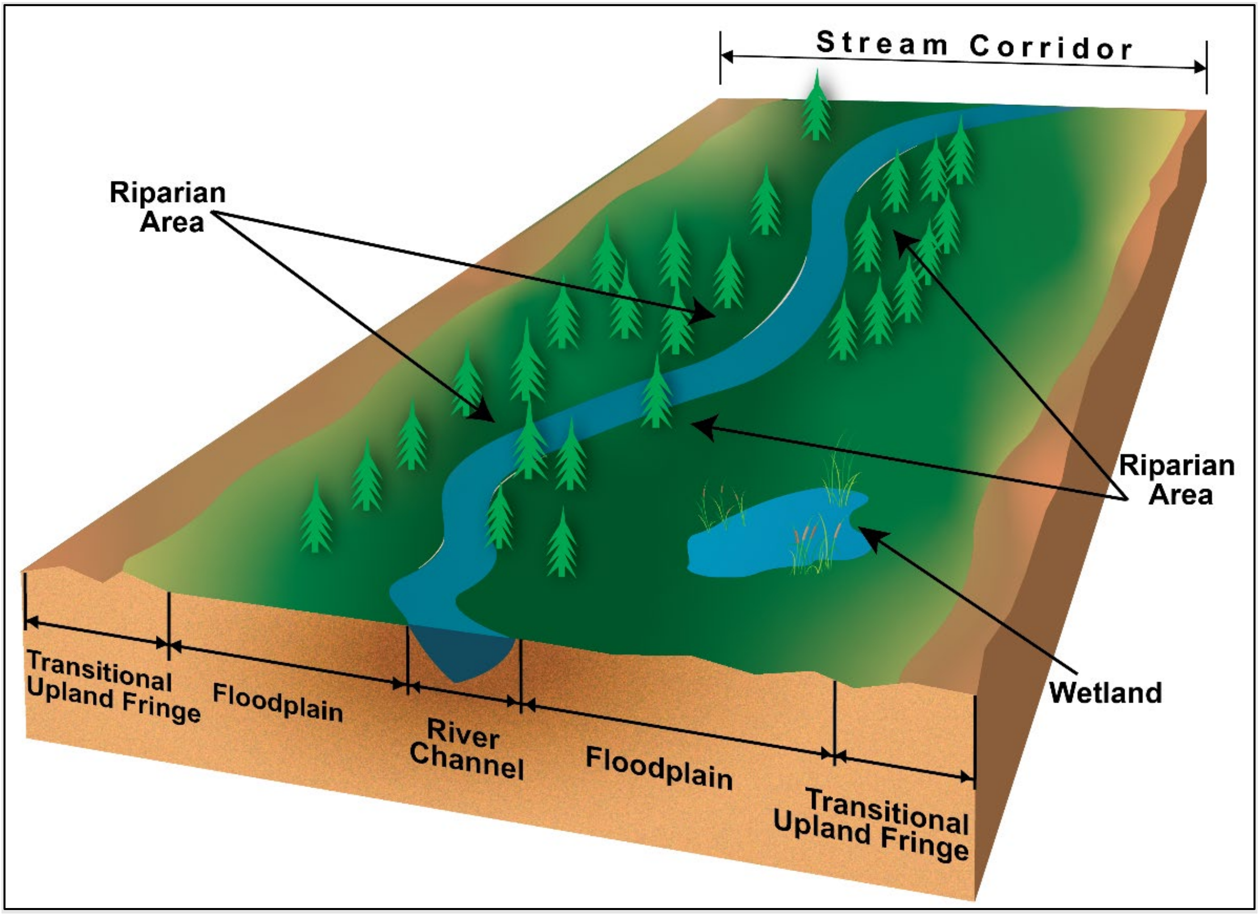


Figure 2.20. Illustration of stream corridor habitat areas.

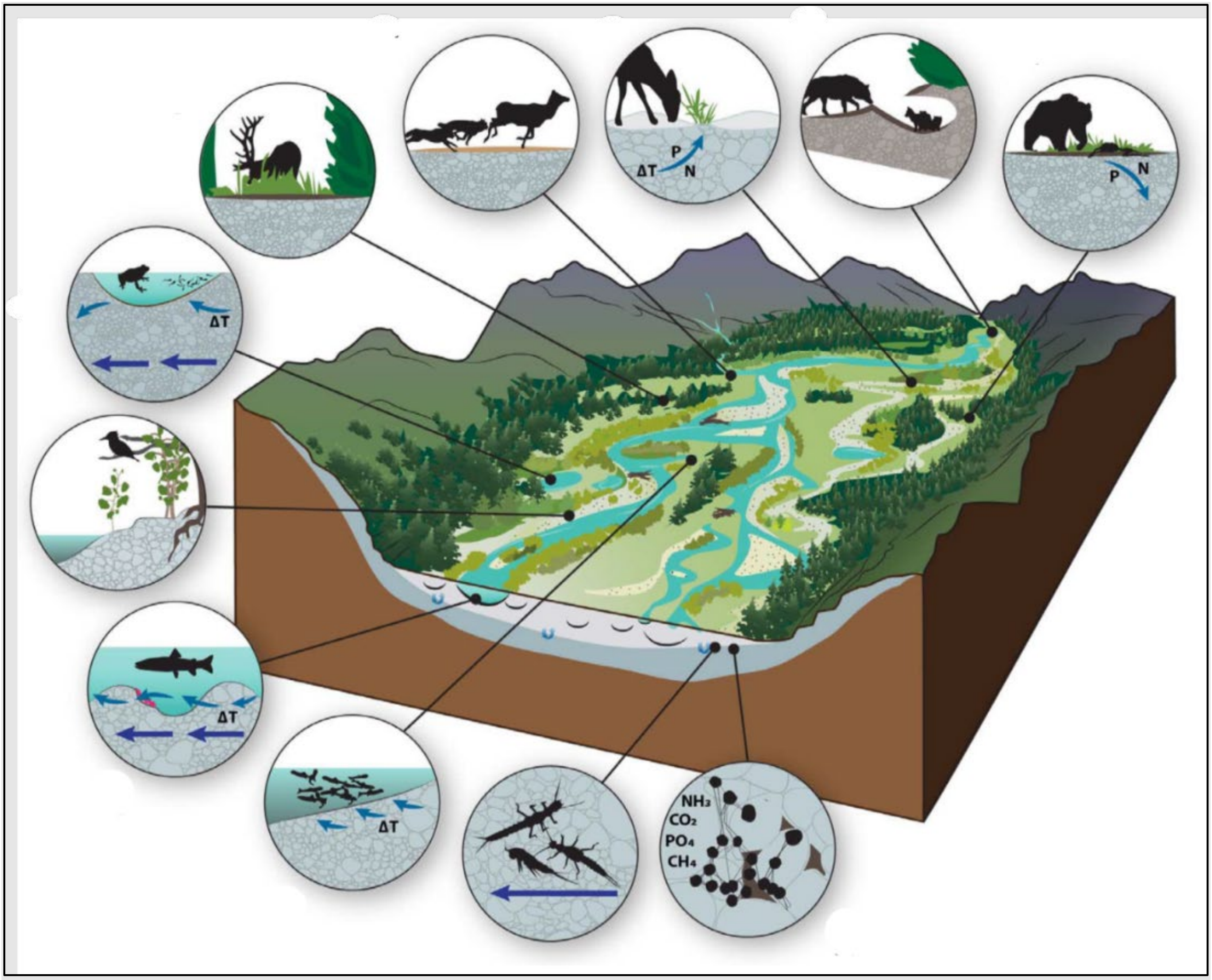


Figure 2.21. Habitats for microbes, insects, juvenile fish, adult fish, birds, amphibians, prey, predators, vegetation, and top species. Source: Hauer et al. (2016) and used by permission.

2.3.1 Riverine

The wetted channel of a river creates a range of habitat types including wetted areas of pools, runs, and riffles, as discussed in HEC-20 Chapter 8. Within these habitats are vertical zones of habitat for various organisms, including the surface, water column, and benthic (bottom) zones (Molles 2005). The type of habitat depends on whether the river is in a humid to arid environment and whether it is perennial or ephemeral. Most rivers and streams are fresh water, but saltwater systems also exist.

While river form is dictated by the physical forces of water flowing through the system, the habitat created by these forces can in return affect flow and channel geometry. Organisms within river systems change from the headwaters or top of the river, down to the mouth or bottom of the river. Vannote et al. (1980) characterize this biological variation as the river continuum concept. As part of the river continuum, leaves and other plants are an important source of energy and the patterns of loading, transport, use, and storage of organic matter along the river influence the habitat and organism presence.

Benthic invertebrates, phytoplankton, and zooplankton are the base of the food chain in riverine habitats. Aquatic and terrestrial arthropods are predominant in the river system, many (such as dragonflies and damselflies) spending their full life cycle in the aquatic environment where they are a food source for fish, amphibians, reptiles, birds, and small mammals. Fish species vary depending on food sources and size of the riverine environment.

Mammals, including muskrats and beavers, rely on and influence riverine habitat. Beavers are “ecosystem engineers” that can significantly influence riparian and aquatic habitats, river morphology, and channel grade (DeVries et al. 2012). As keystone species, beavers create local dams and impoundments that change flow patterns and control the composition and density of plants, water quality, fish habitat, erosion, and sedimentation. Many other organisms that do not reside within the river system rely heavily on the system for food and habitat.

In riverine and other habitats, plant and animal species have coevolved such that they often maintain a balanced ecosystem. Invasive species can disrupt the balance when there are no natural checks and continue to be one of the greatest challenges for managers of habitat and wildlife.

Executive Order 13112 (64 FR 6183 (Feb. 8, 1999)) defines an invasive species as “a species that is not native” to the ecosystem under consideration and “whose introduction [causes] or is likely to cause economic or environmental harm or harm to human health.” Hundreds of introduced plant and animal species inhabit river and aquatic ecosystems, though not all are considered invasive. Invasive species change the dynamics of the system and have negative consequences on the environment, including displacement of the native plant and animal species. Many times, this process results in the displacement or loss of native species or species of concern. Significant losses can result in regulatory protections of native species such as designation as a State species of concern or Federal threatened or endangered species. In arid lands, another special concern of invasive species, such as salt cedar (or tamarisk), is the potential to increase fire frequency and severity by supplying fuel in the form of high levels of dead leaves and branches (Lovich and Hoddle 2020). This issue is compounded because, unlike native riparian trees and shrubs, salt cedar sprouts rigorously after fires, further pushing out native species. Section 8.6. provides additional information on invasive species.

Examples of Invasive Species

- Tamarisk in riparian areas in the Southwest.
- Zebra Mussel in the Mississippi River Valley and Great Lakes.
- Asian Carp in the Mississippi River and tributaries.
- Kudzu in riparian areas in the Southeast and spreading north.

Water quality is an important aspect of riverine habitat affecting both wildlife and human use. The chemical conditions of a river, such as salinity, pH, temperature, and oxygen levels, are important as are other factors, such as the presence of fine sediments. In freshwater systems, salinity and oxygen are two of the main chemical factors affecting habitat. Flow magnitude and mixing, temperature, light, turbidity, and other factors influence water chemistry.

The biological cycles of plant and animal life also influence the water chemistry by adding organic matter. Photosynthesis contributes to the synthesis of available organic compounds within the habitat (known as “primary production”). Primary production is also influenced by evaporation processes and temperature, wherein moisture enters and leaves the system, determining the system’s net primary production (Molles 2005). The organisms responsible for primary production, known as primary producers, form the base of the food chain. In terrestrial ecoregions, these are mainly plants, while in aquatic ecoregions algae predominate.

2.3.2 Riparian

Riparian areas (see Figure 2.20) exist at the interface between the fluvial environment in the channel (described in the previous section) and surrounding wetland and floodplain environments. They typically form a band along both banks of a river and together make up the “riparian corridor.” The width of the riparian corridor reflects the influences of topography near the river, the type and evolutionary history of the watercourse, the shape of channel banks, the extent of the fluvial aquifer, and local groundwater levels in the vicinity of the channel. Riparian areas, such as shown in Figure 2.22, include the forested habitat surrounding rivers or wetlands and are often within the broader floodplain, including frequently inundated floodplain areas. Perennial (and even ephemeral) flows from the waterway maintain riparian habitats.

Figure 2.22. Streamside forest cover stabilizes and shades the channel (Ellicott City, Maryland). Source: FHWA.

The boundaries of riparian areas are dynamic, reflecting the movement of the channel. Riparian areas are a primary supply of sediment, wood, other organic material, and nutrients to the river. They are a permeable barrier through which human-derived and natural debris, waste, contaminants, and pollutants pass to enter the river. Adjacent land use, such as an eroding road ditch or a poorly graded dirt road, can increase sediment loads to a river. Sediment is a common cause of impairments to riverine habitat and water quality. Riparian areas, by filtering water and trapping sediment and nutrients, can provide important mitigation for such pollutants (FISRWG 1998).

The riparian fringe is a transition region between two biological communities, the riparian corridor and uplands. Complexity in topography, flow depths, velocities, and micro-climates within the riparian corridor creates diverse habitats important to a wide range of species. Riparian areas serve as migration routes and stopping points between habitats for a variety of wildlife (NRCS 1996). Biodiversity at the boundary between adjacent biological communities (in this case, the riparian fringe) is often richer than in either of the areas it separates. Many species rely on the riparian corridor or riparian habitat (Friggens et al. 2014).

Because of the availability of water, riparian areas are generally well-vegetated and, often, riparian trees can form a canopy that shades the channel. A variety of native plants can usually be found in riparian areas. Depending on topography, frequency and duration of flow inundation, and hyporheic exchange and ground water levels, riparian vegetation ranges from wetland to upland species. Riparian habitats offer many functions, including temperature lowering, erosion resistance, and habitat for species that rely on the riparian zone. A riparian forest is typically cooler than unforested adjacent uplands, including turfed landscapes and agricultural lands, and can create a cooler water habitat.

As the riverward boundary is a stream bank, riparian areas are naturally destroyed or created by lateral shifting of the channel. Undercut banks and river cliffs are often found where flow impinges on the bank, such as along the outside of river meanders, generating a sharp division between the advancing aquatic zone and retreating riparian zone. Conversely, attached bars are often found along accreting banks, such as along the inside of river meanders, generating a diffuse boundary between the migrating channel and the advancing riparian fringe.

Given their proximity to the river channel, trees in riparian areas provide sources of food for aquatic species and nutrients to the river. Insects and other organic materials are regularly supplied to the watercourse by riparian trees. Riparian trees also provide important shade protection against increasing water temperatures in the river (NRC 2008). Trees are commonly recruited into the channel through a variety of processes, including bank erosion, slope failures, blow-down, beaver activity, and individual tree mortality. Accordingly, riparian forests provide important supplies of wood to the channel that supports a wide range of ecological, physical, and biological functions.

Impairments of riparian areas by human activities, including the construction and operation of transportation infrastructure, are common. Removal of native vegetation for various human activities along riparian corridors can remove shade that moderates stream temperatures and alter or eliminate important habitats and food sources for the animal species they support. Disruption of the filtering function of riparian areas alters the supply of sediment, wood, and nutrients to the river and can cause untreated stormwater to enter waterways directly. Geomorphic responses to disturbance of riparian areas can lead to a variety of physical and environmental impacts, including rapid bank retreat, sudden planform change (see HEC-20 Section 5.5), reduced water quality, and impaired ecological function. Resultant channel shifting may adversely impact transportation infrastructure.

Benefits of Maintaining Riparian Areas

Water and air temperature regulation

Nutrient source

Sediment and pollutant filter

Habitat diversity

Energy dissipation

Erosion buffer

Improved water quality

2.3.3 Floodplains

Floodplains (see Figure 2.20) include the area adjacent to riverine habitat that are periodically or even frequently inundated. Surface or groundwater flows connect riverine, riparian, floodplain, and wetland habitats. Floodplains store and convey flood flows and provide intermittent aquatic habitat when inundated, including spawning areas for some fish species. They contain perennial habitat, such as forest, meadows, wetlands, or ponds, when not inundated. As Molles observes (2005), “rivers and their floodplains form a complex, highly dynamic landscape” that can include the river, riparian forest, and wetland (marsh, wet meadow, etc.) habitat.

Floodplain habitats also evolve as channels migrate, as shown in Figure 2.23. As channels migrate, they progress across- and down-valley and periodically cut off (note the circled cutoff in Figure 2.23). Cutoffs reduce channel lengths and increase channel slopes, increase local velocities, and create a local imbalance of sediment transport capacity that results in upstream bed degradation and downstream aggradation. Vegetation colonizes newly exposed areas and new habitat is created just as other habitats are reduced. Rarely does this activity produce any consistently repeating patterns, but it creates habitat diversity and variability supporting different life stages of vegetation, and therefore, a variety of wildlife sanctuaries. Vegetative succession, in turn, enhances species composition and diversity (Molles 2005).

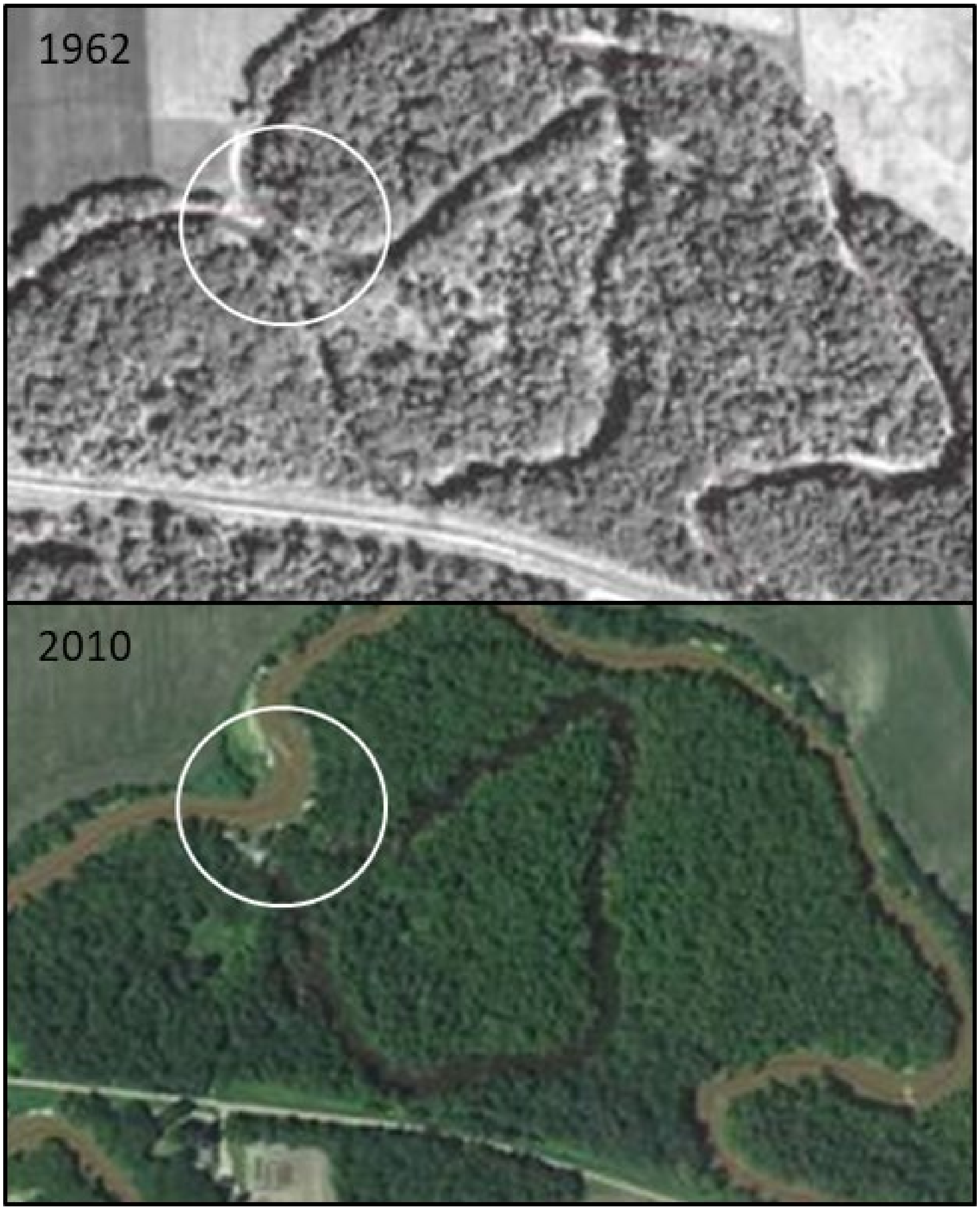


Figure 2.23. Meander cutoff development between 1962 and 2010, Sheyenne River, ND. Image used by permission of WEST Consultants, Inc.

The river-floodplain connection (see Section 2.4) is integral to the ongoing function of the floodplain ecosystem and habitat. Water management projects, such as dams and levees, and encroachments, such as bridges, culverts, and roadway embankments, often impact these connections. Excessive floodplain encroachment by roads (as well as other development) can lead to channel instability and threats to road users and infrastructure. Actions that can create instability include building road embankments that disconnect the floodplain from the channel, increasing channel capacity (channelization), or stabilizing one bank of the channel using a revetment, while leaving the other bank free to erode.

Recognizing the importance of long-stream floodplain connectivity, infrastructure can be designed to avoid substantially blocking, reducing, and in some cases even increasing floodplain conveyance. It is possible to make informed predictions of future channel and floodplain conditions using hydraulic modeling, sediment transport evaluations, reviewing recent and historical trends, and through experience as described later in this manual. Not only can infrastructure design avoid excessive impacts on floodplain processes, but where these processes are already severely impacted, new and replacement infrastructure designs can improve and restore natural processes and habitats.

2.3.4 Wetlands

Wetland habitat is found where there is a permanent to semi-permanent surface saturation or ground saturation during the growing season. Wetland hydrology may include surface and groundwater sources. Where surface water is not present, wetlands may be sustained primarily by groundwater. Wetlands are characterized by permanent or seasonal inundation by water; hydrophytic plant species (adapted to growing wholly or partly submerged in water); and distinct soils, typically mottled, grey, black, blue, or greenish grey colored that have developed in an anaerobic (saturated) environment.

Regional and local differences in climate, hydrology, topography, soils, vegetation, and water chemistry result in a broad geographic distribution of wetlands with diverse characteristics. Wetland scientists categorize wetlands into two general types: tidal and non-tidal. They further classify them as marshes, swamps, bogs, or fens, based on their vegetation and other characteristics (Zeedyk 1996, USEPA 2019).

The presence of water by ponding, flooding, or soil saturation is not always a reliable indicator of wetlands. Many wetlands are seasonally dry, particularly in the arid and semiarid West. The quantity of water present and the timing of its presence, in part, determine the functions and value of a wetland and its role in the environment.

Wetlands provide ecological and societal benefits. For instance, wetlands provide a variety of hydrologic functions (Zeedyk 1996). The USEPA (2018) describes the beneficial functions of wetlands as water purification, water storage and flood attenuation, groundwater recharge, maintenance of instream base flows, processing of carbon and other nutrients, stabilization of shorelines, and support of plants and animals. Wetlands also provide important water quality functions within or adjacent to a riverine or floodplain system. Hydrologically connected wetlands can regulate conductance and pH (Leibowitz 2003). Movement of water through the system provides for filtration of sediments and nutrients. Plants present within wetland systems absorb nutrients and can help clean habitats that may be overcome with certain chemicals such as nutrient loading from waterfowl. Wetlands also provide water storage for plant and aquatic life to flourish (USEPA 2001).

Wetlands serve as home to a wide range of plant and animal species. Wetlands provide an abundance and diversity of habitat types for wildlife, including migratory waterfowl, mammals, amphibians, and aquatic insects. Birds rely on a variety of wetland types for food, shelter, nesting, and rearing needs (Leibowitz 2003). Many mammal species are wetland or riverine dependent, such as beavers and muskrats. These keystone species help develop and maintain wetlands but can also impact roadways and stream crossing. Increased population and development, including transportation infrastructure, have severely encroached on wetland habitat.

Destruction or degradation of wetlands and their functions can lead to serious consequences, such as increased flooding, decline in water quality, and threatened extinction of species (USEPA 2018). The National Park Service estimates that about one third of threatened and endangered species in the United States rely on wetlands for survival (NPS 2016). Human activities and other factors have reduced the total area of wetlands in the contiguous United States by nearly 50 percent, with individual states experiencing dramatically different wetland fates (Dahl 1990, Dahl 2011, USEPA 2016a). Conservation of remaining wetlands and their functions is of critical importance. As wetlands and transportation infrastructure are commonly found in floodplains, they often overlap. Transportation infrastructure impacts to wetlands can include filling, fragmentation, and hydrologic alteration (USEPA and Apogee Research, Inc. 1997). Avoidance, minimization, and mitigation of potential impacts to wetlands are often considered at all levels of transportation infrastructure project delivery.

2.4 Connectivity

River connectivity describes the ease with which water, solids, and organisms can move through a river system (Wohl 2017). This includes the movement and storage of sediment; wood; fish; other aquatic, riparian, and terrestrial organisms; and nutrients while incorporating hydrology, flows of energy, fluvial processes, river functions, and ecosystems. This connectivity has three dimensions—long-stream (longitudinal), cross-stream (lateral), and vertical (hyporheic)—that are important to river forms, processes, and functions. Connectivity governs relationships between the conveyance and storage functions in river channels, corridors, and networks, and it influences both short-term responses/resilience to disturbance and longer-term adjustment/recovery in the river evolution function. Connectivity between the aquatic, riparian, floodplain, and catchment ecosystems at scales ranging from the local to the watershed and region is vital to provision of valuable habitat and ecosystem service functions. By identifying, mapping, and understanding both the links in rivers that create and maintain connectivity, and the natural barriers that interrupt connectivity, transportation professionals can collectively and collaboratively create and sustain highways and transportation infrastructure in the river environment.

2.4.1 Long-Stream Connectivity

Long-stream connectivity governs the degree to which water, sediment, wood, energy, and organisms can move freely through the river network. Generally, a high degree of connectivity benefits river processes and functions, but natural breaks and changes in connectivity are also important. For example, long-stream sediment connectivity in a river can be pictured as a conveyor belt (Kondolf 1994) that transfers sediment from the upland erosion zone to the lowland deposition zone (see Figure 2.4). In a natural river, it can take decades to centuries or millennia for sediment originating in the headwaters to pass through the fluvial system. This is because transport is intermittent and during an event, bed sediment moves much slower and over shorter distances than the water. Therefore, movement along the sediment transfer conveyor belt is sporadic and uneven.

Connectivity between upland erosion and lowland deposition zones is important for the long-stream sediment conveyance system to function efficiently. However, local reductions in long-stream sediment connectivity occur where the valley slope flattens, or the valley widens out and sediment is temporarily stored in a floodplain. Floodplains act as natural capacitors in the sediment transfer system and are important in controlling the relationship between the river sediment transport and storage functions. There are many situations where retention of material or energy (due to naturally limited long-stream connectivity) within a river system is desirable. For example, retention of nitrates or dissolved organic carbon can improve water quality in recirculating dead zones, while wetlands and forest habitats in the river corridor support microbial communities capable of performing denitrification and carbon cycling. Similarly, river corridors that retain wood and other organic matter can support greater biomass and biodiversity.

There are also situations where an artificial barrier, such as a dam on a river or an under-sized culvert on a stream, blocks downstream transport of sediment. Artificial barriers to long-stream sediment connectivity cause undesirable deposition upstream and scour downstream, as illustrated in Figure 2.24, that are often troublesome and difficult to manage. Natural barriers to sediment continuity, such as natural wood jams or beaver dams, often enhance natural river functions such as sediment conveyance and storage.

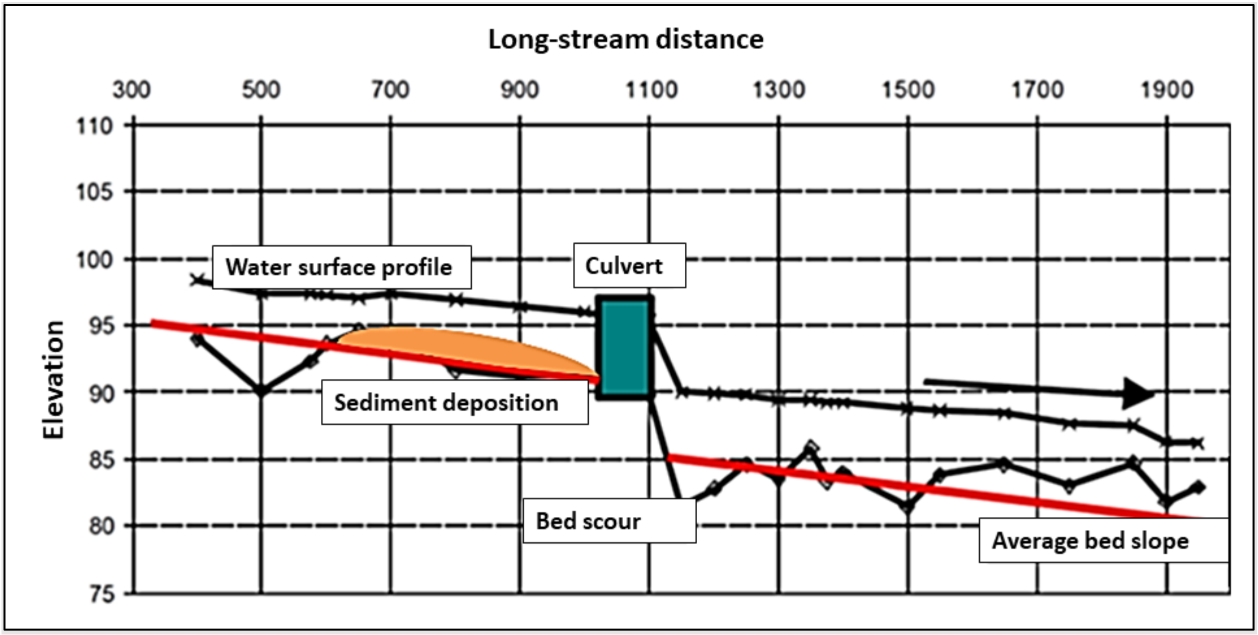


Figure 2.24. Disconnect in long-stream sediment transfer in rivers. Modified from Castro and Beavers (2016).

Many animals follow river valleys and riparian corridors when foraging or migrating seasonally. If their preferred natural pathways are blocked by narrow bridges or culverts, animals are forced to cross the highway. Between July 2020 and June 2021, the United States had 2.1 million animal-vehicle collisions, up 7.2 percent from the previous year, according to State Farm. Deer were involved in an estimated 1.4 million of those collisions. Designing crossings passable by wildlife improves road safety and is also beneficial for wildlife and the natural ecosystem.

Highway infrastructure can impact long-stream connectivity in relation to fish and other aquatic organisms. The U.S. Fish and Wildlife Service (USFWS) estimates there are 2.5 million passage barriers in the United States excluding dams higher than 6 feet (Hartsell undated). Migratory species such as salmon, eels, and lamprey are particularly vulnerable to passage barriers because they need to move both upstream and downstream to complete their life cycles. Resident species are also adversely affected due to habitat fragmentation. Conversely, an unintended benefit of an impassable weir or culvert is that it may prevent invasive, non-native species from colonizing the stream system upstream. In such situations, removing the barrier could expose native species to competition and predation by invasive species. Also, as shown in Figure 2.22, if a perched culvert is preventing channel degradation from progressing upstream, this may benefit both infrastructure and habitats, although the passage barrier for fish and aquatic organisms remains. It follows that while a high degree of long-stream connectivity is usually a positive, it can be a negative. This evaluation depends on which river processes and functions are affected, the context within which they are connected or disconnected, and the consequences of changing their connectivity. In practice, decisions concerning where and when to restore long-stream connectivity are best informed by an interdisciplinary team including natural resource specialists that transportation agencies typically do not have on staff.

Evaluating trade-offs between enhanced long-stream connectivity and lateral connectivity (Section 2.4.2) is also not straightforward. For example, the benefits of restoring channel-floodplain connectivity to natural, pre-disturbance levels (Davies and Gibling 2010, Cluer and Thorne 2014), involve reducing long-stream connectivity. This type of restoration recreates a multi-channel-wetland-floodplain mosaic, but many fish biologists and engineers have concerns about potential loss of long-stream passage and sediment connectivity. Although the trade-offs are likely site-specific, Meyer (2018) provides evidence that reduced long-stream connectivity helps attenuate flood waves while storing sediment and wood without significantly impeding fish and other aquatic organism passage up- and downstream.

Overall, studies of long-stream connectivity indicate that temporal and spatial variations in the degree of connectivity result in complex river processes and dynamic but resilient river forms. Long-stream connectivity also supports long-stream fluxes of water, sediment, wood, nutrients, and organisms and provides for both biodiversity and valuable ecosystem services (Wohl 2017).

2.4.2 Lateral Connectivity

Examples of lateral connectivity include links between hillslopes and channels in headwater erosion zones, between terraces and channels in middle-course, transport zones, and channel–floodplain interactions in lowland, deposition zones. Lateral connectivity between the channel and its floodplain strongly influences river hydrology. When high flows can spread across a fully connected floodplain, flow stages are lowered compared to those in a confined channel, velocities are slowed, energy is dissipated, and flood waves are to some extent attenuated.

Lateral connectivity also significantly impacts sediment transport. For example, in streams with connected floodplains, large volumes of fine sediment are stored in the floodplain, but 50 percent or more of the downstream sediment yield may be supplied to the river through erosion and re-suspension of floodplain sediments. Laterally connected floodplains not only store sediment through deposition during floods, they also release it gradually through bank erosion during in-bank flows. In this way, lateral connectivity allows floodplains to act as capacitors in the sediment transport system, storing sediment at times of intense headwater erosion and sediment abundance, then releasing it again gradually.

Lateral connectivity is fundamentally important ecologically, and disconnection of the channel from its floodplain is partially responsible for loss of some of the conveyance, storage, evolution, habitat functions described earlier in this chapter, as well as reductions in ecosystem benefits in degrading channels (see Figure 2.18). Conversely, an intact and functional riparian corridor provides a permeable barrier between aquatic and floodplain habitats that modulates their connectivity to the benefit of both. For example, lateral connectivity allows floodwater in the channel to spread onto and through floodplain and wetland areas, moderating high stages and velocities in the channel, depositing fine sediments outside the channel, and infiltrating water into the hyporheic alluvial aquifer beneath the floodplain. During dry periods, lateral connectivity allows hyporheic return flow to supplement channel base flows.

However, many floodplains are not flat, and they do not flood or drain in any simple fashion. Lateral connectivity involves natural levees, levee backslopes, side channels, abandoned channels, and back swamps. These features are not only complex topographically due to the range of features they contain, but also because of the variability in vegetation as well, as illustrated in Figure 2.25.

Figure 2.25. Complex connected floodplain with bend cutoff, relic channels, erosion and deposition, infrastructure, and highly variable vegetation cover and land-use.

Floodplain evolution is driven by complex interactions between variable flows and sediment supplies, local erosion, transport and deposition, vertical and lateral movement of the channel, and riparian and floodplain vegetation. Imagine the channel-floodplain system shown in Figure 2.25 at some time in the past when channels that are now relict (i.e., remnant) were active. Now picture the changes that led to the current condition, and how continued evolution develops new channels and features in the future. Any year includes a range of discharges and sediment supplies, and some years include moderate to extreme floods. This variable energy input is met by channel boundaries with variable erosion resistance from differing materials and vegetation creating bank erosion, bar deposition, and meander migration. As channel bends migrate, they progress across- and down-valley, and periodically cut off. The cutoffs reduce channel lengths and increase channel slopes, accelerate local velocities, and create local imbalances of sediment transport capacity that result in localized adjustments to the bed topography. Vegetation colonizes newly exposed areas and new habitat areas are created as others are eroded. The complex and non-linear development and behavior of floodplains is vital to a range of river functions, but it is utterly dependent on lateral connectivity.

Lateral connectivity is greatest in undisturbed channel-wetland-floodplain systems (Figure 2.26a) that spread flood flows across the full width of the valley floor, so that unit stream power is very low. Stream power represents the rate at which the river can do work through, for example, scouring the bed, eroding the banks, or transporting sediment and large wood. It is estimated as the product of discharge, energy slope, and unit-weight of water. Unit stream power is stream power divided by the water surface width. When unit stream power is low, it promotes sediment deposition, wood retention, and nutrient cycling that roughen the floodplain, slow the flow, boost primary productivity, and increase biodiversity. Lateral connectivity is lost when the channel is isolated from its floodplain by artificial levees or road embankments (Figure 2.26b).

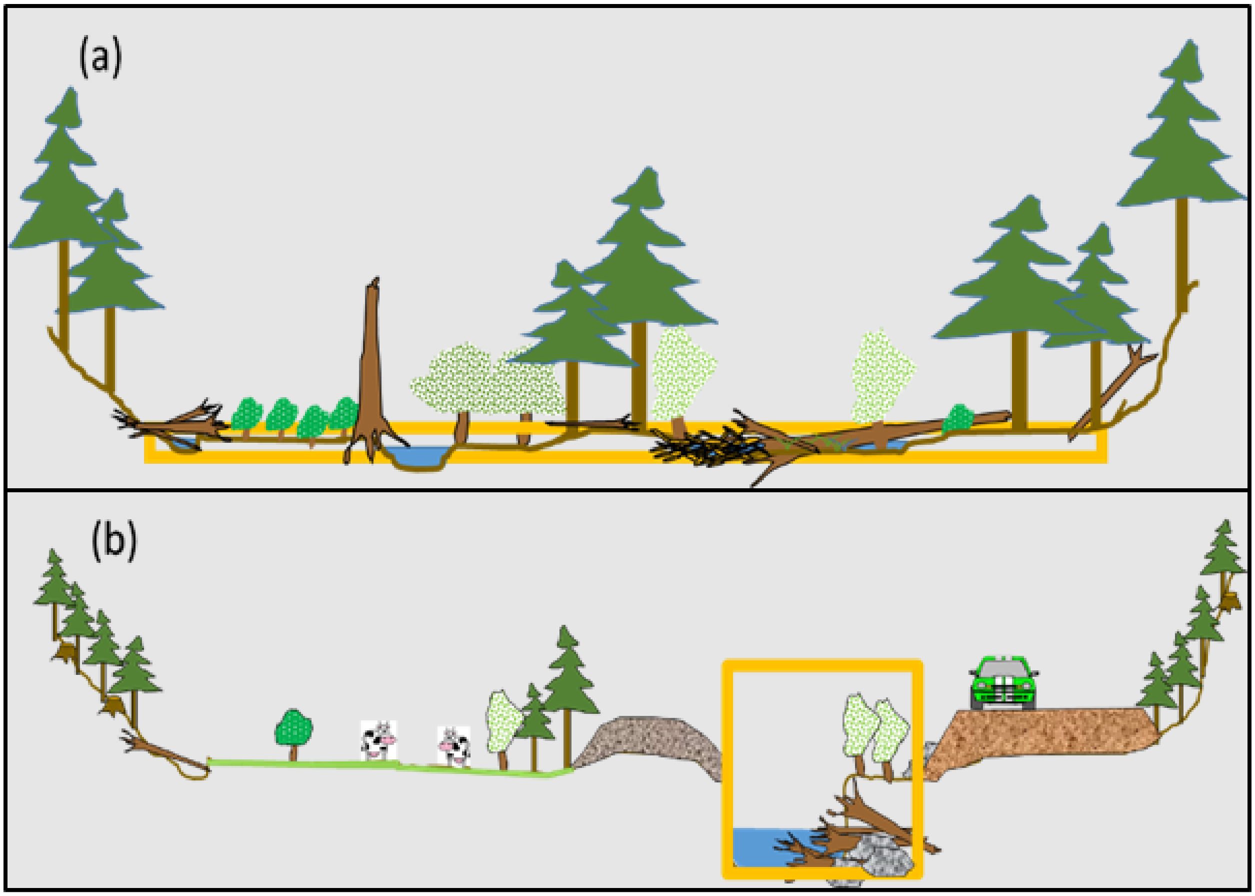


Figure 2.26. Streams with and without lateral connectivity. (a) Natural channel-wetland floodplain complex and (b) stream with encroaching roadway and levee. Source: Diagrams modified from the U.S. Forest Service (Hogervorst and Powers 2019).

In Figure 2.26, the area of the boxes indicates stream power, which is equal in the two images. The height of the box indicates unit stream power. Concentration of floodwater results in high unit stream power that may cause erosion, destabilize the channel (through incision and widening), and threaten adjacent roads and other infrastructure. Mitigation could involve the use of rock and large wood to build protective revetments. Further, as illustrated in (Figure 2.26b), a road running along the valley presents a barrier to animals seeking access to the river from the valley sides and uplands, increasing the risk of wildlife-vehicle collisions (Hubbard et al. 2000).

2.4.3 Vertical Connectivity

Vertical connectivity controls surface-subsurface interactions involving water, sediments, nutrients, and organisms. Hyporheic exchange exemplifies vertical connectivity, which is recognized as crucial to water quality (especially temperature improvement) and the richness and sustainability of river ecology.

Vertical movement of nutrients, leaf litter, large wood, and eggs (fish, aquatic insects, and invertebrates) into the bed, and fish fry and aquatic insects that emerge from the bed are vital early life stages. Vertical connectivity can (like lateral connectivity) improve water quality, modulate sediment dynamics, and affect hydrograph variability.

Alluvial streams comprise linked surface and sub-surface flows that act together as a unified whole (see Figure 2.2) and the hyporheic, alluvial aquifer is important to maintaining base flows during dry seasons and longer droughts. As illustrated in Figure 2.26, vertical connectivity has implications for lateral connectivity. Provided there is lateral as well as vertical connectivity, seepage can recharge the shallow aquifer beneath the floodplain, and inundation of the floodplain can occur through upward seepage and ex-filtration even before overbank flow occurs. Hydrating the floodplain this way benefits both natural ecosystems and floodplain farmers, though waterlogging and saturation of infrastructure foundations, including highways, may be an issue.

Vertical connectivity is generally assured when the channel bed and banks are formed in permeable, alluvial sediments such as clean sands, gravels, and cobbles because these allow hyporheic exchange, as illustrated in Figure 2.27a. But vertical connectivity is generally lost when alluvial bed materials are clogged by excessive deposition of silt-clay sized sediments, or where the channel is artificially lined with impermeable materials such as concrete (Figure 2.27b).

2.4.4 River Connectivity, Response, Resilience, Management, and Restoration

The resistance to change and recovery in a river reflects connectivity during and after a disturbance. An anabranched river that is fully connected to a broad, densely vegetated floodplain is resistant to change during a major flood because the flow spreads across a wide, topographically complex area, which not only stores water but also spreads and dissipates stream power. Therefore, high lateral connectivity creates resistance to channel destabilization.

Dominance of long-stream connectivity over lateral and vertical connectivity optimizes downstream floodwater conveyance and flood propagation. Conversely, a broad alluvial floodplain that is well connected to the channel laterally and vertically can provide substantial surface and shallow aquifer storage, mitigating long-stream, hydrologic connectivity and helping to “tame the flood.” In this way, lateral and vertical connectivity that mitigates long-stream connectivity can reduce downstream flood impacts on people, property, and infrastructure, including roads.

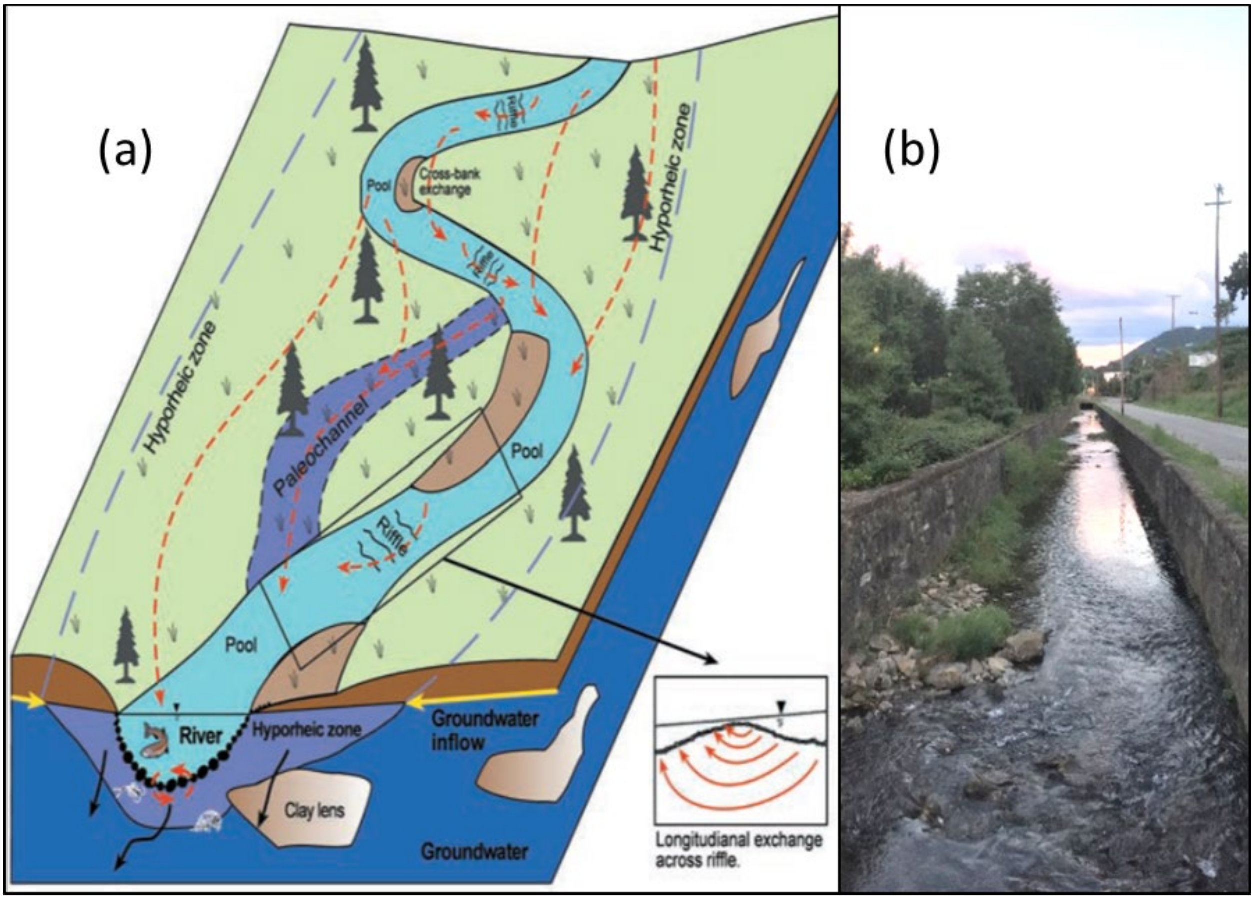


Figure 2.27. Presence and absence of vertical connectivity: (a) full vertical connectivity; (b) complete loss of vertical (and lateral) connectivity in the concrete-lined channel. Source: (a) John Buffington, U.S. Forest Service (b) U.S. Geological Survey, Virginia and West Virginia Water Science Center (photo credit: John Jastram).

Conversely, in an incised, laterally confined, gravel-bed stream with high long-stream connectivity, rapid downstream transport of mobile gravels could leave behind a bed armored by cobbles and boulders. In this case, excessive long-stream connectivity may lead to higher downstream flood risks, the potential for damage to in-stream and near-stream infrastructure, and loss of valuable benthic habitats.

Understanding long-stream, lateral, and vertical connectivity, and how the balance between them changes (especially during high and low discharge events) can help explain not only how other river functions operate, but also how the river is likely to respond to disturbance.

In practice, connectivity is dependent on whether the river corridor-floodplain system is spatially and temporally continuous or fragmented, homogeneous or variable, and wide or narrow. These attributes are likely to be dependent on the cumulative effects of historical development in the floodplain and wider watershed, and the legacies of previous river management and engineering actions.

As illustrated in Figure 2.28, development involving (A) encroachment by buildings, (B) bank stabilization, (C) artificial levees, and (D) dams all act to reduce lateral and long-stream connectivity. Roadways that cross floodplains or that parallel rivers can also reduce lateral and long-stream connectivity. Conversely, simplification of multi-channel planforms, channelization, and channel incision all act to hyper-increase long-stream connectivity, while decreasing or even eliminating lateral and vertical connectivity.

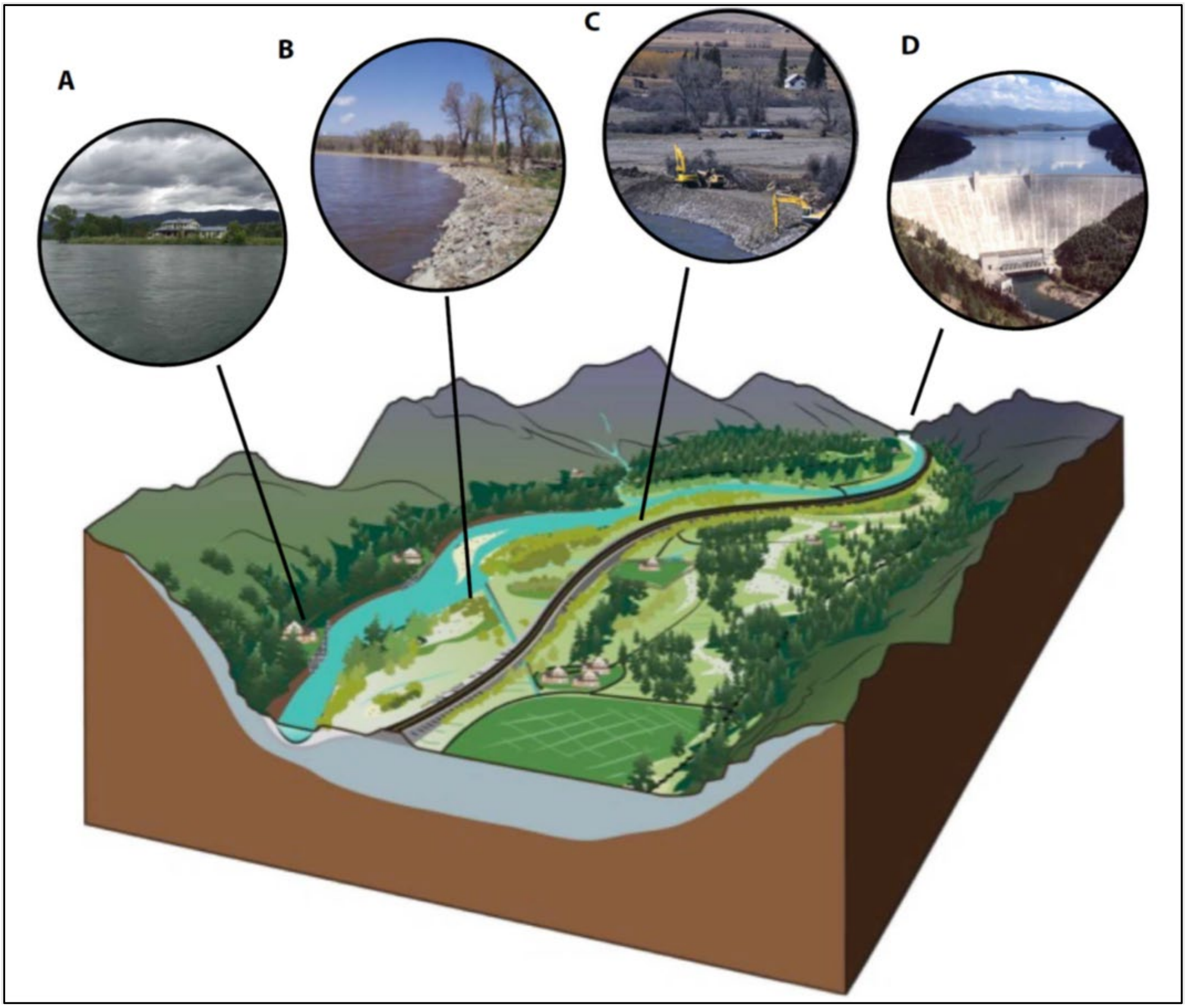


Figure 2.28. Loss of connectivity due to development and river engineering (see text for legend). Source: Hauer et al. (2016).

Prior to settlement and development, rivers with active floodplains naturally featured a fully connected, multi-channel-riparian-wetland-floodplain mosaic (see Figure 2.21). Under these conditions, primary productivity is maximized, and biodiversity reaches the highest levels possible. In addition, the food web is strong, supporting diverse habitats that create a home for riverine species ranging from the microbial to the mega and from the lowest rung on the trophic ladder to the top predator.

In many rivers, full floodplain connectivity was lost long ago and the floodplain cannot be reconnected for myriad practical reasons and constraints. Primary constraints include lack of right-of-way and extensive existing development in riparian and floodplain areas. However, where natural reconnection is possible, reconnection may bring significant return on investment in terms of improved river and floodplain functions. In many situations, partial reconnection can recover some specific functions, such as in-channel flow and sediment conveyance. However, full (or even partial) floodplain reconnection is itself a disturbance that potentially poses a risk to infrastructure.

Improving the connectivity river function can mitigate problems with erosion, deposition, flooding, and channel evolution, while improving road safety. It also can restore and maintain habitats, species, and eco-system functions in ways consistent with environmental regulations and societal values. However, it is important to remember that maximizing connectivity may not necessarily be the right thing to do. Natural rivers and their corridors feature multiple barriers, though many are to some extent permeable, and their functioning varies between flow stages and seasons. When considering improvements to connectivity, the aim is to identify what constitutes the right balance of long-stream, lateral, and vertical connectivity in a project reach and then set targets appropriately. This is best accomplished when highway engineers consult with other stakeholders and interest groups. Though challenging, stakeholder partnerships and multi-functional planning is worthwhile because it can deliver increased, long-term benefits through improved highway infrastructure resiliency and river ecosystem health.

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Chapter 3 - Federal Policy for Highways in the River Environment

Federal policy for highways in the river environment is at the nexus of two broad federal policy arenas:

- Highway engineering.
- River management.

Each of these influences the highway system throughout the country. This chapter provides background on these policy arenas, some applicable FHWA-specific statutes and regulations, and an overview of other Federal statutes and regulations that may affect highway projects in the river environment.

3.1 Federal Highways and Rivers: National Overview

The FHWA has the primary responsibility for Federal policy on highways. Legislation for the Federal road system dates back over a century. The Federal-Aid Road Act of 1916 created the Federal-Aid Highway Program, which funded state highway agencies so they could make road improvements “to get the farmers out of the mud.” This 1916 Act charged the Bureau of Public Roads with implementing the program. The growth of the Federal highway system, including the addition of the Interstate Highway System and concerns about how all these highways affected the environment, city development, and the ability to provide public mass transit, led to the 1966 establishment of the U.S. Department of Transportation (USDOT). The same enabling legislation renamed the Bureau of Public Roads to the FHWA. Currently, the FHWA continues to administer Federal policy on highways and coordinates extensively with other Federal agencies on environmental policies and permits, floodplains, and other compliance issues related to highway program and project delivery.

By contrast, Federal policy on river management is not concentrated in any one agency but dispersed over several according to historical missions. The Federal Emergency Management Agency (FEMA) oversees the National Flood Insurance Program (NFIP). The U.S. Fish and Wildlife Service (USFWS) and the National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) administer and enforce the Endangered Species Act (ESA). Almost every project involving work or activities in rivers is subject to the Clean Water Act (CWA) of 1972, which is administered by the U.S. Environmental Protection Agency (USEPA) in coordination with State governments.

3.2 FHWA Statutes and Regulations

The FHWA provides financial and technical assistance to State and local governments to ensure that the Nation’s roads and highways continue to be among the safest and most technologically sound in the world. The FHWA authority for the subject matter of this manual includes the following statutes and regulations. The section below provides a synopsis of these various authorities as well as pertinent Congressional findings and statements, policy, and guidance.

3.2.1 FHWA Statutes

The FHWA operates under the statutory authority of Title 23 (Highways) of the United States Code (U.S.C.). For the purposes of this manual, relevant sections include:

- **Standards [23 U.S.C. § 109].** It is the intent of Congress that Federally funded projects to resurface, restore, and rehabilitate highways shall “be constructed in accordance with standards to preserve and extend the service life of highways and enhance highway safety.” [23 U.S.C. § 109(n)]. Designs for new, reconstructed, resurfaced, restored, or rehabilitated highways on the National Highway System must consider, among other criteria, the “constructed and natural environment of the area.” [Id. at (c)(1)(a)].

- **Maintenance [23 U.S.C. § 116].** Preventive maintenance is eligible for Federal assistance under Title 23 if a State Department of Transportation (DOT) can demonstrate that it is a “cost-effective means of extending the useful life of a Federal-aid highway.” [23 U.S.C. § 116(e).]

- **National highway performance program [NHPP] [23 U.S.C. § 119].** The NHPP allows the FHWA to provide Federal-aid funds for “[c]onstruction, replacement …, rehabilitation, preservation, and protection (including … protection against extreme events) of bridges on the National Highway System.” [23 USC § 119(d)(2)(B)]. The NHPP also allows Federal-aid funds for “[c]onstruction, replacement …, rehabilitation, preservation, and protection (including … protection against extreme events) of tunnels on the National Highway System.” [Id. at (d)(2)(C)].

- **Surface transportation block grant [STBG] program [23 U.S.C. § 133].** The STBG program allows the FHWA to provide Federal-aid funds for protection of “bridges (including approaches to bridges and other elevated structures) and tunnels on public roads” including “painting, scour countermeasures, seismic retrofits, impact protection measures, security countermeasures, and protection against extreme events.” [23 U.S.C. § 133(b)(10)]. The STBG program also allows Federal-aid funds for “inspection and evaluation of bridges and tunnels and other highway assets.” [Id.]

- **Metropolitan transportation planning [23 U.S.C. § 134].** In the context of metropolitan transportation planning, Congress has found that it “is in the national interest … to encourage and promote the safe and efficient management, operation, and development of surface transportation systems … within and between States and urbanized areas” including taking “resiliency needs” into consideration. [23 U.S.C. § 134(a)(1)].

- **National bridge and tunnel inventory and inspection standards [23 U.S.C. § 144]**. Congress has found that “continued improvement to bridge conditions is essential to protect the safety of the traveling public.” [23 U.S.C. § 144(a)(1)(A)]. Congress has further found that “the systematic preventative maintenance of bridges, and replacement and rehabilitation of deficient bridges, should be undertaken.” [Id. At (a)(1)(B)]. In addition, Congress has also declared that “it is in the vital national interest” to use a “data-driven, risk-based approach” toward meeting these ends.” [Id. At (a)(2)(B)]. Considering these findings and declarations, Section 144 requires the FHWA to maintain an inventory of bridges and tunnels on public roads both “on and off Federal-aid highways.” [Id. at (b)]. The FHWA is also required to “establish and maintain inspection standards for the proper inspection and evaluation of all highway bridges and tunnels for safety and serviceability.” [Id. at (h)(1)(A).] Section 144 also provides an exception to the requirement to obtain a bridge permit from the U.S. Coast Guard for certain bridges over a limited subset of navigable waters. [Id. at (c)(2)].

- **National goals and performance management measures [23 U.S.C. § 150].** Congress has declared that it is “in the interest” of the United States to focus the Federal-aid highway program on certain national transportation goals including Infrastructure Condition, or the objective to “maintain … highway infrastructure in a state of good repair;” and System

Reliability, or the objective to "improve the efficiency of the surface transportation system." [23 U.S.C. § 150(b)].

- **PROTECT Program [23 U.S.C. § 176].** The Promoting Resilient Operations for Transformative, Efficient, and Cost-Saving Transportation (PROTECT) program allows the FHWA to provide grants for resilience improvements through: (i) formula funding distributed to States; (ii) competitive planning grants; and (iii) competitive resilience improvement grants. [23 U.S.C. § 176(b)]. Eligible activities under the PROTECT program include, among others, "resurfacing, restoration, rehabilitation, reconstruction, replacement, improvement, or realignment of" certain existing surface transportation facilities and "the incorporation of natural infrastructure." [23 U.S.C. §§ 176(c)(1) and 176(d)(4)(A)(ii)(II)].
- **Bridge Replacement, Rehabilitation, Preservation, Protection, and Construction Program (or Bridge Formula Program) (Division J, title VIII, Highway Infrastructure Program heading, paragraph (1)).** The Bridge Formula Program provides funding to help repair approximately 15,000 highway bridges. In addition to providing funds to states to replace, rehabilitate, preserve, protect, and construct highway bridges, the Bridge Formula Program has dedicated funding for Tribal transportation facility bridges as well as "off-system" bridges, which are generally locally-owned facilities not on the federal-aid highway system.
- **Bridge Investment Program (23 U.S.C. § 124).** The Bridge Investment Program provides financial assistance for eligible projects with program goals to improve the safety, efficiency, and reliability of the movement of people and freight over bridges; improve the condition of bridges; and provide financial assistance that leverages and encourages non-Federal contributions from sponsors and stakeholders involved in the planning, design, and construction of eligible projects.
- **National Culvert Removal, Replacement, and Restoration Grants Program (49 U.S.C. §§ 6703)].** The National Culvert Removal, Replacement, and Restoration Grant program established an annual competitive grant program to award grants to eligible entities for projects for the replacement, removal, and repair of culverts or weirs that would meaningfully improve or restore fish passage for anadromous fish.
- **Research and technology development and deployment [23 U.S.C. § 503].** In carrying out certain highway and bridge infrastructure and research and development activities, the FHWA must "study vulnerabilities of the transportation system to … extreme events and methods to reduce those vulnerabilities." [23 U.S.C. § 503(b)(3)(B)(viii)].

3.2.2 FHWA Regulations

The FHWA's regulations are found within the Code of Federal Regulations (CFR), Title 23, Highways (23 CFR). The FHWA requires compliance with Federal law and the regulations in Chapter I, Subchapter A, Part 1 of 23 CFR for a project to be eligible for Federal-aid or other FHWA participation or assistance. [23 CFR 1.36]. The following FHWA regulations apply to highway projects and actions interacting with and within rivers and floodplains (paraphrased for brevity):

Scope of the statewide and nonmetropolitan transportation planning process [23 CFR 450.206]. State DOTs must "carry out a continuing, cooperative, and comprehensive statewide transportation planning process that provides for consideration and implementation of projects, strategies, and services that will … improve the resiliency and reliability of the transportation system..." [23 CFR 450.206(a)].

Asset Management Plans [23 CFR 515]. Part 515 establishes processes that a State DOT must use to develop a transportation asset management plan (TAMP). Two notable provisions include:

- **Section 515.7(b).** "A State DOT shall establish a process for conducting life-cycle planning for an asset class or asset sub-group at the network level (network to be defined by the State DOT). As a State DOT develops its life-cycle planning process, the State DOT should include future changes in demand; information on current and future environmental conditions including extreme weather events, climate change, and seismic activity; and other factors that could impact whole of life costs of assets."
- **Section 515.7(c).** "A State DOT shall establish a process for developing a risk management plan. This process shall, at a minimum, produce the following information: (1) Identification of risks that can affect condition of NHS pavements and bridges and the performance of the NHS, including risks associated with current and future environmental conditions, such as extreme weather events, climate change, seismic activity, and risks related to recurring damage and costs as identified through the evaluation of facilities repeated damaged by emergency events carried out under part 667 of this title."

In addition, BIL Section 11105 amended 23 U.S.C. Section 119(e)(4) to require State DOTs to consider extreme weather and resilience as part of the life-cycle planning and risk management analyses within a TAMP (FHWA, 2022c).

Design Standards [23 CFR 625]. Part 625 describes structural and geometric design standards.

- **Section 625.3(a)(1) and § 625.4(b)(3).** The FHWA, in cooperation with SDOTs, has approved the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications. Based on the FHWA's approval, certain National Highway System (NHS) projects must follow those Specifications, including sections related to hydrology, hydraulics, and bridge scour.
- **Section 625.3(a)(2).** Non-NHS projects must follow State DOT standard(s) and specifications on drainage, bridges, and other topics.

Location and Hydraulic Design of Encroachments on Flood Plains [23 CFR Part 650, Subpart A]. One of the FHWA's important river-related regulations, 23 CFR Part 650, Subpart A sets forth policies and procedures for location and hydraulic design of highway encroachments in base (1-percent chance) floodplains. Section 650.111 sets forth requirements for location hydraulic studies to identify the potential impact of the highway alternatives on the base floodplain; these studies are commonly used during the NEPA process. The regulations prohibit significant encroachments on base floodplains unless the FHWA determines that such encroachment is the only practicable alternative. [23 CFR 650.113(a)]. This finding must be included in the NEPA documents for a project and supported information including the reasons for the finding and considered alternatives. [Id.]. The procedures also provide minimum standards for Interstate Highways, set freeboard requirements to account for debris and scour, and require highway encroachments to be consistent with certain established design flood standards for hydraulic structures, including standards from FEMA and State and local governments related to administration of the National Flood Insurance Program (NFIP). [23 CFR 650.115(a)]. Notably, the policies and procedures in this Subpart apply to encroachments in all base floodplains, not just the floodplains regulated by the Federal Emergency Management Agency (FEMA) in the NFIP. [23 CFR 650.107]. Additionally, the Subpart incorporates a requirement for project-by-project risk assessments or analyses. [23 CFR 650.115(a)(1)]. Notable sections include:

- **Section 650.103 [Policy].** This section states that "it is the policy of the FHWA: (a) To encourage a broad and unified effort to prevent uneconomic, hazardous or incompatible use and development of the Nation's flood plains, (b) To avoid longitudinal encroachments, where practicable, (c) To avoid significant encroachments, where practicable, (d) To minimize impacts of highway agency actions which adversely affect base flood plains, (e) To restore and preserve the natural and beneficial flood-plain values that are adversely impacted by highway agency actions, (f) To avoid support of incompatible flood-plain development, (g) To be consistent with the intent of the Standards and Criteria of the National Flood Insurance Program, where appropriate, and (h) To incorporate "A Unified National Program for Floodplain Management" of the Water Resources Council into FHWA procedures." [23 CFR 650.103]

- **Section 650.115 [Hydraulic Design Standards].** This regulation applies to all Federal-aid projects, whether on the NHS or Non-NHS. Federal, State, local, and AASHTO standards may not change or override the design standards set forth under § 650.115 — although certain State and local standards must also be satisfied under that section. That section requires development of a "Design Study" for each highway project involving an encroachment on a floodplain. [23 CFR 650.115(a)].
- **Section 650.117 [Content of Design Studies].** This regulation requires studies to contain the "hydrologic and hydraulic data and design computations." [23 CFR 650.117(b)]. As both hydrologic and hydraulic factors and characteristics lead to scour formation, data and computations applicable to scour should be provided as well. Project plans must show the water surface elevations of the overtopping flood and base flood (i.e., 100-year flood) if larger than the overtopping flood. [23 CFR 650.117(c)].

National Bridge Inspection Standards [23 CFR 650 Subpart C]. This regulation implements requirements of 23 U.S.C. § 144. In addition to the inspection and inventory requirements, the regulation specifically focuses on scour at bridges.

Mitigation of Impacts to Wetlands and Natural Habitat [23 CFR 777]. This regulation provides policy and procedures for the evaluation and mitigation of adverse environmental impacts to wetlands and natural habitat resulting from Federal-aid funded projects.

3.3 Other Federal Agency Statutes and Regulations

Civil engineering projects in the river environment are subject to numerous Federal laws, policies, and regulations. This section describes some of the most common Federal statutes, regulations, and other authoritative guidance that may apply to highway projects.

3.3.1 Rivers and Harbors Act of 1899 [33 U.S.C. § 401 and § 403]

River and coastal highway engineering projects are subject to Section 9 [33 U.S.C. § 401] and Section 10 [33 U.S.C. § 403] of the Rivers and Harbors Act of 1899. Section 9 of this Act restricts the construction of any bridge, dam, dike, or causeway over or in U.S. navigable waterways. Except for bridges and causeways under Section 9 [33 U.S.C. § 401], the U.S. Army Corps of Engineers (USACE) is responsible for maintaining the standards set by and for issuing permits under the Rivers and Harbors Act. Authority to administer Section 9, applying to bridges and causeways, was redelegated to the U.S. Coast Guard under the provisions of the Department of Transportation Act of 1966 (as discussed below).

3.3.2 General Bridge Act of 1946 [33 U.S.C. §§ 525-533]

The General Bridge Act of 1946 requires the location and plans of bridges and causeways across the navigable waters of the United States be submitted to and approved by the U.S. Coast Guard prior to construction. [33 U.S.C. § 525]. The USACE may also impose conditions relating to maintenance and operation of the structure. [Id.]. The General Bridge Act of 1946 is cited as the legislative authority for bridge construction in most cases. Although the General Bridge Act of 1946 originally provided authority for issuing bridge permits to the USACE, subsequent legislation transferred these responsibilities from the USACE to the U.S. Coast Guard.

3.3.3 Transportation Act of 1966 [Public Law 89-670]

The Transportation Act of 1966 transferred the U.S. Coast Guard (USCG) to USDOT.[1] One of USCG's newly assigned duties was to issue bridge permits. This, along with the Rivers and Harbors Act and General Bridge Act, made the USCG responsible for ensuring that bridges and other waterway obstructions do not interfere with the navigability of waters of the United States without express permission of the United States Government. Subsequent legislation amended 23 U.S.C. § 144 to provide certain exceptions to USGC's authority under 33 U.S.C. § 401 and 33 U.S.C. § 525 for bridges constructed, reconstructed, rehabilitated, or replaced using Federal-aid funds. [23 U.S.C. § 144(c)(2)].

3.3.4 National Environmental Policy Act [42 U.S.C. § 4321 et seq.]

The National Environmental Policy Act of 1969 (NEPA) establishes the continuing policy of the Federal government to use all practicable means and measures "to foster and promote the general welfare, … create and maintain conditions under which man and nature can exist in productive harmony, and fulfill the social, economic, and other requirements of present and future generations of Americans." [42 U.S.C. § 4331]. To achieve this goal, NEPA creates a requirement for Federal agencies to consider the environmental impacts of their actions before undertaking them. [42 U.S.C. § 4332(C)].

Section 102(2)(C) of NEPA requires Federal agencies to develop a detailed statement on proposals for major Federal actions significantly affecting the quality of the human environment. [42 U.S.C. § 4332(2)(C)]. Environmental impact statements address items including "the environmental impact of" and "alternatives to" the proposed action. [Id.] FHWA implements NEPA according to the Council on Environmental Quality (CEQ) NEPA regulations at 40 CFR Part 1500 et seq. and the FHWA-FRA-FTA joint regulations at 23 CFR Part 771.

3.3.5 Clean Water Act [33 U.S.C. §§ 1251-1387]

Almost every project involving work or activities in rivers is subject to the Clean Water Act (CWA) of 1972, which is administered by the U.S. Environmental Protection Agency (USEPA) in coordination with State governments. The CWA is the primary Federal statute governing protection of the Nation's surface waters. Engineering of highways in the river environment is often subject to Section 404 of the CWA, which regulates the discharge of dredged or fill material in waters of the United States, including wetlands. [33 U.S.C. § 1344]. This includes the use of dredged or fill material for development, water resource projects, and infrastructure development (e.g., roads, bridges, etc.). The USACE handles the day-to-day administration and enforcement of the Section 404 program, including issuing permits. In circumstances where Section 404 is triggered, permit applicants also obtain a Section 401 certification from the State in which the discharge of dredged or fill material originates. [13 U.S.C. § 1341]. The Section 401 certification

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[1] The 2002 Homeland Security Act, Public Law 107-296 (Nov. 25, 2002), placed USCG under the U.S. Department of Homeland Security.

assures that materials discharged to waters of the United States will comply with relevant provisions of the CWA, including water quality standards.

3.3.6 Endangered Species Act [16 U.S.C. §§ 1531-1544]

Highway engineering projects have the potential to impact Federally listed fish, wildlife, and plants. The purposes of the Endangered Species Act of 1973 (ESA) include conserving "the ecosystems upon which endangered species and threatened species depend" and providing "a program for the conservation of such endangered species and threatened species." [16 U.S.C. § 1531]. It is the policy of Congress that all Federal agencies shall seek to conserve endangered and threatened species and shall utilize their authorities in furtherance of the purposes of the ESA [Id.]. The U.S. Fish and Wildlife Service (USFWS) and the NOAA National Marine Fisheries Service (NMFS) administer the ESA. The USFWS and NMFS conduct consultations with the lead Federal agency when a proposed project may affect Federally endangered or threatened species. USFWS or NMFS involvement in a project depends on the affected species and the nature and extent of anticipated impacts (direct and indirect) to that species and its designated critical habitat. If anticipating a "take" of a Federally listed species, USFWS or NMFS will issue a biological opinion, the terms and conditions of which are binding on the lead Federal agency. [16 U.S.C. § 1536.]

3.3.7 National Historic Preservation Act [54 U.S.C. § 300101 et seq.]

River highway engineering projects are often subject to the National Historic Preservation Act of 1966 (NHPA). Section 106 of the National Historic Preservation Act (NHPA) (commonly called "Section 106") requires Federal agencies to consider the impacts on historic properties of projects that they carry out, approve, or fund. [54 U.S.C. § 306108]. The implementing regulations for the Section 106 process are found in 36 CFR Part 800. Those regulations provide that Federal agencies, in consultation with the Advisory Council on Historic Preservation, the State Historic Preservation Officers (SHPO), and certain other interested parties, identify and assess adverse effects to historic properties and seek ways to avoid, minimize, or mitigate those effects. [36 CFR § 800.4-800.6]. Under Section 106, "historic property" is defined as any prehistoric or historic district, site, building, structure, or object included in, or eligible to be included in, the National Register of Historic Places [36 CFR § 800.16(l)(1); see also 54 U.S.C. § 300311 and § 302102]. The responsibilities of SHPOs are set forth at 54 U.S.C. § 302303.

In addition to Section 106, Section 4(f) of the U.S. Department of Transportation Act of 1966 [23 U.S.C. § 138 and 49 U.S.C. § 303] requires that the FHWA not approve the use of historic sites for a project unless there is no prudent and feasible alternative and the project incorporates all possible planning to minimize harm, or any impacts to historic sites are determined to be *de minimis*. The FHWA's regulations for implementation of Section 4(f) are found at 23 CFR part 774.

3.3.8 National Flood Insurance Act of 1968 [42 U.S.C. § 4001 et seq.]

The National Flood Insurance Act of 1968 instituted the National Flood Insurance Program (NFIP) to help indemnify and reduce impacts associated with floods. The NFIP adopted the area subject to a 1 percent chance or greater of being flooded in any given year (also known as the 100-year flood) as the standard, or base flood, for mapping floodplains. [See, e.g., 44 CFR § 9.4]. The area inundated by the 100-year flood determines the Special Flood Hazard Area (SFHA) on Flood Insurance Rate Maps (FIRMs) developed by FEMA and used to determine flood insurance rates for structures. [See, e.g., 44 CFR § 59.1, which defines "area of special flood hazard"]. FEMA implements the NFIP using its regulations found in Title 44 of the CFR.

The FHWA's policies require projects to be consistent with the Standards and Criteria in the NFIP, where appropriate. [23 CFR § 650.115(a)(5)]. To assist State DOTs in complying with this policy, the FHWA developed coordination procedures for Federal-aid highway projects with encroachments in NFIP-regulated floodplains. FEMA agreed to these procedures by signing a 1982 Memorandum of Understanding with the FHWA.

3.3.9 Wild and Scenic Rivers Act [16 U.S.C. § 1271 et seq.].

This Act establishes a policy to preserve designated rivers "in free-flowing condition" and to protect "their immediate environments … for the benefit and enjoyment of present and future generations." [16 U.S.C. § 1271]. Section 7(a) provides that "no department or agency of the United States shall assist by loan, grant, license, or otherwise in the construction of any water resources project that would have a direct and adverse effect on the values for which such river was established." [16 U.S.C. § 1278(a)]. A water resources project is "any dam, water conduit, reservoir, powerhouse, transmission line, or other project works under the Federal Power Act ... or other construction of developments which would affect the free-flowing characteristics of a Wild and Scenic River or Study River." [36 CFR § 297.3]. "Federal assistance means any assistance by an authorizing agency including, but not limited to, ... [a] license, permit, or other authorization granted by the Corps of Engineers, Department of the Army, pursuant to the Rivers and Harbors Act of 1899 and section 404 of the Clean Water Act (33 U.S.C. § 1344)." [Id.]

3.3.10 Fish and Wildlife Coordination Act [16 U.S.C. §§ 661-666c]

The Fish and Wildlife Coordination Act (FWCA) requires adequate consideration for the "conservation, maintenance, and management of wildlife resources" whenever the "waters of any stream or other body of water are impounded, diverted, the channel deepened, or the stream or other body of water otherwise controlled or modified for any purpose … including navigation and drainage, by any department or agency of the United States. [16 U.S.C. § 663(a)]. This generally includes consultation with the USFWS, the NMFS, and State wildlife agencies for activities that affect, control, or modify waters of any stream or bodies of water in order to minimize the adverse impacts of such actions on fish and wildlife resources and habitat. This consultation is generally incorporated into the process of complying with Section 404 of the Clean Water Act, NEPA, or other Federal permit, license, or review requirements.

3.3.11 Migratory Bird Treaty Act [16 U.S.C. § 703 et seq.].

The protection of all migratory birds is governed by the Migratory Bird Treaty Act (MBTA) [16 U.S.C. §§ 703-712], which generally prohibits the take of any migratory bird or any part, nest, or eggs of any such bird. [16 U.S.C. § 703(a)]. Under the MBTA, it is illegal to "take, kill, possess, transport, or import migratory birds or any part, nest, or egg of any such bird" unless authorized by a valid permit from the USFWS. [Id.]. The regulation 50 CFR § 10.13 includes a list of migratory birds protected by the Migratory Bird Treaty Act (MBTA).

3.3.12 Marine Mammal Protection Act [16 USC §§ 1361-1407]

The Marine Mammal Protection Act (MMPA) protects all marine mammals within the waters of the United States and on the high seas. Implementation of MMPA is jointly shared by NMFS, USFWS, and the Marine Mammal Commission, which provides independent oversight of Federal agencies under the MMPA. The MMPA prohibits, with certain exceptions, the "take" of marine mammals in United States waters and by United States citizens on the high seas, and the importation of marine mammals and marine mammal products into the United States. [16 U.S.C. § 1372]. This means people may not harass, hunt, capture, or kill any marine mammal unless authorized or exempted. [16 U.S.C. § 1362]. The MMPA also includes other prohibitions related to marine mammals. [16 U.S.C. § 1372]. Authorizations and exemptions from these prohibitions are available for certain specified purposes. [See, e.g., 16 U.S.C. § 1374]. Any marine mammal listed as an endangered or threatened species under the ESA automatically has depleted status under the MMPA, which triggers further restrictions.

Context for Resilient Highways in the River Environment

Federal statutes and regulations establish the "guard rails and signage" (or legal framework) for the development of transportation infrastructure in the river environment. The Federal policies reflected in these statutes and regulations serve both to facilitate the movement of people and goods and to sustain the functions of the Nation's rivers and floodplains. Taken together, these statutes and regulations, administered by multiple Federal agencies, reflect national values for economic well-being and environmental stewardship. This manual provides information on methods and tools to realize these values in the planning, development, maintenance, and operation of the Nation's transportation infrastructure.

Chapter 4 - Transportation Development

This chapter describes how the planning, design, construction, and maintenance phases of a transportation project can benefit from addressing the full range of river functions. Decisions made at any of these stages may influence the risks, resilience, and reliability of the infrastructure. This chapter describes the transportation development process and early assessment for planning and preliminary design. It also discusses environmental impacts, impact avoidance, and impact mitigation. Finally, the chapter describes ways to develop more sustainable and resilient projects by considering lessons from nature and by accounting for potential effects of climate change and basin modifications on hydrology, sediment supply, channel evolution, and river ecology.

4.1 Transportation Project Development Process

To develop transportation infrastructure projects in the river environment, professionals from a variety of disciplines work together, drawing on a broad understanding of river and floodplain functions to increase safety and reliability, avoid adverse environmental impacts, accomplish project permitting, and minimize costs. Multidisciplinary team members can reduce overall project risk and enhance reliability and resilience by considering river and floodplain functions at each stage of project development. By thoroughly documenting work conducted in each phase of project development and centrally archiving involved project data, teams can facilitate work efforts for succeeding project phases and possible future projects.

Whatever their setting and scale, transportation projects—from new road alignments to more common replacements, upgrades, and enhancements of existing transportation infrastructure—follow a process like that shown in Figure 4.1. While each phase of a transportation project involves many activities and deliverables, work generally occurs in four stages: planning, design, construction, and maintenance/operations. In some cases, monitoring for compliance with environmental commitments continues after construction is completed. Inspection of bridges, culverts, and other structures may also be part of the post-construction process. Monitoring and inspection are generally well integrated with ongoing operations and maintenance activities, but as is discussed in Section 8.11, can be further developed to provide added benefits to improve the design process, avoid environmental impacts, inform adaptive management, and increase project sustainability.

As Figure 4.1 illustrates, the typical development phases are not completely discrete and linear. Each phase represents its own decision-making cycle, and these interrelated cycles shape the activities and decisions of future stages in the project development process. As State DOT staff consider the full life cycle of transportation assets in accordance with their asset management plans), decisions they make on a given project may help shape future transportation investment choices on other projects. This is particularly true in the river environment, where encroachment in one area of a floodplain could disrupt river functions and impact the safety, reliability, and resiliency of other transportation assets.

Consistent with FHWA statutes and regulations described in Section 3.2, project teams identify improvements for the transportation system and integrate them with local, State, and Federal transportation programs during project planning. They develop a business case for the project, conduct scoping to gather and evaluate details regarding project goals and features, identify project risks, develop a project investment strategy, and determine project responsibilities. Early consultation with regulators and permitting organizations can identify potential issues and incorporate solutions prior to the design process.

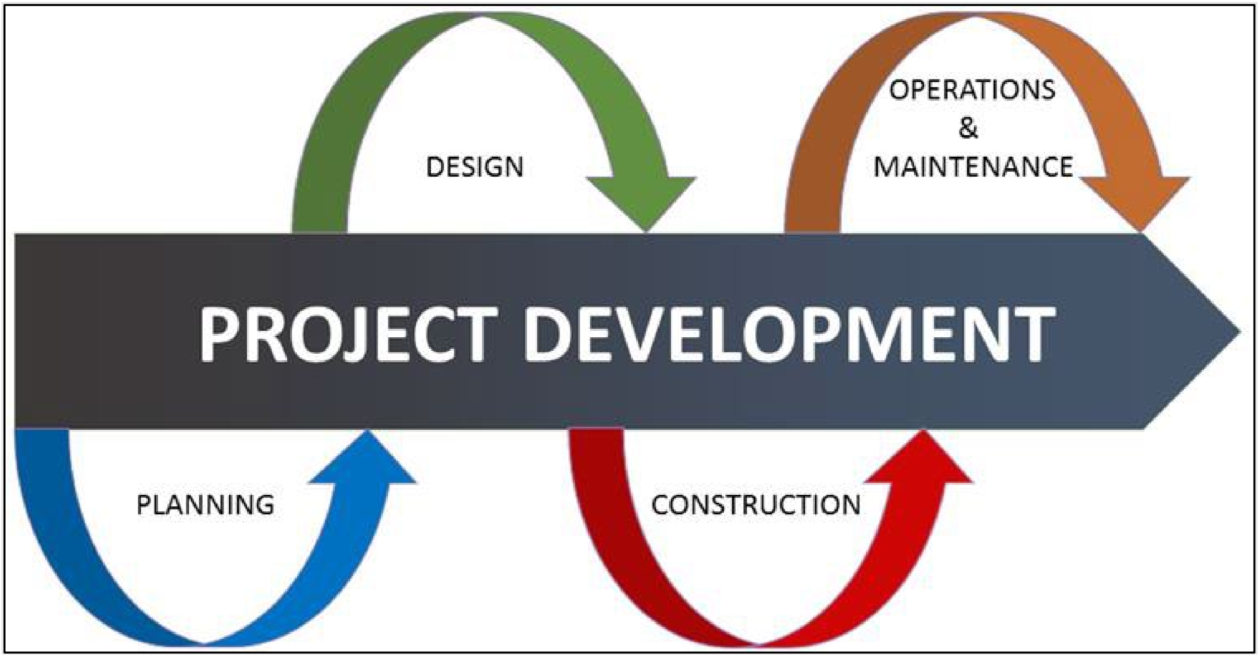


Figure 4.1. Typical transportation project development process.

These activities inform the scope and timing for project implementation. During the planning phase, the project lead and other team members can most easily and effectively identify and avoid long-term problems and "high-regret" decisions associated with undertaking transportation infrastructure projects in the river environment. Section 4.2 discusses early assessment strategies useful for avoiding such high-regret decisions.

The planning phase also presents an opportunity to consider the relationship of a proposed project in the river environment to system-wide strategies and policies for the transportation network, including, for example, ways to advance equity in transportation, promote resilience to a changing climate, and reduce transportation emissions (USDOT, 2022; USDOT, 2021; FHWA 2021). General strategies and policy documents related to advancing transportation equity and promoting resilience on FHWA projects are referenced in Chapter 1 of this manual above. Carbon Reduction Strategies are required by 23 U.S.C. 175(d)(1) and discussed in the FHWA Carbon Reduction Program (CRP) Implementation Guidance. (FHWA, 2022b).

Although processes vary by jurisdiction, when a transportation infrastructure project enters the design phase, a project team formalizes the project scope, schedule, and budget according to the determinations made during project planning. They oversee the development of construction plans and specifications, detailed project construction cost estimates, and eventually selection of the construction team. They also facilitate communication and collaboration between the multi-disciplinary professionals involved at this stage, including senior leadership, engineering and technical experts, environmental experts, and representatives from partnering agencies. In addition, involving operations and maintenance personnel at the beginning of the design phase allows the project team to evaluate maintenance concerns as part of the design process. The project team ensures that all details for construction, including acquiring permits, clearances, easements, and right of way, are considered. Experience has proven that early consultation with relevant Federal and State permitting agencies, particularly for projects with potentially significant environmental impacts, makes the project development process more efficient and reduces the risk of misunderstandings and avoidable project delays.

Transportation professionals involved in the design phase face many decision points regarding how to best avoid, minimize, and mitigate potential impacts on the environment. The project team is more likely to succeed in developing and ensuring adherence to a detailed scope of work and budget by drawing on the expertise of appropriate technical disciplines regarding the geomorphic setting of the project and the physical processes and the expected response of the river to the project.

State Spotlight: Oregon Delivers Hundreds of Bridge Projects with One Programmatic Permit

Between 2004 and 2014, the State of Oregon repaired or replaced hundreds of aging bridges with a single environmental permit (AASHTO 2021), resulting in on-time delivery of the program, cost savings, and creation of environmental and fluvial performance standards still used in streamlined permitting (ODOT 2021).

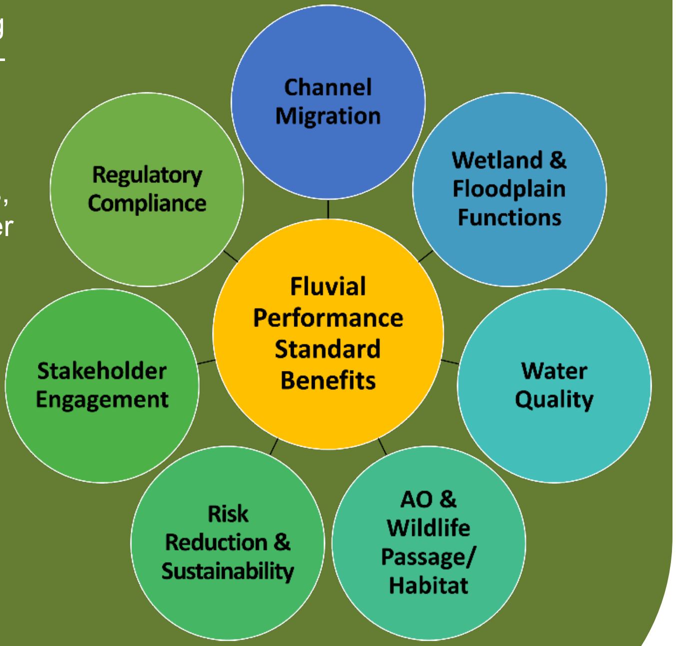
When the Oregon Transportation Investment Act (OTIA III) authorized the Statewide Bridge Delivery Program to repair/replace up to 430 bridges within 10 years, the ODOT realized that project-by-project permitting was infeasible. The lead Federal action agencies (FHWA and the USACE) therefore requested consultation with Federal regulators (NMFS and USFWS) and preparation of a single Biological Opinion (BO) for the entire program (FHWA and USACE 2004).

A crucial part of the consultation was crafting environmental and fluvial performance standards for bridges designed to avoid/minimize impacts to 37 ESA-listed species, while keeping projects constructable and affordable (Bonoff et al. 2006). As well as providing coverage under the Federal ESA, the single, programmatic BO also covered the requirements for the Oregon ESA, Migratory Bird Treaty Act (MBTA), Marine Mammal Protection Act (MMPA), Magnuson-Stevens Fishery Conservation and Management Act (MSA), and Fish and Wildlife Coordination Act (ODOT 2007).

By reducing completion time by two years, this streamlined permitting made the statewide program feasible, and ODOT estimated cost savings at around $54 million. The bridge program saved a further $21.3 million through construction material reuse/recycling (ODOT 2015), with the potential for additional savings on bridge maintenance over the longer term (Cummings and Pyles 2013).

The Federal Aid Highway Program (FAHP) and Standard Local Operating Procedures for Endangered Species – Stormwater, Transport & Utilities (SLOPES STU) programmatic BOs have both adopted the OTIA III environmental performance standards, and between them they currently cover most Oregon bridge projects (ODOT 2021).

The story of Oregon's Statewide Bridge Delivery Program shows that once the relevant Federal and State regulators and action agencies agree on environmentally acceptable performance standards, they can apply them programmatically to cover a wide range of highway bridge projects, saving State DOTs both time and money.



The construction phase of a transportation infrastructure project brings several new professional roles to the multidisciplinary team including a construction project coordinator, contract administrator, construction project engineer, and construction workers. This construction team builds the project in accordance with the plans and specifications of the final design. In this phase, the design and construction teams play a part in: 1) minimizing disturbance of the riparian corridor, 2) managing pollution from construction site runoff and sediment production, 3) adhering to project permits, 4) revegetating areas impacted by construction disturbance with appropriate native vegetation, and 5) protecting against introduction and establishment of invasive species.

Once construction of the infrastructure project is complete, a new team adopts responsibility for ongoing operations and maintenance (O&M) activities. In addition, the newly constructed project represents a new asset to be effectively managed for the long term. O&M team goals vary by jurisdiction and asset type but are generally to ensure the safe, reliable, and effective performance of the project throughout its service life. O&M activities may include monitoring and reporting of long-term project operation and site conditions (e.g., success of site revegetation measures) and periodic maintenance to ensure project performance. Collection and evaluation of monitoring data provides insights regarding the efficacy of the transportation project development process. Lessons learned from evaluation of monitoring data may be used to beneficially modify or improve the project development process and benefit future projects.

Transportation Asset Management (TAM) and Life Cycle Planning (LCP)

Asset management is a strategic process for managing physical assets in a state of good repair over their lifecycle at minimum practicable cost. The FHWA and others have developed resources to aid in TAM and LCP:

https://www.fhwa.dot.gov/asset

https://www.tam-portal.com

https://www.fhwa.dot.gov/asset/pubs.cfm?thisarea=risk

Common constraints in the project development process that can lead to ineffective protection of river functions and undesirable solutions include the following:

- Incomplete project scoping.
- Poorly identified project goals and objectives.
- Incomplete or poor-quality data, such as hydrologic, topographic, or geotechnical.
- Limited right-of-way.
- Incomplete design criteria.
- A flood or drought before establishment of project revegetation.
- Lack of budget for project monitoring and adaptive management.
- Not involving the correct specialists and entities.
- Poor communication with interdisciplinary team, stakeholders, or partners.

4.2 Early Assessment

Early assessment of potential conflicts between planned transportation infrastructure and the river and floodplain environments during the planning phase informs decisions and actions taken in the design, construction, and operations and maintenance phases. Given the benefit of early awareness of these potential conflicts, maximizing the efficiency of this process is of paramount importance. Not only does efficient early awareness improve project delivery and outcomes, it also supports the FHWA's goal of promoting resilience in the Nation's transportation infrastructure. (USDOT, 2021). Indeed, FHWA encourages consideration of climate change and sustainability throughout the planning and project development process, including the extent to which projects align with the President's greenhouse gas reduction, climate resilience, and environmental justice commitments. (FHWA 2021; USDOT, 2021; USDOT, 2022).

It is important to consider climate change impacts and adaptation early in the project development process to ensure that climate resilience is incorporated into the project design to the extent possible and appropriate. Exploratory engineering-informed adaptation evaluations can have the greatest impact on the design features of the project when conducted early in the project development process (FHWA 2017a).

The early assessment process begins with a review of applicable design criteria, as well as Federal, State, local, and other applicable criteria and regulations to identify potential issues that could impact project delivery. At this stage, the project team generally considers the constraints on the design and permitting of the project and modifies the project, as appropriate. State DOTs maintain design manuals that highlight Federal and State design criteria, regulations, and permitting information. Design manuals from local entities may also be available for review. There are also several useful references available related to environmental considerations, including Synchronizing Environmental Reviews for Transportation and Other Infrastructure Projects: 2015 Red Book (FHWA 2015b) as well as the FHWA's Environmental Review Toolkit website (www.environment.fhwa.dot.gov/).

4.2.1 Right-of-Way

Project right-of-way (ROW) needs are an important early consideration. ROW information can be overlain on aerial photography to assess whether a planned project is likely to fit within the existing ROW. Highway encroachments in rivers and floodplains may necessitate grading or scour protection that exceeds existing ROW. Thus, these activities may result in the acquisition of temporary easements or additional permanent ROW. If a project schedule does not allow for this time-intensive acquisition process, or if budget is not available for needed acquisition, then the project can consider alternatives.

4.2.2 Floodplains

This section provides a broad overview of certain laws administered by FEMA. It is not intended as a definitive interpretation of that agency's authority.

Once the delineating geographic extents of the planned project, planners can consider floodplain permitting. Local floodplain administrators are a critical source of information about their codes and whether any floodplain mapping revisions are planned or underway that could impact the project. Specifically, 23 CFR § 650.111(f) states, "Local, State, and Federal water resources and flood-plain management agencies should be consulted to determine if the proposed highway action is consistent with existing watershed and flood-plain management programs and to obtain current information on development and proposed actions in the affected watersheds." The *National Flood Insurance Program (NFIP) Floodplain Management Requirements, A Study Guide* *and Desk Reference for Community Officials*, U.S. Department of Homeland Security (FEMA (2005)) is a comprehensive reference that provides in-depth information on the FEMA floodplain permitting process for community officials and is a useful resource during the permitting process. The FEMA NFIP floodplain permitting coordination can be rather time consuming and require several stages of regulatory and programmatic reviews and approvals. Planners may consider feasible trade-offs, such as no-rise certifications and other approaches, if applicable. The FEMA describes some of the processes in their “Instruction for MT-2 Forms” document (FEMA 2018).

It is important to determine if a proposed project could include floodplain permitting coordination with FEMA through a conditional letter of map revision (CLOMR), if the local floodplain administrator(s) can issue the floodplain permit(s) after approving a no-rise certification, and whether a letter of map revision (LOMR) is required. [See 44 CFR §§ 60.3, 65.12, 72.1, 77.2, 72.4]. The CLOMR and LOMR processes can be very time consuming, so planners may want to consider feasible trade-offs in the design to expedite the floodplain permitting through a no-rise certification rather than a CLOMR and potentially avoid a LOMR.

A planned project can be significantly influenced by the presence of insurable structures because the CLOMR process does not allow the applicant to increase base flood elevations on insurable structures [44 CFR § 65.12(a)(5)]. FEMA defines a structure, “for floodplain management purposes,” as “a walled and roofed building, including a gas or liquid storage tank, that is principally above ground, as well as a manufactured home.” [44 CFR § 59.1]. FEMA defines a structure, “for insurance purposes,” as (1) a “building with two or more outside rigid walls and a fully secured roof, that is affixed to a permanent site;” (2) a “manufactured home” (also known as a mobile home), or “a structure: built on a permanent chassis, transported to its site in one or more sections, and affixed to a permanent foundation;” or (3) a “travel trailer without wheels, built on a chassis and affixed to a permanent foundation, that is regulated under the community's floodplain management and building ordinances or laws.” [Id.].

CLOMR applications also include documentation that the planned project complies with the Endangered Species Act (ESA) of 1973, among other approvals required by Federal or State law, before FEMA initiates review [44 CFR § 60.3(a)(2)]. This process is clarified in Instruction for MT-2 Forms (FEMA 2018).

4.2.3 Geotechnical

Geotechnical considerations can be important drivers of construction cost and schedule. In particular, the elevation of the groundwater table relative to bridge foundations and the presence and elevation of bedrock could influence considerations for foundations and scour. Identified slope hazards are also important design considerations. If the planned project is a replacement of existing infrastructure, the as-built drawings of the existing structure may include boring logs that identify groundwater elevation and bedrock. Bedrock can impact foundation designs, as well as scour estimates and countermeasure designs. Regional studies or geologic mapping are other potential sources that could allow for early identification of bedrock, and site reconnaissance may reveal bedrock outcrops in the channel bed and banks.

4.2.4 Channel Stability

HEC-20 (FHWA 2012a) explains that planners should generally consider channel stability before advancing to more-detailed examinations of hydrology and hydraulics. Not only can structure problems from channel change be avoided, but also potential impacts on river function can be considered to evaluate whether they can be avoided. Where problems cannot be avoided, steps can be taken to minimize, counter, and mitigate.

As an initial step, a review of recent and historical imagery can quickly inform an understanding of channel and floodplain conditions, and specifically whether they present opportunities or constraints on the planned project. If the planned project is to replace existing infrastructure, inspection records can quickly reveal if there are progressive changes, such as bank erosion, channel widening, or bed degradation. Bridge owners maintain inspection records and can make them available for review. Site reconnaissance provides valuable insights on channel stability. Section 5.4 of HEC-20 (FHWA 2012a) provides details on methods for a rapid assessment of channel stability.

4.2.5 Hydrology and Hydraulics

Applicable design standards, criteria, regulations, and project permitting identify the hydrologic design events for the project. For example, a project may need an estimate for a 2-percent annual exceedance probability (AEP) for a design flow. One rapid way to estimate the magnitude of design flows is to search available hydrologic studies and reports, particularly if the planned project is to replace an existing structure. Potential available studies include design reports, reports on hydrology at nearby structures and FEMA flood insurance studies. Where these resources do not exist, regional regression equations that relate watershed characteristics to peak flow are useful tools to quickly estimate design flow magnitudes. HDS 2 (FHWA 2002) and HEC-17 (FHWA 2016) are resources for evaluating the magnitudes of design flows. Many State DOTs publish regional regression equations applicable to their state in their design manuals.

Hydraulic information, particularly depths and velocities associated with design flows, is used to estimate structure dimensions and elevations to provide suitable clearance between the design water surface elevation and the lowest elevation of the structures hydraulic opening, such as the low chord elevation of a bridge deck. This clearance is typically a criterion for hydraulic structure design. The design water surface elevation determined from hydraulic analysis is also used to determine whether a structure, such as a bridge or culvert, or associated roadway approaches may be at risk of overtopping during a flood. Hydraulic information is typically used to evaluate the adequacy of existing and proposed structures relative to current design criteria. A numerical hydraulic model may be available for an existing structure, and reach-scale hydraulic information may be available from FEMA or the local floodplain administrators. New hydraulic models based on the most current information are typically used for design of new hydraulic structures.

4.2.6 Habitat and Vegetation

Project teams can conduct an early assessment of existing habitat types and associated vegetation to determine potential interactions, issues, and permitting. Common rapid assessments for primary habitat types include hydrogeomorphic (HGM) assessment (Brinson et al. 1995, Wilder et al. 2012) and rapid assessment method (RAM). HGM is primarily concerned with wetland habitat while RAM methods evaluate "ecological status of riverine, wetland, and riparian areas" (Brinson et al. 1995). These methods may include a Floristic Quality Assessment (FQA) component, in which the abundance of native vegetation is used as a marker of ecological integrity. Several states including New Mexico (NMRAM), Ohio (ORAM), Colorado (Colorado Vegetation Index of Biotic Integrity), and California (CRAM) developed specific RAM programs that may include assessment in relation to the Clean Water Act (Muldavin et al. 2011, Mack 2001, Rocchio 2007, CWMW 2013). Evaluations include landscape, biotic, and abiotic metrics and many sites can be evaluated in a half day to a day, per the RAM protocol.

Conservative Plants? Plant Communities as Indicators of Biotic and Abiotic Processes

Floristic Quality Assessment (FQA) uses botany to assess the ecological integrity of a region based on plant species composition (Freyman et al. 2015). Analysis is based on determining "coefficients of conservatism" (C values) for individual plant species in the area based on their tolerance to degradation and the degree to which the species is faithful to natural remnant habitats (Freyman et al. 2015). The proportion of conservative plants in a plant community is an important marker of the area's ecological integrity (Wilhelm and Ladd 1988) and can be a valuable tool for wetland assessment and monitoring.

Landscape factors include adjacent and buffer land use, as well as riparian corridor connectivity. Biotic metrics evaluate vegetation community, diversity, structure, and presence of non-native vegetation in riparian and wetland habitats. Abiotic metrics that are evaluated include hydrologic connectivity, microtopography of fluvial geomorphic features, channel and stream bank stability, and soil condition. Evaluation of these metrics is discussed in Section 4.3. The vegetative community can be evaluated in relation to the abiotic factors to determine current stress on vegetation, stability of vegetation to help reduce erosion, and potential changes based on proposed project conditions.

Landscape, biotic, and abiotic factors provide input on the current ecological status of the site and a baseline for evaluating project design needs, impacts, and mitigation. A monitoring team can reassess the site in the future for comparison to original conditions and evaluate biological health.

4.3 Environmental Impacts

Planning, designing, and constructing transportation projects in compliance with environmental regulations and permit conditions contributes to the avoidance of some adverse environmental impacts and conservation of existing river functions. Some environmental impacts may not be avoidable and, therefore, result in mitigation actions. Avoidance begins with recognizing the role of encroachments in impacts, the types of impacts possible, and the sensitivity of different river types to impacts.

4.3.1 Encroachments and Environmental Impacts

Impacts on the river environment begin when construction of a highway encroaches on some part of the river channel, riparian corridor, channel migration zone, or floodplain. Direct impacts end when construction is completed, but short-term responses to disturbance of river forms and processes may generate further impacts following construction. Long-term responses to interactions between the river and the road may also occur and can continue for decades, leading to complex changes to river processes, forms, and functions that may be irreversible. Water quality impacts from roadway pollutants and increased flow volumes may be long-term. Changes in water temperature may result in riparian vegetation loss with short- or long-term impacts depending on revegetation actions.

Encroachment into the river environment occurs most obviously at road crossings (culverts, bridges, fords) but also occurs where the location and alignment of a highway causes a longitudinal stream encroachment. Road crossing encroachments may constrict conveyance causing increased flow velocities and sediment transport potential. These effects, in turn, can have impacts on erosion and scour, and resulting impacts to channel migration and transportation infrastructure stability. The constriction can also induce backwater effects (increased water surface elevation upstream of a constriction) that influence flood risks to surrounding areas, potentially affecting land uses such as residences, roads, agriculture, and habitat. Encroachments may also alter sediment deposition patterns and duration of inundation that can affect vegetation in the floodplain. The environmental impacts of encroachments are amplified if the road crossing approaches or longitudinal encroachments are raised or stabilized further impacting connectivity.

Encroachments are also often a significant issue for aquatic and terrestrial organism habitat and passage. Passage impacts may be problematic during low and normal in-channel flows but are often exacerbated during floods. Habitat impacts in designated special aquatic sites are preferably avoided. Special aquatic sites are geographic areas, large or small, possessing special ecological characteristics of productivity, habitat, wildlife protection, or other important and easily disrupted ecological values. These areas are generally recognized as significantly influencing or positively contributing to the general overall environmental health or vitality of the entire ecosystem of a region. [40 CFR 230.3(m)]. Special aquatic sites may include wildlife sanctuaries and refuges, wetlands, mud flats, vegetated shallows, coral reefs, and riffle and pool complexes.

In addition to a highway's impact on the river and its environment is the impact of changes in the river and its environment on the highway. Usually, adverse environmental impacts go hand in hand with adverse impacts on the highway due to river instability and environmental degradation.

4.3.2 Environmental Impact Types

Inter-related environmental impacts of road encroachments on rivers are physical, chemical, biological, and aesthetic.

Physical impacts stem generally from the construction and presence of the road crossing or longitudinal encroachment, and particularly from measures taken to protect the crossing or highway from being flooded or otherwise damaged by the river. For example, a road crossing often constricts the width of the river channel altering the physical form of the channel, which in turn impacts local flow hydraulics and sediment transport processes. If the approaches to the crossing are embanked to prevent the road from being inundated during high, overbank flows, then water that would have flowed across the floodplain is funneled through the crossing, further disrupting hydraulics and amplifying local flow constriction, velocities, and contraction scour that may result in serious environmental impacts.

Building a road along a valley or floodplain may involve physically straightening the river, which shortens its length and steepens its slope. The river responds through increases in flow velocity and sediment transport capacity that are likely to destabilize the channel and destroy habitat. A further impact on the physical environment occurs when the diverse forms and features (side-channels, bars, shallows, undercut stream banks) characteristic of a naturally complex channel-wetland-floodplain system are replaced by a simple, single-channel with uniform, stabilized banks. Not only are flow hydraulics and sediment dynamics altered, but also other physical attributes such as water temperature, which may increase because of reduced hyporheic exchange or loss of shading.

A somewhat more subtle, but still potentially serious, physical impact of a road crossing or encroachment may be to alter connectivity in the river. Long-stream, lateral, or vertical connectivity may be affected, depending on the type of river and the design of the crossing or encroachment.

Chemical impacts may result from spillages of fuel or lubricants and increased turbidity during construction, though rivers are now largely protected by stringent rules on sediment management and regulations controlling in-water working. Following construction, chemical impacts may range from ongoing polluted surface water and random contaminated sediments intermittently washed off the road by stormwater or because of vehicle accidents, carrier spills, or trash dumping. Consequences of pollutants and contaminants range from reductions in dissolved oxygen, and degradation of other key water quality parameters, to ecotoxicology in vulnerable micro-organisms, plants, fish, amphibians, birds, and even mammals.

Biological impacts can occur in the aquatic, riparian, wetland, floodplain, or terrestrial elements of the river ecosystem. Many impacts result from alteration or destruction of natural vegetation, which may be unavoidable during construction. Loss of native species may be reduced if stringent efforts are made prior to construction to salvage fish, amphibians, and other vulnerable wildlife, and return them to the river following construction.

Aesthetic impacts can result from road construction because the natural appearance of the river-scape is impacted when artificial structures are introduced into it. In the case of road upgrades, aesthetic degradation occurs due to the greater visual impact of a multi-lane highway with complex intersections, compared to, for example, an unpaved, county road. Wild and Scenic Rivers designations may involve special mitigation or severely restrict design options.

Other long-term environmental impacts that may result from road construction or upgrading include heavier vehicular and foot traffic; increased littering, debris loads, and dumping; changes in land-use; intensified recreational pressures due to improved access to the river; and a variety of socio-economic impacts related to further development locally and in the watershed more widely.

4.3.3 Impact Severity and River Characteristics

The nature and potential severity of the environmental impacts of roads that encroach on rivers vary depending on the type of river and the local and watershed settings within which the river and the road are located. The design of the road is also important, and design practices can avoid, minimize, or mitigate many adverse environmental impacts, as described in the next sub-section.

As explained in Section 2.1, rivers may be broadly divided into reaches that predominantly supply, transport, or deposit sediment (see Figure 2.4). This is the basis for the Montgomery-Buffington stream classification depicted in Figure 4.2, which indicates how sensitivity to disturbance and adverse environmental impacts varies along the length of a river, between supply, transport, and deposition reaches.

As shown in Figure 4.2, steep streams with coarse bed materials that flow through narrow valleys are sediment supply reaches. Here, the valley sides are laterally connected to the channel. Immediately downstream of the headwater source of the stream (an un-channeled hollow), the stream bed is formed in coarse material supplied by landslides (termed colluvium) that is only transported downstream by debris flows driven by rarely occurring, extreme floods.

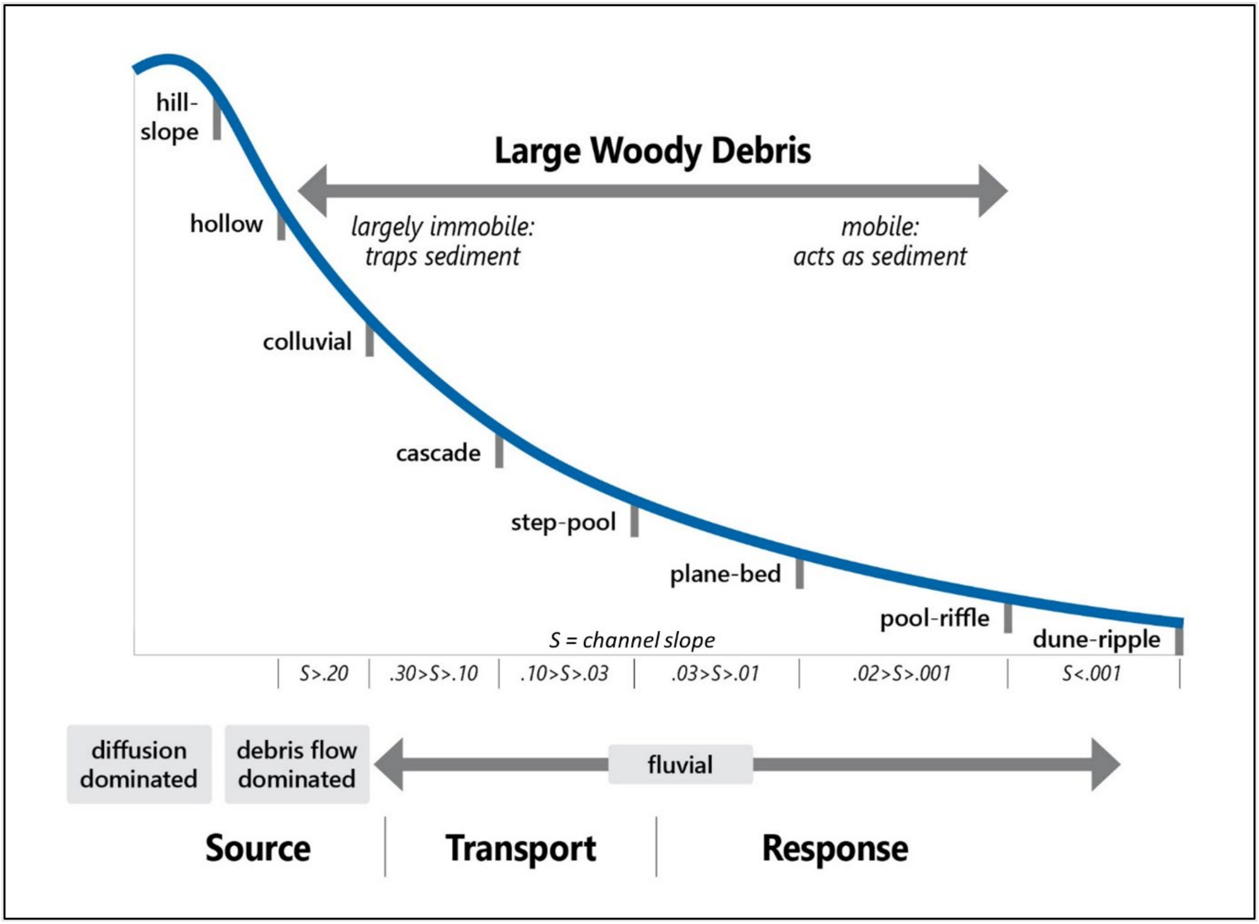


Figure 4.2. Montgomery-Buffington stream classification. Adapted from Montgomery-Buffington (1993).

In colluvial reaches as depicted in Figure 4.2 and Figure 4.3, lack of space means that the road frequently encroaches into the channel, generating direct environmental impacts because part of the channel is filled, destroying plants and vulnerable aquatic and terrestrial species that may be slow to recover. Longer-term impacts are less severe because the stream is unresponsive to disturbance due to controls provided by the geology in which the stream is located. This is because it is not alluvial (i.e., self-formed). However, the road disconnects the valley side from the channel, making it vulnerable to blockage or damage by landslides from the valley side and fluvial erosion from the stream-side. Other environmental impacts such as localized reduction of wood and sediment supply, possible temporary or permanent loss of canopy cover, and restriction to aquatic organism passage (AOP) can result from new encroachments. As Figure 4.4 shows, the crossing generates short-term environmental impacts in the channel and along both margins during construction. It may also generate long-term impacts due to disconnecting the channel from both valley sides and disrupting long-stream flow and sediment connectivity. Bridges and culverts in “supply” reaches are also vulnerable to blockage and damage by debris flows.

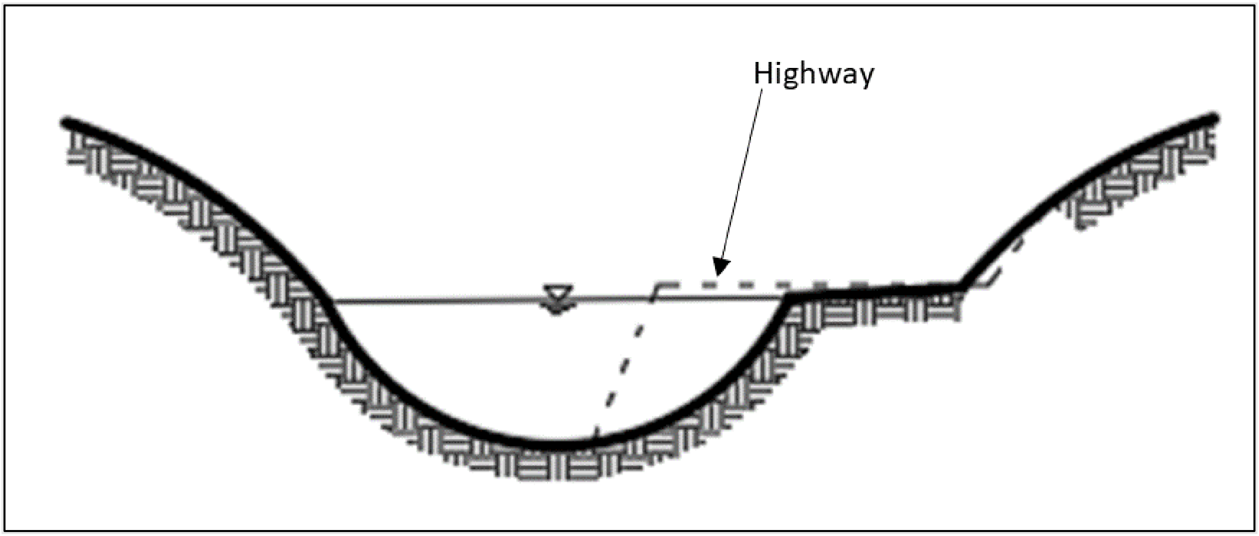


Figure 4.3. Longitudinal encroachment into the channel in a colluvial, sediment supply reach.

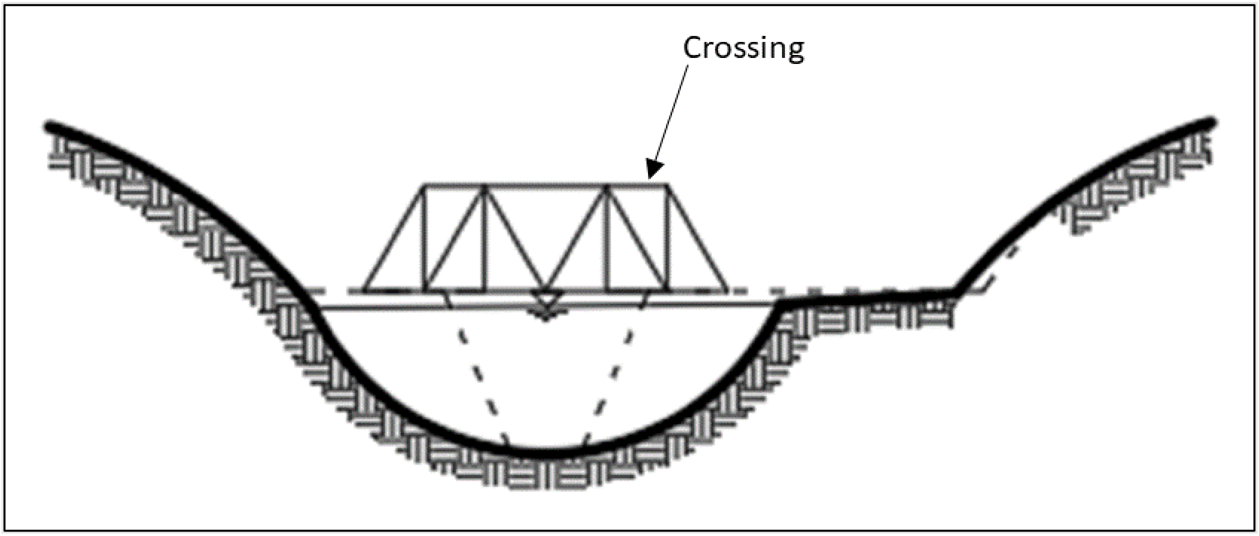


Figure 4.4. Crossing and lateral encroachment constricts the channel on both sides and disconnects it from both valley sides.

As stream discharge increases and bed material size and channel slope decrease with distance downstream, streamflow can transport bed material during normal floods, organizing it first into a cascade or a series of boulder steps interspersed with plunge pools. Cascades have very steep slopes (10 to 30 percent) while step-pool reaches have slopes in the range of 3 to 10 percent. Generally, streams steeper than approximately 3 percent do not build floodplains, and their channels are usually connected laterally to their valley sides via a narrow riparian corridor. Montgomery and Buffington classify cascade and step-pool streams as "transport" reaches, where the rate of sediment transport is controlled by the rate of input from the supply reaches upstream. Under these circumstances, sediment transport is "supply-limited," and sediment is transferred downstream at the same rate it is supplied from upstream. That is, Lane's balance (Figure 2.12) is in dynamic equilibrium.

In cascade and step-pool reaches, highways constructed along the valley often encroach into the channel and disconnect the channel from one of the valley sides as shown in Figure 4.5A.

Crossings disconnect the channel from both valley sides and may disrupt long-stream connectivity as shown in Figure 4.5B. As in a colluvial reach, the immediate environmental impacts of highway and crossing construction result from filling part of the channel, but to this is added destruction of the narrow riparian corridor along one or both sides of the stream. Concentration of flow and stream energy in the narrower channel may increase sediment transport capacity, but as transport is supply-limited anyway, significant bed scour is unlikely and morphological channel responses are muted. However, if encroachment induces severe hydraulic conditions, coarse material armoring the bed of the channel could be disrupted and channel incision could occur. Consequently, consideration of the effects of encroachment on the stability of the channel bed is advisable.

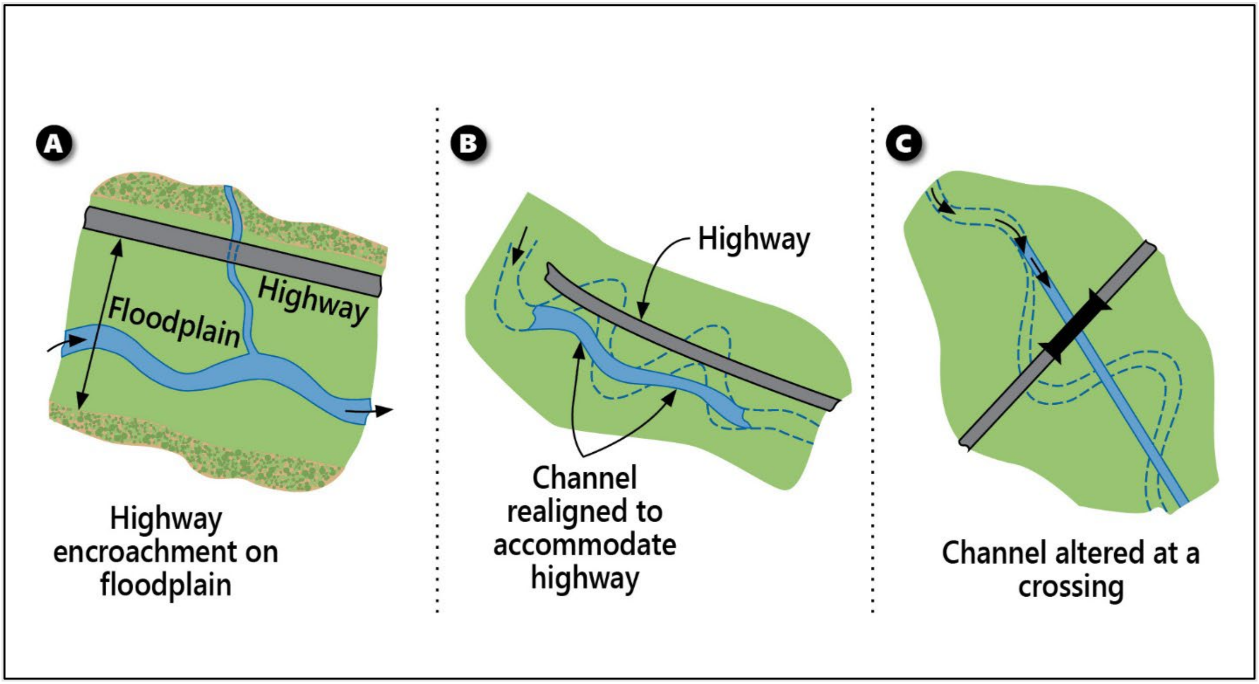


Figure 4.5. Types of channel disruptions leading to environmental impacts. (A) Disruption from longitudinal encroachment in the floodplain and at tributary crossing. (B) Disruption from longitudinal encroachment into the mainstream channel or CMZ. (C) Disruption from cross-stream encroachment in the floodplain and channel at a mainstream crossing.

Longer-term environmental impacts may still result because of increased velocities and lateral erosion into road fill. Typically, revetments are installed to control this situation; however, it is important to recognize that this may result in transfer of erosive energy further downstream.

Encroachments can adversely affect the ecology in the (narrow/discontinuous) riparian corridor and both at the site and potentially further downstream due to the implementation of erosion mitigation measures. As in colluvial reaches, a road that follows the stream along a transport reach disconnects one valley side from the channel, making the road vulnerable to blockage or damage by landslides from the valley side and fluvial erosion of the fill on the stream side, while bridges and culverts are additionally vulnerable to blockage and damage by floods carrying hyper-concentrations of sediment and debris supplied by debris flows in supply reaches upstream.

As discharge increases, and slope and bed material size decrease with distance downstream, the bed material becomes increasingly mobile and reach types trend from plane bed, through pool-riffle to regime (Figure 4.2). See Chapter 5 of HEC-20 for additional information regarding channel forms. As slope decreases below 3 percent, streams form wider riparian corridors and floodplains that separate the channel from the valley sides. Montgomery and Buffington classify plane bed, pool-riffle, and regime streams as “response” reaches, where the rate of sediment transport is controlled by the transport capacity of the stream rather than the rate of input from the transport reaches upstream. Under these circumstances, sediment transport is “capacity-limited” and sediment is transferred downstream at a lower rate than it is supplied from upstream. That is, Lane’s balance tends toward aggradation, which is what builds and maintains the floodplains that characterize these reaches. Response reaches are so named as they are more responsive to disturbance than either supply or transport reaches.

In response reaches, unless a highway is constructed along the valley side or on the toe slope, it likely encroaches into the floodplain to some extent and at tributary crossings as shown in Figure 4.5A. At a minimum, the road generates environmental impacts because some part of the previously floodable area is disconnected from the river.

State Spotlight: Vermont Fluvial Erosion Hazards

In 2013, Vermont amended its state law (24 V.S.A. § 4302) establishing a goal to encourage flood resilient communities. The new law encourages municipalities to avoid new development in “identified flood hazard, fluvial erosion, and river corridor protection areas” and instead to focus new development on “Safer Places to Develop” (State of Vermont 2020). If development in the CMZ, or the fluvial erosion hazard (FEH) area cannot be avoided, mitigate for the flooding and fluvial erosion (State of Vermont 2020). The amendment and the materials developed to support it also encourage municipalities to protect and restore floodplains and upland forested areas for their flood risk mitigation benefits. Vermont also provides increased flood disaster recovery funding to communities that adopt land use regulations that largely prohibit new encroachments within fluvial erosion hazard areas (Vermont Emergency Relief and Assistance Fund).

If the highway is located within the CMZ or riparian corridor, construction may involve re-aligning the river as in Figure 4.5B, which increases the environmental impacts by directly and perpetually altering channel hydraulics, geomorphology, and ecology. Where the highway switches from one side of the main stream to another, it may impede flows along the floodplain, especially if the roadbed is raised above flood level. At the crossing itself, the bridge or culvert may constrict flow (especially during floods) to cause local and contraction scour that disrupts hydraulics, morphology, ecology, and all forms of long-stream connectivity as depicted in Figure 4.5C.

Similar to the situation in supply and transport reaches, the immediate environmental impacts of highway and crossing construction in a response reach result from disruption of, and changes to, channel, riparian, wetland, and floodplain landscapes, vegetation, and ecosystems. However, a wide range of longer-term impacts are also likely, because these reaches are much more responsive to disturbances. As noted above, these long-term environmental impacts are not mutually independent, and they may spread up and downstream to affect the river system. Figure 4.5 illustrates this using the case of a river in a response reach experiencing three kinds of encroachments. That is, the highway construction partially blocks the floodplain, straightens the river planform to fit the road along the valley, and partially channelizes the river to facilitate use of a relatively narrow river crossing.

When connected to its riparian corridor, channel migration zone, side-channels, wetlands, and floodplain, the river functions as an integrated, hydro-ecologic system that is highly productive and well adapted to moderate and benefit from the impacts of floods (as explained in Chapter 2).

Disturbing long-stream, cross-stream, or vertical connectivity in the channel-riparian-wetland-floodplain system therefore results in: 1) an immediate loss of dynamic-balance between river forms and processes (physical impacts), 2) changes in water quality (chemical impacts), and 3) decreased biodiversity (biological impacts).

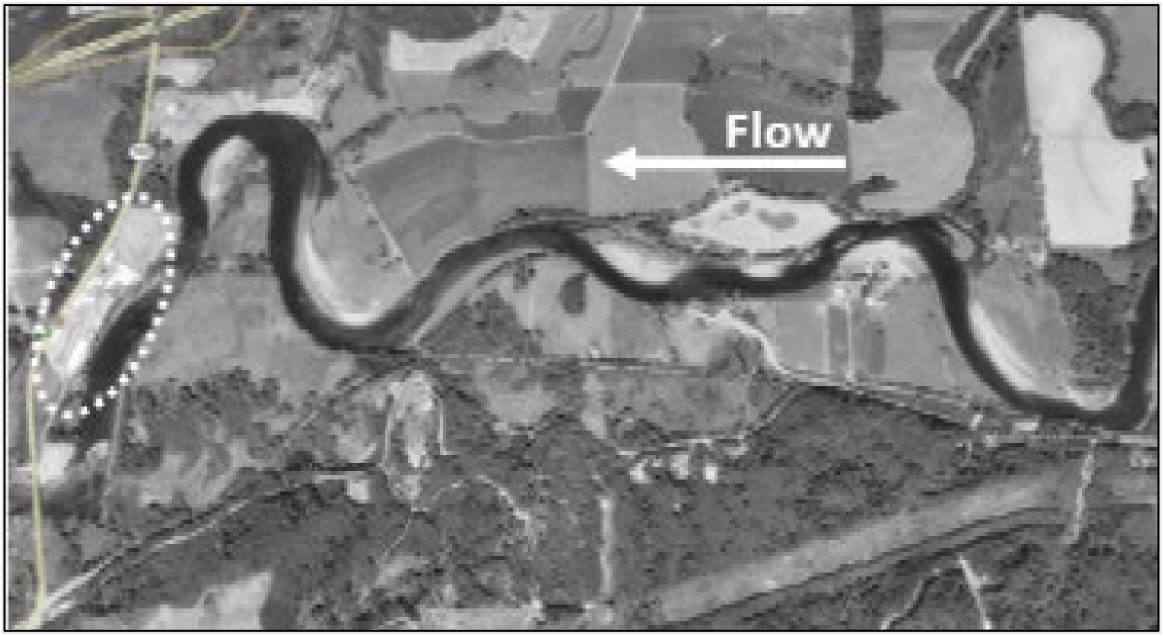
These broad potential environmental impacts may be broken down into a list of more specific potential impacts attributable to specific aspects of highway design and implementation, including:

- Physical destruction or burial of natural features in the channel, riparian corridor, CMZ, and floodplain during construction.
- Locally increased sediment loads and turbidity that disrupt the sediment transport system; disturb aquatic life; smother the eggs of insects, fish, and other aquatic organisms; decrease light penetration; and reduce primary production.
- Generation of local and contraction scour and deposition that changes flow hydraulics, may constitute passage barriers to fish and other aquatic species, and is harmful to bed-dwelling organisms.
- Channelization that simplifies naturally diverse channel forms, hydraulics, bed materials, and vegetation assemblages that provide multiple types of habitats and refuges for wildlife.
- Impairment of river ecosystems that reduces the capacity of the river to process pollutants just as contaminant loadings from road runoff increase.
- Loss of efficacy in nutrient recycling due to adverse impacts on micro-organisms and primary productivity.
- Warming of water temperatures due to loss of shade and hyporheic exchange (i.e., vertical connectivity), with adverse impacts on aquatic organisms and especially fish due to lower oxygen and higher metabolism in warmer water.
- Channelization or channel incision that drains wetlands and the alluvial hyporheic aquifer that helps maintain streamflow during dry seasons and prolonged droughts.
- Creation of barriers to biological connectivity that restricts movement of organisms along/between stream channels, and to/from wetlands, ponds, floodplains, and uplands in ways that may fragment habitat, disrupt foraging, reduce access to refugia, impede migration, and increase the risks of collisions between vehicles and organisms.
- Reduced value of the river for recreation and commerce (e.g., fishing, hunting, rafting, boating) due to changes in hydraulics, sediment loads, morphology, water quality, fisheries, game species, or aesthetics.
- Long-stream channel responses and instabilities that threaten the safety of other roads, bridges, culverts, and infrastructure, requiring additional capital works (e.g., bed scour countermeasures) or increased maintenance (e.g., dredging of shoals and bars) to sustain channel and floodplain conveyance capacity at acceptable levels.
- Lateral channel responses and instabilities that threaten the safety of roads, bridges, culverts, and other infrastructure, requiring additional capital works (e.g., bank protection) or river training structures (e.g., barbs, jetties, dikes).
- In-reach adjustments that may themselves trigger further morphological responses up- and downstream, which may destabilize previously stable, trouble-free reaches.

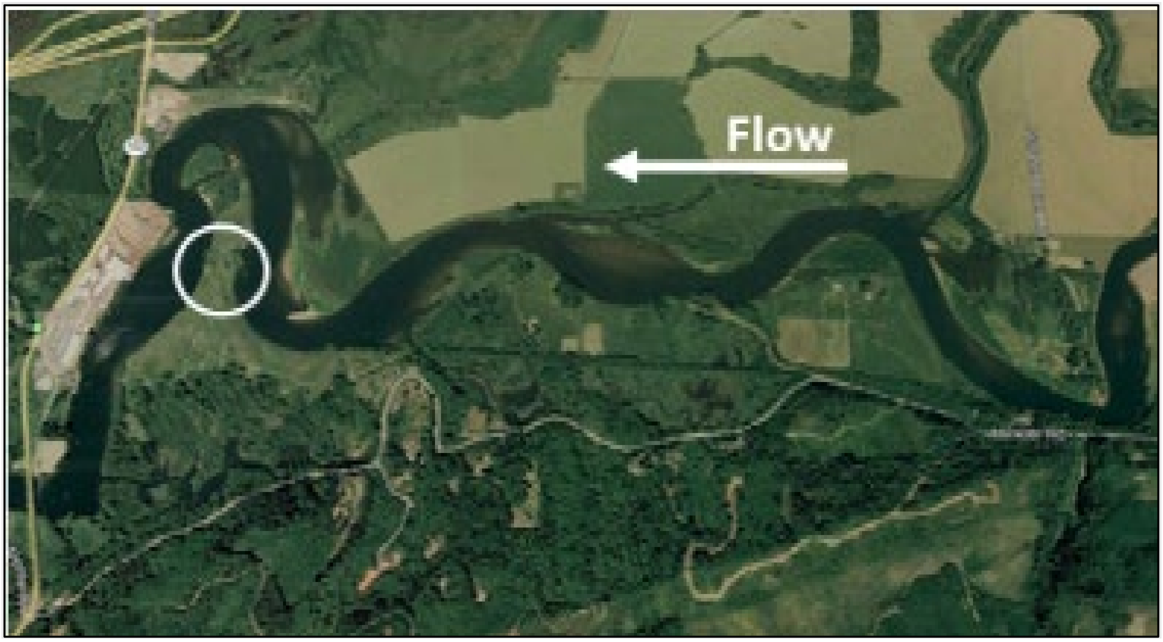
4.4 Impact Avoidance

Rivers are natural transportation corridors. They are located at the lowest elevation in every watershed, the surrounding floodplains are relatively flat, and their headwaters always lead to the topographic divide that separates adjoining watersheds. Because of these characteristics, highways are commonly located near rivers on accompanying floodplains and terraces, and they often cross rivers or their tributaries. As discussed in Chapter 2, alluvial streams are by nature dynamic. Given enough time, the continuing movement of the channel often brings it into conflict with static transportation infrastructure located in the CMZ. Such conflict generally results in environmental impacts, damaged or lost river functions, and the need for frequent/expensive maintenance to keep the highway crossing or encroachment stable and safe over the project life cycle. Recognition of this potential and avoidance of possible impacts is an obvious goal for transportation infrastructure planning and design efforts.

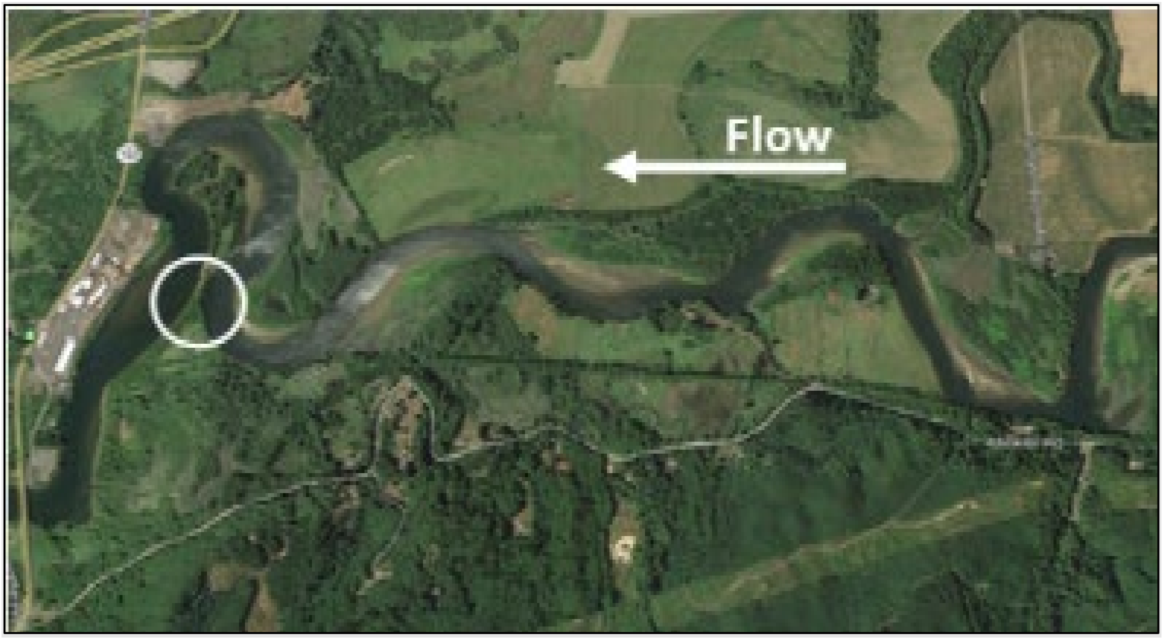
An example of the development of potential impacts associated with progressive channel migration is illustrated in a series of historic aerial photos of the SR 107 highway crossing of the Chehalis River near Montesano, Washington, presented in Figure 4.6. The figure shows how the river meanders in the vicinity of the highway crossing have evolved over a 29-year period. The natural downstream migration of the river meanders is constrained by the location of the highway and river crossing indicated in Figure 4.6A with the dashed oval. This situation has caused the upstream meanders to compress on each other, impinging on the roadway alignment and creating an increasingly acute flow approach angle to the Highway 107 bridge opening as noted by the circle in Figure 4.6B and Figure 4.6C. A cutoff of the meander and a dramatic change in the main channel location upstream of the bridge is imminent. The extreme breadth of the Chehalis River floodplain, significant encroachment on the floodplain by the highway embankment, and the relatively small bridge opening create substantial challenges for avoiding impacts to the highway and bridge infrastructure while maintaining a regionally important transportation corridor.



A. 1990 photo of SR 107 crossing of Chehalis River.



B. 2006 photo of SR 107 crossing of Chehalis River.



C. 2018 photo of SR 107 crossing of Chehalis River.

Figure 4.6. Progressive channel migration in historic aerial photographs of SR 107 highway crossing of Chehalis River near Montesano, Washington.

To manage conflicts between a river and transportation infrastructure, transportation professionals typically have four general options: 1) avoid the conflict by creating an alignment outside of the CMZ; 2) locate the infrastructure in the CMZ to best accommodate channel movement, maximize distance from the channel, and minimize risk of conflict with channel movement; 3) resist the influence of the river by building measures to control it, overcome the associated hydraulic forces, and physically separate river and infrastructure; or 4) a combination of these options. Benefits and limitations of using nature-based solutions for this purpose, such as using native vegetation to resist erosion, are discussed in Section 4.6. Each stage of project development presents choices about how to manage river/highway conflicts, with those involved at the planning stage having the widest range of alternatives to choose from, including identifying and evaluating alternative alignments that minimize locations in the active floodplain.

During the design stage, engineers and other technical experts work together to anticipate and accommodate the potential movement of the river. Among the most critical issues examined during design is the potential for bridge scour, the erosion of the soil surrounding a bridge foundation. Because scour can contribute to or cause of bridge failures, engineers and designers perform analyses to estimate the potential for scour, providing the information necessary to design the foundations of a bridge (FHWA 2012b).

Bridge Scour Impacts by the Numbers

17 damaged/destroyed bridges after 1987's floods in NY & New England.

73 destroyed bridges after floods in PA, VA, & WV in 1985.

23 bridge failures after the 1993 floods in the upper Mississippi basin.

500 damaged/destroyed bridges (cost $130 million) after 1994 GA floods (FHWA 2012b).

In the construction phase, decisions made in the planning and design phases regarding methods for controlling the river, overcoming its associated hydraulic forces, or physically separating the river and the infrastructure project become a reality. Realization of the risks and costs of river/transportation conflicts commonly become apparent in this stage or once the project enters the O&M stage of the project life cycle. As with the Chehalis River example in Figure 4.6, it may take years or even decades after construction to see the full implications of channel changes. During this time, maintenance and operations staff can often make sufficient, if increasingly costly, repetitive remedial repairs and protection measures to forestall the consequences of the conflict between the moving river and static infrastructure.

Many transportation routes in river environments were developed long before the current understanding of river processes and natural river functions. This generally makes relocation of transportation infrastructure to areas outside of the river environment unrealistic, given the economic investment in the existing transportation infrastructure and the widespread surrounding human development. As a result, river/highway conflicts are relatively common and impacts to natural river functions are generally widespread and continuing. As discussed in Chapter 2, typical highway and bridge impacts to river functions include reduced floodplain conveyance, restrictions to river evolution, loss of riverine habitat, and lost connectivity.

Project teams are likely to encounter several expressions of river/transportation infrastructure conflicts including bank erosion (see Figure 4.7), abutment erosion at bridge crossings (see Figure 4.8), scour that can undermine bridge piers (see Figure 4.9), and overtopping erosion at culvert crossings (see Figure 4.10).

Figure 4.7. Impact of bank erosion on a road running along the river corridor.

Figure 4.8. Impact of bank erosion on a bridge abutment.

Figure 4.9. Impact of pier scour, leading to structural failure.

Figure 4.10. Road wash out, a typical impact of culvert overtopping.

Historically, the response to river/transportation infrastructure conflicts has been to resist them by means of riprap, concrete, or other rigid channel lining measures. Arguably, this is due to the magnitude of previous investments made in the existing infrastructure versus the relatively smaller cost of the repairs and protection measures. Typical protection measures involve the placement of riprap as revetments for erosion protection and scour mitigation. As discussed in the following section, increasingly, State and local DOTs, Metropolitan Planning Organizations, and others engaged in transportation infrastructure projects in the river environment are pursuing more environmentally sensitive approaches to erosion and scour protection to protect infrastructure while maintaining or even restoring river functions that may have been lost. These approaches generally consist of hybrid treatments in which teams use a mixture of natural materials such as wood, stone, and native vegetation in conjunction with a riprap revetment, or a steel or concrete structure. Further discussion of the benefits and limitations of using native vegetation for erosion control is presented in Section 4.6.

Outcomes improve when teams considering use of hybrid treatments thoroughly examine the involved risk. Allowing for natural channel adjustments to the greatest possible extent—for example, by widening the riparian corridor or restoring floodplain connectivity—involves the least direct conflict between the river and transportation infrastructure and is likely to represent the project alternative with the lowest calculated risk.

Calculating Risk

Risk may be described as the probability of a failure of the infrastructure occurring multiplied by the consequences associated with the failure. Consequences may include direct economic costs as well as threats to human life, and environmental impacts such as loss of biodiversity, key species, and ecosystem services.

Risk may change over time. The probability of a specific flood magnitude may change because of changes in climate, basin land use/land cover, forest fires, loss of forests due to disease/drought, or glacial retreat. Consequences may also change because of future development. Time is a critical consideration for transportation asset management, especially when considering possible long-term influences such as channel migration.

4.5 *Impact Mitigation*

Transportation professionals seek to avoid, minimize, or mitigate the potential environmental impacts of roads and related infrastructure in the river environment. To do so, they apply multidisciplinary expertise in engineering, geomorphology, biology, ecology, fisheries, and recreation to identify and mitigate potential environmental impacts. The following sections describe impact minimization and mitigation for longitudinal stream encroachments and river crossings.

4.5.1 Longitudinal Encroachments

Reducing or minimizing the adverse environmental impacts of a road that parallels the river is important to maintain lateral and long-stream connectivity. Actions may include:

- Routing the road as close as possible to the edge of floodplain to minimize encroachment.
- Ensuring that tributary crossings meet environmental and fluvial design standards (for details, see the next sub-section on crossings).

- Providing adequate cross-drainage and safe wildlife passage routes/structures to maintain lateral connectivity between the river and areas of floodplain/upland that would otherwise have been cut off by the highway.
- Avoiding encroachment into the channel, floodplain, riparian areas, and wetlands, and, ideally, routing the road outside the channel migration zone.
- Creating an active river corridor that is sufficiently wide to accommodate natural channel evolution and potential future changes in river planform, without the channel interacting with the highway, if, when authorized by law and otherwise warranted, the channel is re-aligned or re-located to make space for the highway. In response reaches, experience indicates that the active corridor would be about 20 times the channel width, with the distance between the long-stream axis of the channel and the highway being at least 10 times the channel width. In urban areas, it is likely that the active corridor has already been constricted, and in such situations further constriction would be avoided. In either case, environmental impacts are minimized by designing the re-constructed channel to mimic the features and morphological diversity of a natural channel. Engineers commonly use either an analytical approach to design naturally dynamic channels (Copeland et al. 2001, Brunner 2010, Stroth 2017) or a suitable "reference reach" (Yochum 2018).
- Minimizing environmental impacts using bioengineering to protect the road embankment from erosion to the greatest extent possible if the highway encroaches into the active corridor or CMZ. Where high flow forces or lack of space preclude bio-engineered solutions, the impacts of revetments that use non-native materials (e.g., steel piles, concrete, wire baskets, rock riprap in sand or gravel-bed rivers) can be minimized by 1) making provision for habitat (e.g., including large wood or planting pockets), 2) reducing interaction between the protection and normal flows to the extent possible, 3) roughening engineered surfaces to avoid high velocities along their face, 4) dissipating energy locally to prevent it propagating downstream during floods, and 5) making provision for wildlife passage at crossings.
- Avoiding reduction in the cross-sectional area if there are places where the highway encroaches into the channel. For example, this may be accomplished by using steeper embankment design, vertical walls, and viaduct/bridge structures. If possible, make allowance for local responses in channel morphology to be accommodated on the far bank and in the channel immediately up and downstream, without triggering wider-scale adjustments (and potential instability) in the river system.

In cases where practical constraints or funding limitations preclude reducing the environmental impacts of a longitudinal encroachment to a level that is acceptable, and there is no feasible alternative route for the highway, recourse may be made to mitigation. However, in some cases highway routes that are sub-optimum may be acceptable without the need for mitigation. This may be the case where:

- The physical and biological setting at the highway make it impractical to maintain or restore a functional stream and floodplain configuration (i.e., the floodplain is naturally constrained within a narrow gorge or naturally width-constrained valley).
- Existing infrastructure and development (such as in urban areas) rule out maintaining or restoring a functional floodplain in any case.

State Spotlight: CMZs in Washington

As a result of significant historic flood damages, King County, Washington, has studied and mapped Channel Migration Zones (CMZs) along eight major rivers in its jurisdiction since 1991. To characterize CMZs, King County considered factors including historical channel locations, geology, basin hydrology, riverbank materials, current channel conditions, abandoned channels and potential avulsion sites, channel migration rates, and existing infrastructure. They used study findings to map severe and moderate hazard areas within the CMZ.

More recently, the state of Washington administrative codes that implement the Shoreline Management Act (SMA) required communities to identify the general location of CMZs and regulate development within these areas on shoreline streams, those with a mean annual flow equal to or greater than 20 cubic-feet per second (Olson et al. 2014). The WSDOT Environmental Manual emphasizes the importance of mapping CMZs to understand and act on the implications of possible channel migration for project longevity (WSDOT 2019).

Highway projects that are unable to completely mitigate unacceptable environmental impacts on-site may be able to mitigate the unacceptable impact(s) by providing an equivalent or greater amount of positive environmental impact off-site. However, on-site management is desirable because of the direct connection between impact and mitigation. It is preferable to identify and negotiate the need for mitigation with the relevant stakeholders and permitting organizations through early consultation. The determination that satisfactory management on-site is impractical should be coordinated with the relevant State and Federal environmental agencies or services. Factors that typically result in off-site mitigation include:

- Unfavorable topography.
- Site hazards (e.g., geologic, hazardous materials, contaminated ground, public safety).
- Conflicting environmental goals and resources (e.g., wetlands, ESA-listed species, cultural resources, environmental justice).
- Excessive/unjustifiable cost relative to the environmental benefit (e.g., need to acquire additional right of way, extra construction, increased maintenance/lifecycle expenditure).

Determining the cost effectiveness of on-site mitigation is project specific and involves consideration of construction and lifecycle costs relative to the value of the environmental resources impacted, the extent and severity of the environmental impacts, the cost of on-site mitigation compared to that borne by similar projects, and the cost of off-site mitigation. Many projects may provide a combination of on-site and off-site mitigation.

Mitigation sites are usually on the same river as the project, adjacent to or upstream of the project. If suitable sites close by on the same watercourse are unavailable, the search for mitigation sites entails moving progressively away from the project, considering habitat quality at potential mitigation sites and the length of stream benefiting from the environmental uplift compared to the length adversely impacted by the road or crossing at the project. As with all environmental mitigation, environmental agencies typically prefer that mitigation is “in kind,” that is, that the features created and species that benefit are the same as those impacted.

State Spotlight: Alabama leverages public participation for environmental mitigation

The Alabama DOT (ALDOT) uses 13 sites to support 95 percent of its wetland mitigation needs, having initially used Federal-aid dollars to support its banking initiative in the 1990s. ALDOT allows public use and recreation at its sites for fishing and non-consumptive activities such as bird watching and hiking. The ALDOT currently allows the Alabama Dept. of Conservation and Natural Resources-Wildlife and Freshwater Fisheries Division (ADCNR-WFF) to use two banks for hunting via memoranda of agreement (MOA). The ADCNR-WFF uses the Crow Creek bank as a Special Opportunities Area (SOA) and offers waterfowl and deer (bow) hunting while the Dozier bank is used as a handicapped hunting area and offers youth dove shoots. Additional sites are being evaluated for other public use possibilities such as outdoor classrooms and ecological studies. The ALDOT finds that long-term sustainability is more likely to succeed when the local community feels ownership of a site. The ALDOT seeks viable partnerships to allow compatible public use and share the maintenance of its sites.

For more on mitigation banking in Alabama visit:

www.environment.fhwa.dot.gov/env_topics/ecosystems/scanrpt/al.aspx

For examples from other State DOTs refer to the FHWA *Environmental Review Toolkit*:

www.environment.fhwa.dot.gov/env_topics/ecosystems/scanrpt/execsum.aspx

Source: B. Butters for Thrive Regional Partnership (© 2020) and used by permission.

Examples of permissible mitigation may include re-establishing or enhancing floodplain connectivity elsewhere along the stream by removing artificial fill (such as redundant levees), removing redundant or abandoned in-stream structures outside the project area, or enhancing/restoring habitat on an impacted stream or wetland with a high potential for environmental recovery. State transportation departments deliver mitigation in a variety of ways. A growing number use mitigation banking to deliver projects that are cost effective, multi-functional, and guaranteed to provide mitigation in perpetuity (Samanns 2002).

4.5.2 Crossings

Severe environmental impacts at proposed crossings (bridges or culverts) may be avoided by moving the crossing to a less sensitive location, where feasible. However, relocations and the associated rerouting of roadways incurs costs, and the new location may present challenges for design and construction, as well as local economy and traffic patterns.

Virtual Public Involvement (VPI)

Several states are successfully increasing public engagement in transportation projects while decreasing cost and time by using innovative virtual public involvement (VPI) techniques. For instance, North Jersey Transportation Planning Authority uses real-time polling as part of live meetings and webinars and the City of Richmond, Virginia, used targeted stakeholder meetings, a “wikimap,” and cloud-based data-gathering to gather field observations from the public.

To learn more about using VPI to improve stakeholder engagement and project decision-making while accelerating project delivery, see:

www.fhwa.dot.gov/planning/public_involvement/vpi/

Usually, however, it is possible to sufficiently reduce environmental impacts. A positive and cost-effective way to achieve this is to follow an environmentally informed design approach. Additional potential benefits of such an approach would include capital and lifecycle cost savings, increased stakeholder project support, streamlined permitting processes, simplified monitoring and inspection, improved river function and overall reduced risks associated with channel instability, and reduced or eliminated need for erosion control or sedimentation countermeasures.

An environmentally informed design approach protects and restores river functions within the channel-floodplain corridor around and through the crossing. This may involve designing highway crossing that consider:

1. Channel processes:
    a. Promoting natural sediment transport patterns for the reach.
    b. Providing unaltered large wood and debris movement.
    c. Allowing for long-stream hydraulic, sediment, and wildlife connectivity of the stream-floodplain system.
    d. Locating bridge abutments anticipating channel migration patterns over the design life.
2. Floodplain processes:
    a. Keeping the highway, embankment, or approach fills outside of the channel migration zone (CMZ) or functional floodplain.
    b. Avoiding artificial constrictions within the functional floodplain.

   c. Installing relief culverts or bridges through existing fills (for use by flows during floods and by wildlife at other times).
   d. Maintaining lateral hydraulic, sediment, and wildlife connectivity between the channel and the floodplain.
   e. Accommodating overbank flow pathways at multiple flood stages by:
      i. Locating bridge opening to maximize floodplain function.
      ii. Providing flood-relief culverts within existing road fill at potential flood flow pathways based on observed flow patterns or floodplain topography.
3. Channel scour:
   a. Making bridge length sufficient to avoid excessive contraction scour at the crossing.
   b. Matching the discharge at which bed load motion begins under the bridge to the discharge at which bed load motion begins in the channel upstream of the bridge.
4. Bridge abutments/piers:
   a. Accommodating maximum expected local and contraction scour.
   b. Avoiding conditions where local scour at abutments/piers adversely affects streambank stability, instream habitat, or long-stream connectivity.
   c. Spacing bridge foundations to allow unimpeded transport of large wood and debris through the crossing, if feasible, by placing abutments/piers outside the active channel.
5. Environmental enhancements and stream restoration:
   a. Restoring riparian areas.
   b. Replacing non-native and invasive vegetation with native species.
   c. Increasing riparian shade, while ensuring trees do not impact road safety.
   d. Removing nonessential, artificial hydraulic constrictions and controls.
   e. Restoring stream-wetland-floodplain complexity.
   f. Restoring habitat and passage for fish, other aquatic organisms, and riparian/terrestrial wildlife, as feasible and appropriate to the watershed context.

Highway stream crossing features suited to minimize adverse impacts to river functions would include:

- Single-span structures (including culverts) that span the active channel width.
- Multi-span structures (including culverts) that span the active channel width, except for piers and interior bents. (Piers are single-column bridge substructures whereas bents have two or more columns.)
- Structures (including culverts) that provide sediment and wood transport continuity through the crossing over the full range of design flows.
- Flood relief bridges and culverts installed within existing road fills at potential flow pathways on the floodplain, based on an analysis of floodplain topography and flow patterns.

- Streambanks and newly exposed floodplains contoured to match and transition smoothly into channel forms both upstream and downstream.
- Removal of artificial constrictions within the functional floodplain that are not an essential component of the structure design, including removal of abandoned bridge supports to below subgrade and removal of abandoned roadway fill or other fills.

Road culvert crossings present unique challenges for minimizing environmental impacts because of their significant potential to impair long-stream connectivity and conveyance of flood flows, sediment, and wood. Consequently, the risks associated with culvert crossings are frequently observed as sediment and debris blockages at culverts inlets, scour at culvert outlets, AOP barriers, frequent maintenance, and increased life cycle costs. Historical culvert design practices have focused solely on passing water, not sediment, debris, large wood, or aquatic or terrestrial animal passage. Safety problems associated with such undersized culverts include:

- Plugging by sediment, debris, or large wood, leading to overtopping and damage/destruction of the road prism.
- Sediment deposition at the inlet due to the backwater effect, leading to overtopping and damage/destruction of the road prism.
- High velocity flows exiting the culvert, resulting in channel scour and potential undermining of the culvert.

In addition, historical culvert design methods often result in high velocities and shallow flow depths within the culvert, long culvert lengths, and excessive drop height at the end of the culvert, as shown in Figure 4.11A, conditions that present barriers to passage of aquatic organisms. Impacts of culverts on the passage of sediment, debris, and wood at culverts is an ongoing condition and maintenance issue for many culverts.

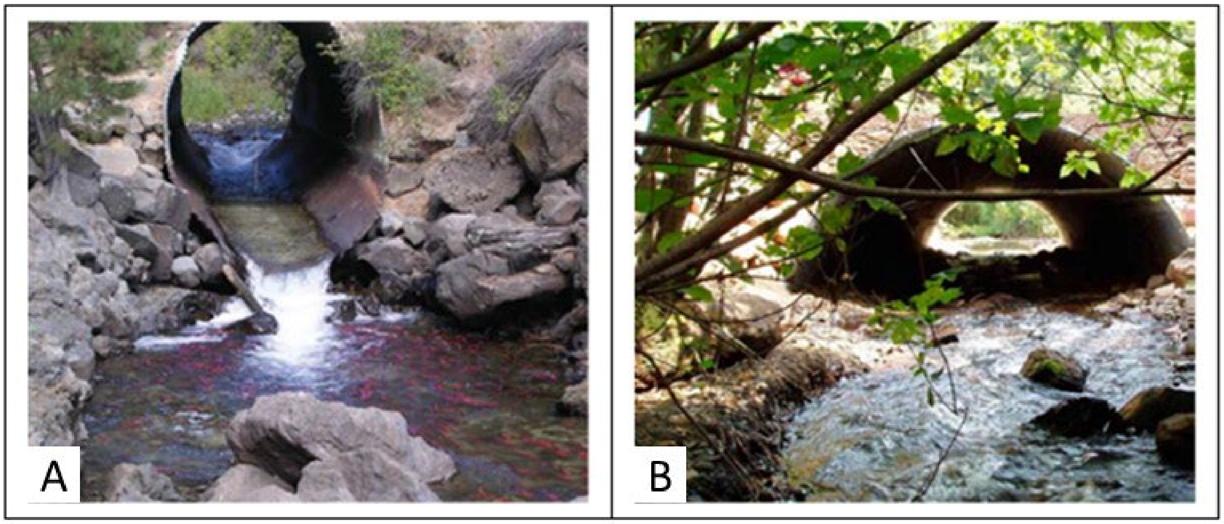


Figure 4.11. Comparison of culverts designed conventionally and using stream simulation. (A) Culvert blocking passage for ESA-listed salmonids designed to convey water with no account of environmental impacts. (B) Culvert designed using stream simulation to minimize environmental impacts and provide passage for native aquatic organisms. Source: FSSSWG (2008).

Stream simulation (shown in Figure 4.11B) is a design approach for culverts to reduce or eliminate risks to AOP and water, sediment, and wood conveyance. The intent of the stream simulation design approach is to reduce risks to people, property, and the environment to acceptable levels while accommodating watershed and climate changes and streamlining the permitting process for the construction of new or replacement culverts. Culverts designed using the stream simulation design approach create conditions through the crossing as similar as possible to those in the natural channel upstream.

The principle underlying stream simulation is that when channel dimensions, slope, and streambed structure are similar, then water velocities, depths, bed materials, and sediment mobility are also similar. Thus, the simulated channel through the crossing can be expected to maintain long-stream connectivity and be just as passable to all aquatic species as the channel up and downstream.

Alternative methods for stream simulation design exist. The USFS, in partnership with USDOT's FHWA Coordinated Federal Lands Highway Technology Implementation Program, published a detailed guide that highway engineers (working in conjunction with multidisciplinary teams) can use to design environmentally sensitive highway crossings nationally (FSSSWG 2008). The first two chapters summarize the consequences of fragmentation in long-stream connectivity and show how connectivity can be preserved or restored at road crossings. The guide also describes the phases of a stream-simulation design applicable to crossings that are being built, replaced, or removed. Table 4.1 provides an overview of the activities involved in the stream simulation process.

Table 4.1. Stream simulation design approach (FSSSWG 2008).

Activity	Description
Assemble team	Identify stakeholders and project team members
Initial assessment	Compile watershed scale information Conduct initial site reconnaissance Establish crossing objectives
Stakeholder engagement	Hold public meetings
Permitting	Pre-application meetings Permit applications
Site assessment	Survey project area Survey reference reach
Stream simulation design	Design simulated channel
Final design and contract preparation	Design structure and road approaches Prepare construction contract
Construction	Build the crossing Complete "as-built" documentation
Maintenance and monitoring	Maintain crossing as needed Monitor performance

Figure 4.12 summarizes the context for the stream simulation design approach including the need for large-scale assessments of the road network and the watershed (outer ring). Moving toward

the center, the project team assesses barriers to passage and establishes priorities for replacement. Next, the team conducts specific site activities beginning with a site reconnaissance followed by design and construction. Following construction, the site is monitored and maintained to insure crossing effectiveness.

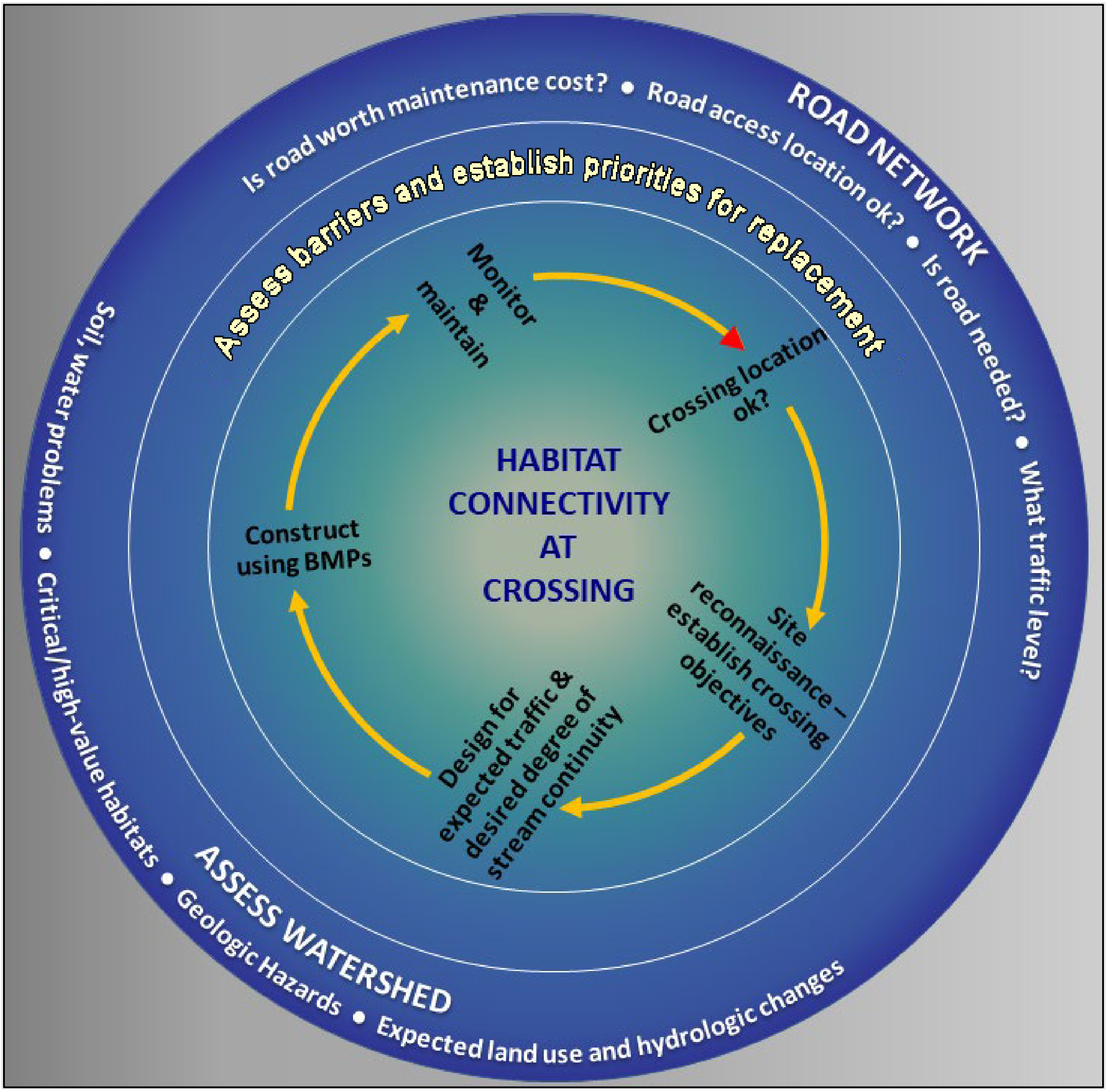


Figure 4.12. General stream simulation context for providing habitat connectivity at road-stream crossings. Adapted from FSSSWG (2008).

The FHWA publication HEC-26 (FHWA 2010a) presents a stream simulation design procedure, methods, and best practices for designing culverts to facilitate AOP. It details a bed stability-based approach that accounts for the physical processes related to the natural hydraulic, stream stability, and sediment transport characteristics of a particular stream crossing. It provides methods to address the AOP issue in culvert design, focusing on physical processes regarding stream stability and continuity of sediment transport.

In cases where practical constraints or funding limitations preclude reducing the environmental impacts of a crossing to a level that is acceptable, and there is no feasible alternative to the location being considered, recourse to mitigation of the impacts is possible.

Mitigation actions are either on-site or off-site. Off-site mitigation actions could also include use of existing mitigation banks, in-lieu fee programs, or other approaches Table 4.2 lists typical situations related to listed species that might involve mitigation. However, NMFS, USFWS, or other State or Federal environmental authorities may request mitigation in other circumstances. It is preferable to identify and negotiate the need for mitigation with the relevant oversight and permitting body through early consultation.

Table 4.2. Example crossing situations that may lead to environmental mitigation (ODOT 2016).

Situation	General Approach for Mitigation
Project cannot fully meet NMFS fish passage design goals.	Remove a similar fish passage barrier in a location to benefit the impacted population. Project may not create a new barrier to spawning and migration of listed species.
Inability to fully treat all the stormwater from the project's contributing impervious area, or inability to fully meet the flow control objectives.	Provide treatment/flow control as close to the project as possible, for stormwater from a comparable contributing impervious area with similar traffic volumes (annual daily traffic volumes).
A net increase in hard armoring or artificial fill, or abandoned fill, in the functional floodplain.	Remove the same quantity of artificial fill in a location to benefit the impacted population. Since the other agencies include mitigation for floodplain fill, the same mitigation can suffice.
Net increase in riprap above ordinary high water or unvegetated riprap below ordinary high water except for scour protection of structures (e.g., bridges, culverts, roads).	Remove the same quantity of hard armoring in a location to benefit the impacted population.
Instream flow control structures.	Remove other barriers in same population.

Highway projects that are unable to completely mitigate unacceptable environmental impacts on-site may be able to provide an equivalent or greater amount of positive environmental impact off-site. The determination that satisfactory management on-site is impractical is coordinated with the relevant State and Federal environmental agencies or services. Factors that typically result in off-site mitigation include:

- Unfavorable topography.
- Site hazards (e.g., geologic, hazardous materials, contaminated ground, and public safety).
- Conflicting environmental goals, available resources, and stakeholder interests (e.g., induced risks to archeological sites, potential for channel migration impacts to existing adjacent developments, migration of invasive species because of AOP restoration).

- Excessive/unjustifiable cost relative to the environmental benefit (e.g., need to acquire additional right of way, extra construction, and increased maintenance/lifecycle expenditure).

Determining that on-site mitigation is not cost effective is project specific, and involves consideration of construction and lifecycle costs, relative to the value of the environmental resources impacted, the extent and severity of the environmental impacts, the cost of addressing them on-site compared to that borne by other similar projects, and the cost of off-site mitigation. It is useful to remember that, even if a highway project includes off-site mitigation of all or some of its environmental impacts, as much on-site management as is practicable is still expected.

Mitigation sites are usually on the same river as the project, adjacent to, or upstream of the project. If suitable sites close by on the same watercourse are unavailable, the search would move progressively away from the project, considering habitat quality at potential mitigation sites and the length of stream benefiting from the environmental benefit compared to the length adversely impacted by the road or crossing at the project. Environmental agencies generally prefer that the species that benefits is the same as that impacted.

Examples of permissible mitigation include re-establishing or enhancing floodplain connectivity elsewhere along the stream by removing artificial fill such as levees, removing redundant or abandoned in-stream structures outside the project area, or enhancing/restoring fish passage on a stream with a high potential for environmental recovery.

4.6 Lessons from Nature

Transportation professionals involved in all phases of the infrastructure project life cycle are becoming increasingly aware of the importance of accounting for river functions where possible to create sustainable infrastructure in the river environment. This awareness creates a need for techniques that recognize the intricate web of physical and biological interdependencies integral to natural functions in the river environment (DeVries et al. 2012, Friggens et al. 2014, Wohl 2017). In contrast with traditional exclusively structural, “hard,” or “gray” infrastructure approaches, these techniques take a holistic approach to meeting the needs of humans while protecting and restoring river functions and come with a variety of names: engineering with nature (EWN), natural and nature-based features (NNBF), “soft” or “green” infrastructure (GI), natural flood management, environmentally-sensitive channel- and bank-protection measures, and others (FHWA 2019b, Bridges et al. 2015, FHWA 2009a, Bridges et. Al. 2018).

4.6.1 Nature-Based Solutions

River management approaches that conserve or recover the river’s capacity to evolve and adapt to change in ways that sustain valuable forms, functions and resilience come with several names. The International Union for Conservation of Nature (IUCN) describes Nature-based solutions (NBS) as “actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing for human well-being and biodiversity benefits.” The FHWA adds that NBS refers to the use of natural materials and processes as an alternative to traditional infrastructure protection techniques and includes both natural and nature-based features (FHWA 2019b).

Similarly, Section 11103 of BIL added a definition of natural infrastructure under Section 101 of Title 23 of U.S. Code as follows:

> The term “natural infrastructure” means infrastructure that uses, restores, or emulates natural ecological processes and —

> (A) is created through the action of natural physical, geological, biological, and chemical processes over time;
>
> (B) is created by human design, engineering, and construction to emulate or act in concert with natural processes; or
>
> (C) involves the use of plants, soils, and other natural features, including through the creation, restoration, or preservation of vegetated areas using materials appropriate to the region to manage stormwater and runoff, to attenuate flooding and storm surges, and for other related purposes.

Executive Order 13690 “Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input” also promotes such NBS and natural infrastructure by requiring agencies, where possible, to use natural systems, ecosystem processes, and nature-based approaches when developing alternatives for consideration.’’ (80 FR 13690 (Jan. 30, 2015), revoked by EO 13807 (Aug. 15, 2017), but reinstated by EO 14030 (May 20, 2021)).

In France and Canada, over the last two decades, allowance for the adjustments essential to supporting dynamic stability has been increasingly managed by giving rivers “espace de liberté,” which translates to “freedom space.” This management approach “promotes a sustainable way to manage river systems and increases their resilience to climate and land use changes in comparison with traditional river management approaches which are based on frequent and spatially restricted interventions” (Biron et al. 2014). In the Netherlands and Belgium, the equivalent management approach is “Making room for the river,” while the current United Kingdom nature-based management paradigm is called “Working with Natural Processes.” In the United States, the USACE promotes NBS through its concept of “Engineering with Nature” (EWN).

In consideration of the discussions presented in the previous sections, the NBS approach to improve or restore natural river functions has inherent applicability to the development and maintenance of sustainable transportation infrastructure in the river environment. The NBS approach improves or restores river functions by employment of natural conditions or engineered measures, incorporating natural materials to create conditions that reduce risk to infrastructure. Natural materials include native vegetation and organic materials such as wood and rock. Incorporating natural conditions includes reconnection or restoration of features important to river function such as floodplains and their associated flood storage, riparian areas, and wetlands. The NBS approach is applicable to all phases of the transportation infrastructure project life cycle.

What is NBS?

Use of natural materials.

Use of natural conditions such as riparian areas, floodplains, and wetlands.

Engineered structures incorporating natural processes and natural materials.

Planning: Integration of NBS methods in the planning stage of a project is consistent with environmental regulations and permits discussed previously; FHWA policies, initiatives [Eco-Logical (FHWA 2006a)], and directives [Order 5520 (FHWA 2014)]; and overall approaches to creating resilient and sustainable infrastructure. Planning allows systematic consideration of ecosystem-level conditions, identification of relevant NBS-based projects, collaboration with stakeholders, and coordination with other agencies to facilitate project delivery. An ecosystem approach is useful for fully assessing river functions and making plans to restore them. While planning beyond project boundaries is not always possible, it may be worthwhile so that habitat conservation may be considered on a broader, ecosystem scale, and can lead to more cost-effective opportunities to avoid and minimize impacts. Common goals among project stakeholders can be identified, relevant data collected and shared, and available resources to accomplish the project can be pooled through the planning process.

Design: Implementing NBS for resilient transportation infrastructure in the river environment involves active participation and collaboration from the spectrum of transportation professionals: planners, engineers, ecologists, environmental scientists, pre-construction engineers, maintenance engineers, financial experts, and regulatory compliance staff. The design team determines the type, size, and location of the project that best meets the transportation performance, risk, cost, and ecological attributes of the project.

Construction: The installation of a nature-based project has a variety of risks associated with it that are typical of any construction effort: schedule, budget, environmental impacts, construction quality, and ultimately overall project performance. Transportation agencies have developed proven procedures to minimize such risks. However, the river environment and NBS approach involve a variety of unique challenges to consider. For example, lack of available contractors with NBS construction experience may involve additional training, obtaining adequate specialized equipment for in-water work and native vegetation to meet project construction specifications may involve advance planning and staging.

Operations and Maintenance: The NBS approach can be followed in maintenance and operations activities in a variety of ways. Often, multiple objectives, such as stormwater management that avoids downstream hydromodification, water quality improvements that meet EPA Total Maximum Daily Loads (TMDLs) [See 33 U.S.C. § 1313(d)], and habitat improvement that satisfies ESA section 7 [16 U.S.C. § 1536], can be achieved by implementing NBS treatments that simultaneously achieve highway goals for safety and cost-efficiency. Providing maintenance and operations staff with appropriate training regarding the purpose and challenges of NBS as a tool to accomplish specific goals and establishing a well-developed operations and maintenance plan including monitoring activities (see Section 8.11) is important for long-term project success. Maintaining open lines of communication with appropriate technical specialists regarding monitoring observations resulting in maintenance actions informs appropriate adaptive management steps.

Common activities where restoration of native vegetation and restoration of natural river functions may be considered include:

- Stormwater management.
- Streambank repairs.
- Erosion control.
- Water quality protection/improvements.
- Habitat restoration/enhancement (e.g., fisheries, wildlife).

Despite the benefits and wide applicability of NBS, it is important to consider and manage the potential limitations and inherent risks involved in its heavy reliance on native vegetation. Where stream stability issues could introduce unacceptable risk to the stability of transportation infrastructure, natural or biotechnical solutions are not sufficient for erosion and scour protection. See HEC-23 for appropriate bridge scour and stream instability countermeasures. Noted limitations of the use of vegetation in NBS include:

- Limited design criteria: Hydraulic design criteria for application of vegetation is typically general (Lagasse et al. 2016). Limited design criteria have been developed that consider specific plant species or plant development stages. Accordingly, the design criteria for projects relying on vegetation are not well known and uncertainty regarding failure thresholds exists.

- Permitting challenges: Permitting can be easier for conventional infrastructure than for that involving NBS (FHWA 2018b). This is attributable to less well-developed design criteria, performance uncertainties, and lack of experience with projects involving NBS. Collaboration with permitting agencies as early as possible in a transportation infrastructure project can help mitigate this challenge.
- Potential for inconsistent performance: Vegetation in the river environment is subject to a variety of factors that can affect its establishment, growth, vigor, and longevity. These factors include planting location, poor planting technique, soils, weather, moisture, depredation, and long duration flood inundation. These influences all may affect the level to which vegetation establishes. Furthermore, many types of vegetation display significant seasonal differences. Inadequate or inconsistent establishment of vegetation and seasonal differences in vegetation may result in inconsistent project performance.
- Ongoing maintenance: Unlike traditional treatments, such as riprap revetments, vegetation changes through time due to environmental factors. Vegetation establishment success may range widely, from vigorous growth to die off. Because the NBS approach focuses on native vegetation establishment, projects of this type involve a potentially long-term commitment to monitoring vegetation establishment and adaptively managing conditions to ensure successful vegetation establishment. Typical maintenance tasks may include monitoring establishment, replanting, irrigation, weeding, mulching planted areas, and eliminating invasive species. Such maintenance activities generally include a long-term and ongoing commitment of resources, which may be challenging to maintain if resources are insufficient or diverted to address other, more pressing needs. Structural components of NBS do not typically involve routine maintenance but may involve adaptive management measures periodically if the structure is not providing the expected benefits, or if it is causing unintended consequences.

4.6.2 Bioengineering

HEC-23 (FHWA 2009a) presents bioengineering as the use of living and nonliving plant materials in combination with natural and synthetic support materials for multiple purposes including slope stabilization, erosion reduction, and vegetative establishment. As such, bioengineering measures are generally consistent with the NBS approach to using natural processes and natural materials to reduce erosion, stabilize shorelines, protect infrastructure, and reduce flood risks (FHWA 2019b). General categories of bioengineering techniques include:

- River training structures.
- Bank armoring and protection for erosion control.
- Habitat improvements.
- Slope stabilization.

Commonly, designers blend bioengineering methods with traditional approaches, such as riprap revetment, to mitigate some of the environmental impacts of purely structural approaches while also benefiting from a greater level of performance certainty where involved risks of project failure are unacceptable. Figure 4.13 demonstrates a typical example of vegetated riprap.

In-depth documentation has been developed regarding technical design methods, conceptual designs for alternative treatments, and project case studies for bioengineering projects (FISRWG 1998, McCullah and Gray 2005, NRCS 2007a, Lagasse et al. 2016).

4.7 Sustainability and Resilience

Inputs of water, wood, sediment, and debris derived from a watershed all influence river form and function and are influenced by regional climate. Land use changes in a basin can dramatically affect the volume and timing of runoff generated from the watershed. Similarly, changes in climate can affect the magnitude, duration, intensity, and type of precipitation in the watershed. If either basin land use or climate conditions change through time, the assumption hydrologic stationarity engineers use to estimate flood magnitude and frequency becomes uncertain (McCuen 2003). By recognizing and planning for such uncertainty and its associated risks, those involved in all stages of a transportation infrastructure project can best achieve project resilience, enhance reliability, and foster long-term sustainability of transportation infrastructure in the river environment.

Figure 4.13. Vegetated riprap along the Red River near Fargo, ND. Image used by permission of WEST Consultants, Inc.

4.7.1 Basin Change

Development within a basin generally increases impervious area and reduces vegetative cover in the watershed, resulting in less infiltration and increased runoff. Developed areas also generally have more efficient runoff collection systems that reduce ponding and reduce the time it takes for runoff to reach an outfall location along a watercourse. Hydrologic modeling is commonly used as part of watershed planning studies to evaluate and compare runoff for existing and expected future basin development conditions and evaluate alternatives for mitigating potential impacts of development for basin runoff. An example of the hydrologic impact of development conditions in a basin is shown in Figure 4.14, where hydrographs for developed and undeveloped watershed conditions are compared. The developed Mercer Creek hydrograph has a significantly higher peak discharge during a 2000 storm event compared to the hydrograph for the nearby undeveloped Newaukum Creek (Konrad 2003).

The increased magnitude and volume of runoff associated with future conditions may have direct and significant impacts on existing infrastructure in the river environment. Design flows for existing infrastructure may be exceeded, surpassing the design conveyance capacity, resulting in unanticipated water surface elevations and excessive hydraulic forces potentially resulting in roadway overtopping or increased scour potential, bank erosion, or channel adjustments such as widening or channel degradation or aggradation. Basin change could also induce overall morphological changes to the river system, such as channel incision. See Section 7.3.3 for a further discussion of long-term bed changes. These responses to the altered basin conditions may adversely affect the overall safety and reliability of transportation infrastructure and induce a variety of unforeseen risks to natural river function. Enhancing the sustainability, adaptive capacity, and resilience of transportation infrastructure thus entails considering the potential for basin land use changes. In recognition of these threats, practitioners should consider existing land use conditions as well as future land use conditions that may exist during the lifetime of the transportation infrastructure (FHWA 2016).

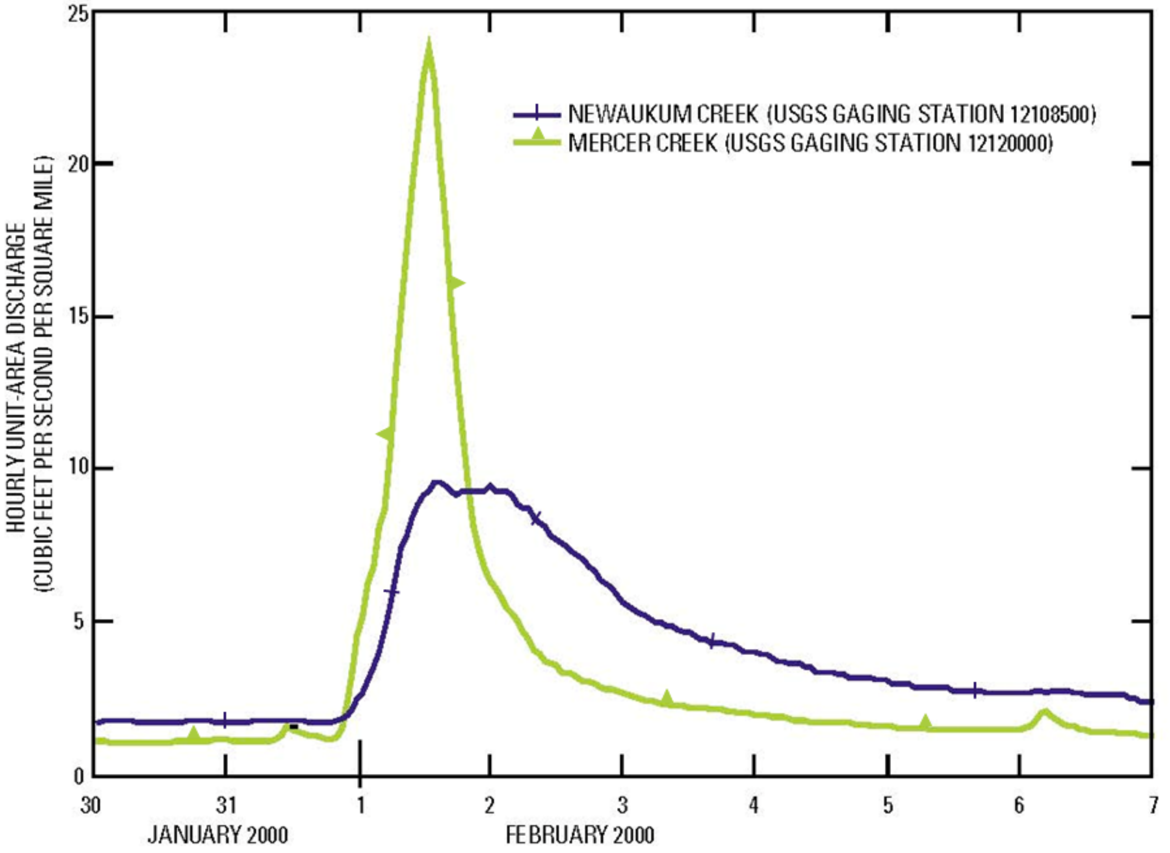


Figure 4.14. Hydrographs illustrating differences in runoff characteristics for developed (Mercer Creek) and undeveloped (Newaukum Creek) watersheds in Washington. Adapted from USGS.

To increase project sustainability and resilience, project teams could use future hydrology estimates for hydraulic design or to identify appropriate mitigation measures for expected impacts from future runoff peaks and volumes. The FHWA and others have developed information regarding development of future hydrology estimates, e.g., FHWA (2016) and Kilgore et al. (2019). Physical control of future hydrologic conditions (such as regional detention/retention ponds) generally includes project implementation within the watershed and, typically, outside of the transportation corridor right-of-way and the purview of a State DOT. Design and construction of projects to accommodate future hydrologic conditions is also limited by the ability to reasonably project future basin development timelines and conditions and by limits on available resources to accommodate future conditions.

4.7.2 Climate Change and Extreme Events

Climate change refers to any significant change in the measures of climate lasting for an extended period (FHWA 2014). Climate change includes major variations in temperature, precipitation, coastal storms, or wind patterns, among other environmental conditions, that occur over several decades or longer (FHWA 2014). Changes in climate may manifest as a rise in sea level as well as in altered frequency and magnitude of extreme weather events now and in the future (FHWA 2014, TRB and NRC 2008). The impacts of a changing climate and associated risks of extreme weather events may affect the lifecycle of transportation infrastructure projects. Sea level rise is of particular concern because of the potential for extensive impacts on the coastal environment and population, including impacts on the transportation infrastructure (FHWA 2014, TRB and NRC 2008). Impacts may include increased flooding due to relative sea level rise and increased impacts of waves during extreme events. Extreme intensity rainfall events can result in runoff conditions that overwhelm storm drainage facilities, disrupt traffic, overtop bridges and increase bridge support scour, damage culverts, and result in costly emergency repairs (FHWA 2016, FHWA 2014, TRB and NRC 2008, Savonis et al. 2008).

As described in FHWA Order 5520 (FHWA 2014), “it is FHWA's policy to strive to identify the risks of climate change and extreme weather events to current and planned transportation systems. The FHWA will work to integrate consideration of these risks into its planning, operations, policies, and programs in order to promote preparedness and resilience; safeguard Federal investments; and ensure the safety, reliability, and sustainability of the Nation’s transportation systems.”

State Spotlight: Considering Climate Change in California

The California Department of Transportation (Caltrans) has been incorporating climate change considerations into its activities since establishing its Climate Change Branch in 2007. Caltrans has developed guidance on the subject, paying particular attention to sea level rise (Caltrans 2011, Caltrans 2013). Local and regional transportation planning agencies are incorporating considerations of climate change into ongoing infrastructure planning, development, and operations.

Climate change affects people as well as transportation assets. The USDOT “Climate Action Plan” (USDOT 2021) noted:

> Climate change has been shown to disproportionately impact vulnerable populations—older adults, children, low-income communities, and communities of color. These communities have less capacity to prepare for and cope with extreme weather and other climate change-related events, such as having fewer options for evacuating or for accessing emergency relief services.

The USDOT “Climate Action Plan,” which was developed pursuant to Section 211 of Executive Order 14008 (86 FR 7619 (Jan. 27, 2021)), presents USDOT’s plan to address the significant and growing risk presented by climate change. The FHWA Policy Framework on Using Bipartisan Infrastructure Law Resources to Build a Better America also highlights FHWA’s policy to make the transportation network more sustainable and resilient to a changing climate — in addition to other key policy objectives such as advancing transportation equity. (FHWA, 2021).

There are three primary sources of uncertainty in projections of both global and regional climate through the end of the century (Kilgore et al. 2019):

- Natural variability, which causes temperature, precipitation, and other aspects of climate to vary from year to year and even decade to decade.
- Scientific uncertainty, as it is still uncertain exactly how much the Earth will warm in response to human emissions, and global climate models cannot perfectly represent every aspect of Earth’s climate.
- Scenario or human uncertainty, as future climate change will occur largely in response to emissions from human activities that have not yet occurred.

Engineers are accustomed to working with uncertainty associated with natural variability. The FHWA has prepared two references for working with the other types of uncertainty and document specific tools and procedures: *Highways in the River Environment – Floodplains, Extreme Events, Risk, and Resilience* (HEC-17) (FHWA 2016) and *Highways in the Coastal Environment* (HEC-25) (FHWA 2020).

Scientists continue to improve the body of knowledge of the physical behavior of the atmosphere, oceans, and ice sheet systems, gradually reducing scientific uncertainty over time. However, for some climate effects there is consensus among climate scientists regarding the direction of change. (USGCRP 2018). For example, global temperature and global sea levels are increasing and the uncertainty is about how much (USGCRP 2018).

Based on the available evidence of rising global temperature and the understanding that a warmer atmosphere can hold more water, many suggest the potential for larger storms with increased magnitude and intensities of precipitation (Meyer et al. 2013, Meyer et al. 2014, TRB and NRC 2008). Higher temperatures may also alter the form in which precipitation occurs, changing typical snowfall to rainfall, which could lead to reduced seasonal snowpack, earlier runoff, increased possibilities of rain-on-snow events, seasonally drier soils, and increased or decreased soil infiltration capacities (FHWA 2016, TRB and NRC 2008).

The third type of uncertainty is scenario uncertainty. This relates to the challenges of projecting future social and economic behavior and development. For the next approximately 30 years, there is little divergence across scenarios because of the limited range of effects from greenhouse gas emissions during that period. However, beyond 30 years, projections of impacts diverge more significantly depending on the scenario (USGCRP 2018).

Although the specific effects of a changing climate in any given region of the country are uncertain, the Fourth National Climate Assessment provides extensive information about projected changes across the United States and by region (USGCRP 2018). Other representative resources with valuable information for transportation infrastructure planning by region include:

- *Climate Change Impact Assessment for Surface Transportation in the Pacific Northwest and Alaska* (Mote et al. 2012).

- *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I* (Savonis et al. 2008).
- *Climate Change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance* (FHWA 2015a).
- "Regional Climate Change Effects: Useful Information for Transportation Agencies" website (FHWA 2010b).

Some transportation agencies have begun to assess vulnerability and a subset has moved beyond vulnerability assessments into adaptation planning. The FHWA has developed a vulnerability assessment and adaptation framework to facilitate the incorporation of climate change in infrastructure planning, design, and engineering (FHWA 2017b). In *Climate Change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance* (FHWA 2015a), the FHWA describes procedures for identifying climate change vulnerabilities, characterizing impacts and risks of those vulnerabilities, identifying objectives, and building adaptive capacities in management, operations, and maintenance activities. The Transportation Research Board has created two volumes on using a cost-benefit analysis (CBA) as a decision-making tool. State DOTs can use this tool as they evaluate the extent to which they incorporate adaptation for climate change or extreme weather into transportation infrastructure design (TRB 2020a and TRB 2020b).

State Spotlight: Fish Passage and Climate Change in Washington

With the development and release of the Washington Department of Fish and Wildlife (WDFW) Final Report regarding the incorporation of projected changes in climate into the design of water crossing structures (Wilhere et al. 2017), WSDOT has been using this information to guide work on replacement stream crossings. For the SR112 Olsen Creek Fish Barrier Removal project, for example, the project team investigated how the change in bankfull width and 100-year peak flow would impact the earlier plans for the Olsen Creek Crossing. Applying the methodology laid out by WDFW to calculate increases in flows at the State Route 112 crossing of Olsen Creek on the Olympic Peninsula resulted in a 23.8 percent increase in 100-year flow, from 306 ft^3/s to 379 ft^3/s. This process showed that a minimum bridge width of 37 feet would pass the 100-year flow without constricting the flow, an increase of five feet. The final design—a 45-foot bridge span—also considered the projected changing climate, the tidal influence at the crossing, and overall fish habitat goals.

The FHWA has outlined a framework to address potential effects of climate change in planning and design of transportation infrastructure in *Highways in the River Environment – Floodplain, Extreme Events, Risk and Resilience* (HEC-17) (FHWA 2016). The general framework not only recognizes uncertainty in the future, but also recognizes that not all plans and projects merit the same level of analysis. The planning and design team for a project will select the appropriate level of analysis from level one (minimal analysis) to level five (detailed comprehensive analysis) considering the risks for the plan/project and the hydrologic service life. Evaluation of risk includes the asset criticality, vulnerability, and cost.

Research continues to determine approaches likely to be effective in addressing the range of potential conditions that may result from climate change (e.g., FHWA 2016, FHWA 2020, and Kilgore et al. 2019). However, there is no broad consensus on specific infrastructure design strategies. USBR has identified general framework for managing infrastructure projects in the stream environment in the context of future climate uncertainty that includes the following approaches:

- Evaluating risk and incorporating tolerances in the initial design, such as a taller or wider bridge, to better accommodate the uncertainties, reduce potential impacts, and increase project sustainability.
- Incorporating actionable, albeit imperfect, projections of future climate and hydrology conditions in the design process.
- Relying on adaptive management strategies in design, such as bridge raising or widening, as more information about future conditions becomes available or as existing conditions change (Sholtes et al. 2017).

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Chapter 5 - Hydrology and Hydraulics for Roads, Rivers, and Floodplains

Transportation professionals involved in all project life cycle phases use hydrologic and hydraulic data and information to make decisions affecting the sustainability and resilience of projects in the river environment.

- Planners consider how the transportation network can best integrate with the functions of rivers and floodplains while meeting the needs of project stakeholders.
- Engineers design safe and efficient facilities by considering hydrologic loadings, hydraulic forces, and their associated risks.
- Scientists identify and characterize potential environmental impacts associated with transportation project impacts on hydrology and hydraulics and determine effective approaches to avoid, minimize, or mitigate them.
- Construction professionals implement projects while managing hydrologic and hydraulic conditions onsite and meeting regulatory and permit conditions.
- Maintenance professionals conduct repair and construction activities to facilitate the reliable operation of projects under the range of hydrologic and hydraulic influences throughout the project life cycle.

In Chapter 2, Section 2.4 outlines the nature and significance of long-stream, lateral, and vertical connectivity. This chapter presents the effects of river hydrology and hydraulics connectivity related to flow frequency, flow duration, channel-forming flows, 1D and 2D modeling, and the hydrologic and hydraulic impacts of crossings (bridges and culverts) and encroachments. Coverage focuses on the hydrologic and hydraulic significance of lateral connectivity between the channel and its floodplain.

5.1 Surface Hydrology

Hydrologic data and information are the basis for hydraulic, geomorphic, and sediment transport evaluations; hydraulic design; and environmental impacts assessments for a project in the river environment. Uncertainties regarding the understanding of project hydrology directly affect the size of structures, potential environmental impacts, project cost, and project life cycle performance. Hydrologic uncertainties may adversely affect project risk, resilience, and reliability, as well as overall project sustainability.

Thorough hydrologic analyses and consideration of hydrologic uncertainties are essential to understanding and minimizing project risks to promote overall project success in the river environment. A thorough hydrologic analysis involves:

- Characterizing the watershed drainage area contributing to the project site.
- Understanding the climatic conditions that contribute precipitation and generate runoff.
- Identifying historic flood events using flow gauging records for the area when available.
- Accessing existing flow frequency estimates applicable to the area.
- Updating or developing flow frequency estimates and identifying geomorphic and ecologically relevant flows related to low, normal, and high stages and durations.

- Identifying potential hydrologic impacts in the project area.

Limitations of resources or available data, such as a long-term, site-specific flow records, may impede the ability to conduct a thorough hydrologic analysis for the project site. For example, use of a simple, regional regression equation correlating flows to hydrologic variables, to determine peak flow flood frequency values for the project site typically provides estimates with significant levels of uncertainty. In such cases, it is important to consider how hydrologic uncertainties could impact subsequent hydraulic, geomorphic, and sediment transport analyses; design efforts; and associated impact assessments. Sensitivity analyses can be conducted to assess the expected range of resulting hydrologic risk. The range of potential consequences revealed by that assessment may justify additional resources or more sophisticated hydrologic analyses.

As discussed in Section 2.4, connectivity governs relationships between the conveyance and storage functions in river channels. Impairments to connectivity may directly affect the frequency and duration of surface water flows. The following sections provide a brief overview of methods for evaluating the magnitude, frequency, and duration of flows. *Highway Hydrology (HDS 2)* (FWHA 2002) provides detailed coverage of hydrologic analysis methods.

5.1.1 Flood Flows

Hydrologists typically use one of three methods to derive flood flow frequency estimates:

- Analytical estimates based on a historic record of peak flow observations from gaging stations specific to the water course of interest.
- Where a historic record of peak flow observations from gaging stations is not available for the watercourse of interest, estimates are derived from hydrologically similar watershed(s) in the region where historic flow data are available. Regression equations are developed from correlating observed flow values to hydrologic variables (i.e., drainage area, forest cover, mean annual precipitation) for the hydrologically similar watershed(s).
- Computer models of physical rainfall-runoff processes for specific rainfall return periods or simulations of long-term precipitation records.

As future flood estimates are based on past observations of runoff or precipitation, a degree of uncertainty is always associated with them. Sources of hydrologic uncertainty include the record of hydrologic observations used in developing the statistical estimates, the statistical distribution used to fit the historic observations, and the general validity of the assumption that past hydrologic observations represent future hydrologic conditions (McCuen 2003). Uncertainty associated with the third approach also stems from several considerations: 1) the parameters used in the model, 2) the mathematical algorithms used to represent rainfall-runoff processes, 3) the historic hydrologic event data available to calibrate and validate the hydrologic model results, 4) the level of experience of the modeler, and 5) the general validity of the assumption that precipitation-frequency is representative of runoff-frequency.

Accommodation of the hydrologic uncertainties in the hydraulic design of transportation infrastructure in the river environment is typically accomplished by using “factors of safety” in design, such as increasing the low chord elevation of a bridge to provide extra freeboard (the vertical clearance of the lowest structural member of the bridge superstructure above the water surface elevation of the overtopping flood). This approach has serious implications for the cost of a project. The FHWA outlines specific steps to address potential effects of general hydrologic uncertainties and those associated with climate change in planning and design of highways in the FHWA manual *Highways in the River Environment – Floodplain, Extreme Events, Risk and Resilience (HEC-17)* (FHWA 2016).

Flow values along a perennial watercourse represent a continuum, varying from the minimum base flow to the most extreme high flow events. The range of potential flows also represents a continuum of flow stage, duration, and energy. Portions of the potential flow range have particular significance for the transport of sediment, wood, and debris, as well as for the morphology and ecology of the channel and floodplain. The same is true for intermittent waterways, except for those periods when there is no flow in the waterway. To design successful transportation infrastructure in the river environment and avoid adverse environmental impacts, it is important to understand the range and duration of potential flows and their capacity to transport sediment, wood, and debris. As discussed in Section 5.1.2, alterations to flow duration can increase the time that stream bed sediments and large wood are mobilized in ways that can lead to stream evolution and adjustments to the channel.

5.1.2 Flow Duration

How much water flows in a watercourse and how long those flow conditions persist is critical information for those planning, designing, building, and maintaining transportation infrastructure in the river environment. This information is typically depicted in a “flow duration curve” (FDC), which is a plot showing the percentage of time that flow is equaled or exceeded during the period of interest. Common analysis periods include annual, seasonal, monthly, and specific construction periods. Depending on the purpose, hydrologists working on a transportation infrastructure project develop FDCs to reflect maximum, average, or minimum annual or monthly flow conditions.

Local Spotlight: Hydrology at Work - Determining Flow Conditions for an In-water Work Period to Protect Salmon

The City of Salem, Oregon, used flow duration information to understand the flow characteristics during the permitted in-water work window for replacement of the Commercial Street Bridge along Pringle Creek. Hydrologists conducted an analysis of the available historic flow records to determine the minimum, average, and maximum discharge; 2-year, 7-consecutive-day discharge; and discharge equaled or exceeded 1%, 10%, 50%, and 95% of time for the entire period of record and each specific month of the in-water work window.

Using flow duration curves to identify changes in watershed runoff through time can be useful for project teams considering the impact and implications of modifications in hydrology upstream resulting from changes in land use, climate variability, or climate change. When designing transportation infrastructure, engineers use flow duration curves to estimate the channel-forming discharge and mean annual sediment transport capacity needed to evaluate annualized, reach-scale aggradation or degradation trends. They also use this information to identify hydrologic conditions for aquatic-species passage, including fish. Flow duration curves characterizing likely flow conditions during construction and operation also inform the work of those planning and preparing for in-water construction and maintenance activities.

Impacts to lateral and vertical connectivity along a watercourse have potential effects on flow duration. Reduced infiltration in disconnected floodplains or altered surface water-groundwater connection can affect groundwater recharge, the magnitude and duration of associated baseflows, riparian vegetation, passage of aquatic organisms through culverts, and the overall availability of critical habitat.

Hydrologists can develop flow duration information using different procedures depending on the availability of data:

- Direct evaluation of historic flow records collected on the stream.
- Application of regression equations developed from correlation of regional flow records.
- Hydrologic modeling of watershed runoff based on long-term precipitation records.

Direct evaluation of historic flow records specific to the watercourse of interest typically provides the most reliable flow duration information. Greater uncertainty is associated with regression equations and hydrologic modeling of runoff.

Hydrologists typically develop flow duration information from historic flow records, such as average daily flows, using the following steps (McKay and Fischenich 2016, Searcy 1959):

1. Identify the range of flows of interest and equal flow increments through the range of flow values.
2. Sort the flow record to determine the number of flow values equal to or greater than each flow increment from Step 1.
3. Determine the percent of time equaled to or exceeded by dividing the value identified in Step 2 by the total number of flows to determine exceedance probability. Determine exceedance as percent of time by multiplying the exceedance probability value by 100.

Table 5.1 shows an example of this process with a dataset having 82 occurrences. The resulting data pairs of percent of time (x-axis) and associated flow value (y-axis) can be plotted as shown in Figure 5.1, creating a flow duration curve. Engineers and hydrologists use the curve to estimate the duration of any flow for which measured data are unavailable. FDCs may be created to represent flow characteristics throughout the year but can also be developed to represent any specific period (i.e., annual, monthly, or seasonal) for the specific application by appropriately parsing the record of historic flow data into the applicable periods.

Table 5.1. Example flow duration computation.

Flow (ft^3/s)	Number of Flows Equal to or Exceeded	Exceedance (%)
45	1	1
40	2	2
35	4	5
30	7	9
25	12	15
20	19	23
15	29	35
10	44	54
5	64	78
1	82	100

For locations where historic gage data are not readily available, regression equations can be applied to estimate the flow duration information (Archfield et al. 2007, Fennessey and Vogel

1990). The U.S. Geological Survey (USGS) StreamStats website (streamstats.usgs.gov/ss/) presents regression equations for this purpose. If an appropriate equation is unavailable, hydrologists may be able to develop site-specific regression equations using gage data from similar watersheds.

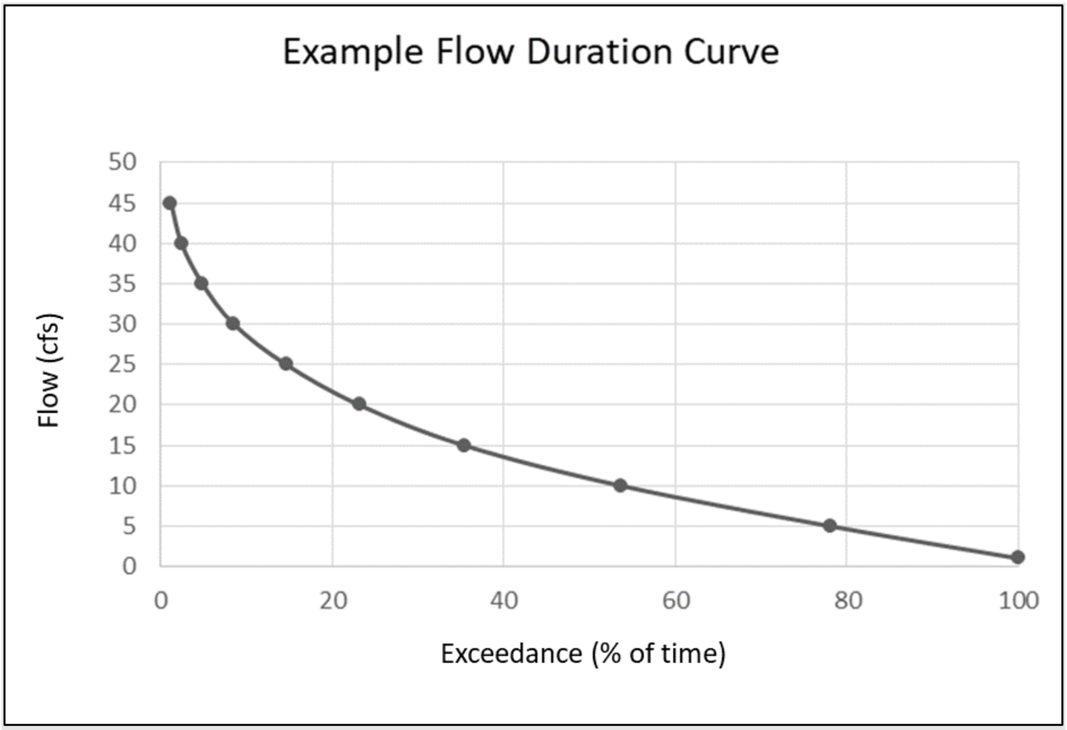

Figure 5.1. Example flow duration curve.

The most technically involved and data-intensive method for computing flow duration information is when hydrologists use continuous simulation hydrologic models. Continuous simulation modeling is based on data from observed rainfall events, which can provide a more detailed representation of the interactions between precipitation, watershed geometry, and land use characteristics (Doyle et al. 2007). By simulating flow and duration using multiple years of hourly (or-shorter) runoff data, continuous simulation modeling can determine changes in soil moisture, evapotranspiration, and runoff. To do this, hydrologists first develop a suitable hydrologic model of the watershed upstream of the point of interest using precipitation, topography, land use, and observed flow data. Preferably, the hydrologist calibrates and validates the hydrologic model based on the record of precipitation data and measured flow data. Hydrologists then use a long-term record of precipitation data to develop a long-term record of simulated flow data and a flow duration curve from the model results.

Figure 5.2 provides an example of flow duration curves developed from a continuous simulation hydrologic model. In this example, the modeler considered multiple scenarios to evaluate the effects of watershed development over the period of 1939 to 2007. The conditions evaluated included: 1) predevelopment (historic), 2) existing conditions (existing), and 3) future conditions (future). The model results demonstrate that without mitigation, flow magnitudes for given durations increase into the future, especially for extreme flood events with very low probabilities of exceedance (e.g., less than 1 in one thousand).

5.2 Subsurface Hydrology

Some of the relatively low-lying areas surrounding the river are moist, saturated, or inundated because of surface and sub-surface connections with flow in the channel. This sub-surface connectivity in the “hydrologic floodplain” allows water to freely exchange between the flow in the channel and subsurface flow in the alluvial aquifer underlying the channel and floodplain. Surface connectivity allows water exchange between the floodplain and channel via side channels and when the water surface elevation in the channel exceeds the bankfull stage or elevation.

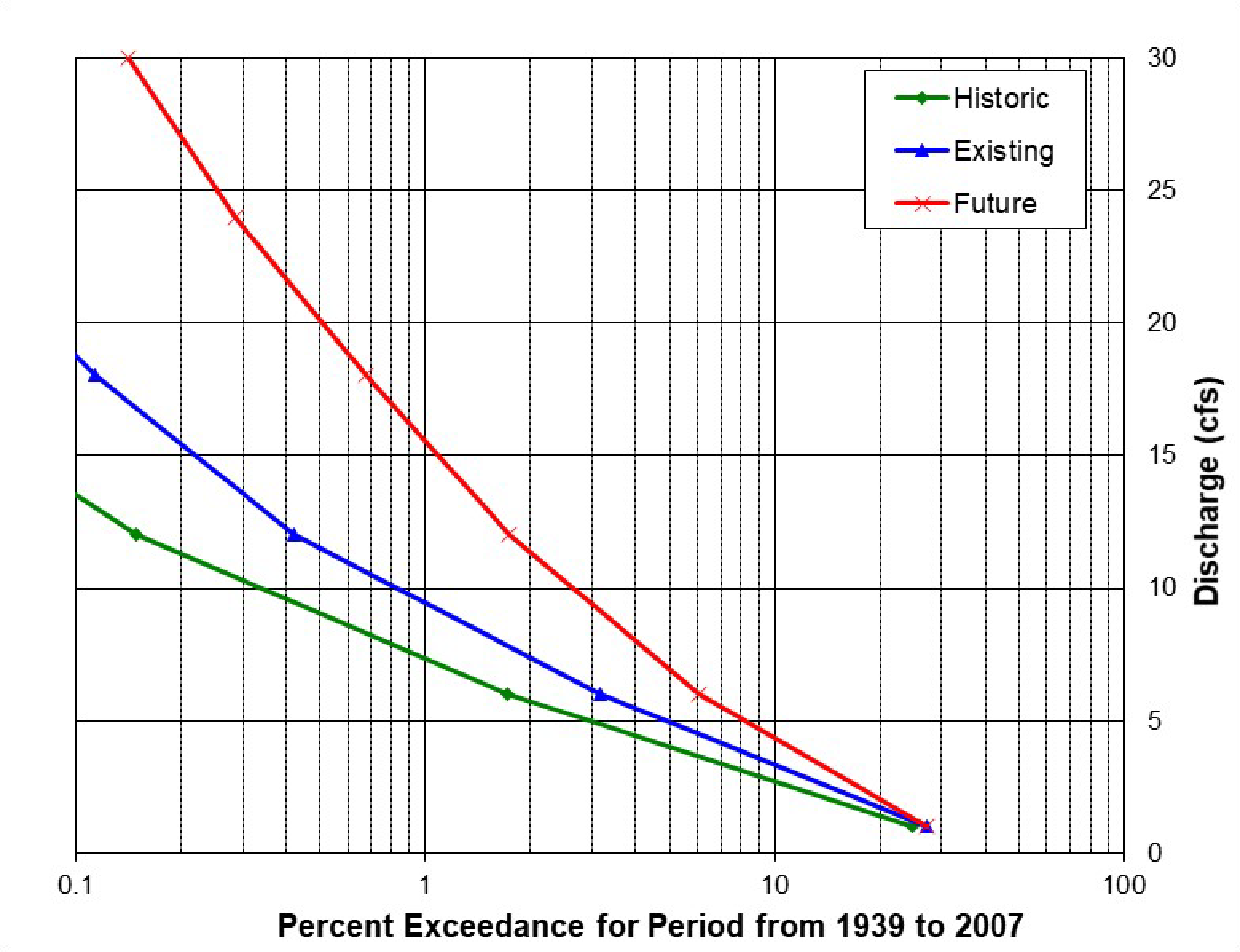

Figure 5.2. Example flow duration curves developed from a continuous simulation hydrologic model.

Channel-floodplain connectivity is important to subsurface hydrology, instream and floodplain habitats, and vegetation. This explains why channel/floodplain disconnection such as channelization or incision can cause hydromodification (alteration of the natural flow of water through a landscape). Such disconnection can also lead to increased hydraulic efficiency that converts a response reach into a transport reach. These changes to long-stream as well as lateral connectivity may generate local and systemic instability.

In a naturally adjusted, dynamically stable reach, the channel and floodplain are fully connected, and the floodplain has the hydrologic form of a wet meadow or woodland. The channel is inset, but not incised, into the floodplain, which comprises a thick sequence of alluvial sediments. The alluvial hyporheic aquifer is close to or at ground level. It is important to note that the hyporheic zone is not always contiguous with the regional groundwater, and that the alluvial aquifer may be perched above the water table. In a fully connected channel-floodplain system, alluvial soils and ready access to water support vegetation characterized by hydrophytic, riparian, wetland species (Figure 5.3A).

When a river is channelized or it incises significantly, the water surface elevations in both the channel and alluvial aquifer lower. Draining the alluvial aquifer may result in hydrophytic plants on the floodplain being replaced by terrestrial and upland species that are adapted to drier conditions (Figure 5.3B). In floodplains developed for farming, hydrological connectivity acts as a form of natural sub-irrigation supporting rich meadow grasses for grazing and reducing or eliminating the need for artificial irrigation of crops.

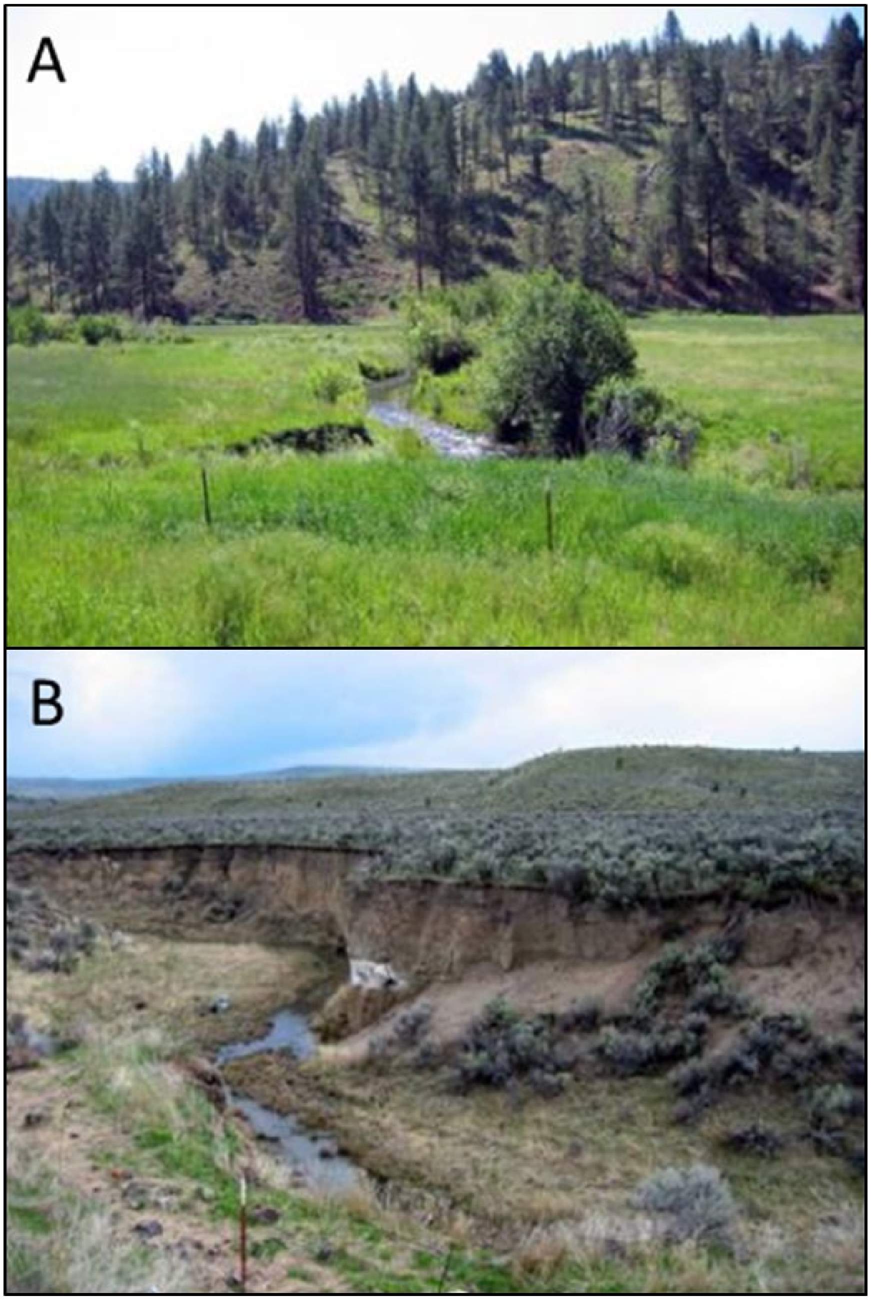

Figure 5.3. Comparison of a hydrologically connected and hydrologically disconnected floodplain. (A) Full hydrologic connectivity in an adjusted channel-floodplain system. (B) Disconnected channel-floodplain hydrology resulting from channel incision. Source: NOAA-NMFS (photo credits: Tim Beechie).

Figure 5.4 shows idealized cross-sections through the respective images shown in Figure 5.3. While Figure 5.3 provides a simple visualization of hydrologic connectivity, in most rivers, sub-surface connectivity is far more complex because the hydrological properties of sediments making up the alluvial aquifer vary between layers.

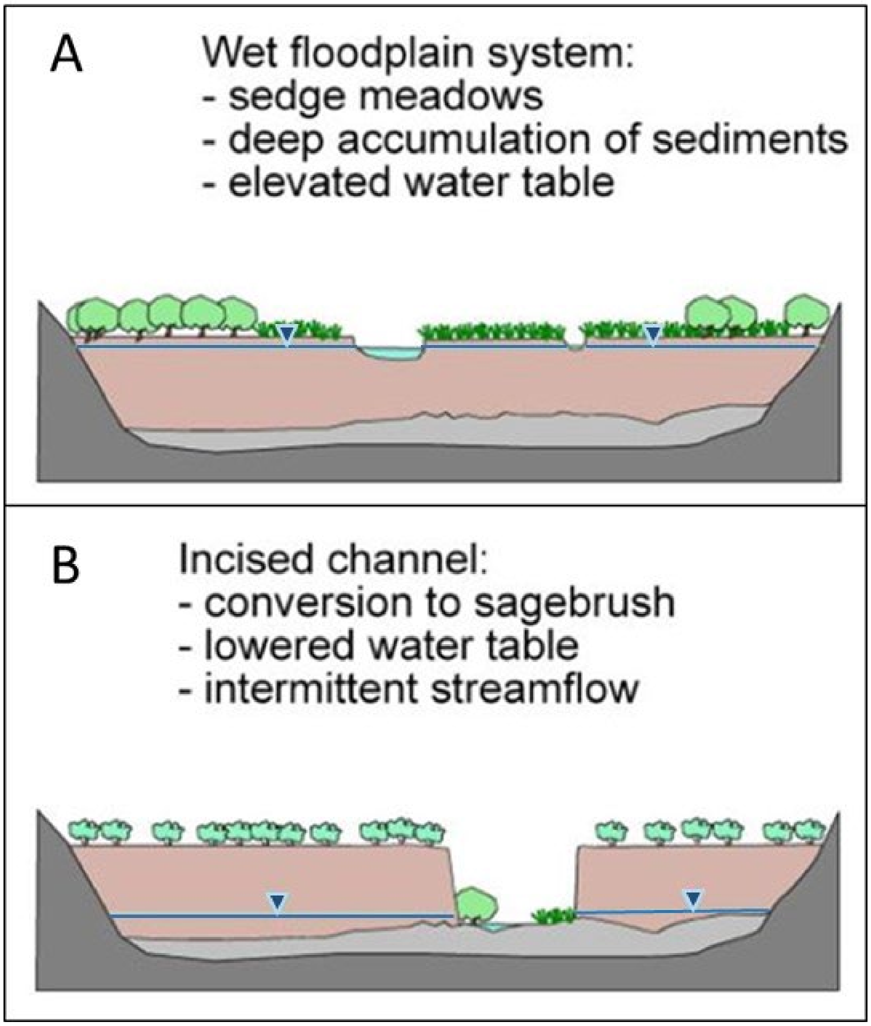

Figure 5.4. Comparison of the alluvial aquifer a hydrologically connected and hydrologically disconnected floodplain. (A) Full hydrologic connectivity in an adjusted channel-floodplain system. (B) Disconnected channel-floodplain hydrology resulting from channel incision.

Figure 5.5 illustrates that floodplain sediments are complex with layers of materials varying in vertical and lateral extent, as well as in their water storage and transmission properties. These properties may range from coarse layers that are highly permeable, but release water relatively quickly during dry periods, to inter-bedded finer-grained layers that are less permeable, but retain water efficiently, even during droughts.

Another important feature of sub-surface hydrologic connectivity between the channel and the floodplain results from the observation that floodplains are not actually level plains. Typically, the highest part of a floodplain is along the natural levee close to the channel because this is where sediment deposition builds the floodplain fastest. On the gently inclined “backslope” of the natural levee, elevations decrease gradually with distance from the channel until they intersect either the phreatic surface of the alluvial aquifer or the regional water table in areas termed “backswamps.” These are marshes, wetlands, and seasonal lakes as illustrated in Figure 5.6. Beyond the backswamps there may be older, higher ridges created by levees and bars built up by abandoned channels.

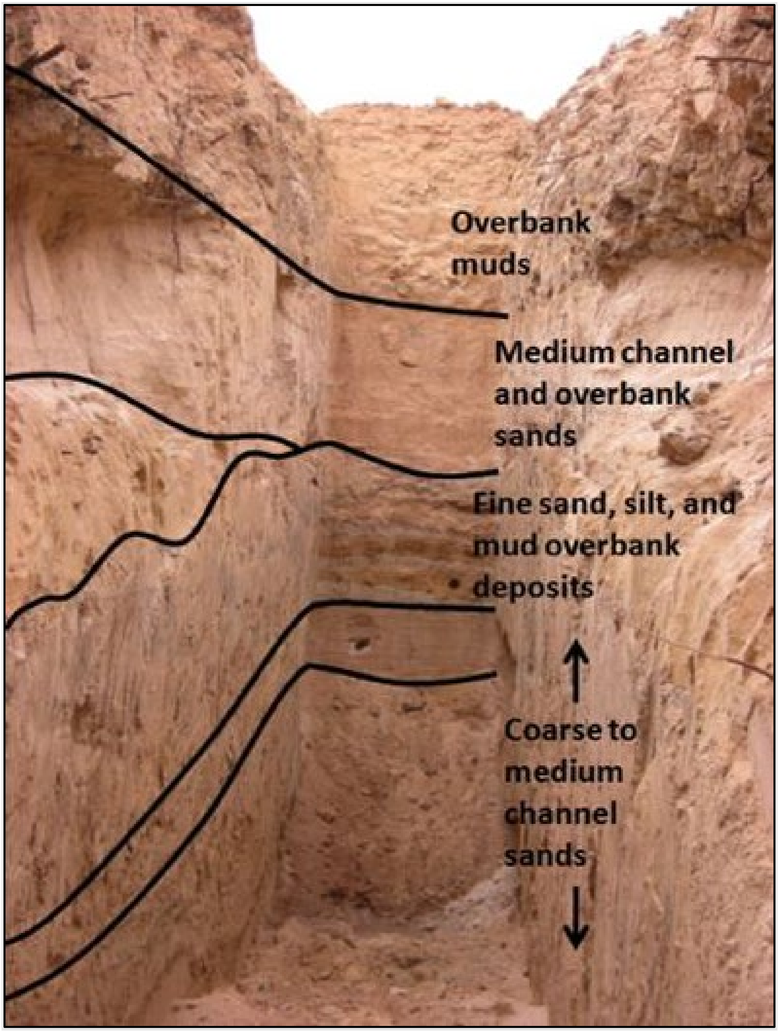

Figure 5.5. Soil pit in the floodplain of Strzelecki Creek, Australia, revealing complex layers of alluvial sediments ranging from mud to fine, medium, and coarse sands. Adapted from Larsen et al. (2016) and used by permission.

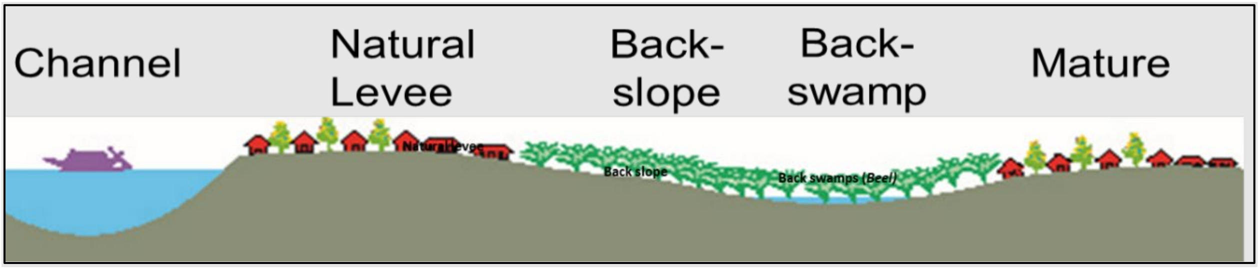

Figure 5.6. Schematic cross-section showing the terrain of a typical floodplain.

This topography is significant because when the water level rises in the channel, the additional pressure drives seepage through the alluvial aquifer and raises the water table in the backswamps until it approximately matches that in the channel. This inundates some of the backslope and mature floodplain well before it reaches bankfull stage and starts to inundate the floodplain by spilling over the natural levee. The outcome is that in natural, hydrologically connected floodplains, inundation usually spreads out progressively from the low marshes, wetlands, and seasonal lakes. In well-connected floodplains, the sudden and destructive impacts of major river floods that over-top (or breach) the natural levee are often somewhat muted because floodwaters surge into areas that are already inundated. Exceptions occur where cutoff walls beneath artificial levees prevent sub-surface hydrologic connectivity and during flash floods driven by extreme rainfall events in small, steep headwater streams and intermittent watercourses.

Figure 5.6 is a simplified view of floodplain topography. Landforms in real floodplains are as complex as the sediment layers and soil horizons that underlie them. As shown in Figure 5.7, the surface of the floodplain is a tangled mixture of ridges, sloughs, and depressions related to past floods, channel migration, and the distributions of relatively coarse and fine sediments.

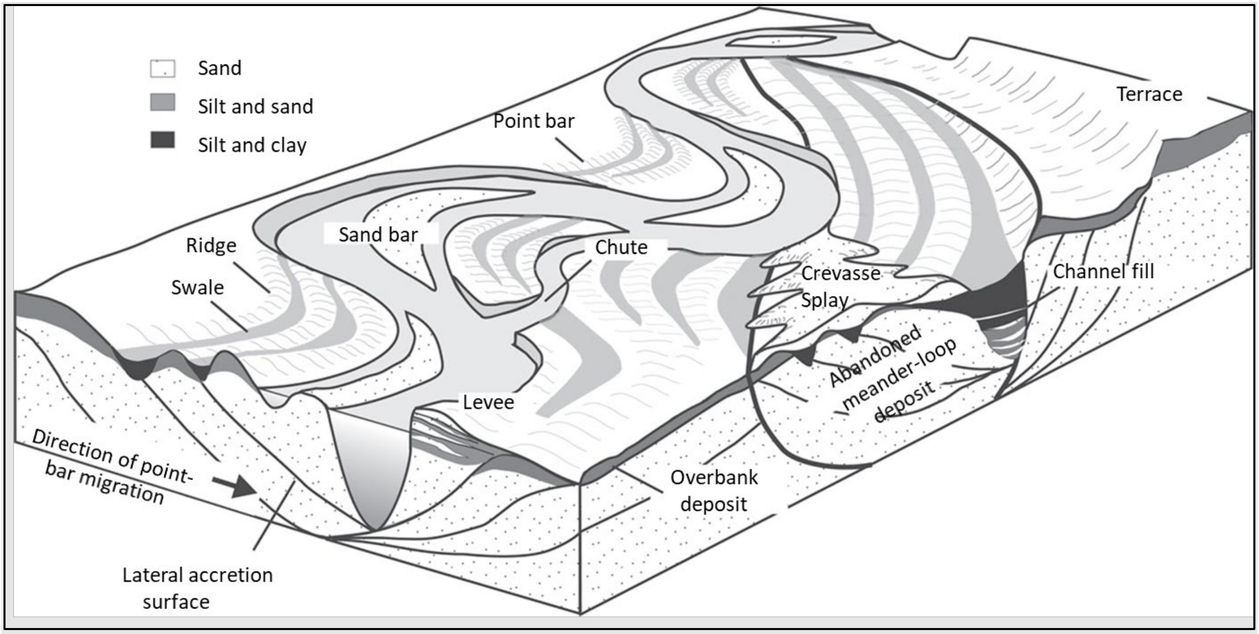

Figure 5.7. Schematic representation of the complexity typical of floodplain topography and sediments. Image used by permission of E. Wohl (© 2019).

5.3 River and Transportation Structure Hydraulics

Based on the identified hydrologic information, hydraulic analyses are conducted to develop critical information pertinent to addressing issues relevant to all phases of the project life cycle. Hydraulic analyses may involve a variety of techniques, including application of hydraulic engineering formulas and hydraulic modeling.

Hydraulic models can be either physical, laboratory-based, scaled models or mathematical, computer-based algorithms. Mathematical models are commonly used as they are generally very cost effective to apply, they make evaluating multiple modeling scenarios feasible, and the computational resources are widely available. Physical models are typically only used to evaluate unique structural features involving complex hydraulic conditions, such as spillways of dams, where uncertainties exist in the ability of current mathematical algorithms to directly represent them. In situations where physical models are employed, mathematical models are typically also developed and results between the two types of models compared.

Mathematical models are commonly used to represent river hydraulics and hydraulic structures such as bridges and culverts. A variety of mathematical hydraulic models is available for application. These models include rigid and mobile bed models in one, two, and three dimensions. The specific type of hydraulic model selected for use is generally related to the project conditions, data availability, and funding (FHWA 2012c). One dimensional models have been the most common hydraulic analysis tool for decades but use of 2D models for transportation hydraulics is increasing. The FHWA (2012c and 2019a) has identified the benefits of 2D hydraulic modeling for complex bridge hydraulics and scour analysis. The following sections discuss hydraulic modeling techniques and the hydraulic impacts of bridges and culverts.

5.3.1 Hydraulic Modeling

Engineers use mathematical hydraulic models to represent physical processes as a cost-effective means of simulating existing and alternative hypothetical conditions. By comparing model results, engineers estimate the expected benefits and potential impacts and assess the relative feasibility of the available alternatives. Specifically, engineers seek to determine water surface elevations and velocities for the flow conditions in and around the hydraulic structures in the river environment to assess backwater, scour, and bank and channel stability. In addition to the water surface elevations and velocities, the models also compute flow depth, flow area, area of inundation, and other information that is fundamental to successful project planning, development, and operation. Engineers also use hydraulic model results to assess potential project impacts on river functions.

Sediment transport analyses and models (see Chapter 7) are founded on flow hydraulics. Primary considerations for the development of hydraulic models for sediment transport analyses include:

- The specific objective of the sediment transport evaluation (e.g., long-term process simulations or event-based evaluations).
- The resolution of the model relative to involved topographic features affecting the velocity of flow (e.g., flow contraction or expansion).
- Calibration and validation of hydraulic conditions for relevant flows and associated sediment transport conditions.
- Maintaining consistency between the hydraulics represented in non-sediment transport and sediment transport versions of a hydraulic model (when two models are needed) considering that model calibration may involve model parameter adjustments.

Uses of Hydraulic Analysis

- Determination of depths, velocities, and water surface elevations.
- Hydraulic forces on structures and channel boundary.
- Hydraulic conveyance capacity and expected freeboard.
- Backwater effects of structures and channel modifications.
- Identification of floodplain impacts.
- Identification of morphological significant flows.
- Sediment transport capacity changes.
- Long-term aggradation and degradation potential.
- Scour potential evaluation.
- Bank erosion potential and erosion protection design.
- Ice and debris passage and potential impact forces.
- Fish passage conditions.
- Potential hydraulic conditions during construction.

Overall, greater certainty in hydraulic information translates directly to greater certainty in conclusions regarding sediment transport and predictions regarding river channel changes including aggradation, degradation, and scour.

Several factors influence hydraulic conditions, including changes in flow, irregular flow boundaries, variable hydraulic roughness, changing channel slopes, and sediment transport. For rivers where storage of water in floodplain areas is insignificant, engineers commonly assume steady-state flow conditions representing the peak discharge of a flood event. Steady flow (or steady state) models typically have a consistent discharge throughout the model simulation. Models that account for the change of flows throughout a flood event are called unsteady flow (or unsteady state) models.

The earliest hydraulic models considered flow in only one direction (a one-dimensional or "1D" model) along the channel (direction x) and used simplifying assumptions to address the reality of flow occurring in the other potential directions: across channel (direction y) and vertically (direction z). Hydraulic models have become increasingly sophisticated with improved understanding of hydraulic processes, greater ability to mathematically represent the physical processes, and increasing computing power for conducting the involved computations.

Engineers still use 1D models widely, for example, for calculating hydraulic parameters at individual cross-sections oriented perpendicularly to the direction of flow. In 1D model conceptualizations, channel and floodplain flows operate semi-independently, with the channel and floodplain regions as shown in Figure 5.8. This figure is an idealized representation of a cross-section encompassing a channel and its floodplain. Region 1 is the main channel, Regions 2 and 3 represent the floodplain in the left and right overbank areas adjacent to the channel, respectively. By convention, the left and right designations correspond to the perspective of an observer looking at the cross-section in a downstream direction. As depicted, the discharge in each region is calculated separately, with the overall discharge being the sum of discharges in regions 1, 2, and 3. It is assumed that water and momentum exchanges between regions are small enough to be negligible.

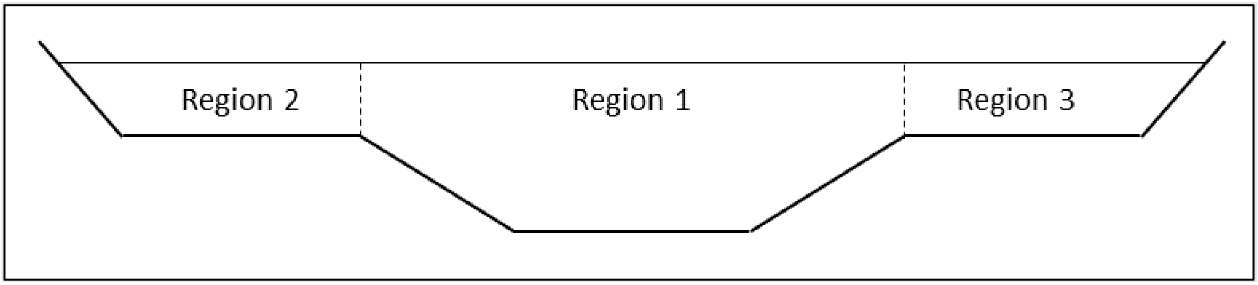

Figure 5.8. 1D hydraulic models represent channel-floodplain systems as consisting of three semi-independent regions.

Figure 5.9 shows a typical 1D hydraulic model profile output. This figure represents a longitudinal profile of the watercourse and a bridge (located approximately mid-way along the study reach) considered in the model. The profile represents data at each channel cross-section included in the model. The x-axis of the figure represents distance along the main channel and the y-axis represents elevation. The profile extends from the downstream-most cross-section considered (at the 0 ordinate on the x-axis) to the upstream-most cross-section location. Accordingly, and by convention, the streamflow direction is from right to left on the graph. Both the lowest ground elevation (the thalweg) and calculated water surface elevation for the flow considered in each cross-section is represented in the profile. In this case, as the legend indicates, the flow being modeled is the 100-year (1-percent AEP) flood event. The figure reflects that the calculated water surface elevation overtops the bridge by approximately three feet. The depth of overtopping is seen to be greater at the upstream extent of the bridge, indicating a backwater effect caused by the bridge structure.

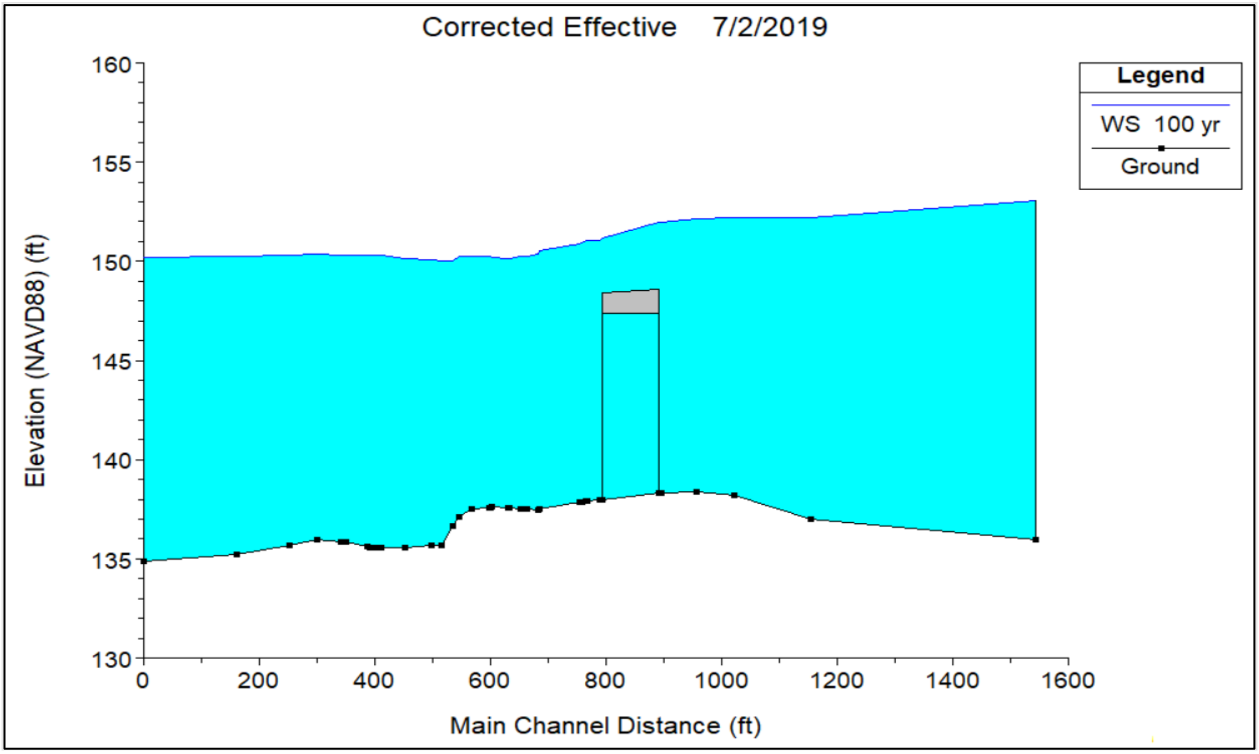

Figure 5.9. Typical water surface profile determined by 1D modeling.

Two-dimensional hydraulic models consider flow in two horizontal directions (x and y). They are increasingly used, given their fewer simplifying assumptions, as skills and familiarity with these models become more common, and as the data needed for their development becomes more widely available. Figure 5.10 shows a typical 2D model output for the hydraulic conditions of a bridge opening. It is an overhead visualization of relative flow velocity magnitude and direction around and through the bridge opening. The roadway approaches to the bridge are shown in the model as above the water surface elevation extending from the upper left corner to the lower right corner. The opening of the bridge is in the approximate middle of the figure. The bridge structure itself is not depicted. The general flow direction is from the upper right to the lower left corner. Velocity magnitude is reflected by the length of each particle trace (tail), with the highest velocities (through the bridge opening in this case) depicted by the longest particle traces. The visualization indicates that flow is contracting, and flow velocities are increasing as it enters the constricting bridge opening. Flow expands and decelerates as it exits the bridge opening. Downstream of the opening, the flow circulation pattern indicates that most flow bends to the right (downstream of the bridge). The flow pattern suggests the significant contraction of flow through the bridge could have implications for contraction scour within the bridge opening and potential effects on the bridge abutments.

3D models consider flow in three directions (X, Y, and Z). They are commonly applied to evaluate hydraulic conditions in a localized area when a complete representation of the flow field is desired, such as in the vicinity of a structure. Generally, 3D models are used in complex circumstances as they are more computationally intensive.

Selection of an appropriate hydraulic model for a specific application is made based on knowledge of the available models' capabilities, the hydraulic complexity, and the data available for model development. Numerous publications discuss the governing equations of hydraulics and the capabilities of specific models (FHWA 2019a, FHWA 2012c, Babister and Barton 2012). Table 5.2 presents a summary of the typical practical applications for 1D, 2D, and 3D hydraulic models.

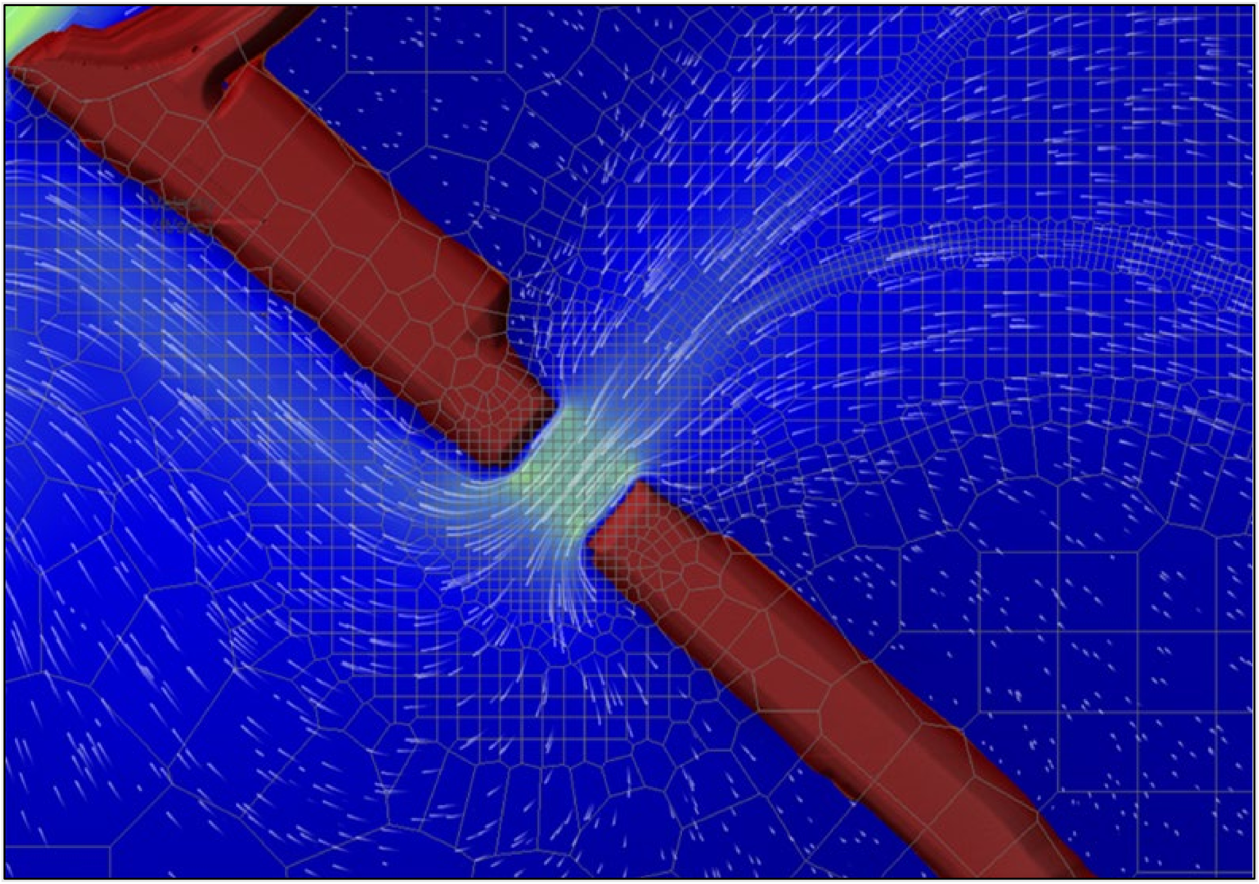

Figure 5.10. Particle circulation at a bridge opening simulated by 2D modeling. Image used by permission of WEST Consultants, Inc.

Sediment transport is inherently related to the hydraulics of flow since the flow creates the shear, drag, and lift forces on the channel boundary that induce sediment movement. Hydraulic model results can be used to evaluate the sediment transport imbalances driving aggradation, degradation, deposition, scour, and, in some cases, lateral channel movement. The accuracy of sediment transport evaluations is therefore directly related to the accuracy of the hydraulic modeling. Sediment transport has long been known to be extremely sensitive to flow velocity (Colby 1964). For example, a 20 percent inaccuracy in predicted flow velocity can be expected to translate into 50 to 100 percent inaccuracies in associated estimates of sediment transport.

Quantitative evaluations of sediment transport in the river environment generally start based on 1D hydraulic modeling because 1D models are easily developed, include the least amount of data for model development, use the least computational resources, and provide useful boundary condition information for other multi-dimensional models. Long-term simulations of sediment transport and analyses of long river reaches (several miles to hundreds of miles) also commonly use 1D hydraulic models given their relatively low amounts of input data and fewer computational resources. 2D modeling is generally restricted to shorter reaches, typically less than 10 miles, and for shorter simulation time periods, typically individual events and simulation periods of up to a few years. Given their intensive computational demands and massive data output, 3D models are generally only used to represent short-term sediment transport phenomena, such as scour for a specific flow condition.

Table 5.2. Typical applications for 1D, 2D, and 3D hydraulic models.

Application	1D	2D	3D
Rivers and floodplains	X	X	
Bridges	X	X	
Culverts	X	X	
Engineered Channels	X	X	
Stormwater Facilities	X	X	
Reservoirs	X	X	
Complex structure Hydraulics			X
Aquatic Organism Passage	X	X	
Sediment Transport	X	X	
Estuaries	X	X	X
Coastal Hydraulics	X	X	X

5.3.2 Channel-Floodplain Hydraulics

The hydraulic floodplain is the relatively low-lying area surrounding the river that stores and conveys surface water. Lateral connectivity allows flow to access the floodplain through side channels and, more generally, at discharges that exceed the bankfull capacity of the main channel.

Channel-floodplain hydraulics are interrelated, with both water and momentum being exchanged between channel and overbank flows. As discussed in Section 5.4, bankfull flows that occur prior to overflows into the floodplain have the greatest significance to the shape of the channel. In straight channel-floodplain systems, momentum exchange is driven by intense turbulence, interface vortices, and secondary flows generated in the shear layer between main channel and floodplain flows as illustrated in Figure 5.11. The presence of trees and other types of roughness that slow flow on the floodplain can increase the intensity of shearing and momentum transfer that tends to keep flow out of the floodplain. Conversely, if main channel roughness exceeds that of the floodplain, this tends to divert flow onto the floodplain, increasing the potential for over-bank scour and a possible channel avulsion. Modifications made in the main channel or the floodplain can affect the distribution of flow between those locations which could have ramifications for surrounding development (e.g., alterations to water surface elevations and areas of inundation). It is important to conduct thorough hydraulic evaluations of these effects by adjusting roughness coefficients, examining the flow distributions, or other assessments.

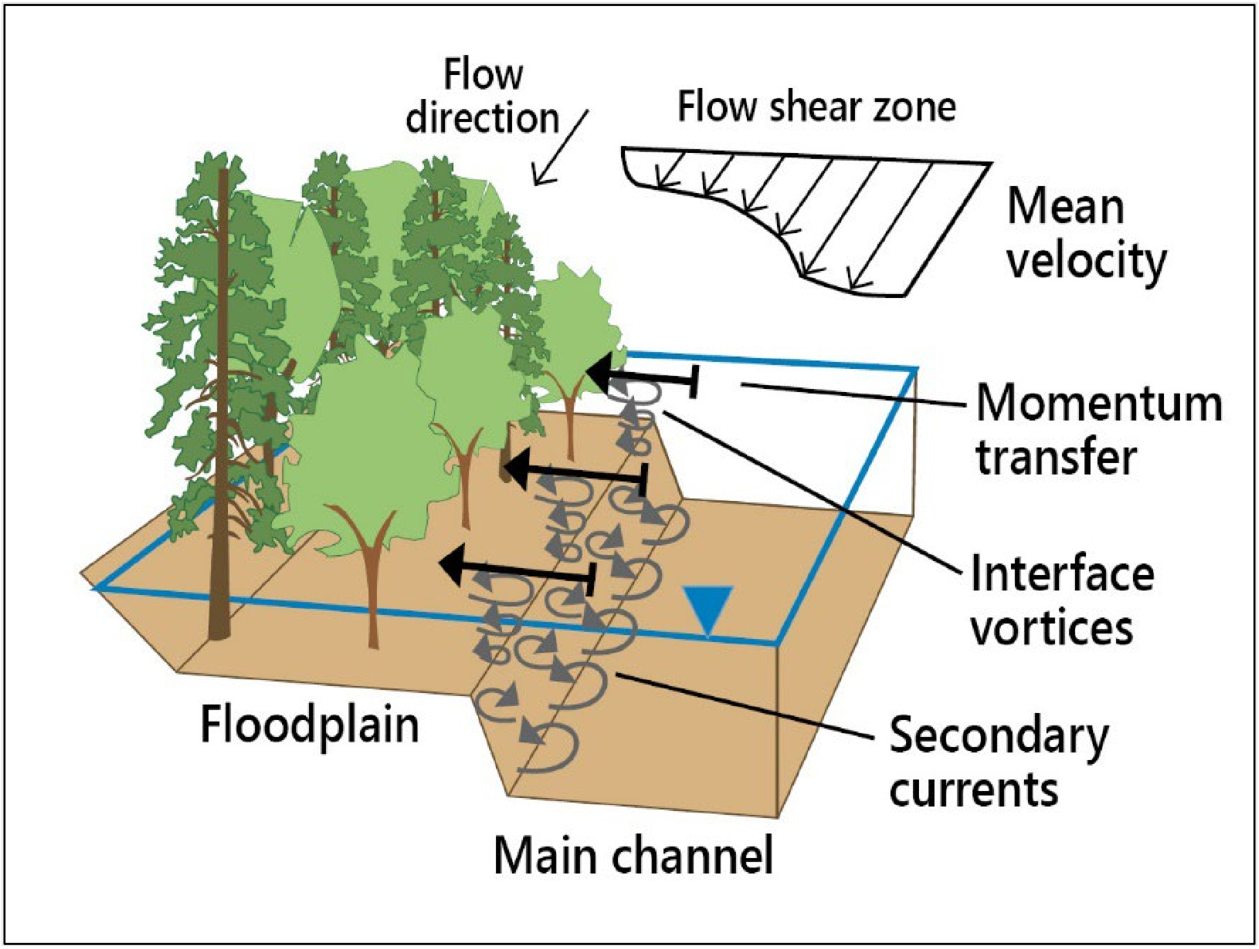

Figure 5.11. Schematic representation of interface vortices and secondary flows transferring momentum in the shear layer between main channel and floodplain flows. Adapted from Västilä (2015).

5.3.3 Impacts of Bridges and Culverts

Hydraulic engineers perform hydraulic analyses to support bridge and culvert design and bridge scour evaluations including evaluating changes in flow patterns caused by the hydraulic structures. While hydrologic impacts of bridges and culverts on flood hydrology are infrequent, crossing structures often impact flood hydraulics substantially. During large out-of-bank flows, bridges and culverts may create substantial backwater and contribute to upstream flooding. Flow velocities in bridges and culverts are higher than upstream whenever the structure opening conveyance area is less than the upstream channel and floodplain conveyance area. This is especially the case when backwater affects upstream hydraulic conditions. Essentially, backwater is the additional depth needed to increase the velocity to pass the flow through the smaller opening. Therefore, bridge and culvert designs often focus on limiting the amount of backwater while providing adequate clearance between the water surface and the bridge deck, or the crown of the culvert. Increased structure openings lower backwater and decrease velocity, which in turn decreases scour and scour protection. Hydraulic analysis for bridge and culvert design that also meet environmentally informed design standards (fluvial performance standards) offers a variety of advantages for permitting and avoidance of impacts to river functions (Section 4.5.2).

The backwater also represents a volume of water that is temporarily stored until the hydrograph recedes. When increasing a bridge or culvert opening, the engineer evaluates whether this reduction in backwater and upstream storage could increase downstream flooding. For conditions found in Kansas, McEnroe (2006) concluded that few culverts and even fewer bridges produce enough storage that enlarging the structure opening would increase downstream flooding. For other locations where this may not be the case the engineer can perform unsteady hydraulic modeling to determine the potential impact. It is important to recognize that even small impacts to downstream flood levels could have regulatory implications. In cases where the approach roadway or the bridge or culvert already overtops, enlarging the opening is unlikely to increase downstream water surface elevations unless the roadway elevation is also raised. For situations where the downstream impacts of structure enlargement are minor to negligible, the benefits of enlargement can be substantial including reductions in backwater, upstream flooding, scour, and road overtopping. If there is an effect on the downstream hydrograph it may be closer to the unobstructed condition (McEnroe 2006). In all cases when there is uncertainty regarding potential benefits and impacts, hydraulic modeling is a valuable tool.

Bridges can affect in-channel flow conditions when piers (especially piers skewed to the flow), abutments, abutment protection, wood, and debris block a substantial portion of the channel. Similarly, culverts affect in-channel flow conditions when they are undersized or when culvert barrels become substantially blocked with sediment, wood, or debris. To minimize these conditions, engineers design bridges and culverts so that during in-channel flows, they do not impede the conveyance of water and sediment, maintaining continuity of conveyance function between the upstream and downstream reaches as discussed in Section 4.5.2. When this is not the case, there may be increased erosion or deposition upstream, downstream, or at the crossing. Sustainable bridge and culvert design also provides for potential future lateral and vertical channel adjustments. When not considered, or because of changing watershed conditions, culverts may become perched well above a degrading downstream channel (see Section 2.4 for an example). Bridges and open-bottom culverts can accommodate some channel lowering.

Figure 5.12 and Figure 5.13 show the opposite situation with channel and floodplain aggradation. When the interstate culvert and frontage road bridge depicted in these figures were first constructed, they met all design standards, including bridge freeboard, culvert headwater allowance, and backwater limits. Through time the channel and floodplain aggraded 8 to 10 feet and merged into a broad bulrush wetland. The top of the culvert now becomes submerged at even the lowest flows. With the culvert partially blocked, the consequences estimated during a 50-year (2-percent AEP) event include: 1) the Interstate and frontage road would overtop, 2) the bridge deck would be submerged, 3) the culvert would far exceed headwater allowances, and 4) the crossing would produce over 10 feet of backwater. This level of extreme aggradation could not have been anticipated when these structures were originally designed, but informed by this history, engineers designed the replacement structures to accommodate a substantial amount of future aggradation.

In-channel flows can be affected when bridge abutments and abutment protection block part of the channel. This may result from an undersized bridge, but often occurs when a channel migrates into the abutment area. As the channel migrates, one bank remains fixed by the abutment, the other bank continues to move, narrowing, and often deepening the channel. If the abutment protection was not designed to accommodate this movement, costly and difficult countermeasure construction can be expected.

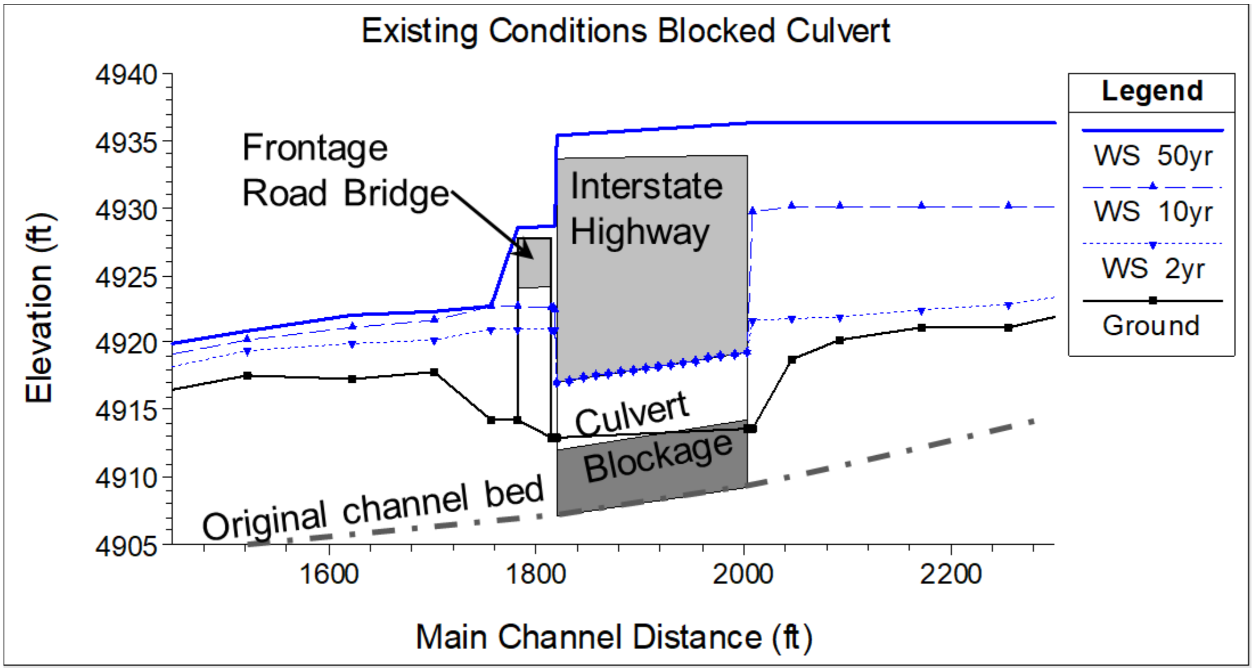

Figure 5.12. Example of bridge and culvert partially blocked by channel aggradation.

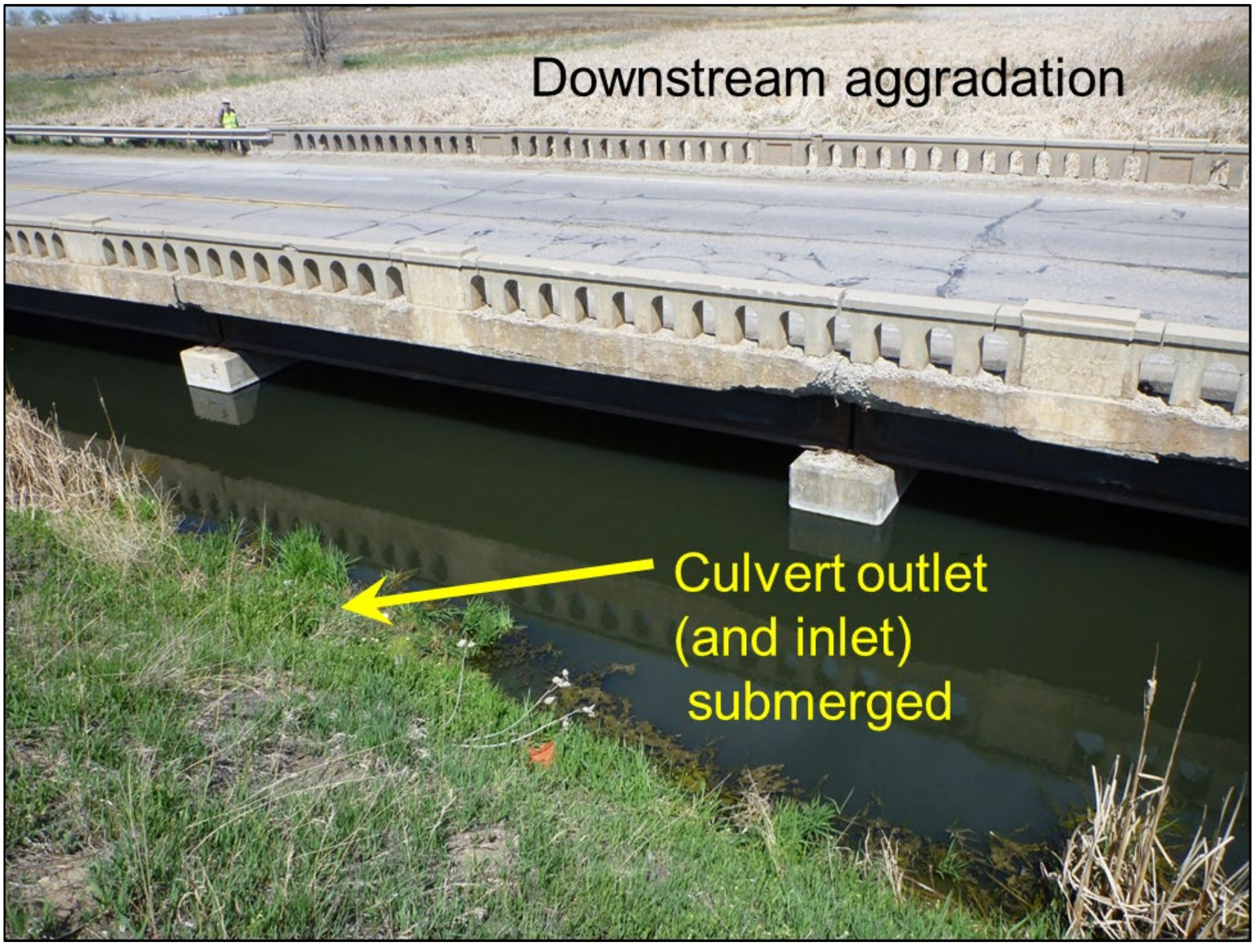

Figure 5.13. Loss of bridge and culvert capacity from downstream aggradation.

Figure 5.14 shows an example of the effects of channel migration on the US 61 crossing of the Wapsipinicon River near DeWitt, Iowa. The figure shows the alignment of the channel in 1980, soon after the highway and bridges were constructed. The engineers located the bridge opening to span the channel as it was at the time of construction. However, the channel moved into conflict with the bridge during subsequent bend migration. Geomorphological forecasting indicated that, in the absence of countermeasures, the channel would naturally migrate through the area of the north abutment.

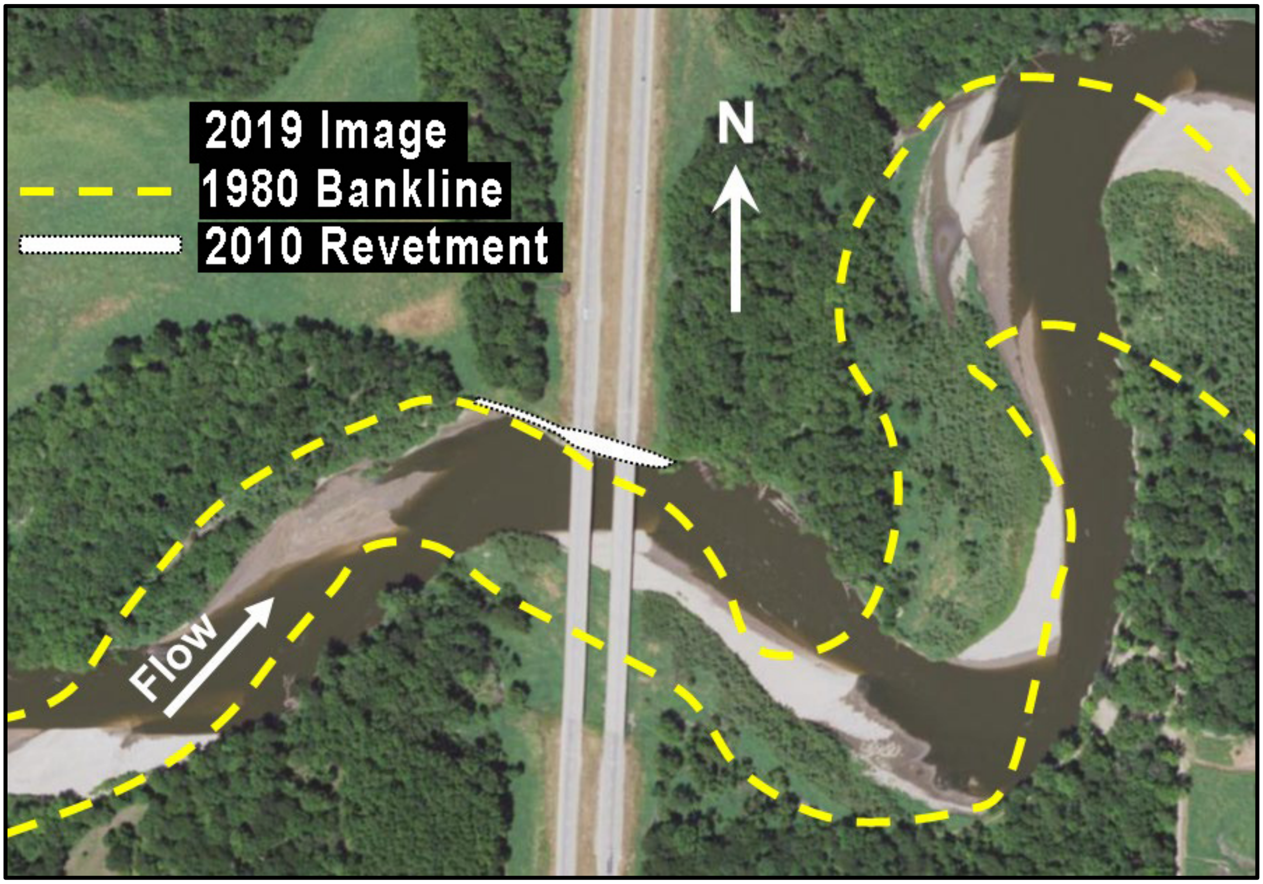

Figure 5.14. Channel migration at the US 61 crossing of the Wapsipinicon River near DeWitt, Iowa. Source: original image from the National Agriculture Imagery Program (NAIP).

Point bar deposition and vegetation are decreasing the bridge openings at the south end of the bridges, resulting in a narrowed channel. The reduced opening increases flow velocities within the bridges during floods, which can increase contraction scour and upstream backwater. The bridges were constructed at a skew to follow the earlier channel alignment but could result in flow alignment issues from future channel movement. As the bends continue to migrate down valley the issues at the north end of the bridge may shift to the south end. The next upstream bend appears to be moving east and could reach the south abutment. If this occurs, channel revetment and additional abutment protection may need to be placed there.

Bank erosion along the north end of the bridges is now controlled with a riprap revetment, which appears to have been reinforced around 2010. The revetment not only includes about 250 feet of abutment protection under the bridges but extends as bank protection for another 200 feet upstream of the crossing. The potential future channel alignment could create an extreme angle of attack on the piers, resulting in much greater pier scour potential and increased chance of collecting wood and debris. Wood and debris not only increase pier scour potential but can increase lateral loading on the piers and involve removal by bridge maintenance staff. The potential issues at the south end of the bridges may well not occur during the service life of the structures, so these issues can be addressed when the bridges are replaced.

The impacts of bridge and culvert hydraulics can be controlled in the planning and design process. Crossing structures can be sized to meet appropriate hydraulic design standards and fluvial performance standards to limit impacts for in-channel and flood flows. Structures may also be impacted when channels adjust laterally and vertically, often leading to costly and difficult remedial actions. Channel adjustments can be accommodated during design and the impacts on structures can be avoided when they are evaluated and anticipated. A unique illustration of this situation is that of highways crossing alluvial fans, where there is potential for channels to avulse or shift into old historic channel locations. To accommodate this potential, additional appropriately sized crossing structures may be placed at historic or anticipated channel locations. For more on this issue, see HEC-20, Lagasse et al. 2004, and Section 6.3 and Section 8.9 of this document.

5.4 Channel-Forming Flows

The form and functions of a natural channel inherently relate to the range and duration of flows the channel experiences and the materials in which it exists. Most natural channels are “alluvial” channels that continuously adjust their shape within sediments transported by the flow in response to flow magnitude and duration. The significance of any individual flow magnitude on the overall shape of the channel depends on its ability to move the sediments and its relative frequency and duration. Some researchers (FISRWG 1998, Dunne and Leopold 1978) indicate that a single representative discharge may be used to determine a stable alluvial channel geometry. Engineers sometimes refer to this representative discharge as the “channel-forming” or “dominant discharge.” In concept, this is the single, steady-state discharge which, if it were to occur continuously, would form the same channel as the irregular, natural, long-term hydrograph.

Engineers working on a transportation infrastructure project in the river environment can use an estimate of the channel-forming discharge for several purposes. First, they can use it to design an approximation of a stable channel in a similar hydrologic/geomorphic setting. For example, they could conduct hydraulic modeling to assess the capacity and conveyance characteristics for alternative channel configurations for the channel-forming discharge. Second, engineers could use the estimated channel-forming discharge to evaluate the expected long-term stability and potential adjustments for a given channel reach. For example, they could use the channel-forming discharge in a sediment transport model to understand the relative trend of a reach for dynamic stability, aggradation, or degradation.

Engineers commonly use one or more of the following three methods to estimate the channel-forming discharge for a stable alluvial channel:

- Estimation of the bankfull discharge.
- Estimation of the recurrence interval for a flow that fills the channel before spilling onto the floodplain.
- Determination of the effective discharge based on integration of flood frequency and sediment transport relationships.

Since all the methods have specific limitations, it is important to verify the channel-forming discharge estimates using morphologically relevant field indicators whenever possible. Field indicators useful for determining bankfull stage include breaks in slopes between the channel and adjacent floodplains, the highest elevation of depositional features (e.g., point bars), changes in sediment gradations from coarse to fine, vegetation changes (see Figure 5.15), and exposed plant roots (Wolman and Leopold 1957, Dunne and Leopold 1978). As in Figure 5.15, these bankfull indicators are not always entirely straightforward. In this image, for example, if only looking at the right bank, it may be assumed that bankfull is higher than was ultimately determined by observing the lower vegetation line on the left bank. Several other factors can similarly complicate interpretation of bankfull stage indicators including unrecognized channel instability or non-alluvial conditions and effects of droughts or extreme floods.

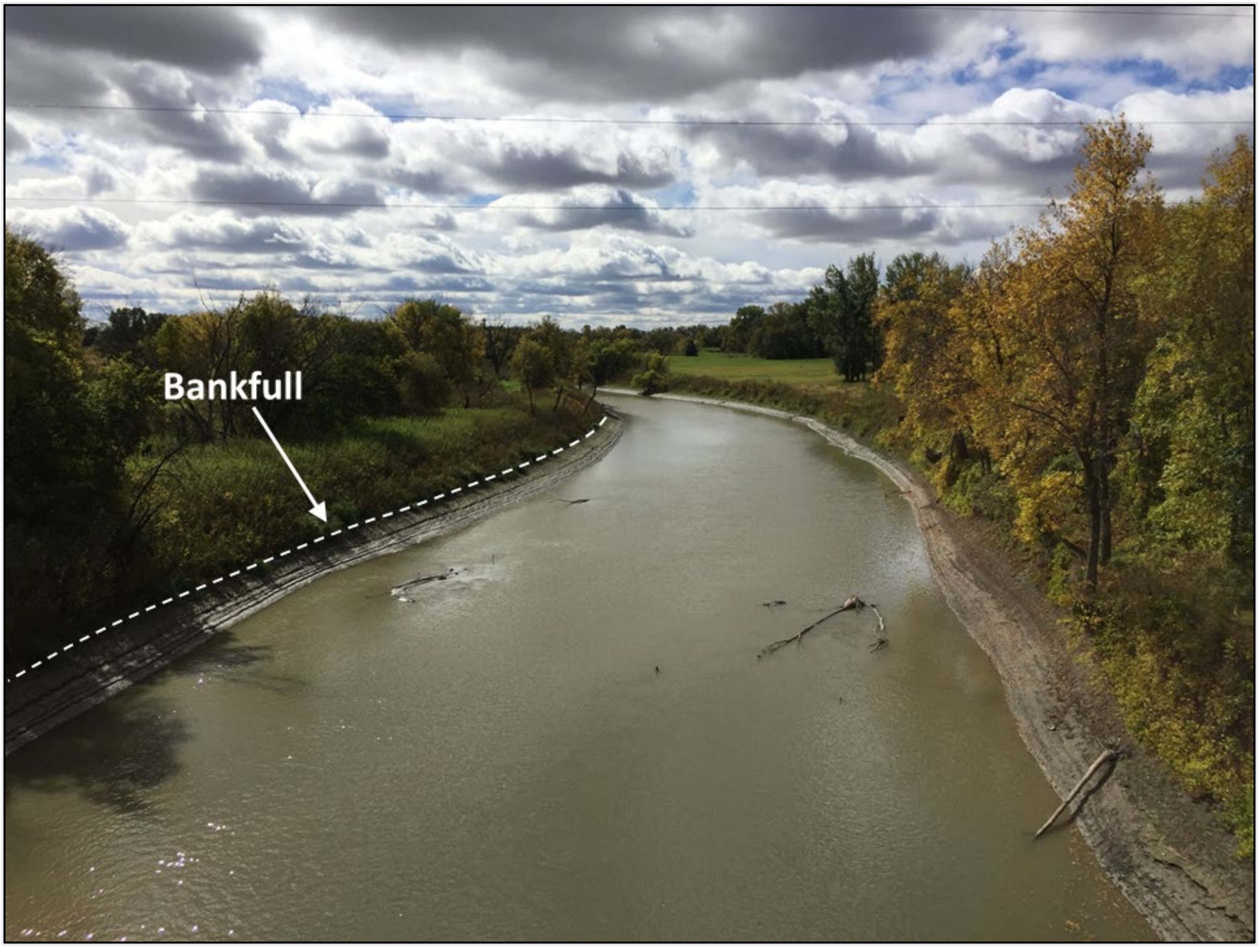

Figure 5.15. Riparian vegetation used as a bankfull indicator in the field. Image used by permission of WEST Consultants, Inc.

5.4.1 Bankfull Discharge

The bankfull discharge is the maximum discharge that the channel can convey without spilling onto its adjacent floodplain. The concept is most relevant for watercourses with a discernable floodplain and assumes channel stability. Measurements of bankfull stage indicators in an unstable (degrading or aggrading) or non-alluvial stream reach are, therefore, generally not valid. Specific procedures for determination of bankfull discharge are presented in numerous publications (Rosgen 1996; Copeland et al. 2000).

Building on the discussion in Section 2.4, hydraulic interactions in connected channel-floodplain systems significantly impact local and mean velocities, boundary shear stresses, water surface elevations, and habitats in the channel as well as on the floodplain. Generally, when flow spills onto the floodplain, the in-channel proportion of discharge decreases, and velocities and shear stresses may be lowered. As discussed in Section 5.3.2, this reduction in hydraulic efficiency helps explain why in-channel sediment transport can decrease when the floodplain is inundated, and why bankfull discharge is often taken to represent the channel-forming flow. Conversely, floodplain discharges, velocities, and turbulence are increased by momentum gained from in-channel flows, coarse suspended sediments are deposited close to the channel (building natural levees), and fine suspended sediments are carried further into the floodplain before being deposited.

Engineers determine the bankfull discharge from the bankfull stage, identified from field indicators previously described, by developing a stage-discharge relation for the site from either actual field measurements or hydraulic modeling. Recognized uncertainties associated with hydraulic calculations of stage are associated with assumptions regarding starting water energy slope and hydraulic roughness. By calibration of model parameters to specific field measurements of flow, engineers can reduce such uncertainties. The bankfull stage is generally associated with a break in the slope of the stage-discharge relation as seen in Figure 5.16.

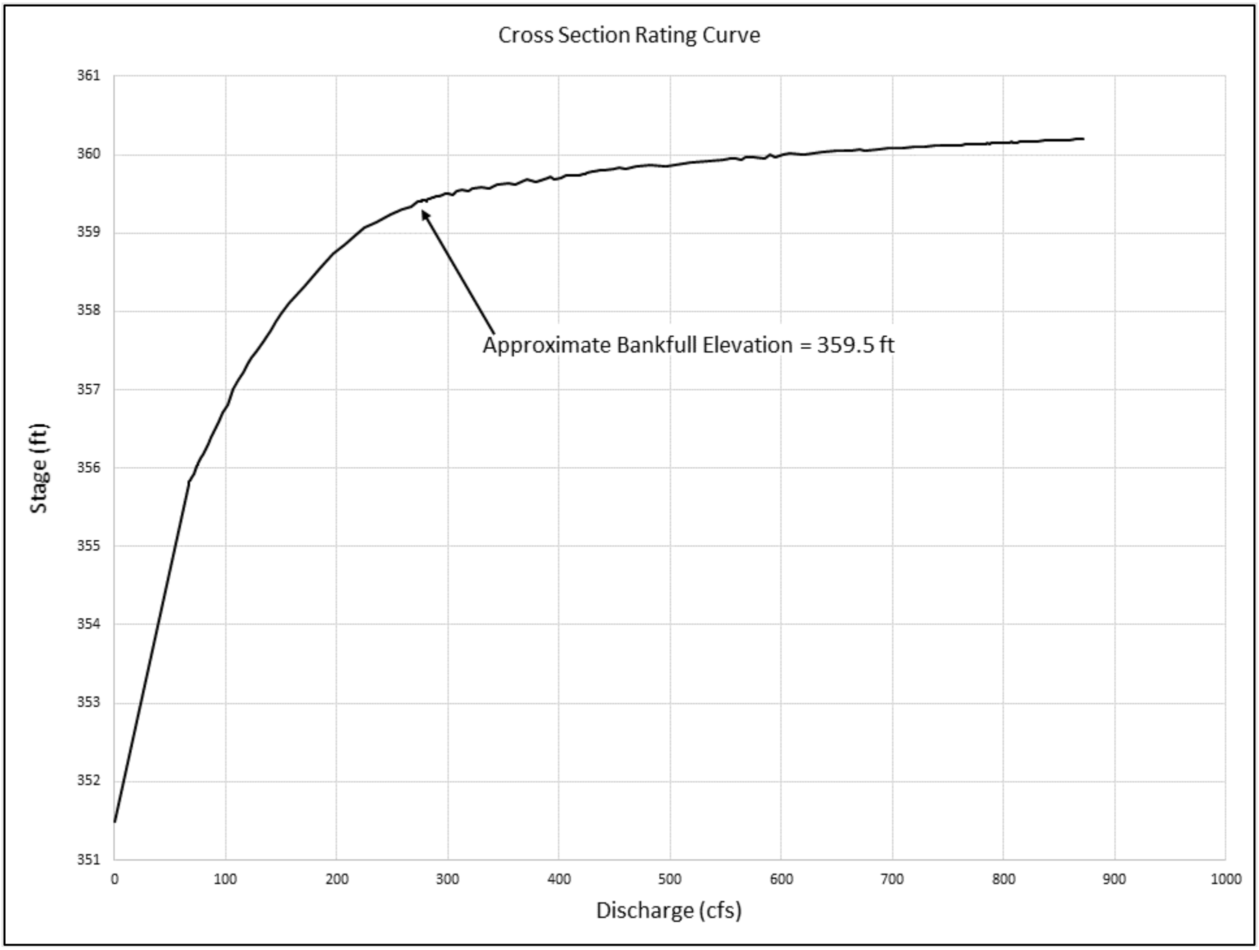

Figure 5.16. Cross-section rating curve showing estimated bankfull elevation.

5.4.2 Fixed Return-Period Flow

A second method for estimating the channel-forming flow uses the principle that the channel-forming flow has a particular return interval. Characteristically, the bankfull discharge is a relatively frequently occurring event with a return period of between 1.5 and 2 years (0.67- and 0.5-percent AEP). However, researchers have noted that bankfull discharge frequencies vary with regional hydrologic characteristics (Williams 1978). In arid climates with flashy runoff characteristics, bankfull discharge frequencies tend to be much larger, whereas more humid areas have lower bankfull frequencies. Given these significant differences, it is prudent to use regionally based estimates of the return period for bankfull flow return period and morphologically significant field indicators to verify bankfull flow estimates. Research (Gregory and Madew 1982) has indicated that calculating the return period for a bankfull discharge based on an "annual exceedance series" is more accurate than calculations based on an annual maximum series. Using this method, return periods for bankfull discharge are often shorter than 1 year.

5.4.3 Effective Discharge

The third method for estimating the channel-forming flow is to calculate the "effective discharge," that is, the discharge that transports the largest fraction of the annual load of sediment comprising the channel bed (bed material) over a period of years (Biedenharn and Copeland 2000). Wolman and Miller (1960) stated that the channel-forming discharge is a function of both the magnitude of the event and its frequency of occurrence, which is the same principle that determines the effective discharge. The effective discharge concept integrates the flow duration curve and a bed-material sediment rating curve to estimate the discharge that does the most work in forming the channel. Figure 5.17 graphically represents the integration of frequency of the transport (curve A), sediment discharge (curve B), and the integration of the two as the sediment discharge (curve C). The peak of curve C occurs at the discharge that is most effective in transporting sediment. This discharge is the effective discharge.

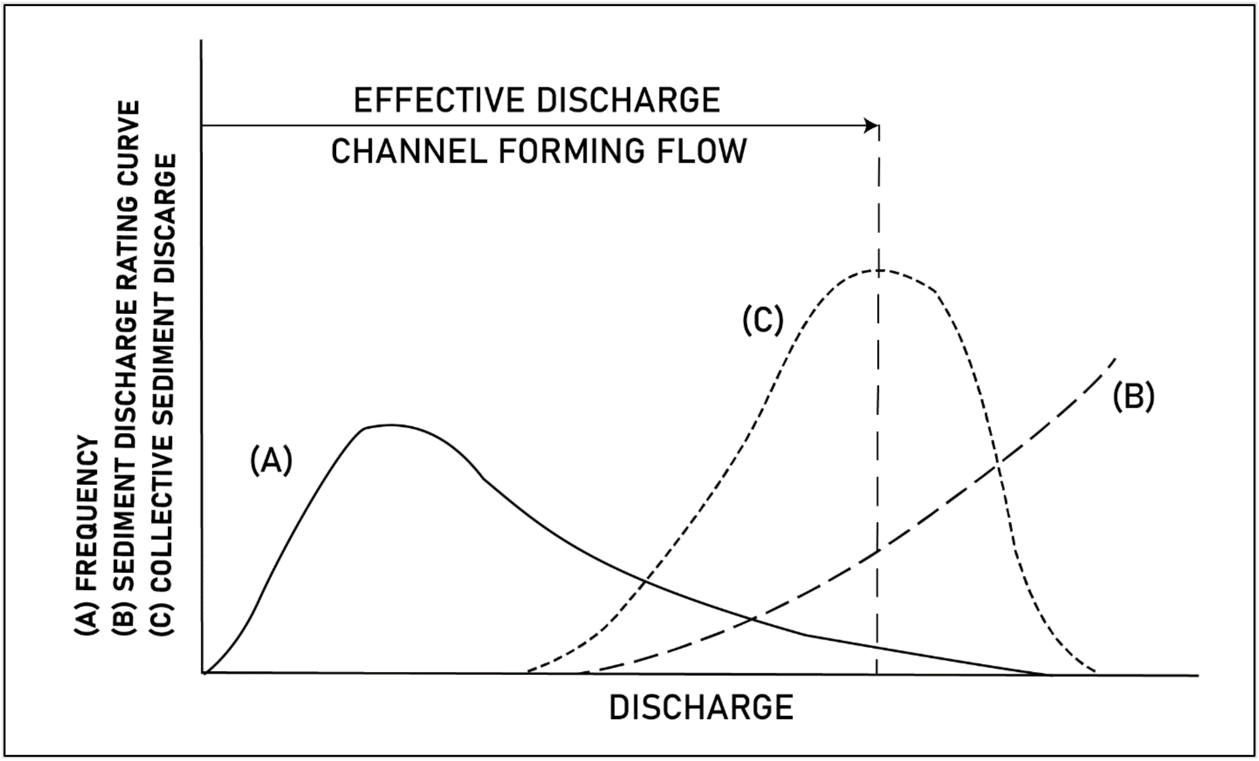

Figure 5.17. Effective discharge/channel-forming flow.

Effective discharge is determined by: 1) determining the flow-frequency distribution from available flow duration data, 2) constructing a bed-material load rating curve, and 3) integrating the flow frequency distribution and bed-material load rating curve to produce a bed-material load histogram displaying the sediment load as a function of discharge for the period of record. The histogram peak indicates the effective discharge. For a detailed discussion of the procedures to compute the effective discharge, see Biedenharn et al. (2000).

Selection of a method for calculating the channel-forming discharge, involves consideration of data availability, physical characteristics of the site, and available resources. Cross-checking estimates of the channel-forming discharge derived from multiple methods helps reduce uncertainty in the final estimate.

5.4.4 Impact of Channel-Floodplain Connectivity on the Effective Discharge

Channel-floodplain connectivity is also central to the effective discharge concept, which underpins calculation of the bankfull discharge used when designing dynamically stable channels. Below, the effective discharge concept is extended to response reaches with fully connected floodplains, where sediment output is smaller than sediment input.

As explained in Section 5.4, the effective discharge is widely used to represent the channel-forming flow. The effective discharge is usually calculated as the flow doing the most sediment transport (see Figure 5.17, above), based on the magnitude-frequency concept first published by Wolman and Miller in 1960. While this is correct, later development of magnitude-frequency analysis by Hey (1979) indicates that it is true only for reaches that are dynamically stable—that is, where the sediment input is matched by the sediment output, which depends on capacity of the river to transport incoming sediment downstream and out of the reach. Thus, while sediment input and output are the same in a transport reach, this is not the case in a response reach, where there is net storage of sediment because input is larger than the sediment output.

In a development of Wolman and Miller’s magnitude-frequency diagram shown in Figure 5.18, Hey accounts for this sediment imbalance using different sediment rating curves for sediment input (that is, supply from upstream) and sediment transport capacity (that is, output to downstream). Figure 5.18 (A) shows separate cumulative curves for sediment input and output. Figure 5.18 (B) shows the difference between the input and output sediment load curves from (A), which is the net sediment deposition. In this case, the peak of the difference between the input and output curves is the flow causing the most deposition.

This analysis shows that in a depositional, response reach where the channel is connected to its floodplain, the effective or channel-forming flow is no longer the flow doing most sediment transport but is instead the flow doing most deposition. This is logical because the geomorphic process that dominates formation and maintenance of the channel-floodplain system is the accumulation of sediment that builds the floodplain. Hey (1979) concluded that the flow depositing the most sediment is smaller and has a shorter return period than the flow transporting the most sediment. Lower bankfull discharges explain why bankfull channels in response reaches tend to be smaller than those in transport reaches and why they inundate their floodplains more frequently and for longer durations in most years.

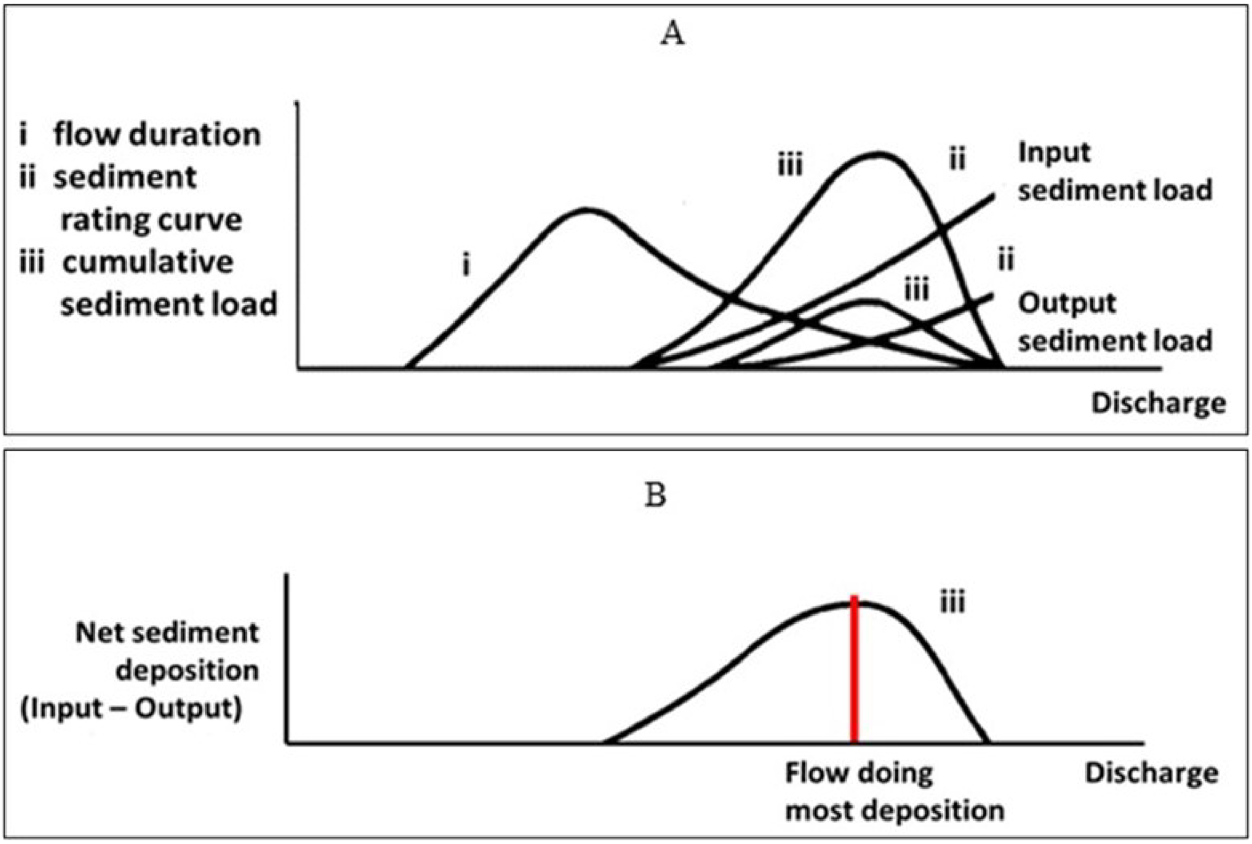

Figure 5.18. Magnitude-frequency analysis for a depositional response reach with a fully connected floodplain. (A) Separate cumulative curves for sediment input and output. (B) Difference between the input and output sediment load curves from Figure A, which is the net sediment deposition. Adapted from Hey (1979).

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Chapter 6 - Fluvial Geomorphological Evaluations

Engineers and scientists conduct fluvial geomorphological evaluations to identify controlling physical processes affecting the form and function of a watercourse. By identifying, characterizing, and understanding the physical processes occurring, these engineers and scientists can explain the existing form and functions of the watercourse, and provide a basis to predict how the fluvial system could respond to proposed actions. During planning and design phases of a transportation infrastructure project, fluvial geomorphic evaluations allow the project team to understand the existing state of river functions and environmental conditions. This in turn enables them to develop transportation infrastructure in the river environment that preserves or even restores important river functions by avoiding adverse environmental impacts.

The USGS maintains a website “Fluvial Sediment and Geomorphology: Resources for Monitoring and analysis” (www.usgs.gov/fluvial-sediment-and-geomorphology). The site has technical manuals, software, tools, and techniques that support fluvial geomorphology evaluations.

The following sections present specific methods for conducting fluvial geomorphic evaluations. Section 6.1, Data Collection, describes the collection and evaluation of data useful for geomorphic investigations. Both office- and field-based procedures for collection and evaluation of relevant data are reviewed. Section 6.2, Gage Analysis, describes analysis methods and information that can be derived from streamflow gage records relevant to geomorphic evaluations. Section 6.3 describes methods for lateral migration analysis of channels. Section 6.4 describes information regarding the form and function of rivers derived from channel profile interpretation. Section 6.5 describes the use of bridge inspection records as a long-term record for evaluating channel stability. Finally, Section 6.6, Stream Interpretation, reviews the processes, methods, and objectives of the three-level approach for conducting fluvial geomorphic evaluations.

6.1 Data Collection

The following sections describe data and information for conducting geomorphic office-based and field-based evaluations. Analysis starts with an initial desktop evaluation of readily available data and follows with field data collection and analysis. The descriptions include identification of specific sources for each major data type discussed.

6.1.1 Desktop Evaluation

A desktop evaluation is the first step in many fluvial geomorphological evaluations. The purpose is to gain familiarity with the site, stream, and watershed using available records and online resources. It is also useful for planning what stream reconnaissance is needed before visiting the site. Viewing aerial imagery is an excellent approach to gaining an initial impression of the site and surrounding area, and can make use of Federal, State, local, and industry websites. Desktop evaluations then branch into a process of discovery, drawing on many other resources, which may include FEMA maps and studies, USGS maps and gage data, and information from bridge and site landowners.

6.1.1.1 Aerial and Satellite Imagery

Websites such as Google Earth, Bing Maps, and others can be a useful place to begin. These and similar resources are an excellent way of viewing the site, changing perspective and altitude, moving along the channel up- and downstream, and visually inspecting the watershed. Google Earth enables the user to review historical aerial photos of the area, which can allow identification of changes to the system, especially erosion, channel planform evolution, channel alignment movement, land use, and infrastructure development. For example, Figure 2.3 shows aerial images of a river and floodplain from 2009 and 2018. In many locations, the Google Earth website can provide a perspective and panoramic street-level views of river environments, highway encroachments, and bridge crossings.

Aerial and satellite images can also be downloaded from several government agency websites. For example, the USDA hosts the Geospatial Data Gateway (gdg.sc.egov.usda.gov) and the USGS hosts EarthExplorer (earthexplorer.usgs.gov). These websites are a repository of current and historical aerial imagery, with many images dating to the 1950s or earlier. Users can view available data for the selected state/county or location. The National Agricultural Imagery Program (NAIP) produces aerial imagery that can be downloaded by state and county or by latitude/longitude. The NAIPs can be accessed on the Geospatial Data Gateway and EarthExplorer. State and County websites can also be good sources of aerial imagery.

6.1.1.2 Flood Insurance Studies

FEMA conducts Flood Insurance Studies (FIS) and produces Flood Insurance Rate Maps (FIRMs) for many communities. An FIS is a comprehensive study of the river that runs through a community. It includes a hydrologic study conducted to determine the frequency and magnitude of peak flood discharges and development of a hydraulic model to determine flood elevations. The 1-percent annual exceedance probability (AEP) water surface elevations and flood boundary at the time of the study are mapped for flood insurance and floodplain land use development purposes. An FIS does not represent future conditions. The date an FIS was completed and its accuracy in representing current conditions are valid considerations.

FIS hydraulic models generally include the effects of all major road crossings. Flood profiles produced from the FIS (detail from FIS profile shown in Figure 6.1) highlight the locations of road crossings, give a sense of whether flood events pass through bridges or overtop the roadways, and estimate the amount of backwater produced at the road crossing. Backwater associated with a bridge crossing is the increase in upstream water level compared to a no-bridge condition. See Section 5.3 for more on the concept of backwater and bridges. In Figure 6.1 the profile indicates that the bridge causes approximately 2 feet of backwater for the floods greater than the 10-percent ACE flood.

In most cases, the FIS hydraulic models can be requested and acquired from FEMA or local floodplain administrators. These models are considered only as a starting point for more detailed bridge and channel hydraulic modeling as they may not represent current conditions and may use older modeling techniques. FEMA studies and maps are available through the FEMA Map Service Center. Available resources include changes pending final approval and approved changes not yet included in current mapping. Actual flood levels may be significantly higher or lower than shown in the FIS profiles and mapping. The road, bridge, culvert, and channel information contained in the hydraulic model are a valuable geometric snapshot at the time of the study.

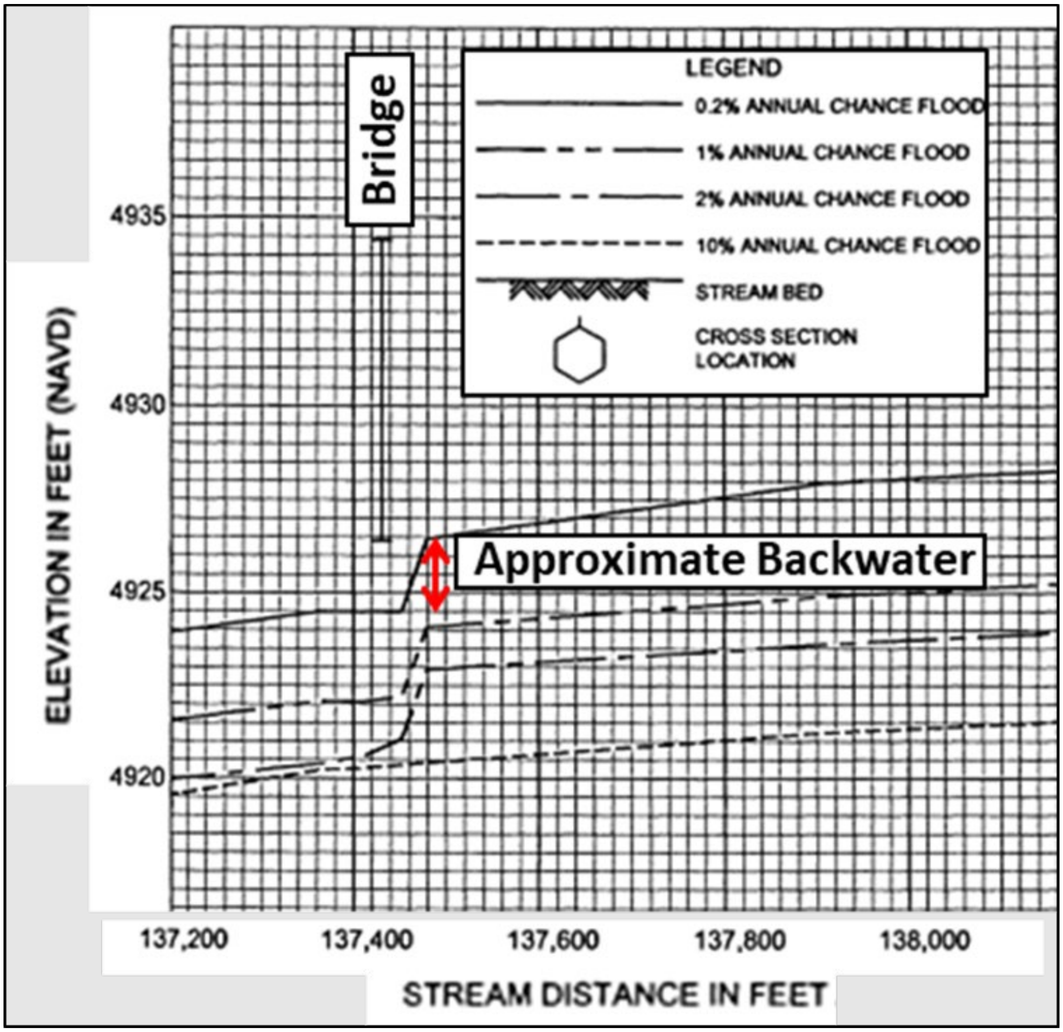


Figure 6.1. Detail from FIS profile showing 10% through 0.2% annual chance flood (or AEP) flood profiles and road crossing. Source: FEMA.

6.1.1.3 USGS Quad Maps

USGS quadrangle maps (or quad maps/sheets) were originally published at a scale of 1-inch equals 2,000 feet (1:24,000 scaling). These maps show topography (elevation contours), hydrography (water bodies), and land use information. Digital copies of current and historic USGS maps can be obtained from the USGS website. As shown in Figure 6.2, these maps can provide a historic perspective on river, road, crossing, and other infrastructure conditions dating back over a century. This figure shows that over a 106-year timespan the Sacramento River in Deadmans Reach has filled earlier channel locations and reoccupied abandoned channels, that bridge and road alignments have been modified in response to channel evolution, and that a USGS gage is located downstream of the bridge. While the contours presented on a quad map are generally inadequate to support hydraulic modeling, they are sufficient to determine reach-averaged valley slope, which is helpful when estimating a normal depth boundary condition for hydraulic modeling (FHWA 2012c).

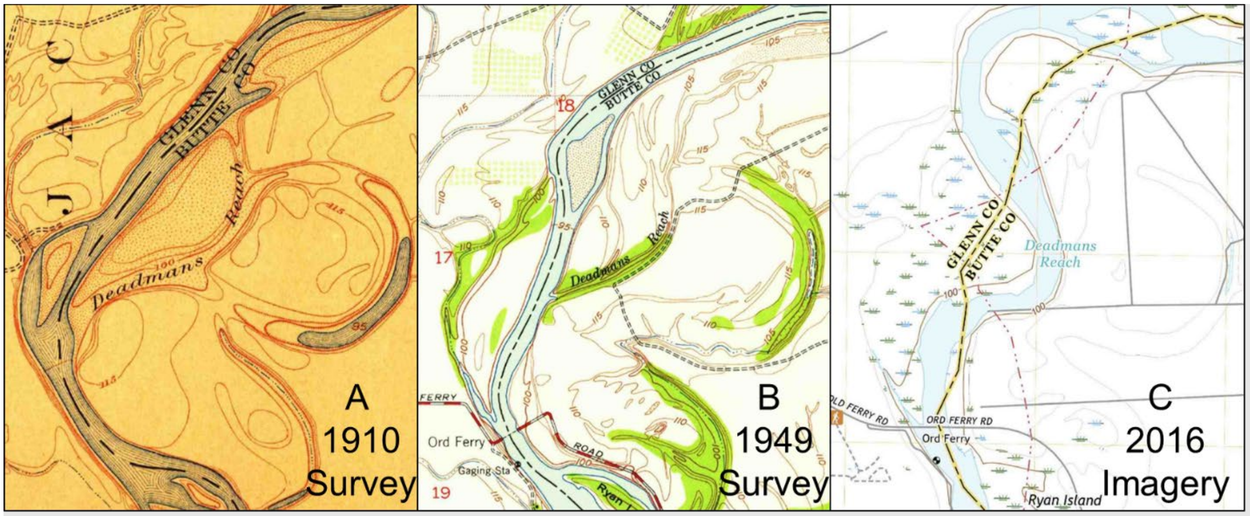


Figure 6.2. Comparison of USGS topo maps dated (A) 1910, (B) 1949, and (C) 2016 showing channel evolution in the Deadmans Reach of the Sacramento River, California. Source: USGS.

6.1.1.4 Geological and Soil Maps

The National Geologic Map Database is a collection of geologic maps that can include bedrock types, sediment deposits, soil types, faults, water features, flood channels, and flood deposits. The maps can be accessed through the USGS website and are produced by the USGS often in partnership with State Geological Surveys. These are helpful maps when conducting geomorphic analysis and upland erosion studies as a part of sediment transport analyses.

6.1.1.5 Dams

The National Inventory of Dams is a searchable database of more than 90,000 dams nationwide and is based on information provided by State and Federal dam regulators. The appropriate State or Federal regulatory authority for a given dam may have more up-to-date information than is found in the database. The database is available at nid.sec.usace.army.mil/. For information on dam removals, see: www.usgs.gov/centers/cdi/science/national-dam-removal-database-a-living-database-information-dying-dams. Dams often impact downstream sediment and flow regimes, and their removal can restore connectivity. The benefits of some dam removals may only occur after an initial heavy sediment release that can last for months to years.

6.1.1.6 Hydrologic and Sediment Data

Peak and mean-daily flow data can be used in hydrologic analyses such as flood frequency analyses and flow duration curves (Sections 5.1 and 6.2). The USGS hosts a vast quantity of hydrologic and sediment transport data available for public use. Hydrologic data are an extremely important sector of the USGS data. There are over 850,000 station years of USGS data for waterbodies throughout the United States. Records available for download include rainfall, stream levels and flows, reservoir and lake levels, and water quality data. Many of these gaging stations record streamflow (discharge) every 15-minutes (Figure 6.3), as well as peak discharges (Figure 6.4), mean-daily flows, and stage-discharge relationships. Most of the gaging stations throughout the United States are managed by the USGS, but some are managed by State agencies. Data from USGS gages are accessible at maps.waterdata.usgs.gov/mapper. If there are no USGS gages near the study site, the desk study can include searching for gages operated by the State, regional water management agencies, tribes, local governments, hydroelectric utilities, or nonprofit organizations, such as watershed councils.

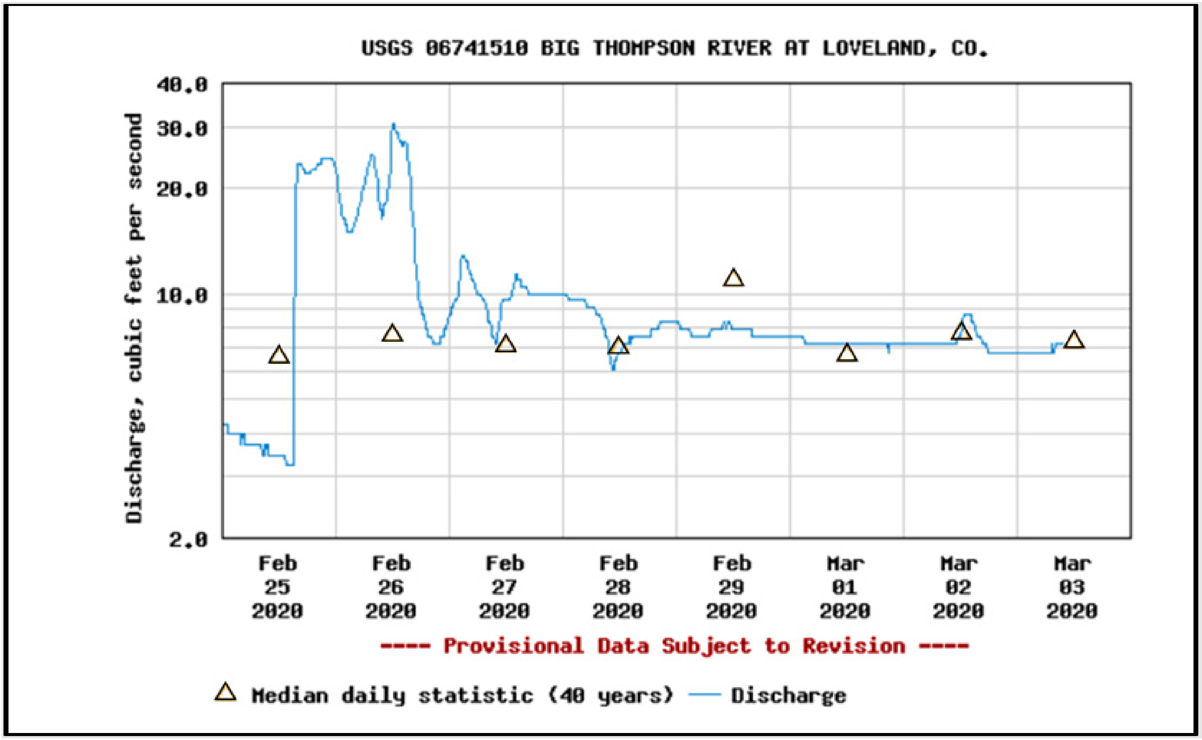


Figure 6.3. Example of instantaneous (15-minute) discharge data available for download from the USGS stream gage website. Source: USGS.

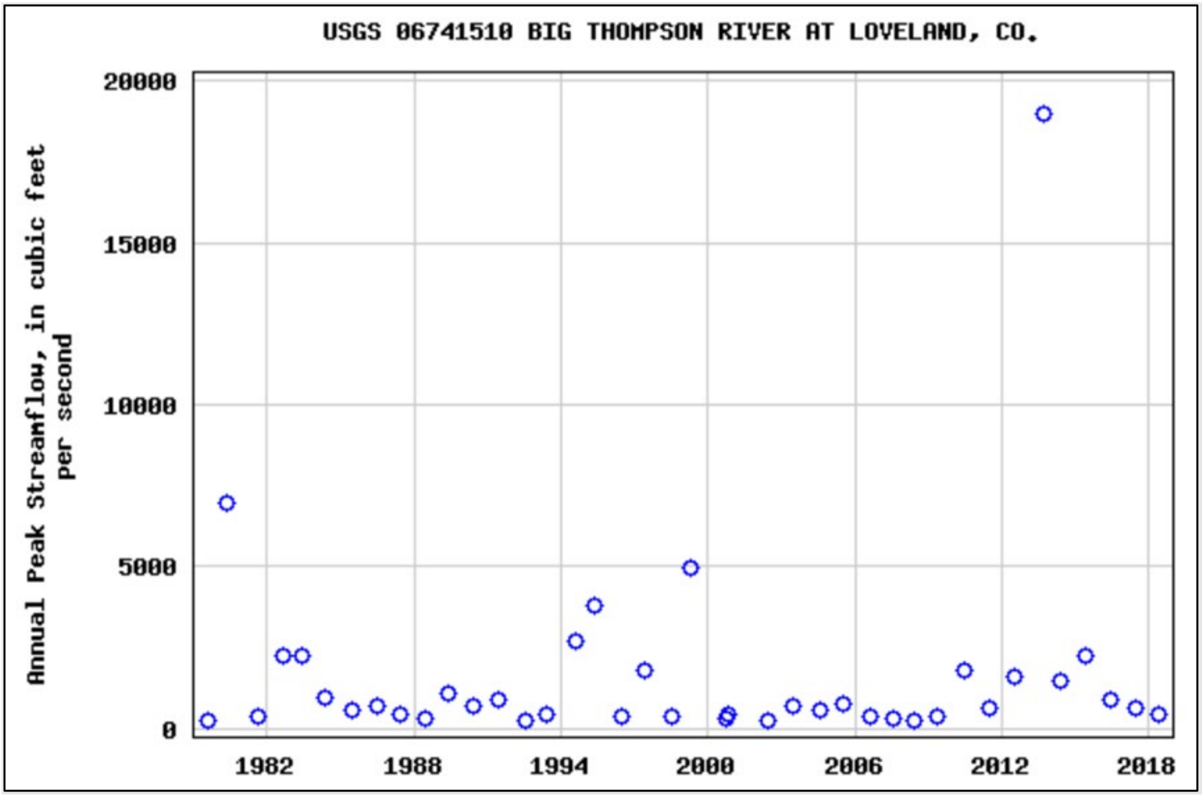
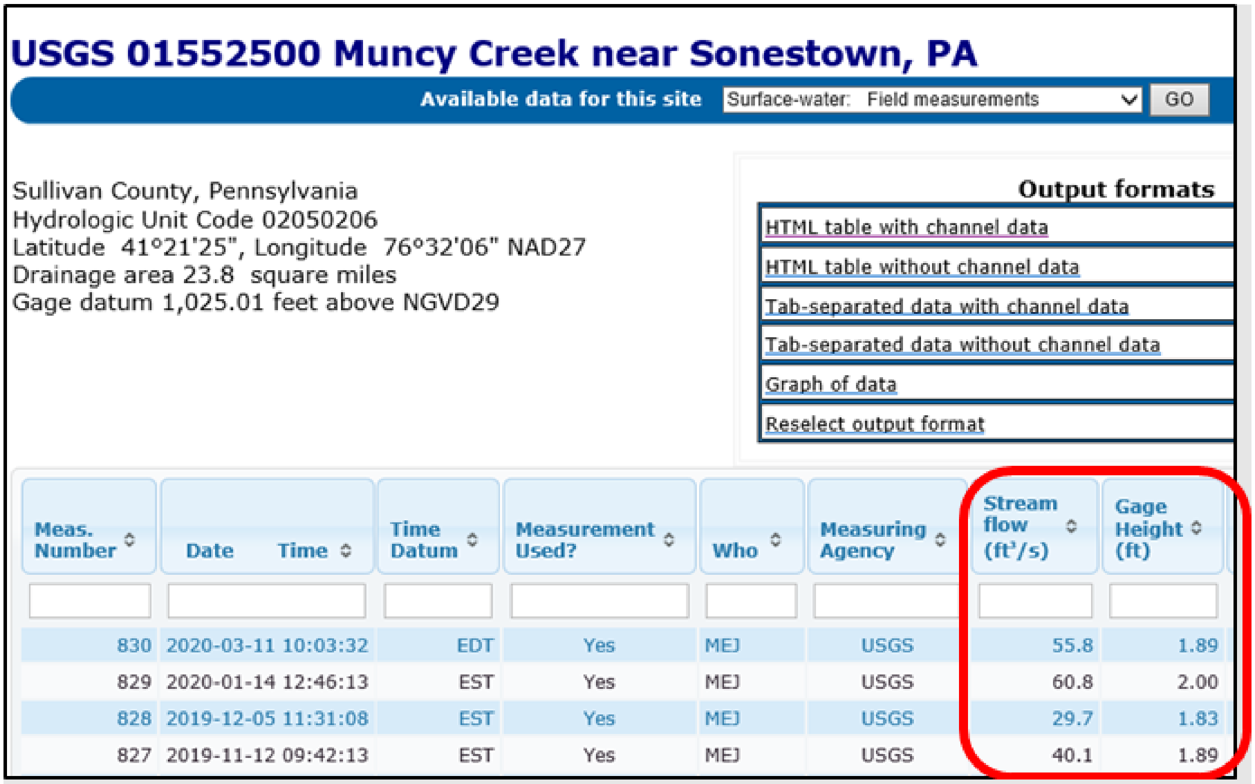


Figure 6.4. An annual peak streamflow record available for download from the USGS stream gage website.

Section 6.2 describes estimating the amount of aggradation and degradation that has occurred at a gage location (gaging station) by using field measurement data recorded for the gage. Field measurement data typically are collected to establish a relationship between depth of flow (stage) and discharge at the gage location. Field measurements are also taken periodically by the USGS to verify the accuracy of or update the stage-discharge relation. These field measurements include discharges measured at or near the gage along with the stage level recorded at the time. For example, the table in Figure 6.5 shows part of 830 streamflow measurements made in Muncy Creek since 1940. The record includes channel cross-section area, width, average velocity, and other information; the measurements only correspond to the discharge measurement location, which may be several hundred feet from the gage location.



USGS 01552500 Muncy Creek near Sonestown, PA

Sullivan County, Pennsylvania
Hydrologic Unit Code 02050206
Latitude 41°21'25", Longitude 76°32'06" NAD27
Drainage area 23.8 square miles
Gage datum 1,025.01 feet above NGVD29

Output formats

- HTML table with channel data
- HTML table without channel data
- Tab-separated data with channel data
- Tab-separated data without channel data
- Graph of data
- Reselect output format

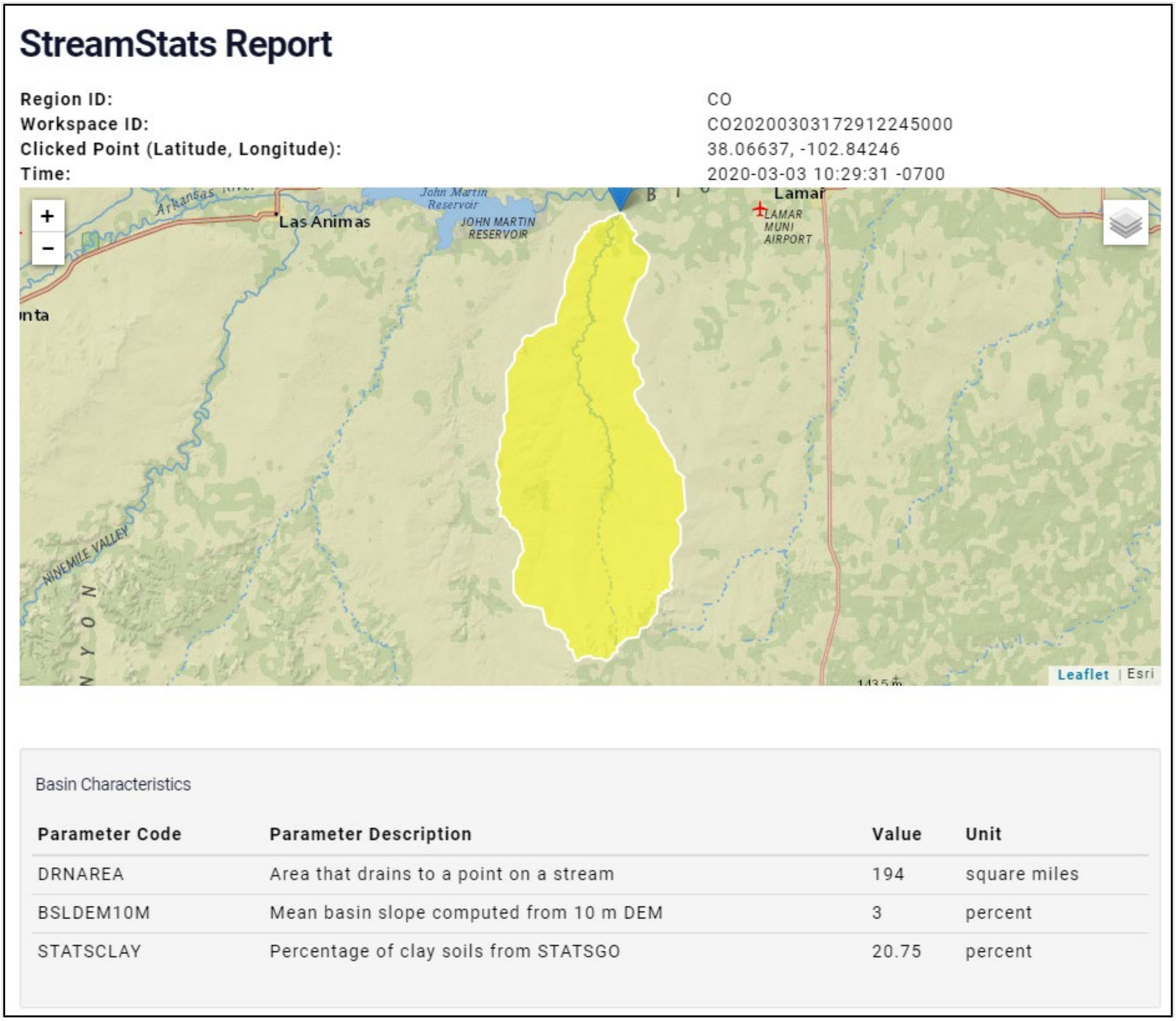
Meas. Number	Date Time	Time Datum	Measurement Used?	Who	Measuring Agency	Stream flow (ft³/s)	Gage Height (ft)
830	2020-03-11 10:03:32	EDT	Yes	MEJ	USGS	55.8	1.89
829	2020-01-14 12:46:13	EST	Yes	MEJ	USGS	60.8	2.00
828	2019-12-05 11:31:08	EST	Yes	MEJ	USGS	29.7	1.83
827	2019-11-12 09:42:13	EST	Yes	MEJ	USGS	40.1	1.89

Figure 6.5. Field measurement data from USGS Gage 01552500, Muncy Creek near Sonestown, PA.

Some stream gages include sediment data as well as discharge data. These data are listed as “Water-Quality: Field/Lab Data” under the available data for the site. When the rate of sediment transport is measured, typically only the measured suspended sediment concentration is listed. Chapter 7 presents detailed descriptions of sediment transport loads. It is important to note that the reported concentration does not include the entire suspended load because the sampler does not reach the bed. However, these data can provide insight into the overall sediment transport conditions.

Sediment transport rating curves (transport rate versus discharge) can be developed when the suspended sediment concentration data are paired with field-measured discharge data. Occasionally, the measured size gradation of the measured suspended sediment is provided with the suspended sediment concentration data. However, the bed load component of the total sediment load is rarely measured. The USGS, in cooperation with the FHWA, condensed 275,950 suspended sediment concentration values from 7,477 monitoring locations into a database application to facilitate regional or local analysis (FHWA 2009d) and developed a software tool to facilitate development of multi-segment sediment-transport rating-curves (Granato 2006).

The USGS also hosts StreamStats (streamstats.usgs.gov/ss), a web-based GIS application that can be used to map the upstream contributing watershed for any point on any stream in the United States, and which provides basic basin characteristics and streamflow statistics for the selected location (Figure 6.6). StreamStats is especially useful when estimating flows in ungaged watersheds.



StreamStats Report

Region ID:	CO
Workspace ID:	CO20200303172912245000
Clicked Point (Latitude, Longitude):	38.06637, -102.84246
Time:	2020-03-03 10:29:31 -0700

Basin Characteristics

Parameter Code	Parameter Description	Value	Unit
DRNAREA	Area that drains to a point on a stream	194	square miles
BSLDEM10M	Mean basin slope computed from 10 m DEM	3	percent
STATSCLAY	Percentage of clay soils from STATSGO	20.75	percent

Figure 6.6. Basin characteristics included in a USGS StreamStats report for a small, ungaged stream.

6.1.1.7 Bridge Design and Inspection Information

Design plans, as-built drawings, and inspection and maintenance records for bridges, culverts, bank protection structures, and river training works can often be obtained from the owner of the infrastructure. For example, bridge plans provide geometry, dimensions, and elevations of the deck, abutments, and piers that can be useful for developing a hydraulic model. As-built drawings show differences between the design and actual construction, and inspection records document changes in structure, channel cross-section, and countermeasures through time. Each type of information can be used to evaluate changing conditions at the bridge. Design drawings and plans may also indicate the design-depths of footings, foundations, and piers. Boring logs included on plans provide information on the soil and rock types, geotechnical properties, stratigraphy, and spatial variability.

6.1.1.8 Digital Elevation Models

The USDA Geospatial Data Gateway (gdg.sc.egov.usda.gov) and the USGS EarthExplorer (earthexplorer.usgs.gov) are excellent sources for Digital Elevation Models (DEMs) for a project location. DEMs are digital representations of ground surface topography and although the term often refers to gridded data it can also be used to refer to any digital representation. DEMs can be used for developing topographic (above water) portion of hydraulic models. DEMs are organized by state and county.

Data needed to develop DEMs can be obtained from several methods, including traditional land surveying, photogrammetry, light detection and ranging (LiDAR), and Structure-from-Motion (SfM). Traditional surveying methods generally are used to develop topographic data for relatively small project areas. Historically, photogrammetry has been used to develop data for larger project areas using aerial photography, but it has been generally superseded by LiDAR. LiDAR data are available as part of the National Elevation Database (NED) (ned.usgs.gov)) and the United States Interagency Elevation Inventory (coast.noaa.gov/inventory). Raw LiDAR includes vegetation and other objects, so processed “bare-earth” LiDAR is generally appropriate for DEM development. Traditional surveying methods are also used to fill in areas where LiDAR can miss information, including densely vegetated areas and frequently below-water areas of channels (FHWA 2019a). Various resolutions and accuracies are available depending on the date and location. Some locations have datasets from multiple years which can be helpful when considering geomorphological changes and channel migration. In recent years, SfM methods involving Unmanned Aerial Systems (UAS) and photogrammetric techniques have been applied to collect data for development of DEMs. SfM is generally applied to smaller scale project areas than LiDAR data acquisition.

States and local governments sometimes develop and share DEMs or LiDAR data from other projects. Because DEMs may have different vertical and horizontal datums, it is important to identify the datum for all data to be able to convert to a common reference.

6.1.2 Stream Reconnaissance

Knowledge of a project site’s characteristics is valuable to the project team. It facilitates understanding of site conditions, involved physical processes, site constraints and sensitivities and communication within the team and to stakeholders. The project manager, key team members, and other interested stakeholders commonly visit a site at the beginning of a project as part of a brief, multi-disciplinary familiarization meeting, which is useful for identifying and reviewing project objectives and issues associated with the site. The scope of a site visit is dependent on the size and complexity of the project.

Stream reconnaissance is a geomorphological technique providing a structure for field observation and for the recording and interpretation of stream forms, processes, and functions (FHWA 2012a, Zevenbergen et al. 2011, Thorne 1993). It involves collecting primary data to fill data gaps or provide supplementation of secondary data identified through the desktop study. The scope of field reconnaissance is dependent on the involved issues and the availability of data and information. A reconnaissance trip is a structured activity that involves planning, equipment, and time in the field, but which yields important understanding of the stream that can only be built based on first-hand knowledge.

Typically, there are two primary goals of stream reconnaissance. The first is to expand on the observations and secondary data previously studied at the desktop level. As an example, aerial photographs may suggest a vegetation type and density that is different from what is seen up close. Similarly, topography, channel features, land use, and vegetative cover may have changed since the most recent images and maps were created.

The second goal is to collect additional data only discernible from close observation and measurement. Local features like high-water marks indicated by trash-lines, scour holes, under-cut banks, and bedrock outcrops may not be discernible in aerial photographs and LiDAR-based DEMs. Stream reconnaissance data collection would also include measurement of field indicators of bankfull flow.

Travel and logistics for fieldwork can be expensive. Proper preparation before a reconnaissance trip improves the likelihood of efficient and successful data collection, and can include:

- Planning stream reconnaissance extent and access locations.
- Securing permission for entry.
- Health and safety considerations.
- Equipment lists.
- Data collection sheets.
- Printed maps and aerial photography.

A plan for what area to cover can be developed in the office beforehand based on aerial photos, topography, and other information gathered during the desktop effort, such as issues raised and project objectives. While the primary interest may focus on a stream crossing, it is generally helpful to walk well upstream and downstream of the site to observe and collect data. Ideally, both sides of the channel can be accessed directly from the stream crossing, but this can be hindered by difficult terrain, thick vegetation, and obstacles like fences. Aerial photos can help anticipate some of these difficulties as well as identify additional access points. Anticipating flow conditions can help assess whether the channel is wadable. If private property intersects the study area, contact and arrange

Field Study Safety Considerations

Equipment:

- First aid kit.
- Water and food.
- Insect repellant.
- Sunscreen.
- Durable footwear.
- Waders.
- Appropriate clothing for weather conditions.
- Communicator (2-way radio, cell phone).
- Lifejacket.
- High visibility safety vest.
- Official identification.

Be prepared for:

- Ticks, biting and stinging insects.
- Animals (venomous snakes, aggressive dogs).
- Plants (poisonous, thorny).
- Walking hazards (uneven or slippery ground).
- Geotechnical hazards (collapsing banks, unstable riprap).
- Heat/cold exposure.
- Medical emergencies.
- Vehicles.
- Other people (surprised or aggressive).
- Deep or swiftly moving water.
- Weather.

permission from the landowner beforehand and have documentation on hand during the trip to help avoid misunderstandings. Something as simple as wearing a high visibility safety vest can go a long way to calming property owners and the public.

Walking through a riparian environment can be physically challenging. Developing a Health and Safety Plan (HASP) in the office helps identify issues that may be relevant to the field work. Hazards in the field include tripping and falling injuries, environmental exposure, and becoming separated from others. A general HASP includes the location of the nearest medical treatment center, a list of local plants, insects, and animals to be avoided, and emergency contact information for those in the field. Important safety precautions include:

- Providing an itinerary to someone who is not on trip.
- Checking in after the trip is completed.
- Having CPR and first aid training.
- Preparing for potential weather conditions.
- Packing water and food for the entire trip and individual carry when away from vehicles.
- Using traffic cones and warning signs where traffic is present.
- Wearing high visibility safety vests.
- Wearing personal flotation devices when working around water.
- Working in groups of at least two to be able to communicate and follow the fieldwork HASP.

Working in and around moving water can present unique safety hazards, and it may be appropriate to complete water hazard and rescue training. .

This list of considerations is not exhaustive. Ultimately, individuals are responsible for taking precautions based on risks of the particular situation.

A variety of materials and equipment is useful in collecting data during a reconnaissance trip. It is important to record observations with photos and detailed notes as it may be some time before the information is revisited back at the office. Field materials/equipment might include:

- Maps showing overlays of aerial photography, topography, and access locations and other points of interest.
- Field notebook.
- Digital camera (ideally with built in GPS).
- Hand-held GPS unit.
- Small ruler or similar reference scale for photographs (Figure 6.7).
- Shovel.
- Sediment sample bags.
- Long tape measure and extendable stadia rod for measuring depths and distances.

Figure 6.7. Small scale used to show size of in-place material. Image used by permission of Tetra Tech, Inc.

The stream reconnaissance may include surveying or identifying locations for subsequent cross-section surveys to support development of hydraulic models. Depending on the needs of the hydraulic model, the field crew surveys points and cross-sections with sufficient detail to develop contours, especially in the vicinity of a bridge, culvert, or other infrastructure. Survey points include major breaks in slope and can include changes in material or ground cover. In a channel, the minimum number of points includes top and toe of banks, water's edge, thalweg (lowest point or invert), and additional survey points to accurately represent the channel geometry.

Cross-section data can be collected with basic equipment such as a survey level and stadia rod. More sophisticated equipment, including robotic total stations, high accuracy GPS systems, and velocity meters can be used to gather additional information that may be needed for the modeling effort. However, all equipment has limitations and the choice of what equipment to use is determined by those with experience conducting this work. These advanced pieces of equipment are often expensive and involve additional training.

Even when a LiDAR-based DEM is available, it is frequently beneficial to collect additional topographic information to support hydraulic modeling. LiDAR can misrepresent surface elevations below thick vegetation, and standard (red) LiDAR does not penetrate water. Additionally, the available LiDAR dataset may be too old to capture recent changes to channel form and floodplain topography. Ideally, bathymetric data are collected with survey equipment and composited into the LiDAR-based DEM to create a seamless surface. The density of data collected depends on the specific needs of the analysis. One-dimensional (1D) hydraulic modeling (previously discussed in Chapter 5) generally benefits when cross-sections are surveyed every few channel widths and, as described in *Two-Dimensional Hydraulic Modeling for Highways in the River Environment: Reference Document* (FHWA 2019a), two-dimensional (2D) modeling typically involves more detailed surveys for the development of a DEM that is then used to create the 2D mesh. Collecting water-surface elevations at each cross-section along the length of the study area creates a set of data that, when correlated with the discharge at the time, can be used to help calibrate a hydraulic model. Discharge can be determined from a nearby gaging station, or if none is present within an acceptable distance, a project site specific discharge measurement can be collected at the same time as the water surface elevation data. It is useful to identify physical conditions that control the stage-discharge relationship at a specific location (e.g., the presence of an overflow weir, spillway, or bedrock constriction). It may be difficult to recognize all significant features in the field because natural topography and geology could act as controls at different discharge magnitudes. For this reason, it is helpful to collect as much topographic data as time allows, as the incremental cost of one more cross-sections may be small compared to the value to the subsequent analysis.

HEC-20 Section 5.4 (FHWA 2012a) provides information on conducting a rapid assessment of channel stability. This method assesses 13 stability indicators and scores each on a numerical scale. It is designed to be conducted without requiring detailed measurements or surveys by certified land surveyors and indicates a general potential for stability issues. HEC-20 also includes (Section 5.2) a more comprehensive stream reconnaissance approach that involves characterizing aspects of the entire river valley and detailed measurements of channel dimensions and sediment layer thicknesses. Common to both protocols is the framework of sheets and checklists to guide the data collection. In summary, projects benefit from a general characterization of channel features, and riparian and floodplain conditions.

6.1.3 Bed and Overbank Material

Bed material refers to the mixture of sediment that makes up the bed of a river channel. It can range in size from mud to large boulders. The size and make-up of the bed material is used to perform analyses such as estimating hydraulic roughness, incipient motion, scour, and sediment-transport capacity. Sediment particle size is the primary way bed material is described and is the most important property. Engineers commonly assume a single density for all the particles because they are derived from the same parent materials in the watershed.

Overbank material derives from the channel banks and adjacent floodplain. While much of the description of bed materials also applies to overbank materials, this section includes discussion of important differences.

6.1.3.1 Material Size

HEC-20 classifies sediment size as shown in Table 6.1:

- Coarse: particles greater than 2 mm, which includes gravel, cobbles, and boulders.
- Fine: particles between 2 mm and 0.0625 mm, commonly described as sand.
- Cohesive: particles smaller than 0.0625 mm, commonly described as silt and clay.

More detailed categories are commonly used, and these are described in HEC-20 Table 2.1. Soil cohesion is influenced by a range of soil properties and roots can act to bind sediments. Coarse and fine materials are noncohesive.

Table 6.1. Sediment size classification.

Class Name	Size (mm)
Boulder	4,000-250
Cobble	250-64
Gravel	64-2
Sand	2.0-0.062
Silt	0.062-0.004
Clay	0.004-0.00024

Bed materials often include particles from multiple size categories. A way of representing this variation is called a soil gradation, which is commonly calculated by passing a soil sample through a series of progressively smaller mesh sieves and weighing the material collected on each sieve screen (see Section 6.1.3). A particle that cannot pass through a particular opening, for example a 32-mm opening, is recorded as 32 mm. Figure 6.8 shows a gravelometer, which measures the intermediate axis of a pebble or cobble in the same way that a sieve measures sand. Field personnel determine the particle size distribution of sediment making up the bed or bars in the channel with it during site visits.

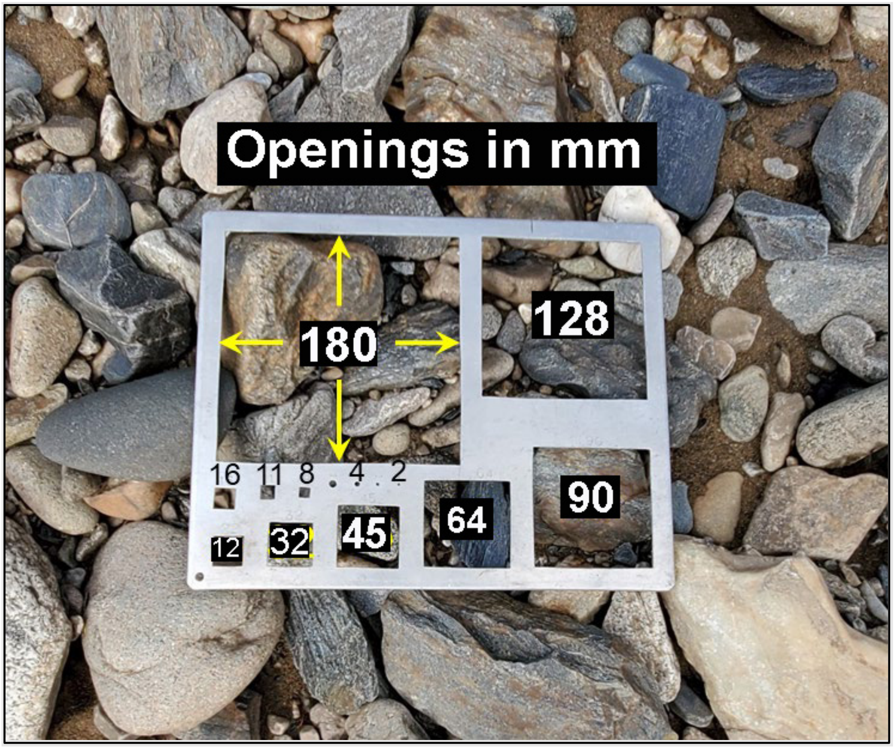


Figure 6.8. Gravelometer placed on bed sediment to be sampled. Image used by permission of Tetra Tech, Inc.

A gradation curve describes the percentage of the sample smaller than each size threshold determined by the number of sieves or the openings in a gravelometer (see Figure 6.9). The median particle size (D_{50}) is commonly used as a representative statistic for describing the sediment characteristics of a river. The D_{50} is the particle size for which 50 percent of the material is smaller and 50 percent is larger, by mass, and provides a general description of channel bed types. For example, a river with a D_{50} in the gravel range (2 mm to 64 mm) is referred to as a gravel-bed stream or river.

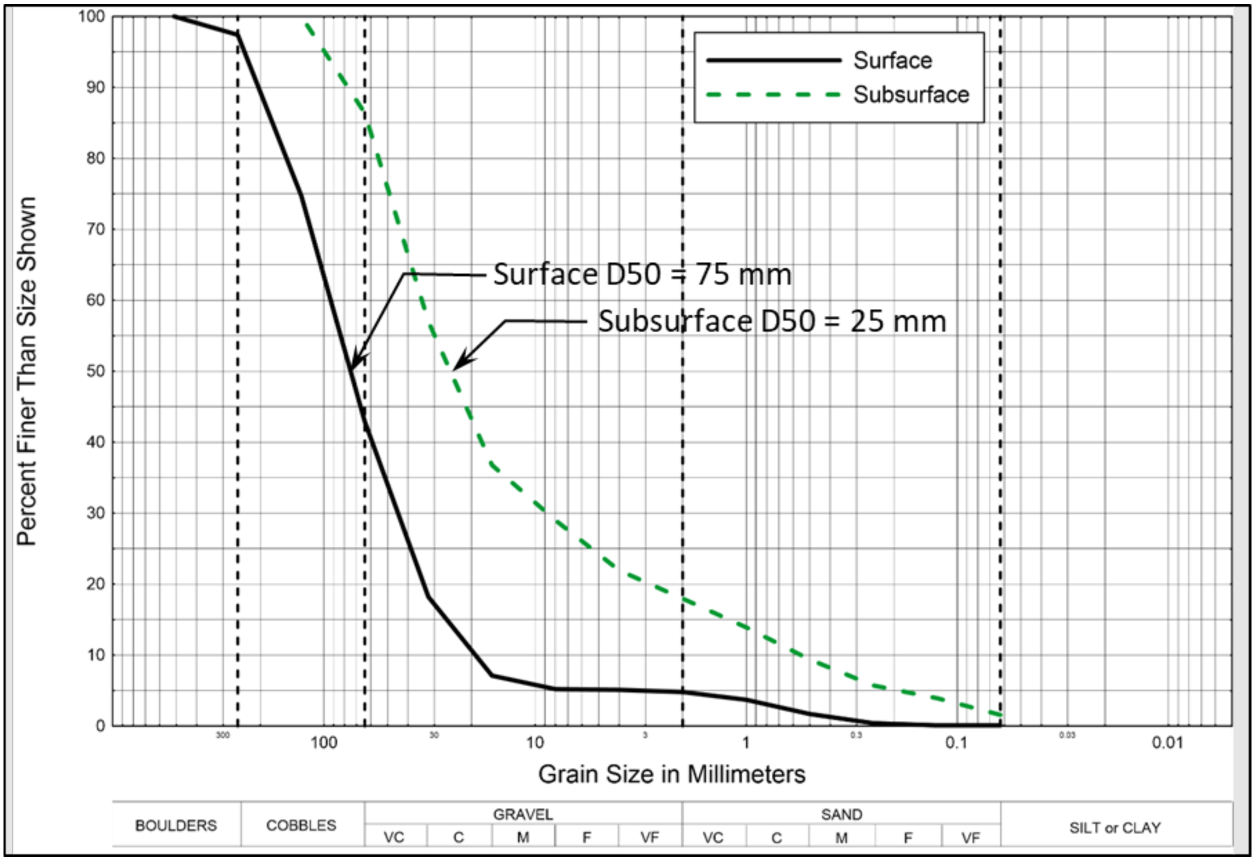


Figure 6.9. Gradation plot showing two bed material samples.

6.1.3.2 Material Layers

As flow in a channel rises and falls, the river often sorts the bed sediment into a surface layer and one or more subsurface layers within the channel. The surface layer includes material resistant to movement during lower flows as shown in Figure 6.10. This figure also shows that there may not be a distinct surface and subsurface layer, but many layers showing deposition from a range of events. A sample of the surface layer provides a good indication of the material that creates roughness in the channel and can help estimate a Manning's n roughness parameter for hydraulic modeling and incipient motion calculations. HEC-20 (Sections 3.4.4 and 6.4.2) provides information on Manning's n and incipient motion.

The thickness of the surface layer is generally considered to be about the size of the largest particle in the layer. Thick surface layers with larger material are referred to as "armor" or "pavement" because they are generally resistant to movement at all but the highest flows. The gradation curves in Figure 6.9 demonstrate an armor surface where the finer material has been "winnowed" vertically. Most sediment transport models also include multiple layers in their computations. The subsurface layer represents most of the mass of the channel bed. This material represents the gradation that is available during mobile-bed conditions and active sediment transport. For this reason, a sample of the subsurface layer is often used for many sediment transport calculations including volumetric transport rates and aggradation/degra-dation trends (Bunte and Abt 2001).

In many sand-bed systems, the distinction between the surface layer and subsurface can be minor because fine grain sediments are easily transported and any surface layer that forms is relatively thin. Therefore, it is generally acceptable to use a single gradation to represent both sand layers.

Figure 6.10. Sediment sample hole demonstrating the coarse armor layer and several gravel and sand layers below. Image used by permission of Tetra Tech, Inc.

6.1.3.3 Sampling Methods

There are three general types of bed material sampling methods: volumetric (grab), grid, and area. The volumetric method is based on the sample weight and grid sampling is based on the count of a subset of the surface particles. The area method counts all the surface particles within an area.

A grab sample, the volume of material typically collected by shoveling or scooping, is almost exclusively used to collect a subsurface sample. The sample is passed through a series of sieves to determine the gradation curve. The USACE provides a minimum recommended sample size depending on the maximum sediment particle size as shown in Table 6.2 (USACE 1986). Tools for collecting the sample range from a shovel and a bag to more complex tools for collecting submerged samples in a variety of conditions. Edwards et al. (1999) and Bunte and Abt (2001) provide additional information on sample collection.

Table 6.2. Sample size based on maximum particle size.

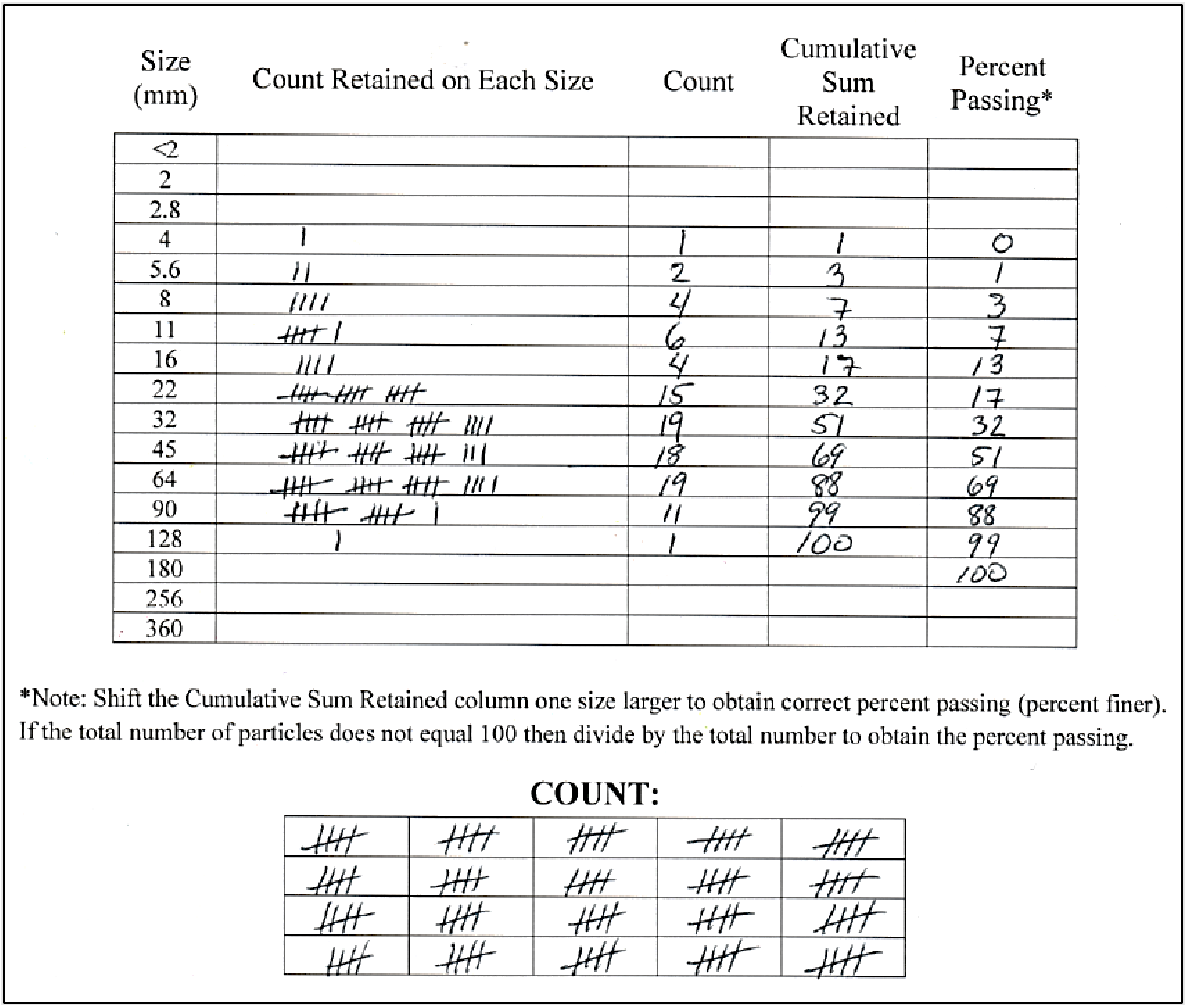
Maximum Particle Size, in (mm)	Minimum Sample Size, lb (kg)
6 (150)	500 (230)
3 (75)	140 (64)
2 (50)	40 (19)
1.5 (37.5)	20 (8)
1 (25)	10 (2.5)
0.75 (19)	2.2 (1)
0.5 (12.5)	0.7 (0.3)
0.375 (9.5)	0.3 (0.15)

While there is often no practical difference between surface and subsurface layers in sand bed systems, in coarse-bed systems it is important to avoid surface material when collecting the grab sample. An appropriate technique to collect a grab sample is to manually clear away the surface material to allow for a clear scoop of subsurface material.

If the sediment is so large that a grab sample would be impractical to remove from the site and transport for later analysis, it is possible to sieve the material on site. The process is time and labor intensive and is most easily performed in an open, dry work area. In general terms, material is scooped out and placed on large tarps to drain. The drained material is then weighed and processed through large sieves and the largest particles measured using a gravelometer (Figure 6.8). It is possible to classify an entire sample this way, though it is more likely that only the larger fractions are classified onsite and the smaller material is removed and analyzed offsite. Field sieving often separates and grades particles sizes greater than 45 mm using a gravelometer and field sieves for sizes between 45 and 16 mm. The total weight of the material smaller than 16 mm is recorded and a portion of that material, typically 20 pounds, is transported and analyzed offsite. Bunte and Abt (2001) provide a detailed description of the process.

The second method, grid sampling, is usually reserved for surface samples of gravel and other coarse beds with or without armor layers and involves measuring the intermediate axis of randomly selected sediment particles on the bed surface. By sampling a large enough number of particles, typically 100, the gradation curve created by the sampled particles represents the distribution of the bed surface. Wolman (1954) developed the pebble count approach (a form of grid sampling), which is applicable on exposed bars, in shallow water, or in other locations where it is safe to walk and handle the bed material on the ground.

For a pebble count, one person collects the sample by walking along a path and measuring a randomly selected (eyes averted to avoid bias) sediment particle at each step. The sample collector measures the size of the particle with a gravelometer and reports the size to a second person who records the measurement on a data collection sheet as shown in the example in Figure 6.11. The walking path can be along a line with samples taken at a predetermined length, or it can be an arbitrary course within the desired sample area. A preferred method to avoid bias is to set out a 100-ft tape and measure each particle at a spacing no closer than approximately twice the largest particle size that may be encountered. A 1-ft increment is often appropriate and valid results are obtained only when the increment is held constant throughout the sample collection process. If a large particle is under two or more increments, count it for each increment. If the particle is too large to pick up, the size can be approximated with a tape measure.



Size (mm)	Count Retained on Each Size	Count	Cumulative Sum Retained	Percent Passing*
<2				
2				
2.8				
4	𝍷	1	1	0
5.6	𝍷𝍷	2	3	1
8	𝍷𝍷𝍷𝍷	4	7	3
11	𝍸 𝍷	6	13	7
16	𝍷𝍷𝍷𝍷	4	17	13
22	𝍸 𝍸 𝍸	15	32	17
32	𝍸 𝍸 𝍸 𝍷𝍷𝍷𝍷	19	51	32
45	𝍸 𝍸 𝍸 𝍷𝍷𝍷	18	69	51
64	𝍸 𝍸 𝍸 𝍷𝍷𝍷𝍷	19	88	69
90	𝍸 𝍸 𝍷	11	99	88
128	𝍷	1	100	99
180				100
256				
360				

*Note: Shift the Cumulative Sum Retained column one size larger to obtain correct percent passing (percent finer). If the total number of particles does not equal 100 then divide by the total number to obtain the percent passing.

COUNT:

𝍸	𝍸	𝍸	𝍸	𝍸
𝍸	𝍸	𝍸	𝍸	𝍸
𝍸	𝍸	𝍸	𝍸	𝍸
𝍸	𝍸	𝍸	𝍸	𝍸

Figure 6.11. Surface sample data sheet.

Samplers typically collect 100 particles to obtain a representative sample and gradation curve (Hey and Thorne 1983). As shown in Figure 6.11 the retained size is recorded. The percent passing (percent finer) is determined in the collection sheet by shifting values in cumulative sum retained column down one row (one size class) to create the percent passing column as shown in Figure 6.11. If the number of particles is not 100, the percentage is based on the total particles in that sample. The National Engineering Handbook provides additional discussion on special cases (NRCS 2007b).

The pebble count approach has limitations. In urban environments, it can be difficult to determine which stones are native and which have been brought in from the surrounding environment. Identifying particles with eyes averted frequently misses particles smaller than 2 mm and particles smaller than 8 mm are typically underrepresented (Fripp and Diplas 1993). When the sampling area is submerged, the likelihood of missing smaller material increases. Using a frame grid improves the ability to identify smaller particles and is used when surface material is limited to gravel and smaller sizes. This technique involves placing the frame on the bed surface and measuring the particle identified at each grid intersection. Because the data collector can scrutinize each specific particle, it is less likely that smaller particles are overlooked. Typically, 100 particles are collected with this approach and recorded in the same manner as the pebble count including counting particles multiple times if they fall under multiple grid intersections.

The final method, area sampling, is a surface sampling technique intended to measure all particles in an area, including small particles that may be overlooked in grid samples. Samples can be collected by taking a photograph that is analyzed by specialized recognition software. The FHWA Hydraulic Toolbox can be used to develop gradation curves from grid samples or from images (www.fhwa.dot.gov/engineering/hydraulics/software/toolbox404.cfm).

Researchers have evaluated whether the alternative sampling methods yield reasonably equivalent gradations. If the same material is sampled, percent finer by weight of a volume (volumetric samples) is roughly equivalent to percent finer by count of a surface (grid samples) (Kellerhals and Bray 1971).

6.1.3.4 Sample Location

Because the results of the sample analysis are used in subsequent hydraulic and sediment transport analyses, selecting a representative location for sampling is important. Selection of the location depends on the intended use of the collected sample. If the intended use is to characterize bed material load, the heads of bars are often good locations for surface and subsurface samples. Bar head samples are typically taken during low flow conditions. Areas with uniform flow conditions, such as the crossings between meander bends, are potentially good candidates for samples representative of bed roughness. Locations that would be poor choices for sampling to represent sediment transport and bed roughness include tributary mouths, riffle crests, concentrations of wood or debris, downstream of eroding banks, and areas of constriction or expansion. Due to their possible influence on flow velocity and depth or associated conditions of scour, bridge crossings and other in-channel structures are typically also poor choices for sediment transport or bed roughness samples. However, if the sample is to be used to represent conditions at a specific location, or associated with a hydraulic structure, it is appropriate to sample at that location or structure. For bridge scour analyses, samples are often collected upstream and at the bridge. Subsurface samples at bridges can provide useful data for bridge scour analyses. The number of samples also depends on the intended use.

Bed material in sand bed systems is often well-mixed and may vary little with depth in the channel bed. Variations in gradation often occur over long distances along the channel but can also vary laterally. In these systems, samples from multiple locations across a single cross-section where lateral variation is significant provides more representative gradation information. Multiple gradation curves are then developed for each sample and averaged to create a representative gradation for the cross-section.

Coarse-bed systems often have a high degree of variability in sediment profile both with depth and width. Sampling sites are generally limited to exposed or shallow submerged areas. The heads of point bars and mid-channel bars are commonly selected sites because of the likelihood of finding representative material at a location that can be easily sampled (NRCS 2007b).

6.1.3.5 Overbank Material

Sediment material that makes up the channel banks and floodplain is often distinctly different from the bed material. Depending on the stability of the channel, the bank material may or may not be a significant source of the sediment transported. As illustrated in Figure 6.12, tall, exposed banks may reveal multiple layers. Samples of bank material can help in assessing bank stability as well as in the design of bank protection.

A common approach to sampling bank material is to photograph or sketch the visible layers to indicate the layer thickness and collect a grab sample from each distinct layer (Figure 6.12). Bank material gradation often does not vary significantly in the downstream direction, meaning fewer bank samples upstream and downstream are needed to characterize a large area. As with bed material samples, it is important to avoid taking samples at locations that are not representative of average bank conditions.

Figure 6.12. Channel bank with multiple sediment layers. Image used by permission of Tetra Tech, Inc.

6.2 Gage Analyses

Long-term streamflow gages provide a wealth of information useful for geomorphological evaluations. Although a stream gage may not be in the project reach of interest, a nearby gage can provide useful information. The following sections describe various analyses useful to geomorphologic evaluations that can be conducted by using data and information collected at long-term flow gage locations. More information on stream gage analyses is available in HDS 2 (FHWA 2002) and HEC-17 (FHWA 2016).

6.2.1 Flood History

Flow records collected at long-term gages provide detailed insight into the conditions associated with major flood events. Maintenance personnel and records can provide information on structure performance if flooding occurred recently. Knowledge of the magnitude, timing, and duration of large floods is useful for understanding related information regarding major overbank flow paths; the relative conveyance capacity of channels, bridges, and culverts; and the scope and extent of historic flood damages to property and infrastructure. Significant geomorphic changes, such as rapid channel migration or avulsion, channel enlargement, and sediment deposition may also be explained by examination of historic flood information. Historic flood data can also be useful for calibration and validation of hydrologic and hydraulic models.

6.2.2 Aggradation/Degradation/Widening Trend Identification

A stream gage record is a chart of river stage versus time. Each stage data point for the specific discharge is obtained from a rating curve established from stage-discharge measurements for the gaging location. The USGS establishes rating tables based on field measurements collected over a period of months or years. Once a rating table is established, additional field measurements are collected to assess the rating table accuracy over time. If the additional field measurements indicate that the current rating table is no longer accurate, the USGS creates a new rating table based on the most recent field measurements. Comparing stage values from consecutive stage-discharge ratings for a specific discharge can indicate increasing (likely resulting from channel aggradation) or decreasing (likely from channel degradation or widening) stage trends over time. This type of evaluation is called a specific gage analysis.

Figure 6.13 shows the results of an example specific gage analysis. Consistently increasing or decreasing trends over a period of many years for a stream gage record indicate that the stream is not in equilibrium at that location. The specific gage analysis in Figure 6.13 indicates a long-term and consistent trend of channel degradation along the Atchafalaya River between 1940 and 1980. Since 1980, the data indicate channel degradation has ceased; stages at all evaluated flows were consistent up to 2020. Ideally, investigators consider specific gage analyses in conjunction with other independent sources of historical evidence. For example, surveyed cross-sections, historical photographs, and bridge inspection reports indicating exposed pile caps or abutment footings might provide corroborating evidence that lowered water surface elevations were caused by degradation, rather than other possible causes.

Significant high flows and hydraulic control structure installations/alterations (e.g., water diversions, adjustable weirs, removal of a dam) have the potential to impact stream gage records dramatically in a relatively short period of time. It is important to note the timing of such events in the evaluation of stream gage records to determine whether these events have any impact.

An underlying assumption in a specific gage analysis is that the flow and stage measurements and developed rating tables are accurate. Inaccurate data resulting from incorrect flow or stage measurements have the potential to artificially create or mask trends for periods in the record. The underlying assumption of accurate data and associated trends can generally be verified by evaluation of related information such as historic channel cross-section and profile survey data, observations of channel bank heights, and scour monitoring data for nearby bridge structures. Practically, flow and stage measurements best represent more frequently occurring lower flows which best reflect aggradation and degradation trends. High flows tend to exhibit a higher variability in stage since flows that overtop the channel banks are often subject to seasonal variations in roughness, and complex two-dimensional flow patterns that may affect stage and flow relationships. High flows are also experienced less often than the lower flows, providing relatively few data for evaluation of stage.

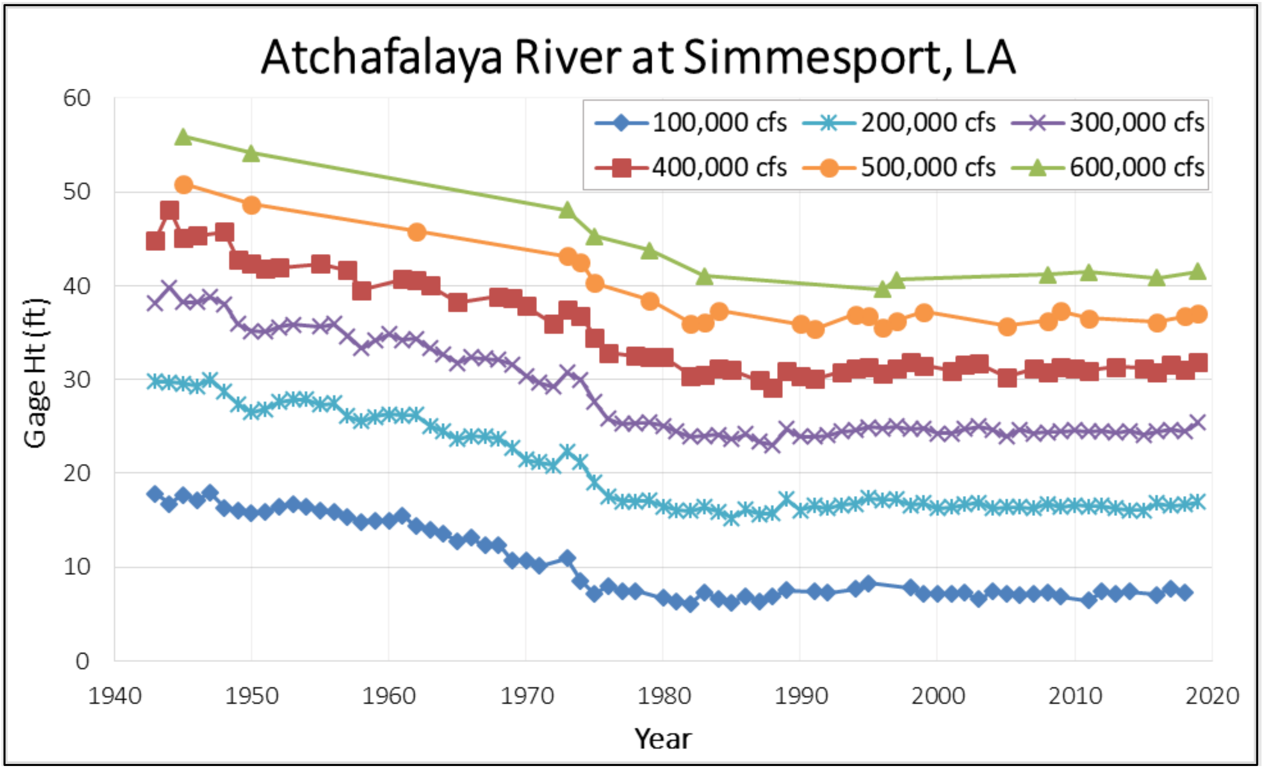


Figure 6.13. Specific gage analysis for the Atchafalaya River at Simmesport, LA. Image used by permission of D. Biedenharn (© 2020).

An example of an analysis for USGS gage no. 05064500 on the Red River at Halstad, Minnesota is shown in Figure 6.14. The stage at the Halstad gage dropped approximately 3 feet in a relatively short period of time between 1992 and 2000. This likely resulted from replacement of the State Route 200 bridge in 1999. The most recent rating curves indicate that a long-term decrease in stage for the medium and high flows has continued after the short disruption in the rating curve following the bridge replacement. However, the low flow stage has exhibited only a small decrease in elevation over the entire period of record. This suggests that the low flow channel geometry has remained fairly stable, while the higher elevation portions of the channel may be increasing in cross-sectional area (likely the result of bank failures), resulting in lower stages over time.

Figure 6.15 shows a stream gage plot for the Maple River at Mapleton, Iowa. It shows gage heights at the time of flow measurements with data grouped by flow range. As shown in Figure 6.15, flows less than 50 cfs (cubic-feet per second) closely track the channel bed elevation because depths are shallow. Since 1941 the channel has degraded approximately 8 feet, but the trend suggests that the bed is stabilizing. This plot shows that even the highest flow measurements have a trend of lower water surface elevation through time. Therefore, the incising channel is also losing floodplain connectivity through time.

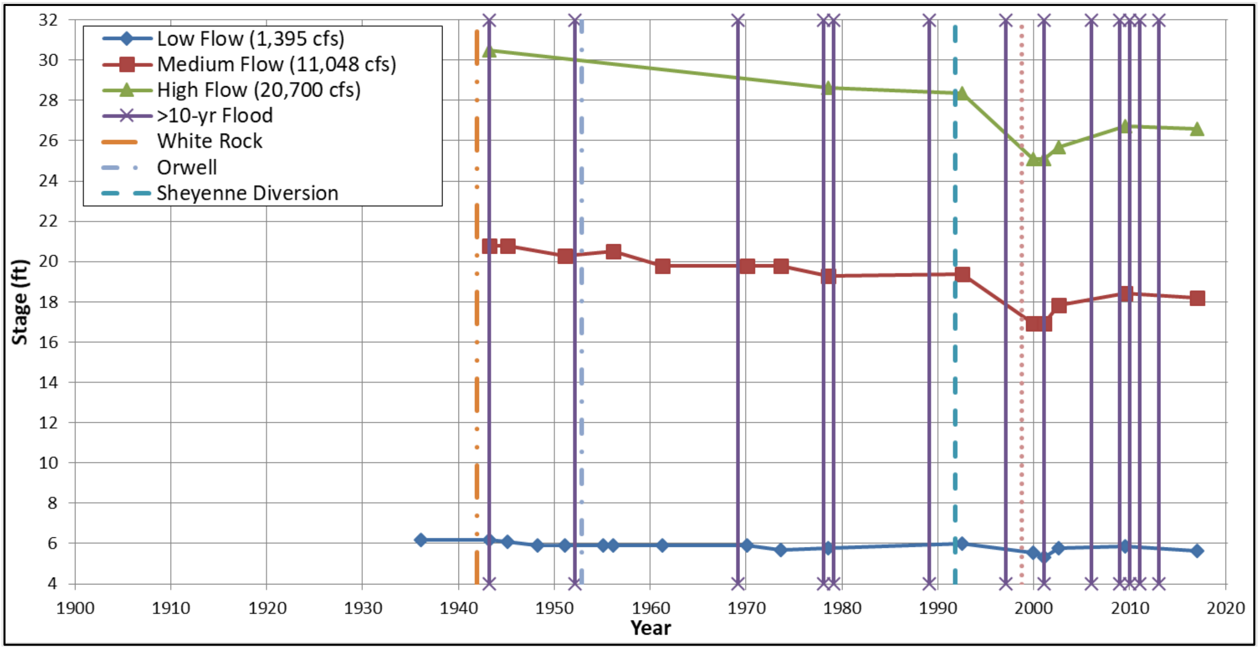


Figure 6.14. Gage plot for Red River at Halstad, Minnesota (#05064500). Image used by permission of WEST Consultants, Inc.

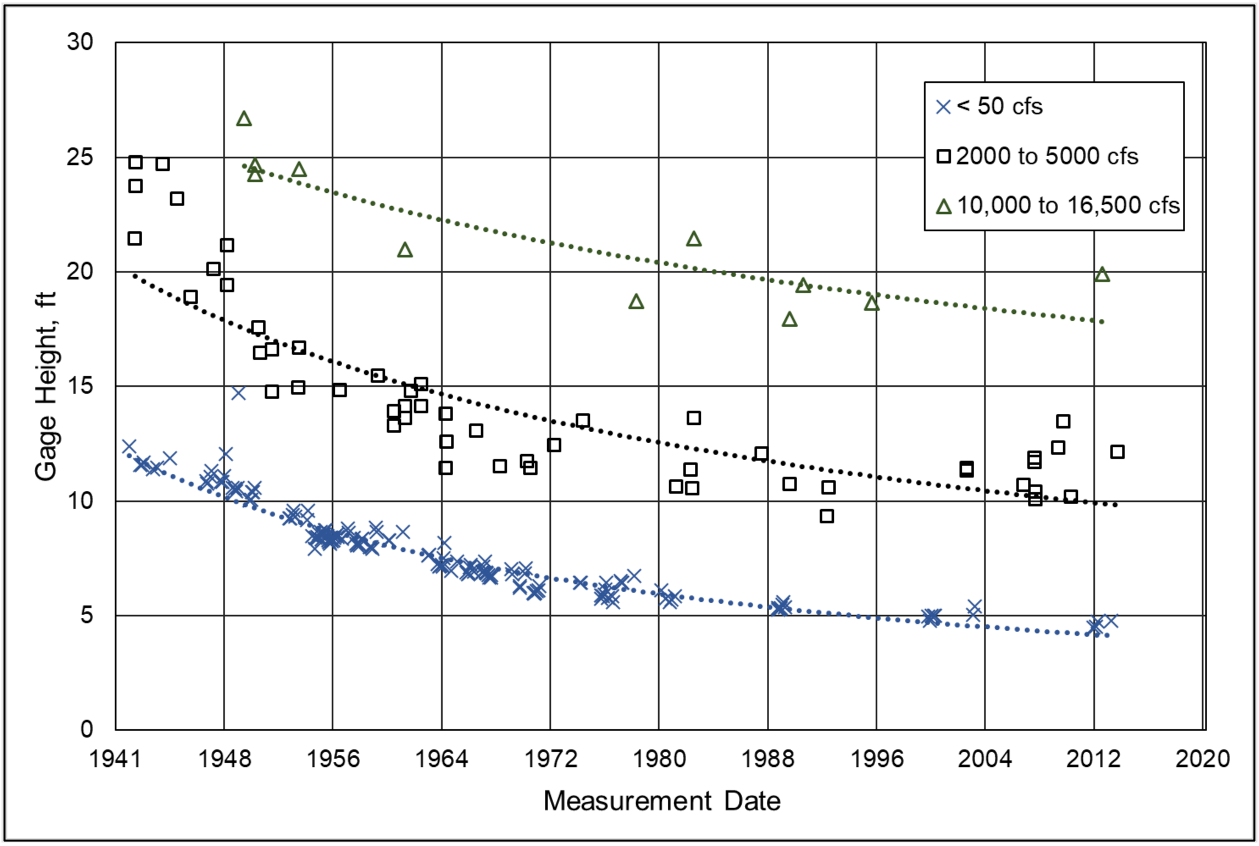


Figure 6.15. Stream gage plot using by flow range for the Maple River at State Highway 175 in at Mapleton, Iowa (USGS Gage 06607200).

Figure 6.16 displays the same data for the Maple River grouped by decade and illustrates the lowering of stage for each flow through time. It shows that the entire flow range has been affected by the channel degradation. It also illustrates why the USGS regularly repeats flow measurements to update the stage-discharge relationships (rating curves) at the gage. Each group of data has the appearance of a stage-flow rating curve. It is suggested that interpretations, such as these, of gage records be corroborated using other evidence such as field observations, bridge inspection measurements, and aerial photography.

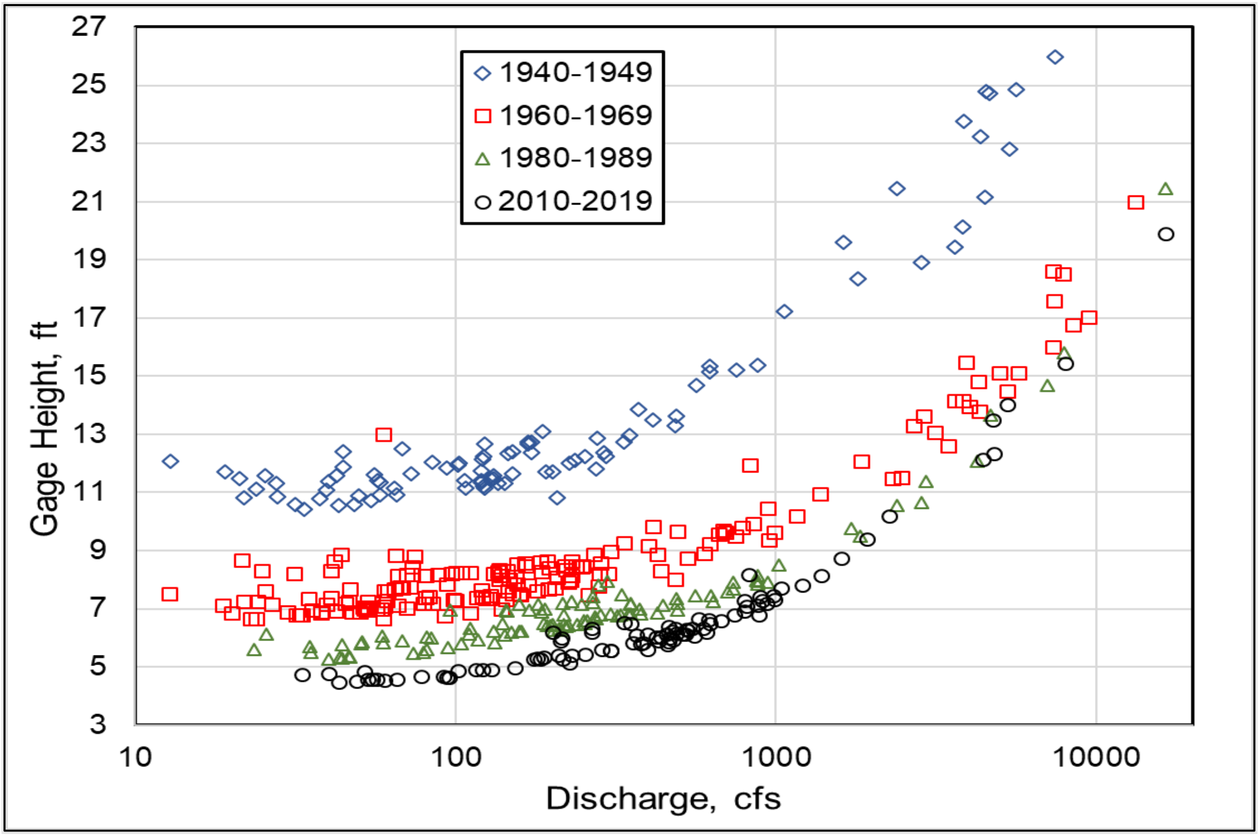


Figure 6.16. Stream gage plot by decade for the Maple River at State Highway 175 in at Mapleton, IA (USGS Gage 06607200).

6.3 Lateral Migration Analysis

Channel migration is a natural, and typically incremental, process of bank erosion that includes channel shifts across and down valley and can include channel widening. Channel migration has significant implications for the design and protection of bridges, road encroachments, and other infrastructure. Geomorphologists perform channel migration analyses to:

- Evaluate potential threats and impacts to existing facilities.
- Develop an approximate timeline.
- Locate and design a new bridge or highway to accommodate anticipated channel migration.

A channel migration problem at a bridge or road may only become apparent decades after construction. Channel migration may be exacerbated by basin-wide factors such as land use changes, gravel mining, dam construction, removal of vegetation, and climate change. Remedial actions, such as constructing spurs or installing bank protection, may become important to protect the infrastructure. Relocating the road away from the channel can also be considered. When bank protection locks in the location of a bend, the continued migration of adjacent bends can create new channel stability issues at the protected bend or elsewhere along the channel corridor.

Local and system-wide factors influence channel migration. The morphology and behavior of a given river reach is strongly determined by the sediment and water discharge from upstream. Therefore, any significant modification of sediment load and water discharge because of human or natural factors, can impact local rates of channel change. Even without changes to the supply of water or sediment, progressive lateral migration can occur to adversely affect highway structures.

Historical aerial photographs, mapping, surveys, and DEMs (see Section 6.1.1.8) are common resources in the toolbox for evaluating lateral migration. This section organizes channel migration evaluation methods in the following categories:

- Meander belt width delineation.
- Regional methods, including:
    - River Corridor Planning (Kline 2010).
    - Channel Migration Zone (Rapp and Abbe 2003, Olson et al. 2014).
    - Fluvial Hazard Mapping (Jagt et al. 2020).
- Map and aerial photograph comparisons.

6.3.1 Meander Belt Width Delineation

The meander belt width is the area along the valley floor that a meandering channel has historically occupied. Geomorphologists use this meander belt as a tool for planning by considering that the historical behavior of the river is an indicator of the area the river may occupy in the future.

The geomorphologist determines the meander belt width by drawing two lines encompassing the outside limits of past and present meanders recognizing that a channel can move across or down the valley. The width may be extended further to allow for erosion or a factor of safety. The lines in Figure 6.17 show a potential meander belt for a reach of the Bear River, Utah based on 2018 aerial imagery. More detailed investigations can incorporate geologic controls or other features that can reduce or expand the meander belt. These include the use of topographic maps, soils maps, and geologic maps to further inform the meander belt delineation.

Meander belts can be developed from a variety of data. Figure 6.18 and Figure 6.19 show examples of aerial imagery and LiDAR data for the Lamoille River, Vermont. The aerial image shows the active channel and relic channel features across the floodplain. Through time, vegetation and agricultural practices obscure these relic features. The LiDAR mapping clearly shows the river has moved across most of the valley floor with lighter shading showing more recent activity. It is reasonable to assume the channel can reoccupy any location in the floodplain in the future, though the timeframe for reoccupation cannot be directly inferred.

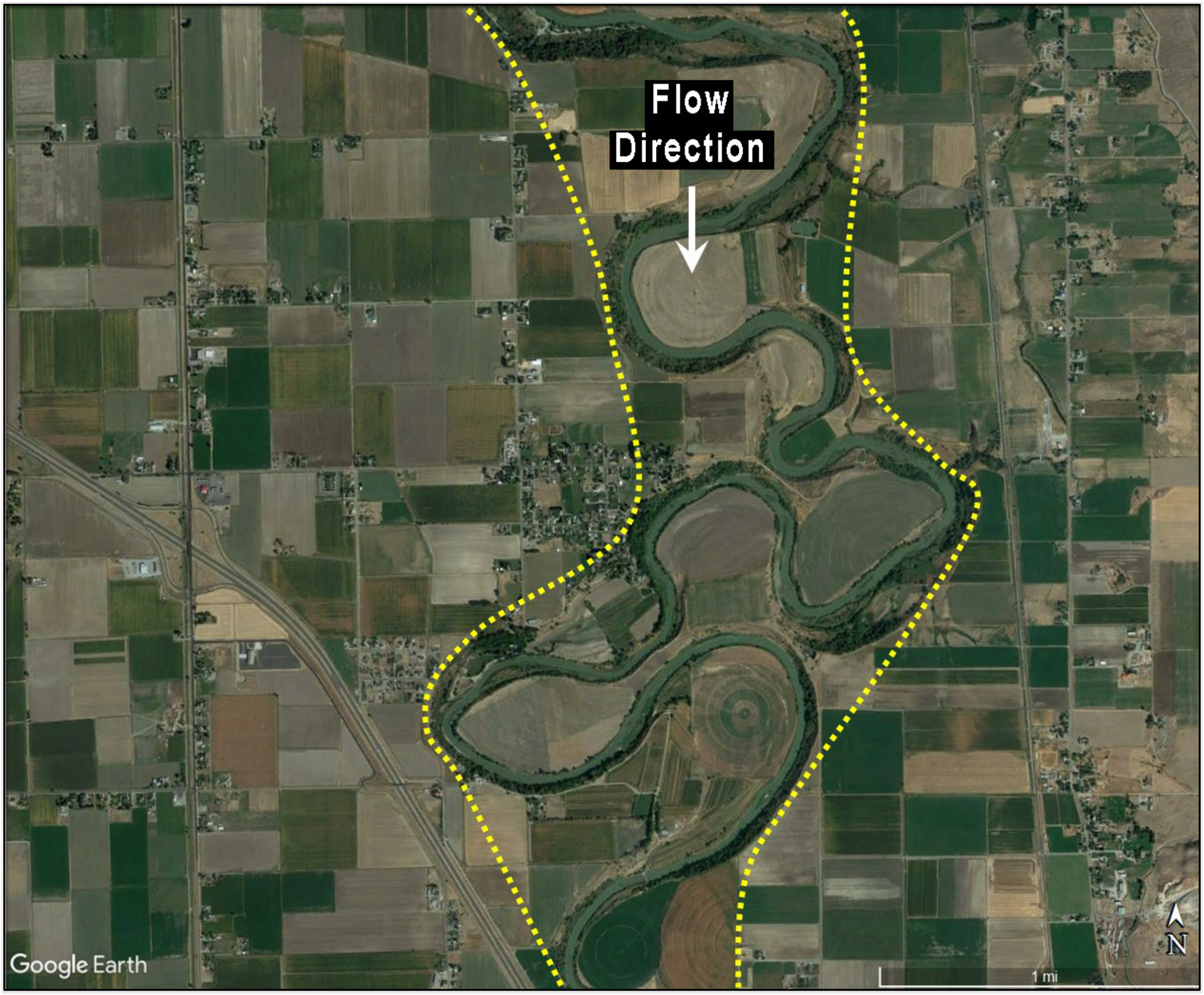


Figure 6.17. Dotted lines illustrate a potential meander belt width based on 2018 aerial imagery for a reach of the Bear River, UT.

6.3.2 Regional Methods

Several States have developed procedures for evaluating Channel Migration Zones (CMZs) appropriate for their region. When planning transportation systems, delineating the CMZ may be beneficial to avoid putting new infrastructure potentially at risk of damage or destruction, whether the location of the channel shifts gradually or changes course abruptly during a flood. See Sections 2.2.4 and 4.4 for additional discussion of CMZs. This section describes methods from Vermont, Washington, and Colorado, as examples. Many other approaches are available in other regions.

Vermont developed the River Corridor Planning Guide (Kline 2010) that illustrates a procedure to delineate a width the active river may occupy. The process includes evaluation of channel planform, geology, and structures.

Figure 6.18. Aerial Image existing and former channel locations of the Lamoille River, Vermont. Source: Vermont Agency of Natural Resources and used by permission.

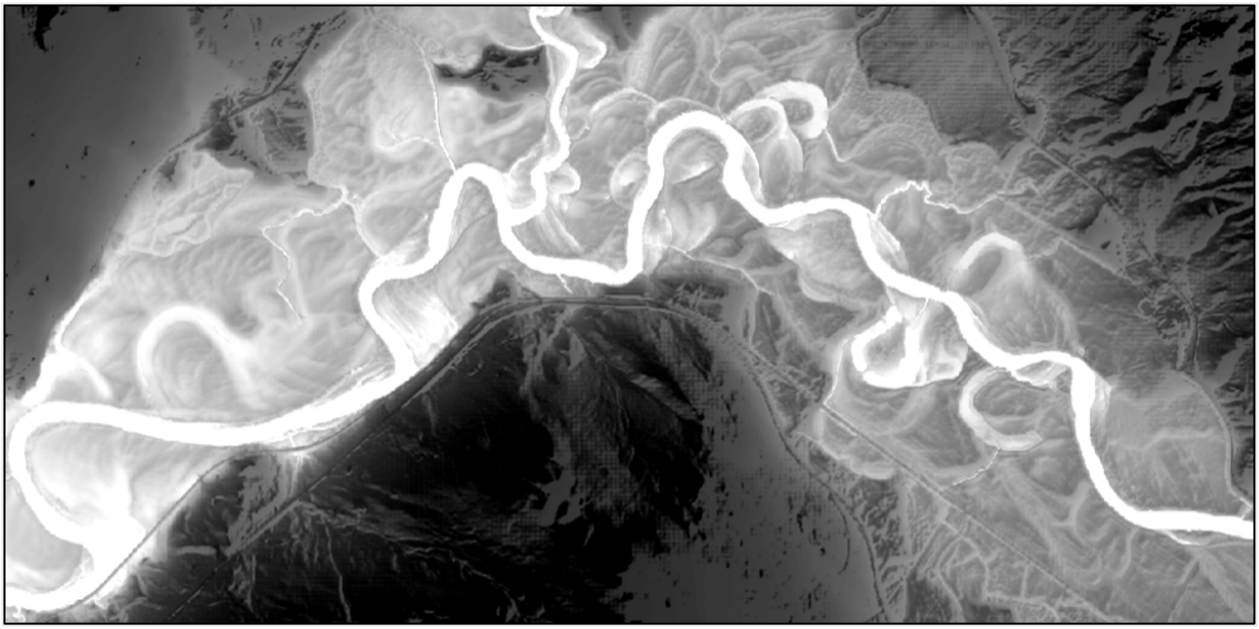


Figure 6.19. Enhanced elevation view of LiDAR data-derived DEM showing old channel and meander scars of the Lamoille River, Vermont. Source: Vermont Agency of Natural Resources and used by permission.

Washington State developed a procedure that uses landforms and characteristics of the valley bottom to evaluate past channel migration activity to delineate the Channel Migration Zone (Olsen et al. 2014). The CMZ includes characterization of zone types including a Historical Migration Zone (HMZ), Avulsion Hazard Zone (AHZ), Erosion Hazard Zone (EHZ), and the Disconnected

Migration Area (DMA) as illustrated by an example in Figure 2.19. Rapp and Abbe (2003) provide a full description of each zone.

Colorado's Fluvial Hazard Zone (FHZ) methodology extends the methods developed by Vermont and Washington. Jagt et al. (2020) describes fluvial hazard mapping based on two primary delineations: 1) the active stream corridor where a stream channel within a river corridor may widen or migrate and 2) the fluvial hazard buffer where movement in the active stream corridor might result in erosion or mass wasting of hillslopes adjacent to the floodplain. The delineation of the active stream corridor considers the geomorphic setting of the channel and establishes urban, fluvial signature, meander belt, and headwaters protocols based on the channel characteristics. The delineation of the FHZ relies on analysis of LiDAR data to develop a Relative Elevation Model (REM) to visualize and identify relic channels, floodplain surfaces, and alluvial terraces.

State Spotlight: Colorado's Fluvial Hazard Zones

Following Colorado's 2013 floods, the Colorado Emergency Watershed Protection (EWP) Program, funded and administered by the National Resources Conservation Service and managed by the Colorado Water Conservation Board (CWCB), conducted substantial watershed master planning in flood-affected watersheds (Jagt et al. 2020). One focus was developing a technical protocol to identify and map fluvial hazard zones (FHZs) to help with stream corridor management, flood preparation and impact mitigation, and improved land use decisions (Jagt et al. 2020). While the project included some collaborations with local transportation agencies, in response to the same flood events, the Colorado Department of Transportation (CDOT) pursued a more traditional approach to defining flood risks in their I-70 Corridor Risk & Resilience Pilot. There, CDOT used FEMA FIRMs as the basis for its determinations of future flood risks for bridge and road overtopping and debris (Flannery 2017).

6.3.3 Map and Aerial Photo Comparisons

Geomorphologists commonly compare series of historical aerial imagery, maps, and surveys to determine past channel migration rates and the direction of channel bend movement. This approach is a practical strategy in a variety of stream corridor environments.

For example, comparing aerial imagery from two or more historical periods for the Lamoille River, Vermont (discussed in Section 6.3.1) reveals channel movement. Using aerial imagery from 1995 (Figure 6.20) and 2018 (Figure 6.21), a comparison demonstrates that in places the channel has migrated up to 160 feet, approximately one channel width, over the 23-year period, a rate of approximately 7 feet per year.

Any specific year or time-period may have more or less channel movement. Given the relative widths of the channel and floodplain it appears that the channel could occupy any part of the floodplain in a span of around 200 years or less, and issues with bridge crossings and roadways can occur. For example, the channel west of the farm buildings has moved much closer to the road.

HEC-20 (Section 6.3) provides a detailed description of the approach for overlaying aerial images for channel migration analysis. The accuracy depends on the number and quality of sequential aerial photos and maps. The method can be used on a single bend but has greater value when several bends are included.

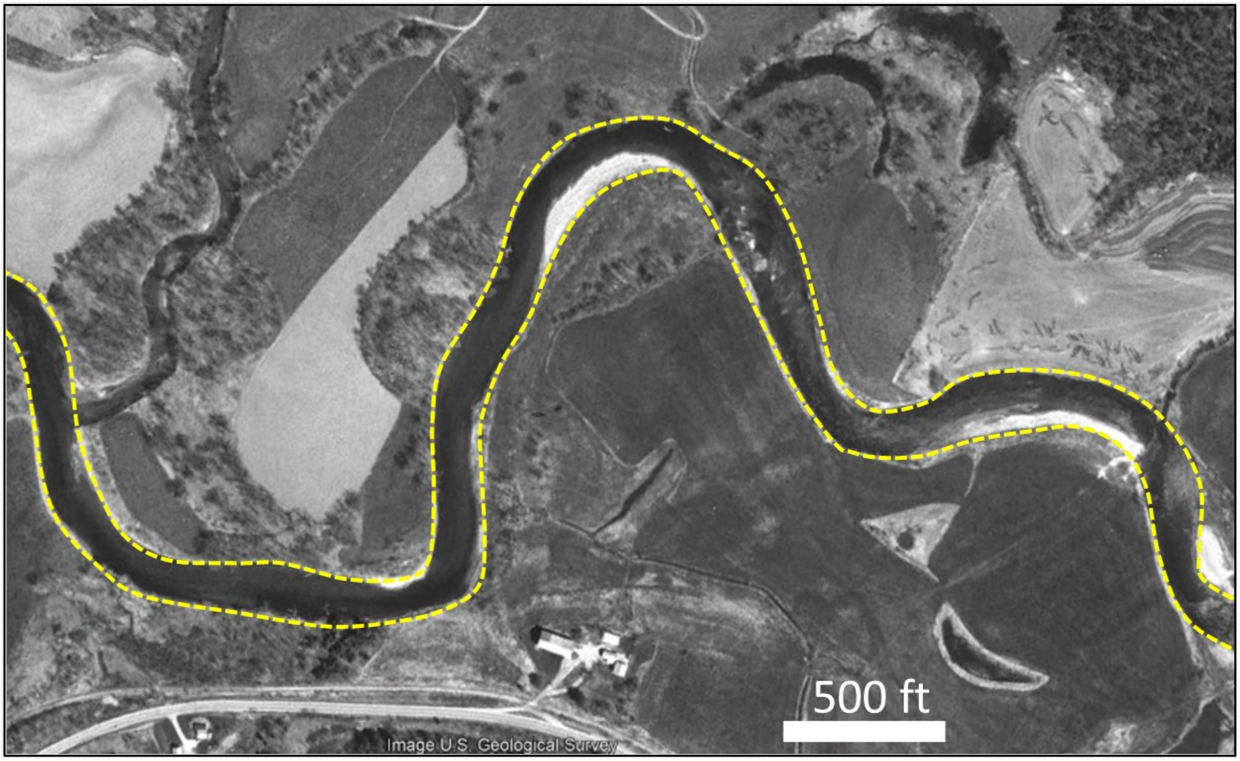


Figure 6.20. 1995 aerial photograph of the Lamoille River, Vermont with dashed line tracing channel banks.

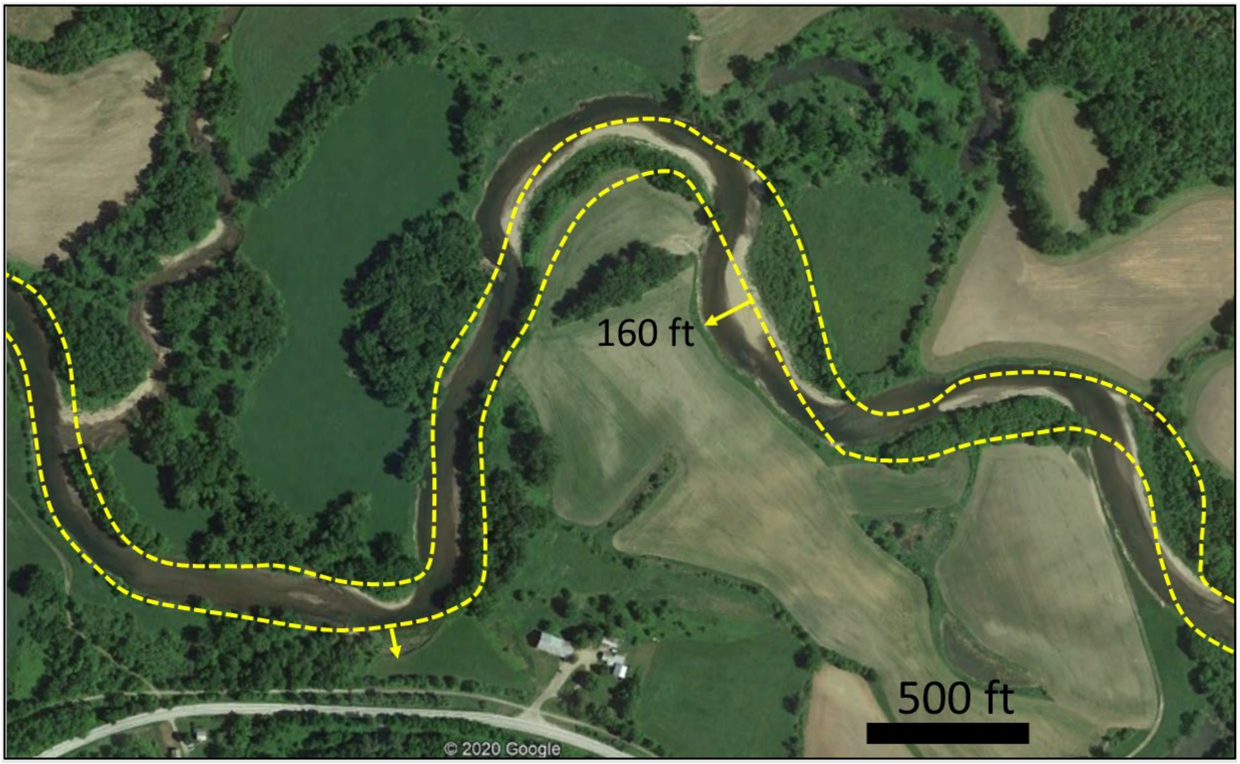


Figure 6.21. 2018 aerial image of the Lamoille River, Vermont with dashed line tracing 1995 channel banks.

Geographical information systems (GIS) and other software provide a powerful tool for channel migration analysis. Several aerial images are georeferenced to a common projection so that the various datasets can be compared. The bank lines are identified and digitized, and circles or arcs of best fit are drawn on the outer bank of each bend to establish the average bankline position, the radius of curvature of the bend, and the bend centroid position.

Figure 6.22 shows an example of the best fit arcs to a series of meander bends based on 1990 aerial photography of the Maple River in Iowa. A detailed description of the method used to fit a circle to the outer bankline of a meander bend is provided in Appendix B of *Methodology for Predicting Channel Migration* (Lagasse et al. 2004). These arcs can then be used to determine migration rates and direction, and to estimate future bend migration characteristics. Figure 6.23 shows the channel bank lines based on 2015 aerial imagery. The arrows in Figure 6.23 show the direction and magnitude of the bank migration based on the change in bend position between 1995 and 2015. With these rates and directions of channel movement bend 5 is poised to erode into the roadway embankment. Although bend 3 poses a future threat, it appears that the migration of bend 2 could likely cut off bend 3 first.

The methods described in this section provide useful information for planning and design. However, none are a precise method for predicting exact channel location at a particular future time. Projecting future base flows and extreme events that would affect the channel is an uncertain process and soil, geology, and vegetation conditions are often highly variable. Other features, including channel revetments to protect property, transportation corridors, and other infrastructure can, at least temporarily, limit migration. Therefore, future channel positions and rates of migration can vary from what the results of these analyses suggest.

6.4 Channel Profile Assessment

Engineers evaluate river profiles to understand river form and function. The slope of the channel fundamentally determines the rate of energy dissipation. Overall changes in channel slope generally reflect changes in river form. Characteristically, channel slope varies with position in the watershed, with steeper channels found upstream in watershed headwaters. Flatter channels are typically at the lowest elevations near the mouth of the watershed. Many natural and human influences affect the channel profile. By identifying slope changes from the channel profile, engineers assess the current river form and how it would likely respond to hydrologic or hydraulic change, as reflected in Lane's balance (see Section 2.2).

Changes in tributary inflows, flow diversions, sediment supply, sediment transport capacity, and geologic or hydraulic controls influence channel profiles. Abrupt discontinuities in a profile usually reflect hydraulic constrictions that induce scour and locally lower the channel bed, often in the vicinity of hydraulic structures such as bridges or culverts. Profile slope changes over long reaches often reflect changes in watershed runoff or sediment yield, typically associated with land use and land cover changes.

Changes in the downstream grade control of a river or stream may also create a sediment imbalance. Changes could include removal of instream structures such as dams or lowering of receiving water elevations. Examples of the latter include incision of a receiving river or stream and lowering of a reservoir or lake pool elevation.

Most culverts act as hydraulic controls since their hydraulic capacity is generally small relative to flood flows. Water and sediment tend to pond upstream of many culverts. This interrupts the supply of sediment to areas downstream and may result in downstream channel erosion. Over time, this may cause significant long-term adjustments to the channel form both upstream (aggradation) and downstream (degradation) of the culvert. Culverts designed using stream simulation techniques, discussed in Section 4.5, can mitigate this issue.

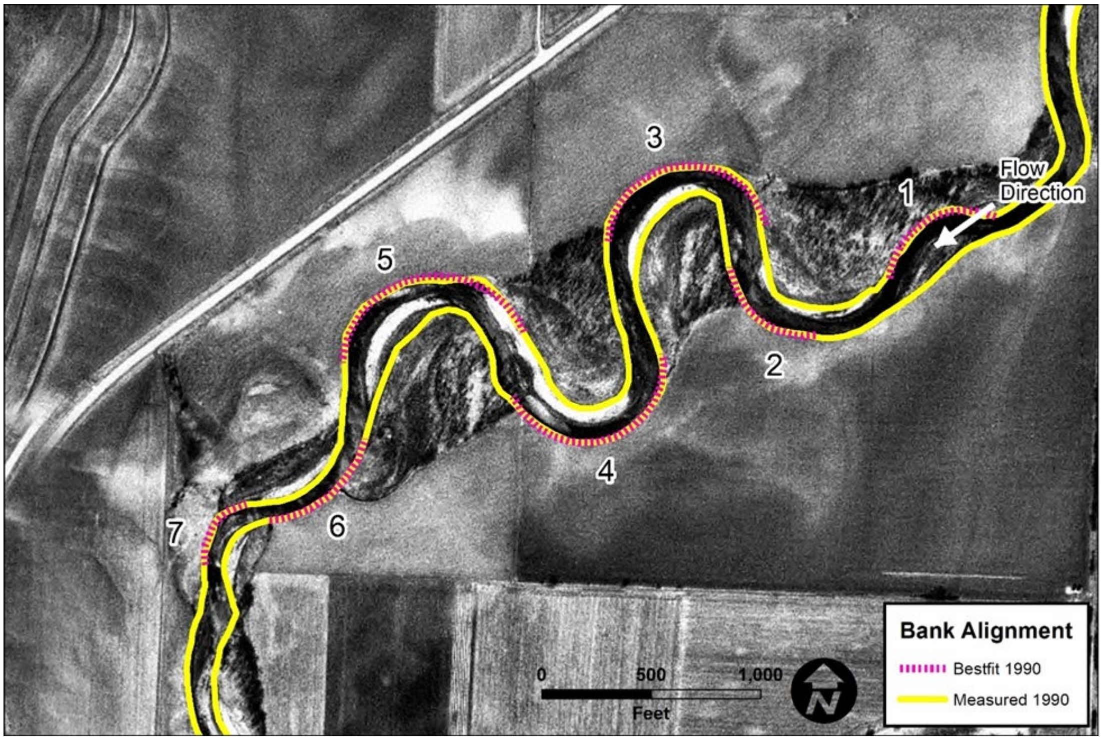


Figure 6.22. Digitized channel alignment and best-fit curve based on 1990 aerial photograph of the Maple River, Iowa. Source: USDA.

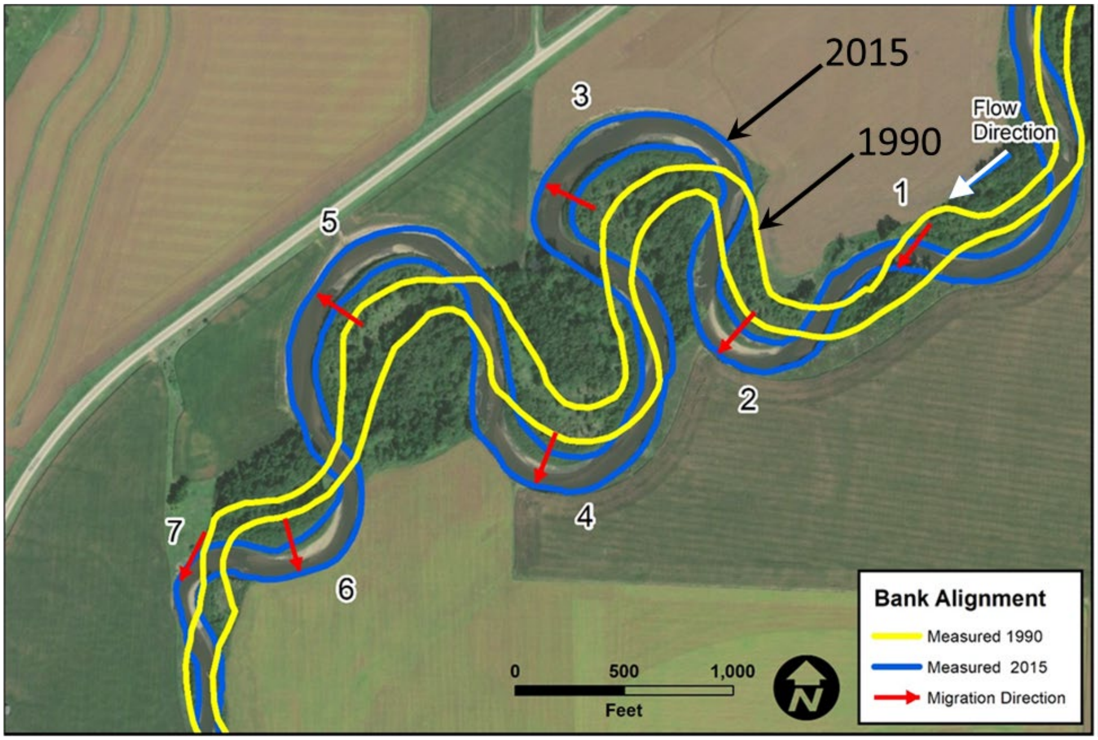


Figure 6.23. Digitized channel alignment based on 2015 aerial photograph of the Maple River, Iowa. Source: USDA.

Figure 6.24 shows an example of an abrupt discontinuity in a stream profile at a culvert. The presence of a concrete box culvert temporarily halted a knickpoint from progressing further upstream (i.e., the culvert unintentionally served as grade control). Unless the material beneath the box culvert is non-erodible, the knickpoint migrates upstream until the slope of the downstream channel has adjusted itself sufficiently so that the sediment transport capacity in the eroding reach is in equilibrium with the supply of sediment to it.

Figure 6.24. Knickpoint at downstream end of a box culvert along Alamogordo Creek, NM. Image used by permission of WEST Consultants, Inc.

Figure 6.25 shows the potential downstream channel degradation and culvert outlet scour in the context of a channel reach with a culvert. A difference of 3.5 feet exists between the culvert outlet invert and the bottom of scour hole downstream of the culvert. The photo in Figure 6.26 depicts the pronounced elevation drop from the downstream sill of the culvert to the low flow water surface along the downstream. The elevation drop is a common aquatic organism passage barrier.

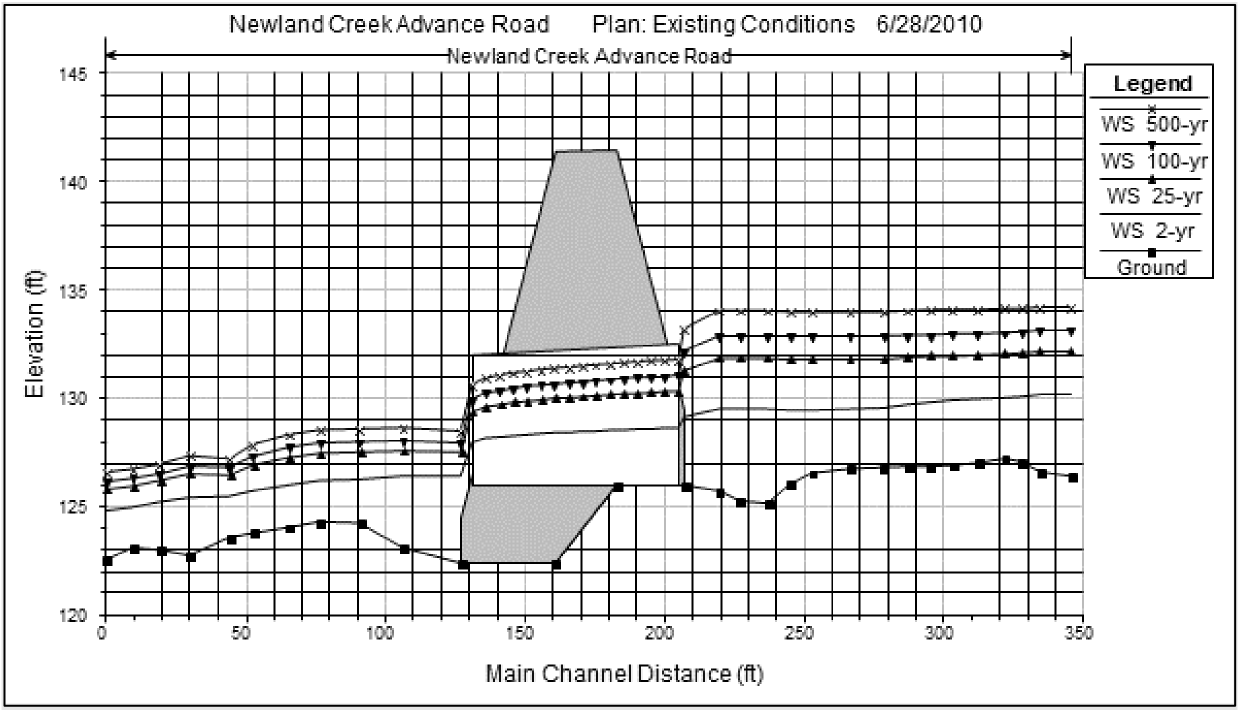


Figure 6.25. Channel profile at a Newland Creek (Oregon) culvert. Image used by permission of WEST Consultants, Inc.

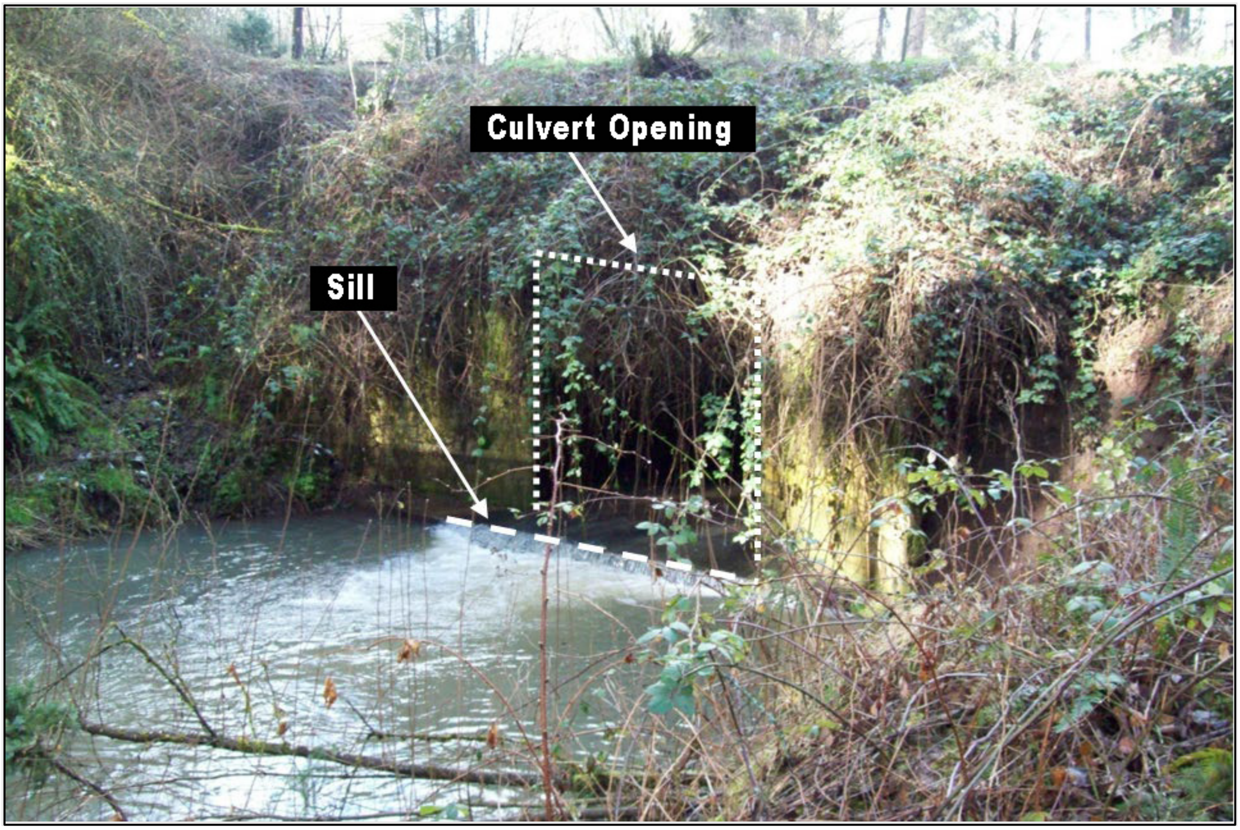


Figure 6.26. Looking upstream at the outlet of a culvert carrying Newland Creek (Oregon). Image used by permission of WEST Consultants, Inc.

Removing a culvert that has been in place for a significant period involves consideration of potential impacts to river form and function. For example, culvert removal could result in instabilities caused by differences in channel elevations, channel slope, and bed material size that have developed between the upstream and downstream channels. Erosion may occur in the channel reach upstream of the culvert where deposited sediments have been stored; deposition of those eroded sediments along the downstream channel reach may also result. The erosion of the channel upstream of the former culvert location may manifest as development of a knickpoint and progressive incision of the upstream channel bed, bank erosion of oversteepened channel banks, and channel widening. Adjustments along the upstream and downstream reaches would be expected to continue until an equilibrium develops between the upstream sediment supply and the downstream channel's ability to transport it.

The hydraulic constriction caused by a bridge, its abutments, and the approach embankments accelerates the flow causing characteristic "contraction scour" as described in HEC-18 (FHWA 2012b). Figure 6.27 illustrates relatively slow flow upstream of the bridge and faster flow through the opening because of the constriction caused by the bridge that accelerates the flow through the relatively narrower hydraulic opening of the bridge. Higher flow velocities increase the sediment transport capacity of the flow. This effect induces scour of the riverbed in the vicinity of the structure.

Figure 6.28 shows an example of the channel bed adjustment and scour induced by a bridge. The types of scour impacts illustrated in this figure are commonly associated with under-sized bridges. Methods for mitigation of such impacts are described in Section 4.5.

Figure 6.27. View downstream at the Imnaha River Bridge at Lewis Road, Oregon. Image used by permission of WEST Consultants, Inc.

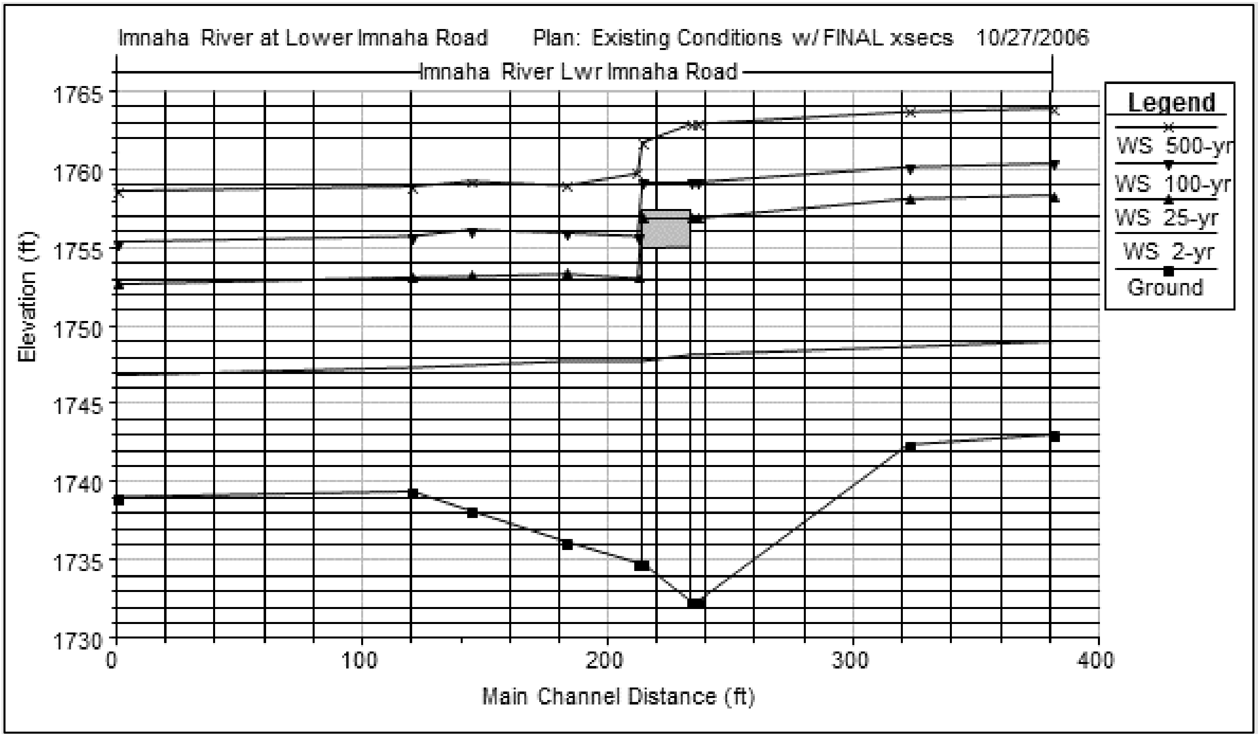


Figure 6.28. Channel profile illustrating scour impacts in the vicinity of a bridge along the Imnaha River, Oregon. Image used by permission of WEST Consultants, Inc.

Figure 6.29 shows an example of the effect of reduced upstream sediment supply caused by the upstream Garrison dam. This profile indicates a long-term trend of channel degradation associated with the reduction in sediment supply from the contributing watershed. The figure shows that the dam has the greatest effect closest to it (at the upstream end of the reach). The magnitude of channel degradation decreases with downstream distance from the dam, corresponding to the increasing uncontrolled tributary drainage area and associated sediment supply from the watershed.

Whether an analysis relates to a culvert, bridge, or dam, plots of the channel profile, hydraulic variables, and sediment sizes are useful for understanding changes in the hydraulic and sediment transport conditions of a river. Plots of hydraulic variables might include water surface elevations, mean channel velocity, mean channel flow depth, and width/depth ratio derived from hydraulic modeling. These plots can summarize information over a range of relevant flows, such as the channel-forming discharge, design flows, historic flood events, or future conditions. Plots of bed material sediment size characteristics along the channel profile are also informative. Sediment sizes typically evaluated include 100, 84, 50, or 16 percent finer by weight.

In addition to constructed features in river channels, profile plots can reveal natural hydraulic controls caused by rock outcrops or other erosion resistant features. In general, analysts can identify, similarities and differences in the forms along the river profile that can be useful for evaluating alternative scenarios for designing new or modifying existing transportation infrastructure.

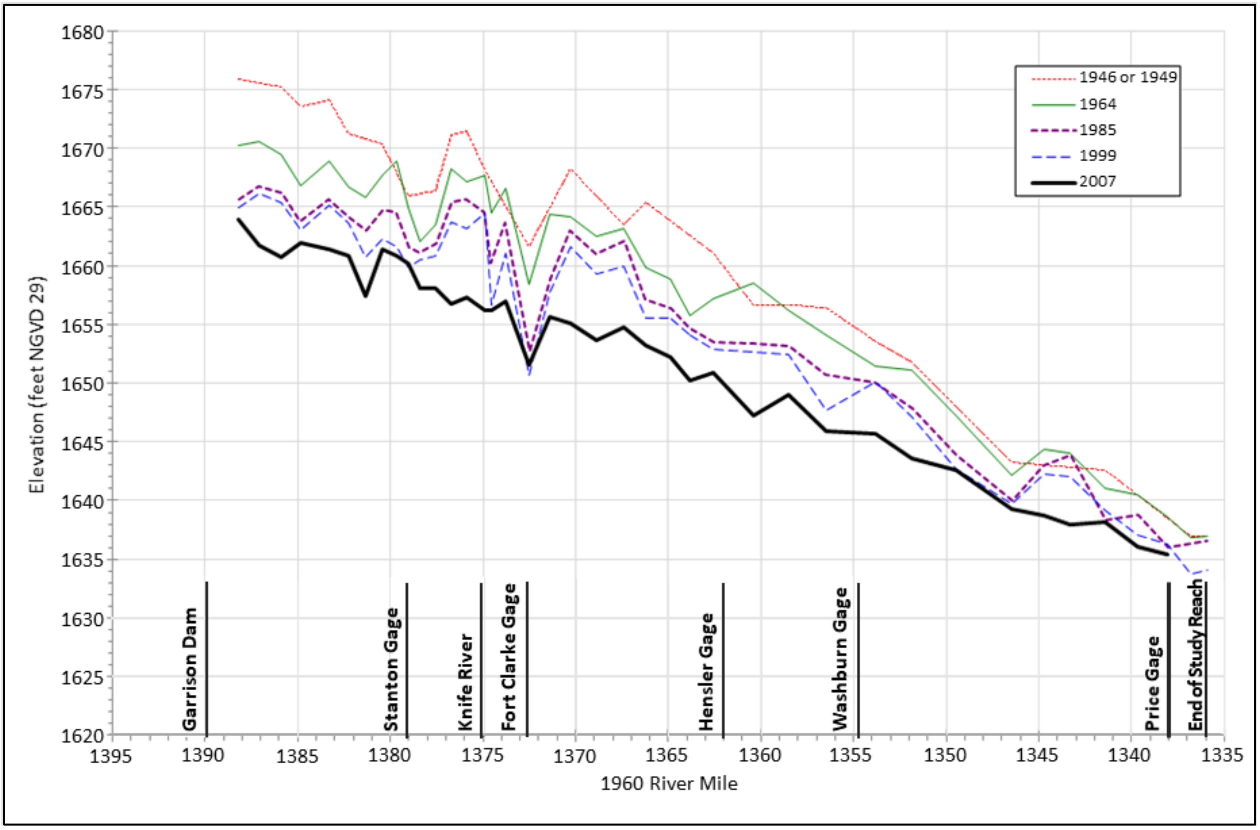


Figure 6.29. Total channel average bed profile of the Missouri River showing the effect of reduced upstream sediment supply caused by the upstream Garrison dam.

6.5 Bridge Inspection Records

Bridge inspections are important for monitoring conditions of existing bridges. In addition, the channel cross-section data collected during bridge inspections over time represents a long-term record useful for evaluating channel stability including identifying and anticipating potential problems at existing bridges. The long-term record can also inform design decisions for replacement bridge projects, resulting in more resilient designs.

Collection of channel cross-sections is required during bridge inspections (AASHTO Manual of Bridge Evaluation (MBE) 2.4.1(2) (2008), incorporated by reference in 23 CFR 650.313, 650.317). Comparison of these cross-sections to bridge design sheets, scour information, and boring logs provides useful information when planning repairs or designing replacement structures.

Bridge inspection records, including channel cross-sectional information, may be useful for evaluating channel stability when comparing measurements over time and space. Figure 6.30 provides measurements showing channel degradation and widening. Approximately 5 feet of degradation and 30 feet of widening occurred between 1967 and 1985. From 1985 to 2002, there was no further degradation but an additional 20 feet of widening. Although the cross-section from 2002 appears artificially flat, the degradation has reached a resistant soil layer that lowers gradually, primarily because of weathering rather than erosive forces. The widening, however, may remain a concern.

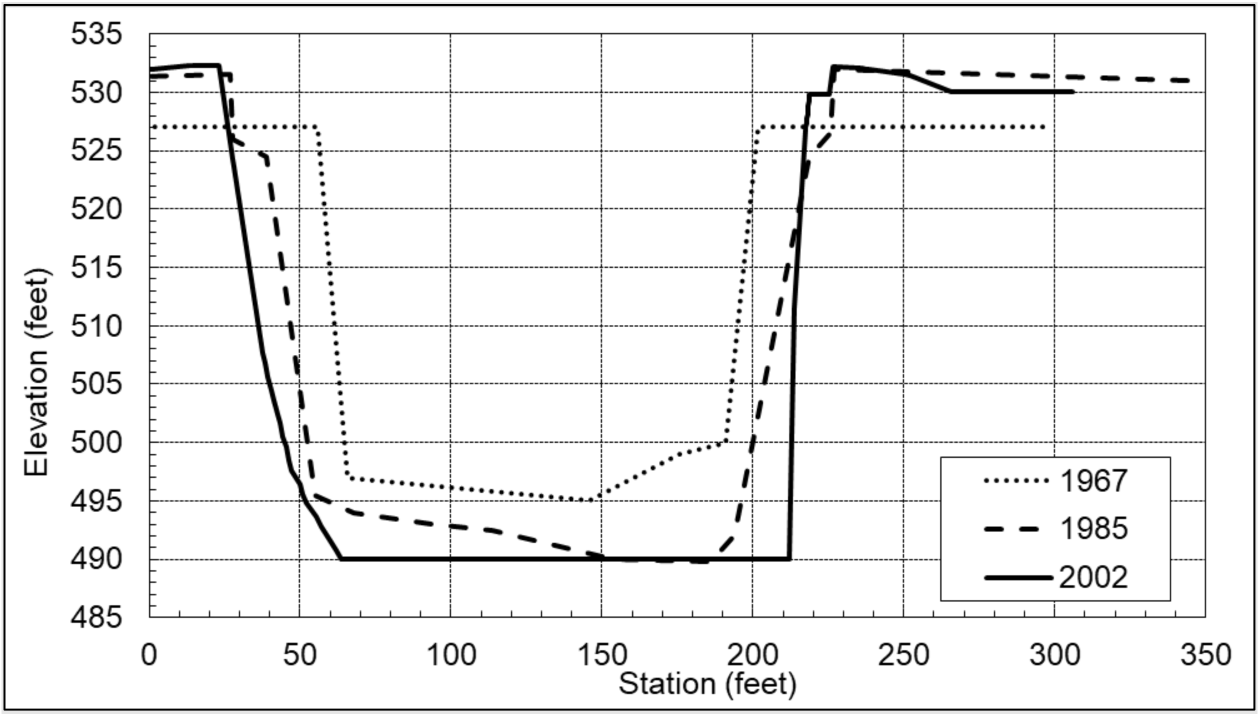


Figure 6.30. Streambed profile measurements demonstrating change over time at a bridge.

When inspection records are compared over time and among several bridges along the same stream, the results can reveal changing rates of aggradation or degradation along a river reach as shown in Figure 6.31. This type of analysis can be particularly valuable when evaluating whether changes are localized or driven by greater watershed processes. For example, bed scour at one bridge could be indicative of changes in hydrology caused by land use change in the contributing watershed or base-level lowering. It is noteworthy that what appears to be relatively minor change of only a few inches per year can produce substantial degradation over long periods. While the information presented in Figure 6.31 is insightful for considering long-term trends, using biennial bridge inspection records provides more detailed information.

Streambed elevations are important as a basis for evaluating the condition directly at piers and abutments. Regularly spaced observations along the bridge provide further value, as shown in Figure 6.32 from data provided by the Colorado Department of Transportation. The length of the bridge between abutments A1 and A4 is 308 feet, with two piers (P2 and P3) located one-third and two-thirds along the bridge. Measurements are all referenced to the low chord of the bridge. The channel is in the left third of the bridge opening, and measurements are more densely spaced around the channel. While the right overbank shows little change between 2015 and 2019, the channel invert shifts about 20 feet over 6 years and the channel invert lowers 2.4 feet over this period. If measurements were only collected at the piers and abutments, this channel change would not be evident. An alternative to collecting the measurements at regularly spaced intervals is collecting measurements at meaningful channel and floodplain features, such as the thalweg, toes of banks, tops of banks, and other breaks in slope. This information then allows for more reliable interpretation of channel stability.

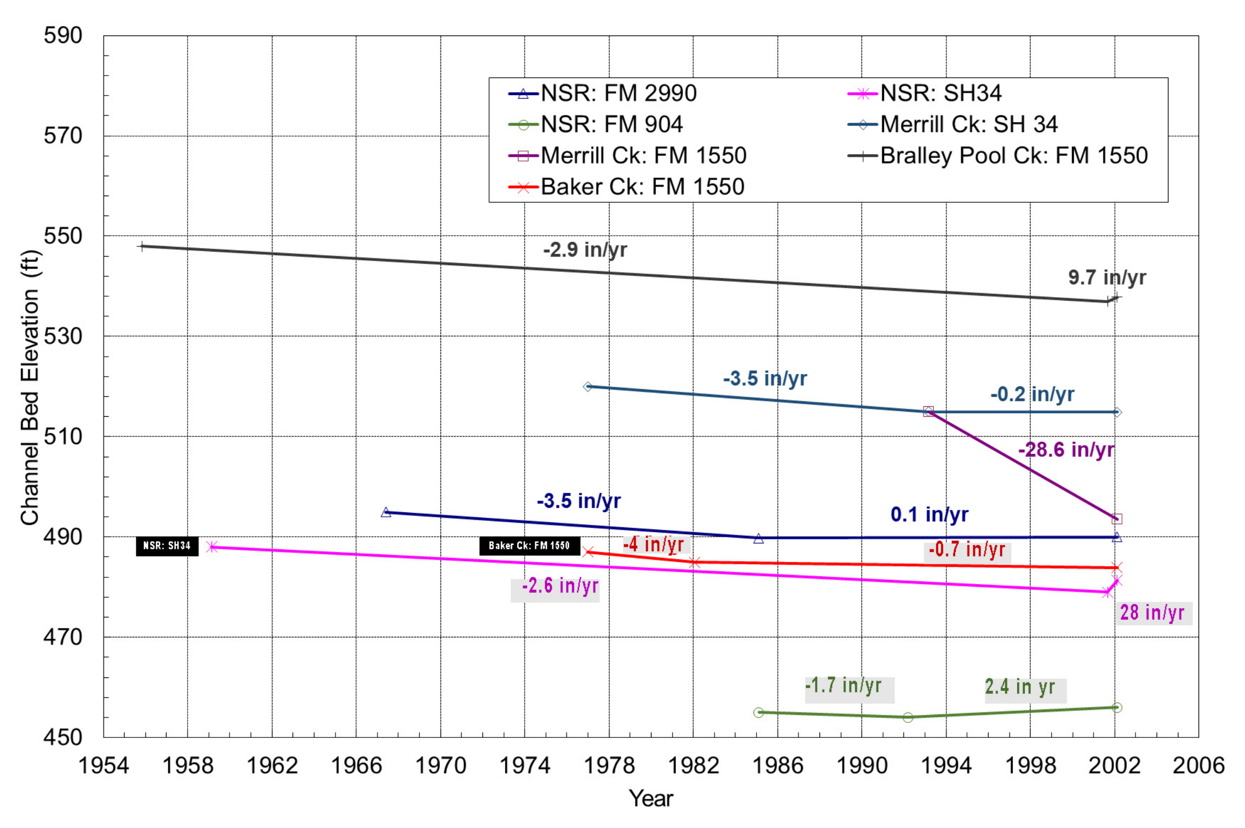


Figure 6.31. Streambed measurements demonstrating change over time and space in a watershed.

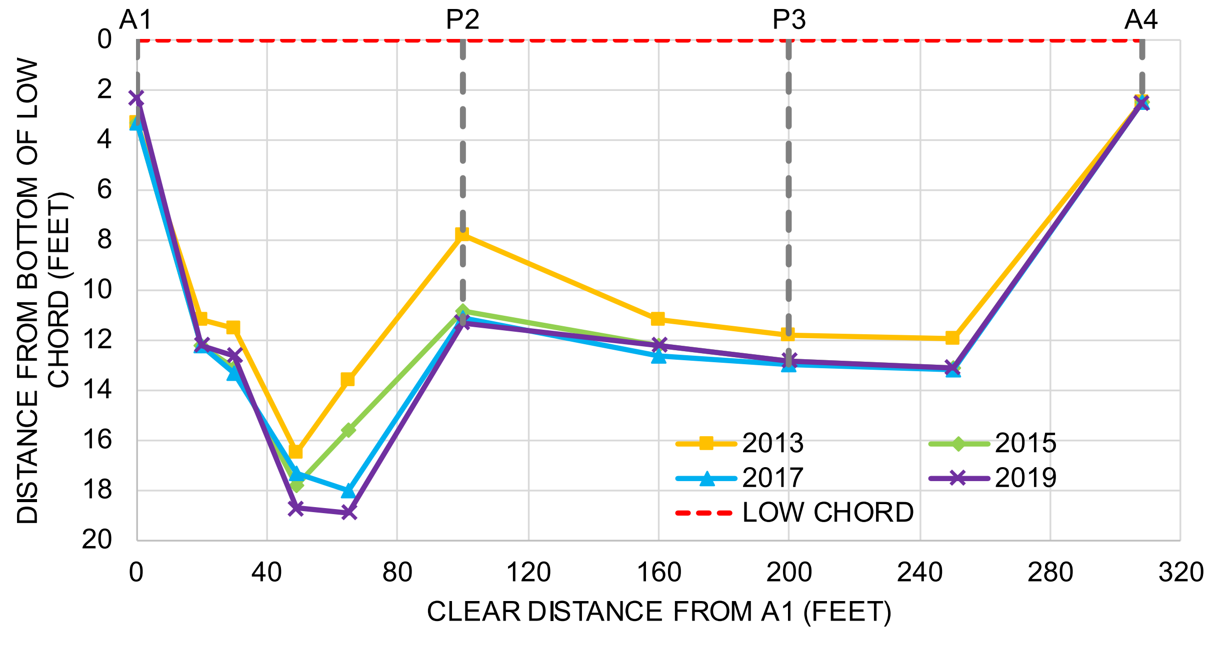
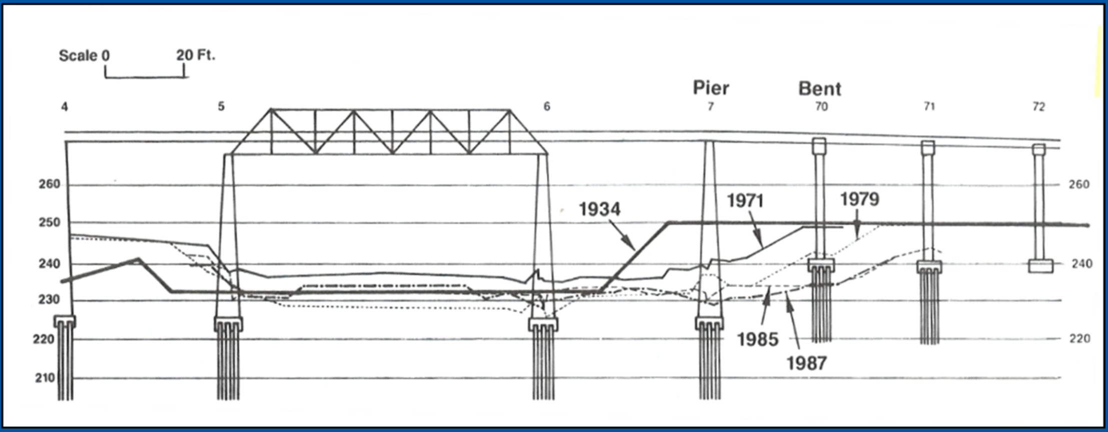


Figure 6.32. Biennial inspection measurements showing channel change. Data used by permission of the Colorado Department of Transportation.

Post-Failure Analysis: Hatchie River Bridge

On April 1, 1989, effects of stream stability and scour of the Hatchie River near Covington, Tennessee led to the collapse of the US-51 bridge, resulting in eight deaths (see HEC-18 Section 10.5 (FHWA 2012b) and (NTSB 1990)). The bridge was supported by seven pile-supported piers across the main channel and 135 pile-supported bents on the floodplain; the bents were not installed to the same depth as the main channel piers. Bridge inspection cross-sections compiled as part of the post-failure analysis document identified changes in the cross-section geometry, including migration of the main channel, between 1936 and 1987 as shown in the figure below. The National Transportation Safety Board determined that the probable cause was the migration of the main river channel. This collapse illustrates the importance of the use of channel cross-sections collected during bridge inspections. The cross-section geometry records show the value of inspecting the profile of the streambed and floodplain, not just at abutment and pier locations, and using the measurements to evaluate stream stability and scour.



6.6 Stream Interpretation

This section provides an overview of modern stream interpretation. In the 1990s, growing application of geomorphic principles and analyses in highway engineering revealed a need for interpretive approaches that were objective, repeatable, and cost-effective. Multiple interpretive approaches to geomorphic stream interpretation are in common use. Many stream interpretation methods derive from one of the following approaches:

- Three level approach (Simons, Li and Associates 1982).
- Montgomery-Buffington (Montgomery and Buffington 1993).
- Natural Channel Design (Rosgen 1996).
- Stream Reconnaissance (Thorne 1998).
- River Styles (Brierley and Fryirs 2000).

6.6.1 Interpretive Approaches

Although stream interpretation approaches have different theoretical and empirical foundations, they are all basically similar. For example, most methods are scalable to a range of geographic coverage, ranging from the site scale to a watershed or regional scale. Also, each assumes users possess basic interpretative, numerical, and analytical skills in applied geomorphology. The approaches are also structured to accommodate different levels of analysis that progress from simple qualitative evaluations that are rapid and relatively inexpensive to quantitative, computer modeling that is data and resource intensive.

The evaluation of geomorphic conditions of a watercourse is generally conducted in three levels of analysis with each succeeding level building on the data and conclusions developed in the prior level as shown in Figure 6.33 (Simons, Li & Associates 1982). The specific scope and number of analysis levels is dependent on the scope of the project.

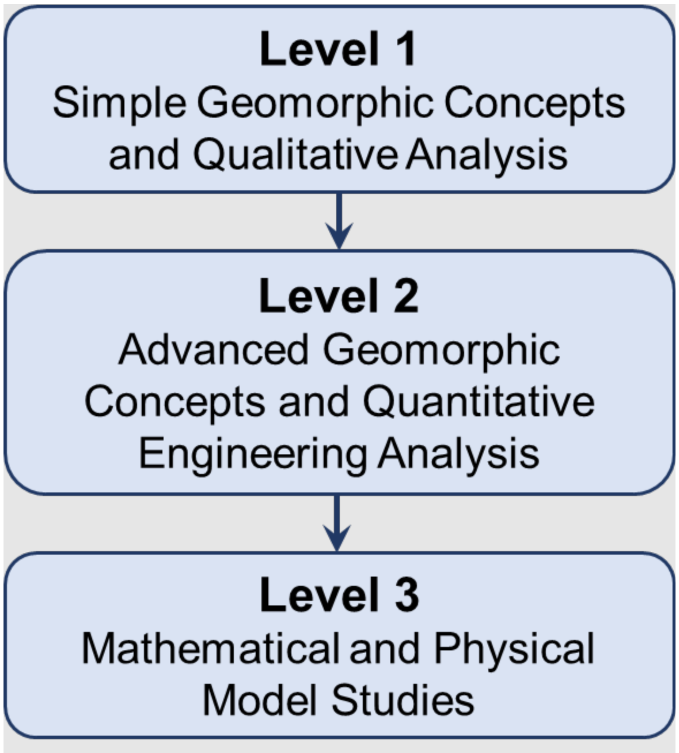


Figure 6.33. Three-level approach to stream interpretation conceived by Simons, Li and Associates (1982).

The first level identifies and extrapolates past changes in the river system emerging from natural and human-induced events to qualitatively predict the potential response of the river. This level of analysis relies on collection, evaluation, and interpretation of information from a wide variety of sources. Potential information sources for level 1 are listed in the text box below.

The second analysis level is semi-quantitative. It uses GIS tools and the principles of geomorphology, hydrology, hydraulics, and sediment transport to perform analyses and inform planning and design. Potential analyses for level 2 are listed in the text box below.

Design teams typically prepare conceptual design plans for project alternatives as part of a level 2 analysis. Using these methods, the design team establishes the relative impacts of past activities as well as the probable response of the system to alternative management plans.

The third level is fully quantitative. It uses physical and computer models of hydrology, hydraulics, and sediment transport to evaluate existing and proposed conditions and results in quantitative predictions of expected project impacts.

Potential Level 1 Information Sources

Previous study reports and models.

Aerial photographs.

Geology and soils maps.

Land cover data.

Historic surveys and topographic data.

Climate data and flood histories.

Stream gaging records and stage-discharge curves.

Sediment size distributions.

Sediment transport rating curves.

Floodplain mapping.

Historical observations.

Design or as-built plans.

Monitoring data.

Field reconnaissance.

Potential Level 2 Analyses

Quantifying flow magnitude, frequency, and duration.

Evaluating gage records.

Estimating bankfull discharge.

Evaluating connectivity.

Determining hydraulic conditions.

Identifying geologic controls, sediment sources, and sediment sinks.

Determining geomorphic reaches.

Estimating the sediment budget.

Identifying expected impacts to hydrology, hydraulics, sediment transport, and river form associated with proposed actions.

Successful application of any stream interpretation approach or level of analysis to a specific highway project matches the level of stream interpretation to:

- The level of risk associated with the potential short and long-term impacts of the project to people and their property (including road users, pedestrians, cyclists, landowners, and the public), protected wildlife species, and the environment.
- The need to reduce uncertainties related to geomorphology and the stream's sensitivity to disturbance.

A risk screening matrix, as shown in Figure 6.34, is a tool for determining the appropriate level of stream interpretation analysis to support project objectives. The matrix could help highway project managers select the appropriate level of stream interpretation based on the potential for the crossing/encroachment to create impacts to the stream and the potential sensitivity of the stream to impacts (Thorne et al. 2014).

Stream interpretation generally runs in parallel with related tasks in environmental permitting and engineering project management (Figure 6.35). Throughout the process, interdisciplinary collaboration is important because fluvial geomorphological forms, processes, and responses are linked to stream and watershed hydrology, hydraulics, sediments, biology, and engineering.

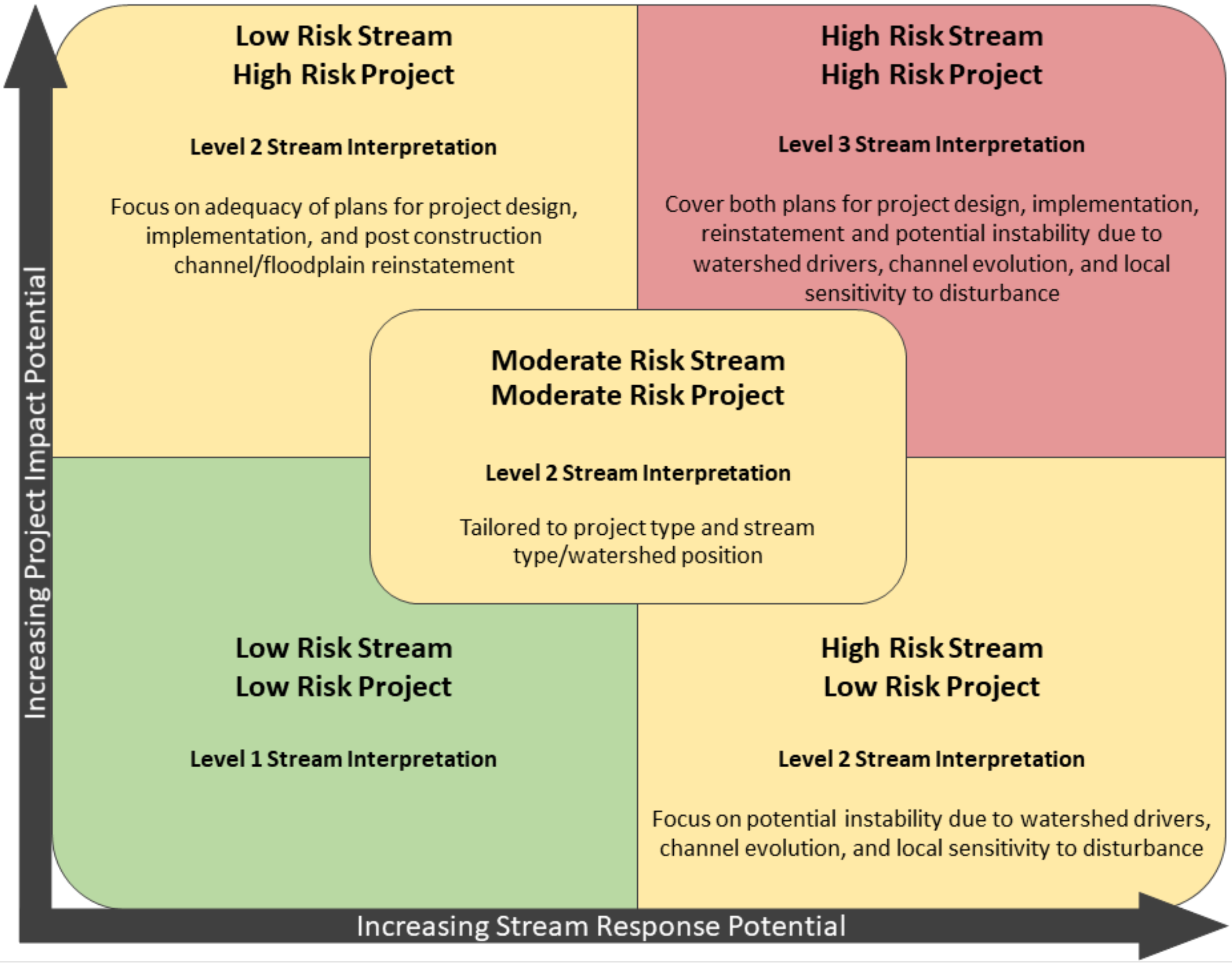


Figure 6.34. Risk matrix for selecting the appropriate level of stream interpretation. Adapted from Castro et al. (2015) and used by permission.

Experienced in composing a geomorphic evaluation, the project design team blends elements of different approaches, selecting only those needed to address project-specific, geomorphic issues and risks. In selecting the elements to put into an evaluation, the design team's goals are to:

- Answer specific geomorphic questions posed by project planning, design, permitting, construction, and monitoring phases.
- Supply insights and understanding needed to support the project generally, and to reduce uncertainties and associated risks to acceptable levels.
- Work within the resources, personnel, and time available to support fluvial geomorphological evaluation and stream interpretation.
- Satisfy project stakeholders and interest groups concerning the outcomes of the stream interpretation and the reliability of the underlying science.

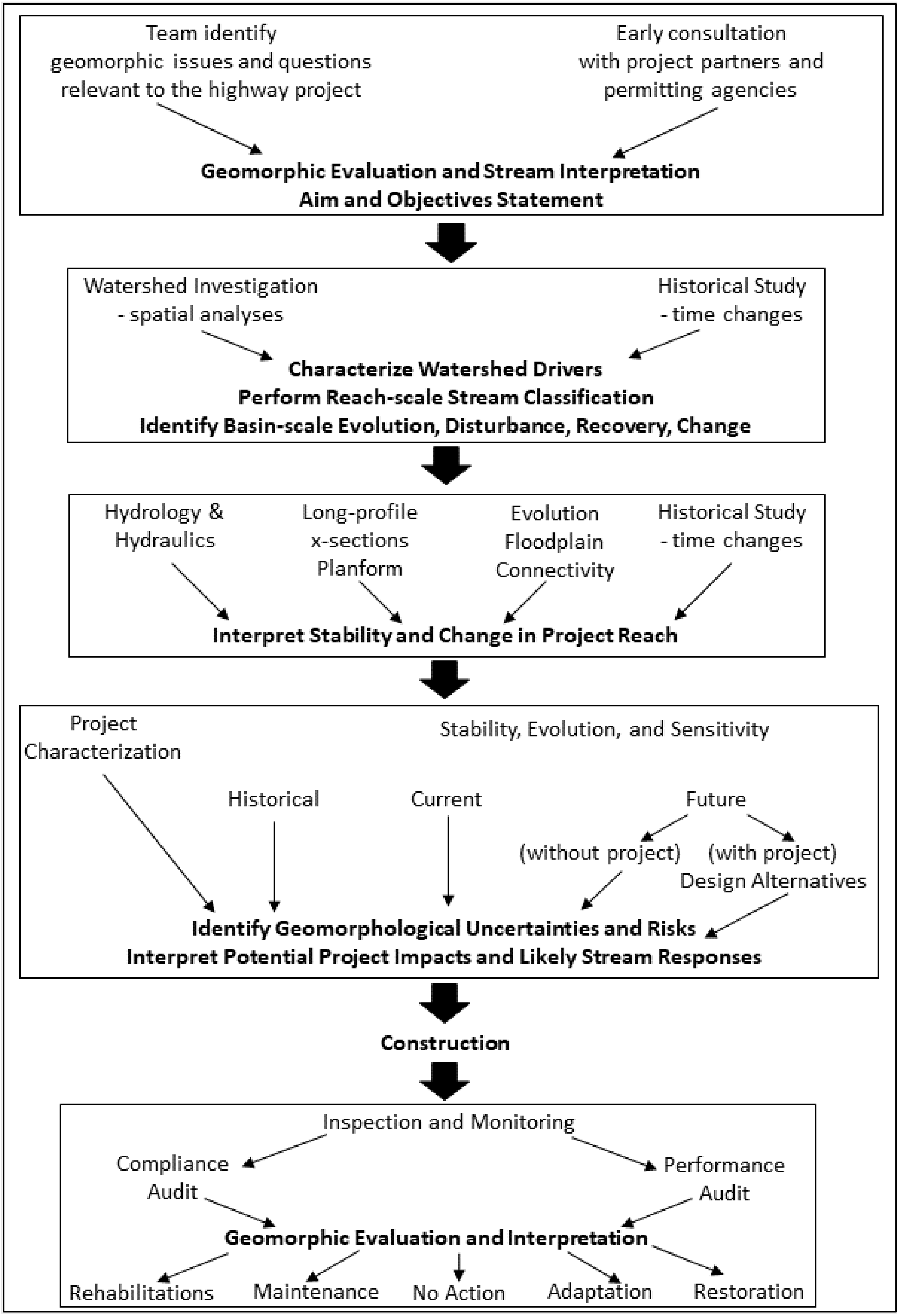


Figure 6.35. Stages in a project-centered geomorphic evaluation and stream interpretation. Adapted from Thorne (1998).

While the scope and composition of geomorphic evaluation and stream interpretation are project-specific, a generic framework for any highway-related project might include the following sequence of activities:

1. Determine the project attributes in terms of type (highway crossing or encroachment), the severity and geographical extent of impacted channel and floodplain functions, and the existence of corrective plans (monitoring to detect potential longer-term impacts, maintenance, and adaptive management).
2. Characterize watershed drivers of stream forms, processes, stability, and evolution in the project reach including dominant hydro-regime and sediment yield.
3. Determine the scale of direct disturbance to the channel and floodplain associated with the project.
4. Classify the project reach using Montgomery-Buffington (1993) (i.e., sediment source, transport, or store (response) reach).
5. Classify the channel in the project reach based on its riparian corridor/historical migration rate/channel migration zone (Rapp and Abbe 2003), cross-section geometry, bed and bank stability, long-stream profile, grade control (natural or artificial), planform pattern, and degrees of lateral connectivity or confinement.
6. Establish current evolution stage in the project reach (i.e., dynamically stable, aggrading or degrading, widening or narrowing, laterally migrating, changing planform, avulsing).
7. Find examples of historic and recent natural events, engineering interventions, and management actions that disturbed the project reach, and use records of morphological responses to those disturbances to assess its stability/resilience/sensitivity to disturbance.
8. Identify project design options that could avoid/reduce/mitigate adverse environmental impacts and, where appropriate, improve connectivity, resilience, and natural evolution in the fluvial system.

Through research and experience, geomorphologists have developed a broad suite of stream interpretation elements (i.e., geomorphic assessments and analyses) for stream interpretation (Thorne 1998, Thorne 2002, FHWA 2006b, Castro et al. 2015). These elements are available for project engineers and scientists to address the questions posed by the project team, regulators, and other stakeholders described above. These elements are summarized in three categories:

- Watershed drivers (Table 6.3).
- Reach-scale stability and change (Table 6.4).
- Potential project impacts and likely stream response (Table 6.5).

The full array of elements can appear daunting. However, the full array is only needed in large, high profile, well-funded highway projects where application of the elements is commensurate with the risks. The array represents a menu from which elements are selected to satisfy project needs. The objective is not to learn everything possible about the stream, but to understand enough about stream stability, function, and sensitivity to reduce geomorphological uncertainties and risks to acceptable levels, recognizing that they cannot be eliminated entirely.

Any of these elements can be addressed at level 1, 2, or 3, depending on the degrees of morphology-related uncertainty and risk that are acceptable, and the data, expertise, and resources (time and money) available to support stream interpretation. These elements can generate outputs that range from indicative to diagnostic and can be applied at spatial scales extending from large watersheds to project reaches or single stream crossings.

Table 6.3. Interpreting watershed drivers, present and past.

No.	Element	Resources Used	Studies Used to Support Selected Level of Stream Interpretation 1. Basic interpretation using conceptual, qualitative assessments. 2. Advanced interpretation using GIS spatial analysis tools. 3. Quantitative interpretation using computer modeling.
1	Basin hydrology	Rain and stream gage records Remote sensing images/data DEM, topo, soils, land-cover maps Existing hydro-studies + models	1. Hydrological assessment using existing records or StreamStats 2. GIS-based analysis using existing records, rainfall-runoff relations, surface runoff drainage patterns, stream ordering, network analysis 3. Hydrologic modeling of the watershed using a continuous simulation computer model
2	Fluvial system hydraulics	Stream gage records Regional curves or StreamStats Existing hydraulic studies/models	1. Qualitative assessment of fluvial system hydraulics 2. GIS-based analysis of flows paths and connectivity in the fluvial system 3. Hydraulic modeling to route runoff through network to project reach
3	Land-cover, land use impacts, & encroachments	Maps Agricultural surveys Thematic satellite imagery	1. Qualitative assessment of watershed vegetation, land-use, hydro-mod 2. GIS-analysis to evaluate impacts of development and encroachments 3. Hydraulic modeling to establish project reach development impacts
4	Geomorphology (inc. geology, soils, & bio-geomorphology)	Existing topo. Geol. & soil maps Fault and lineament maps Remotely-sensed images Fieldwork	1. Qualitative assessment of watershed landforms and processes 2. GIS-analysis to characterize sub-basins, valleys, floodplains, long-valley profiles, local base level controls, degrees of confinement 3. Reduced complexity geomorphic modeling of basin & fluvial system
5	Basin sediment yield	Sediment rating curves Inputs and outputs from Elements 1-4	1. Qualitative assessment of watershed sediment sources and dynamics 2. GIS-based analysis of sediment load (Qs) sources, connectivity & delivery ratio 3. USLE & process-based modeling of sediment delivery to project reach
6	Identification & classification of geomorphic reaches	Inputs and outputs from Elements 1-5 Field spot-checks to validate desk-based reach boundaries and classes	1. Subjective division of drainage system into geomorphic reaches and designate as by type and as source, transport or response reaches 2. GIS-analysis to delineate and classify geomorphic reaches 3. Reach-scale sediment budgeting to classify geomorphic reaches
7	Historical study: basin evolution, disturbance, recovery, change	Historical maps, photos, and accounts Historical satellite images Past river surveys and profiles Info. From agencies &, residents	1. Narrative history and chronology of watershed stability and change 2. GIS-based spatial analysis of historical watershed development 3. Use of models developed in Elements 1-5 to link historic disturbances to responses in the fluvial system over longer timespans

Table 6.4. Interpreting reach-scale stability and change, present and past.

No.	Element	Resources Used	Studies Used to Support Selected Level of Stream Interpretation 1. Basic interpretation using conceptual and qualitative assessments. 2. Advanced interpretation using GIS spatial analysis tools. 3. Quantitative interpretation using computer modeling.
8	Channel-forming flow	Outputs from Elements 2, 4, & 5 in Table 6.3	1. 1.5- to 2-year return interval flow 2. Bankfull discharge 3. Effective discharge
9	Cross-sectional geometry & stability	Cross-sections from past surveys, models, or cut from a DEM + field surveys, or drone survey plus SfM	1. Comparison to generalized hydraulic geometry equations 2. Comparison to stable reference reaches on same or similar stream 3. Comparison to stable cross-section based on an analytical method
10	Long-stream profile: slope, controls, & scour potential	Available maps, DEMs, plus outputs from Element 4 Channel surveying in the field	1. Inspection of long-stream profile and bed material description 2. Specific gage analysis 3. Hydraulic and sediment transport modeling to calculate mass balance
11	Planform, bank stability, riparian corridor/CMZ	Current and historical maps, DEMs, plus outputs from Element 4 Field surveys	1. Desk study of available maps, aerial images, plus empirical analyses 2. GIS-based spatial analysis of historical and current maps and images 3. Bank stability analysis and planform evolution modeling
12	Stream evolution stage	Current and historical maps, DEMs, plus outputs from Elements 4, 8-11, and 14, plus field surveys	1. Assessment based on hydraulic geometry and entrenchment ratio 2. Professional judgment based on a channel or stream evolution model 3. Two-dimensional morphological modeling (e.g., SRH, Delft-3D, AdH)
13	Connectivity	Outputs from Elements 2 to 12 plus inputs from parallel environmental and engineering studies (Figure 6.35)	1. Desk study of available information to support professional judgment 2. GIS-based spatial analysis of historical and current information 3. Ecosystem and biogeomorphic analyses and modeling
14	Historical study: disturbance, reach process-response, and change	Historical maps and accounts Historical satellite images Past river surveys and profiles Info. From local agencies, residents	1. Narrative history and chronology of stability and change in project reach 2. GIS-based spatial analysis of historical reach stability and change 3. Use of methods and models developed in Elements 9-12 to link historic disturbances to morphological responses in the project reach

Table 6.5. Interpreting potential project impacts and likely stream responses.

No.	Element	Resources used	Studies Used to Support Selected Level of Stream Interpretation 1. Basic interpretation using conceptual and qualitative assessments. 2. Advanced interpretation using GIS spatial analysis tools. 3. Quantitative interpretation using computer modeling.
15	Characterization of biogeomorphic project risks	Project drawings, CAD plans, road specifications, design alternatives, mitigation options	1. Descriptions of main project attributes, standard design, plus CAD 2. Custom design plus GIS-based analyses of road & river interactions 3. Computer models simulating the crossing/encroachment
16	Historic stability, evolution, and sensitivity	Outcomes of Elements 1-14	1. Qualitative descriptions of past, present, and future stream stability and change 2. Spatially explicit, semi-quantitative maps and accounts of past, present and future stream stability, evolution, and change 3. Hydraulic or morphological computer models of past, present, and future stream stability and change
17	Current stability, evolution, and sensitivity	Outcomes of Elements 1-14	1. Qualitative descriptions of past, present, and future stream stability and change 2. Spatially explicit, semi-quantitative maps and accounts of past, present and future stream stability, evolution, and change 3. Hydraulic or morphological computer models of past, present, and future stream stability and change
18	Future “without project” river and floodplain stability, evolution, and change	Outcomes of Elements 1-14	1. Qualitative descriptions of past, present, and future stream stability and change 2. Spatially explicit, semi-quantitative maps and accounts of past, present and future stream stability, evolution, and change 3. Hydraulic or morphological computer models of past, present, and future stream stability and change
19	Alternative designs in “with project” futures	Project design alternatives and plans for avoiding, minimizing, mitigating environmental impacts	1. Qualitative descriptions of the potential project impacts and stream responses 2. CAD or GIS-based, spatially explicit, semi-quantitative maps and accounts 3. Computer models of potential project impacts and stream responses
20	Geomorphological uncertainties and risks	Outcomes of Elements 15-19	1. Qualitative assessment of geomorphic uncertainties and risks 2. Semi-quantitative assessment of project risks 3. Quantitative uncertainty and risk calculations

Professional experience and judgment regarding data quality, reliability, and resolution, combined with local knowledge of the project watershed, reach, and site affect the levels, approaches, technologies, and resolutions selected and applied for the geomorphic stream interpretation. Ongoing advances in remote-sensing, especially the use of unmanned aerial vehicle- mounted instruments (for example, see Woodget et al. 2017), cloud-based data storage, and geographic information systems are helpful in collecting and managing primary data and accessing secondary data. Not only is the amount of quantitative, spatially referenced geomorphic data expanding, but so are the range, quality, and quantity of that data, and the capacity to analyze and use it to calibrate/validate physics-based models and drive data-based models.

The growing availability of data and analytical techniques increases the ability to evaluate and interpret geomorphology cost-effectively at level 2 or even level 3. However, in many highway contexts, project and geomorphic risks are low, and a level 1 treatment may be all that is warranted. Even when a project team plans level 2 or 3 treatments, a qualitative, conceptual model of the stream is a good initial step. The remainder of this section describes what is included in each of the three categories of evaluation and interpretation set out in Table 6.3, Table 6.4, and Table 6.5.

6.6.2 Watershed Drivers – Present and Past

Inputs of flow, sediment, and wood from the watershed drive stream processes. These, in turn, interact with materials forming the channel bed, banks, and floodplain to support stream functions in the project reach. Quantities and time-distributions of water, sediment and wood depend on the attributes of the basin draining to the project reach, including topography, geology, hydrology, hydraulics, soils, vegetation, land-use, and development (past and present). While the contributing basin controls the inputs to the project reach, it may also be affected by channel changes downstream. For example, degradation or aggradation downstream of the project reach may trigger incision or aggradation, respectively. Table 6.3 summarizes tools applicable to interpreting watershed drivers at levels 1, 2, or 3.

Evaluating and interpreting watershed drivers is primarily a desk-based study using documentary information including maps, remote-sensing data, and routinely collected records. Where such sources are lacking, information from river and watershed agency staff, local governments, and long-time residents/landowners within the region may be available. Successful retrieval of such archival and anecdotal information demands excellent inter-personal skills and consistent follow-through. Some fieldwork is essential for spot checks to “ground-truth” information derived mostly by remote-sensing. When interpreting a watershed, a collection of at least some primary data and information through direct observations and measurements in the field is beneficial even if interpretation relies mostly on secondary data compiled from pre-existing sources.

The geomorphologist compiles the outcomes of watershed interpretation in file notes or an integrated report detailing historical and current characteristics of the contributing basin, flow regime, sediment regime, and wood loading relevant to the highway project. In many cases, a complete interpretive report includes a classification of the study stream(s) into geomorphic reaches according to the Montgomery-Buffington (1993) classification (bedrock, colluvial, alluvial, incised, alluvial fan) or an alternative method, and as sediment source, transport, or response reaches. Figure 6.36 illustrates an example of the source/transport/response classification based on a desk-top evaluation that was validated using limited fieldwork.

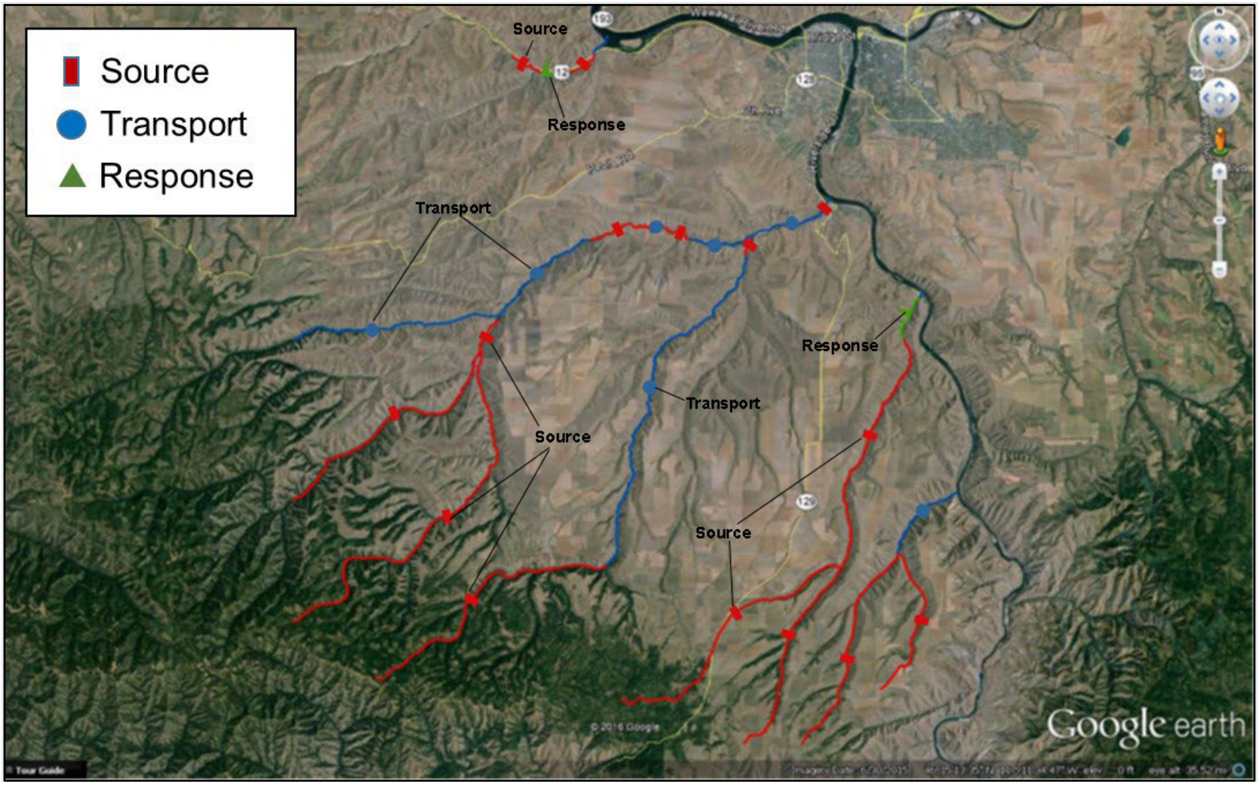


Figure 6.36. Reach classification for Snake River tributaries in Asotin County, Washington.

6.6.3 Reach-Scale Stability and Change – Present and Past

Interpretation of watershed drivers provides the geomorphic inputs and boundary conditions for detailed evaluation of flow functions, morphological adjustments, and sensitivity to disturbance in the project reach. Interpreting reach-scale fluvial geomorphology demands both desk-based and field investigations. Table 6.4 summarizes tools applicable to interpreting reach-scale stability and change. Unless a level 1 qualitative treatment is adequate, or sufficient data are already available for the project reach, fieldwork may include measurements or determinations of:

- Discharges, velocities, and long-stream water surface profiles.
- Cross-sections, planforms, and floodplain topography (or creation of a DEM).
- Bed and bank material properties and bank failure mechanisms.
- Sediment transport rates and wood loadings.
- Rates of bed scour/fill, bank erosion, and planform change.
- Grade controls.

These parameters are important to inform semi-quantitative (level 2) analyses, or calibrate hydraulic, morphological, and bank stability models used at level 3, as well as to match the scope and level of reach-scale observation, data collection, analysis, and interpretation to the type and construction footprint of the project. The skill of the design team leader lies in delivering the fieldwork to achieve this goal within the resources available. For a project undertaken in-house, the timescale, coupled with the existing workloads of staff with adequate training and experience in engineering geomorphology, may determine how an adequate outcome can best be achieved. If project planning and design is outsourced to a consultant, available funding is more likely to be the limiting factor. In practice, reach-scale geomorphic investigations and interpretations usually rely on level 1 stream reconnaissance supplemented by targeted measurements of key stream forms, processes, and functions performed at level 2 or 3.

Cross-sectional hydraulic geometry is fundamental to reach interpretation, especially in relation to the channel-forming flow. Stability may be inferred when channel dimensions conform to those expected from regional relationships expressing, for example, channel width as a function of watershed drainage area or a rational stable design method, and when they do not, disparities indicate whether the channel is out of adjustment vertically (incised/aggraded) or laterally (too narrow, over-wide).

The shape of the long-stream bed profile supports calculation of the slope, bed shear stress, and stream power, plus identification of natural or artificial features that control the long-stream profile. Identification of grade control features, such as natural bedrock outcrops or constructed bed sills, supports the assessment of the potential for bed lowering caused by scour or degradation.

The level of lateral channel instability in a reach can be assessed based on current, historical, and field sources of information. Useful inferences can be drawn from current air photos or satellite images showing the planform pattern (straight, meandering, braided, or anabranching), and whether there is a continuous riparian corridor. Historical switching between these patterns can be detected from old maps/images, and rates of lateral migration can be estimated by comparing maps/images with different dates. Features in the floodplain topography (e.g., meander scars, ox-bow lakes in a DEM) are also informative. The possibility of channel avulsion (when a stream leaves one course and adopts a new one) is indicated by abandoned channels identified in desk or field studies.

In reaches that are vertically unstable, geomorphologists infer the stage of stream evolution by considering its cross-sectional attributes, its lateral connectivity (or lack of connectivity) to the adjacent floodplain, and its long-stream relation to the reaches immediately upstream and downstream. Figure 6.37 illustrates a site with significant vertical instability resulting in a channel that is far deeper and wider than a stable, regime channel, as well as disconnection from its floodplain. The figure also shows the contrast between the channel downstream of the road crossings and the undisturbed channels upstream. This is because the highway crossing culverts are acting as unintended grade controls.

To create a more robust understanding of the reach, geomorphologists not only evaluate the present forms and functions, but also study historical forms and functions. Historical study establishes occurrences, rates, and sequences of past adjustment and change. Matching records of floods, droughts, major sediment transport events, and other disturbances to records of channel instability, evolution, and change informs the understanding of the links between watershed drivers and local morphological responses and indicates stream sensitivity to disturbances.

At this stage of stream interpretation, the team can evaluate the fluvial geomorphology of the project reach and its connectivity in the long-stream (reaches and watershed up and downstream), lateral (confining valley sides or floodplains), and vertical (hyporheic aquifer) directions. Evaluation may be predominantly qualitative (level 1 assessment); GIS-based, semi-quantitative and spatially referenced (level 2 analysis); or fully quantitative and spatially referenced (level 3 modeling). In practice, evaluation is likely to be based a mixture of the three levels, as appropriate to the project and stream.

Figure 6.37. Example of the consequences of vertical instability at Crowder Creek, Leake County, Mississippi. Image used by permission of D. Biedenharn (© 1985).

6.6.4 Potential Project Impacts and Likely Stream Responses

Based on evaluation and interpretation of watershed drivers (Section 6.6.2) and reach-scale stability and change (Section 6.6.3) a project team understands not only the current fluvial geomorphology of the project reach, but also the historical sequence and chronology of the events that brought this particular stream to its current condition. This section addresses how such understanding is used as a foundation for the team to consider potential project impacts and likely stream responses. Table 6.5 summarizes some of the tools for this future-oriented assessment.

No two streams have precisely the same evolutionary history, which means that each stream is on a distinct evolutionary path, described as the phenomenon of "path dependency." Path dependency shapes the trajectory and rate of future evolution in a stream. With this insight, the project team can forecast the future evolution of the stream and its likely response to implementation of project design alternatives.

Assessment of possible stream futures considers first what may be expected in a project reach in a baseline or "without project" future. In this scenario, the geomorphologist considers the existing condition of dynamic stability or gradual recovery/adjustment following the last disturbance, and whether the present condition is likely to continue, at least in the short- (3 to 5 years) to medium-term (5 to 10 years) future in accordance with a stream evolution model (e.g., Figure 2.17 and Figure 2.18). The near-term to medium-term future for alternative project configurations ("with project") is compared to the "without project" baseline to identify likely geomorphological impacts on the stream. In addition, how the stream's responses may impact the project, the fluvial system up- or downstream, and the wider environment is compared between the "with project" and "without project" conditions.

Over the longer term (10 to 30 years), it is likely that the stream can be disturbed by significant future events that either trigger dynamic adjustments or initiate a new cycle of evolution. For example, for 16 years following the 1980 eruption of Mount St. Helens in Washington, sediment yields in the North Fork of the Toutle River declined gradually toward the pre-disturbance value, as shown in Figure 6.38. However, a major flood in 1996 and a channel avulsion in 2006 both partly reset the recovery curve, interrupting and delaying the return of annual sediment yields in ways that could not have been forecast in 1980.

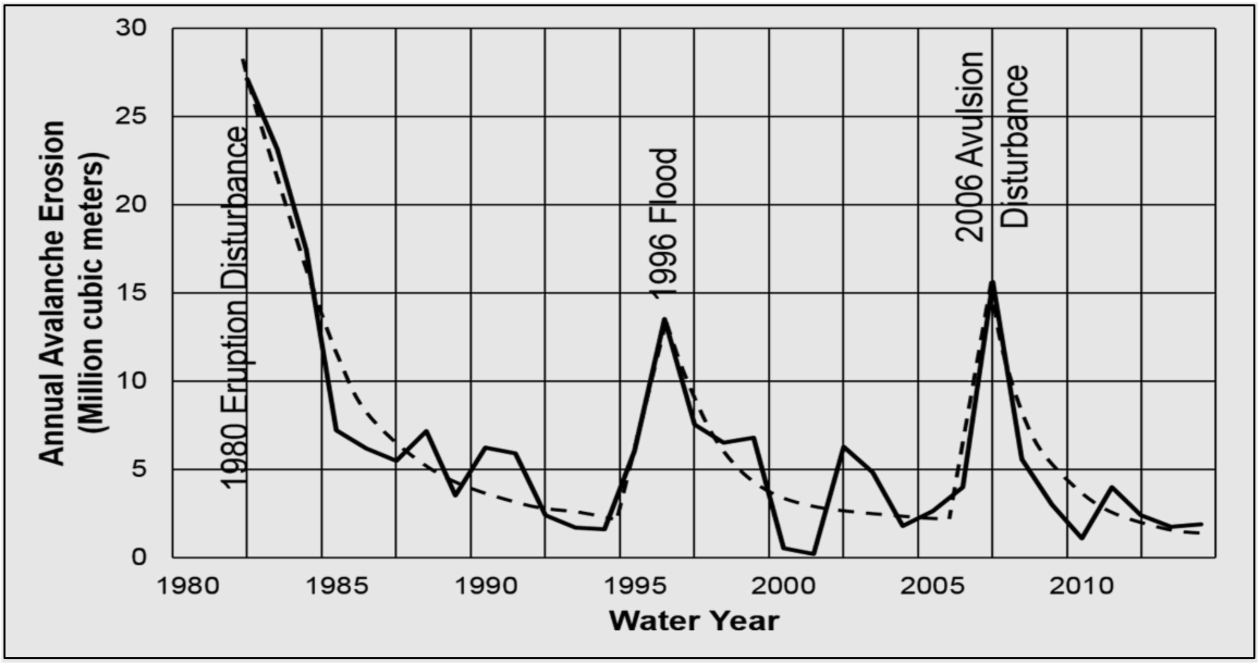


Figure 6.38. Measured annual sediment yields to the sediment retention structure, North Fork Toutle River, Washington. Solid line indicates annual average sediment yield from erosion of the debris avalanche at Mount St. Helens. Dashed line indicates recovery of elevated sediment yields toward the pre-eruption level. Adapted from Sclafani et al. (2017).

Watershed changes resulting from wildfires may also have differential effects on sediment and runoff yields to stream systems that evolve as the watershed recovers. These, and other, potential disturbances could pose a challenge to forecasting longer-term because the nature, timing, and magnitude of future events is highly uncertain and cannot be predicted deterministically.

If the design life of a project is such that long-term forecasting is desired, the project team can use scenario modeling to estimate the range of possible future conditions. In scenario modeling, technical specialists in hydrology, geomorphology, and development planning collaborate to envision several plausible, possible futures. Then, instead of projecting a single outcome in the project reach, multiple runs of conceptual or numerical models generate a range of plausible outcomes. The project team considers this range of outcomes in the planning and design process, so that future geomorphological risks to people, property, and the environment are acceptable throughout the service life of the project. This can be achieved in three ways:

- Locating and designing the crossing or encroachment to remain operational and safe even under a “worst case” scenario.
- Locating and designing the crossing or encroachment to “fail safe” under a “worst case” scenario.
- Include in the project design a program of long-term monitoring, maintenance, and adaptive management that ensures that risks remain acceptable no matter how the future unfolds (see Section 8.11).

6.6.5 Completing a Stream Interpretation

The first step in interpreting project impacts and likely stream responses is to characterize the crossing or encroachment (element 15 in Table 6.5). For low-risk projects, this can be based on description of the main project attributes and design features, but more commonly the basis is provided by CAD drawings or GIS layers, combined with details of the design specification, materials, construction methods, and maintenance schedule. When a range of options is being considered, the way each design alternative interacts with the stream is considered (element 19 in Table 6.5).

In parallel to characterizing the project, the team responsible for stream interpretation uses the outcomes of the geomorphic evaluations and interpretations listed in Table 6.3 and Table 6.4 (elements 1 to 14), as the basis for interpreting the historic and current stream stability (elements 16 and 17 in Table 6.5), evolution, and sensitivity to disturbance. In element 18, the baseline future for stream stability and evolution is forecast, based on synthesis of the outcomes of elements 16 and 17. This forecast may be qualitative and descriptive, spatially referenced and semi-quantitative, or fully quantitative and model-based, depending on need and resources.

Element 20 completes the stream interpretation process. It involves qualitative assessment or quantitative analysis of all project-related geomorphic uncertainties and risks. These include current and future uncertainties and risks posed to the highway by channel adjustments in dynamic-equilibrium; continued evolution triggered by past disturbances; and the stream’s sensitivity to disturbance, including disturbance associated with construction, operation, and maintenance of the crossing or encroachment. These assessments and analyses also include consideration of current and future uncertainties and risks posed to the stream by construction, operation, and maintenance of the crossing or encroachment.

Chapter 7 - Sediment Transport Modeling

The FHWA reference documents HEC-20 (FHWA 2012a) and HDS 7 (FHWA 2012c) include discussions of sediment transport concepts. This chapter expands on those discussions and provides information on sediment transport analyses for evaluating river and transportation interactions. The chapter also describes several computer model platforms and common sediment transport equations. The first section provides background information; the rest of the chapter is more technical in nature and provides information useful when predicting or modeling sediment transport. Other references on sediment transport include Vanoni (1975), Simons and Şentürk (1976), Julien (2010), and Garcia (2008).

The information in this chapter considers the three levels of analysis discussed in Chapter 6 and in more detail in HEC-20 (FHWA 2012a). The levels range from the application of simple geomorphic concepts and other qualitative analyses (Level 1), to using customary hydrologic, hydraulic, and sediment transport engineering concepts (Level 2), to the application of mathematical and physical modeling studies (Level 3). Although the complexities often place sediment transport evaluations in Level 3, many sediment transport evaluations can be conducted using Level 2 approaches with hydrologic and hydraulic information developed during design. Level 1 approaches are also valuable in identifying risks to transportation facilities and identifying dominant processes along stream segments. Level 1 analyses often provide the basis for deciding whether a Level 2 or 3 sediment transport analysis is warranted. In some cases, Level 2 or 3 analyses may be unwarranted because sediment-related issues do not pose significant risks to the project. Nevertheless, the information and understanding gained from field reconnaissance and a Level 1 sediment transport analysis is almost always worthwhile.

7.1 Sediment Characteristics and Movement

This section describes fundamentals related to sediment characteristics and movement relevant to understanding the fluvial system and assigning rates of sediment supply in numerical models. Topic covered include:

- Sediment sources and sinks.
- Types of sediment loads.
- Sediment transport measurements.
- Sediment load and concentration relationships.
- Sensitivity to velocity.

Each of these topics plays a role in performing sediment transport analyses, developing sediment transport models, and evaluating the results of these analyses and models.

7.1.1 Sediment Sources and Sinks

Just as water discharge is an input to hydraulic models, sediment inflows are inputs for sediment transport analyses and models. The analysis objectives and the dominant processes acting in a river reach largely determine the relevant sediment sources. That is, the effort of establishing sediment sources is tailored to the specific problem. For example, the dominant sediment source may be the upstream channel, but in some cases this source may be negligible or non-existent. A model developed to address contraction scour (see Section 7.3.1) may only include the upstream channel supply, while a model addressing aggradation and degradation may include tributaries, potential bank erosion, and other sources.

Areas of sediment accumulation are referred to as sediment sinks. Sediment sinks are often an important component to sediment transport models, especially when considering channel aggradation or sediment storage on the floodplain. Reservoirs act as substantial artificial sediment sinks where flow velocities are too low to move coarse sediment. Even silts and clay particles can settle out and be trapped in large reservoirs. Other sediment sinks include reaches backwatered by downstream constrictions during high flows.

Because the channel bed is available as a sediment source at all flows, channel bed material is a common sediment source. A characteristic of the bed material is that it can become armored, or coarsened, through the removal of fine material by winnowing. When this occurs, fine sediment can be transported over the otherwise immobile channel bed. At higher flow rates, the armor layer may be disrupted, mobilizing particles on the bed surface, and exposing finer subsurface material.

As illustrated in Figure 7.1, in addition to the channel bed, other sediment sources and sinks occur along the river corridor. Tributaries can be sources of sediment coarser or finer than that in the mainstem. A tributary supplying coarse material can produce a fan or delta at its confluence with the mainstem, which may act as a local grade control (see Section 8.1).

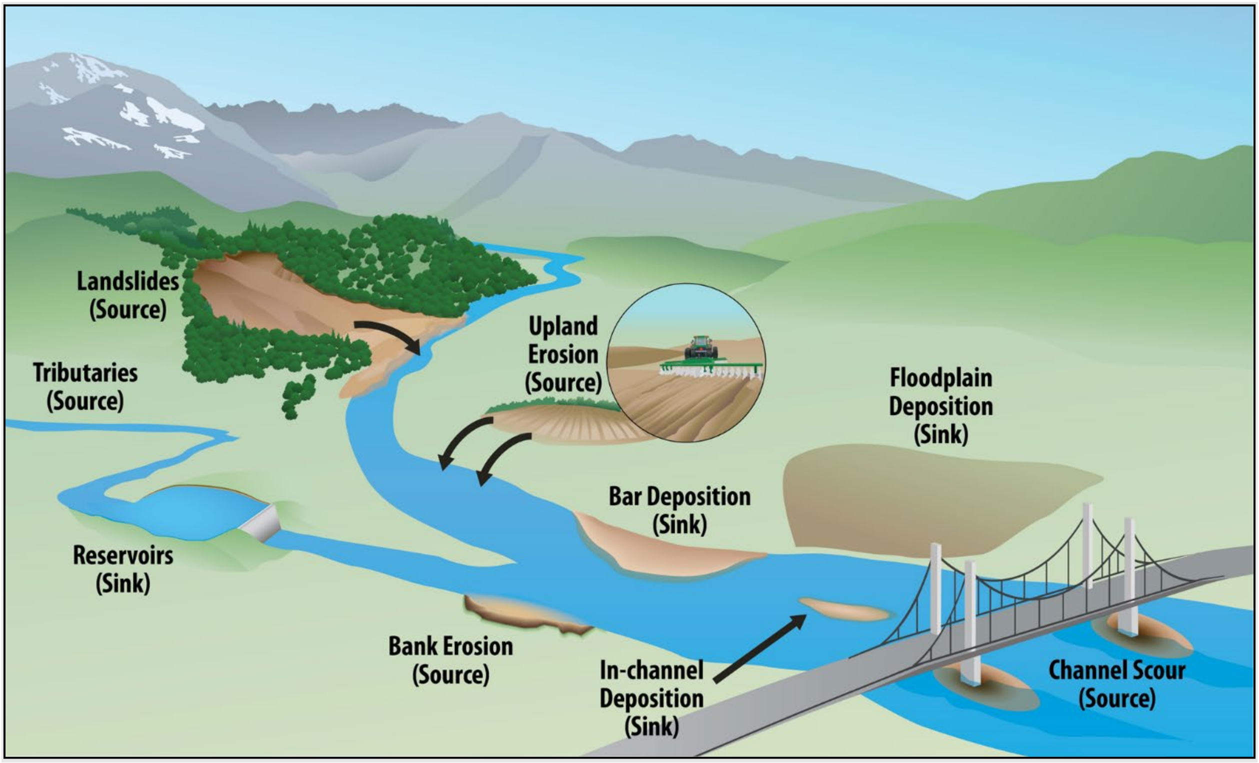


Figure 7.1. Sediment sources and sinks along a river.

Bank erosion is often a major source of sediment entering the stream system. Much of the sediment from the bank is finer than the bed sediment as banks are often comprised of floodplain deposits. Slumped and sloughed bank material can deposit at the toe of the bank, remaining there until the stream transport capacity is great enough to entrain and transport the slumped material downstream.

Nationally, suspended sediment concentrations in streams and rivers vary greatly as a function of climate, soils, and vegetation (Langbein and Schumm 1958, Rainwater 1962, Nash 1994, Simon et al. 2004). Langbein and Schumm (1958) showed that under natural conditions maximum sediment yields occurred in landscapes at the transition from desert scrublands to grasslands because these areas had the highest effective precipitation without robust vegetation density. Simon et al. (2004) developed suspended-sediment transport curves for the 84 ecoregions of the conterminous United States at bankfull flow volumes. A FHWA research effort (FHWA 2009d) also developed regional planning-level sediment transport curves over a range of flows for the 84 ecoregions of the conterminous United States.

Examples of sediment sinks are channel bars (especially point bars), reservoirs, fans, deltas, and floodplains, especially during high flow events when floodwaters spill out of the banks and onto the hydraulically connected floodplain. As the water spills out of the channel, coarser sediment deposits near the channel, creating natural levees. Wider and flatter river reaches can have lower sediment transport capacities causing sediment deposition. However, as discussed in Section 7.3.4, narrower channels may also have reduced sediment transport. Sediment sinks can be naturally occurring in rivers and channels but can occur upstream of constrictions such as at under-sized bridges or culverts, grade control structures, and low-water stream crossings. Channel erosion can occur downstream of such sediment sinks if the sediment transport capacity exceeds the sediment load exiting the sink.

Each of the data collection and analysis methods described in Chapter 5 can contribute to identifying sediment sources and sinks and in assessing their relative contributions. Desktop data collection provides information that can be used to identify trends in channel bed elevations, migration, and width. Stream reconnaissance and interpretation further identify prevailing geomorphic processes and controls. These data can be used to identify and quantify the sediment sources and sinks in the river system or within a river reach.

An imbalance of sediment supply and sediment transport capacity can lead to long-term aggradation and degradation, which are practical considerations for evaluating the future condition of bridge foundations. Sediment transport analyses typically focus on an individual river reach and rarely consider the entire basin, such as the one illustrated in Figure 7.1. Consequently, sediment supply is material transported to the upstream boundary of that reach. At the reach scale, aggradation along the channel occurs if the sediment supply from the sources exceeds the stream's capacity to transport sediment. Aggradation can lead to loss of hydraulic capacity, loss of freeboard, increased road overtopping, and increased potential for artificially trapping wood and debris at highway crossings. Degradation occurs when the stream's capacity to transport sediment exceeds the supply from upstream sources. Degradation can expose bridge foundations prompting project teams to implement protection countermeasures. Channel entrenchment resulting from degradation reduces or eliminates vertical and lateral connectivity in the fluvial system and may degrade or destroy important and valuable stream functions.

Figure 7.2 illustrates contraction scour occurring when upstream flow contracts and accelerates to pass through a bridge opening or culvert. Contraction scour occurs in the vicinity of crossings that reduce the cross-sectional area compared to upstream in the approaching channel and floodplain. This contraction increases velocities so that sediment outflow exceeds the upstream sediment inflow, especially during a flood. Contraction scour at a bridge or culvert is a much simpler and shorter-term sediment imbalance where the sediment source is limited because it is localized to the crossing and because contraction scour occurs primarily during floods.

Considering Lane's balance (Section 2.2.2), bridge backwater reduces the energy slope upstream of the bridge and can reduce the sediment supply to the bridge opening. Within the bridge the energy slope is higher than upstream, and the increased sediment transport capacity generates contraction scour. During the flood hydrograph rising limb, the contracted area becomes a sediment source, i.e., sediment exiting the area is greater than the upstream supply. During the flood hydrograph recession, the channel sediment inflow typically exceeds the outflow, and the contraction scour hole can partially or fully refill. Accordingly, post-flood evidence of contraction scour at a bridge may not be readily apparent, making it difficult to gather information of the scour effects at structures after the flood recedes.

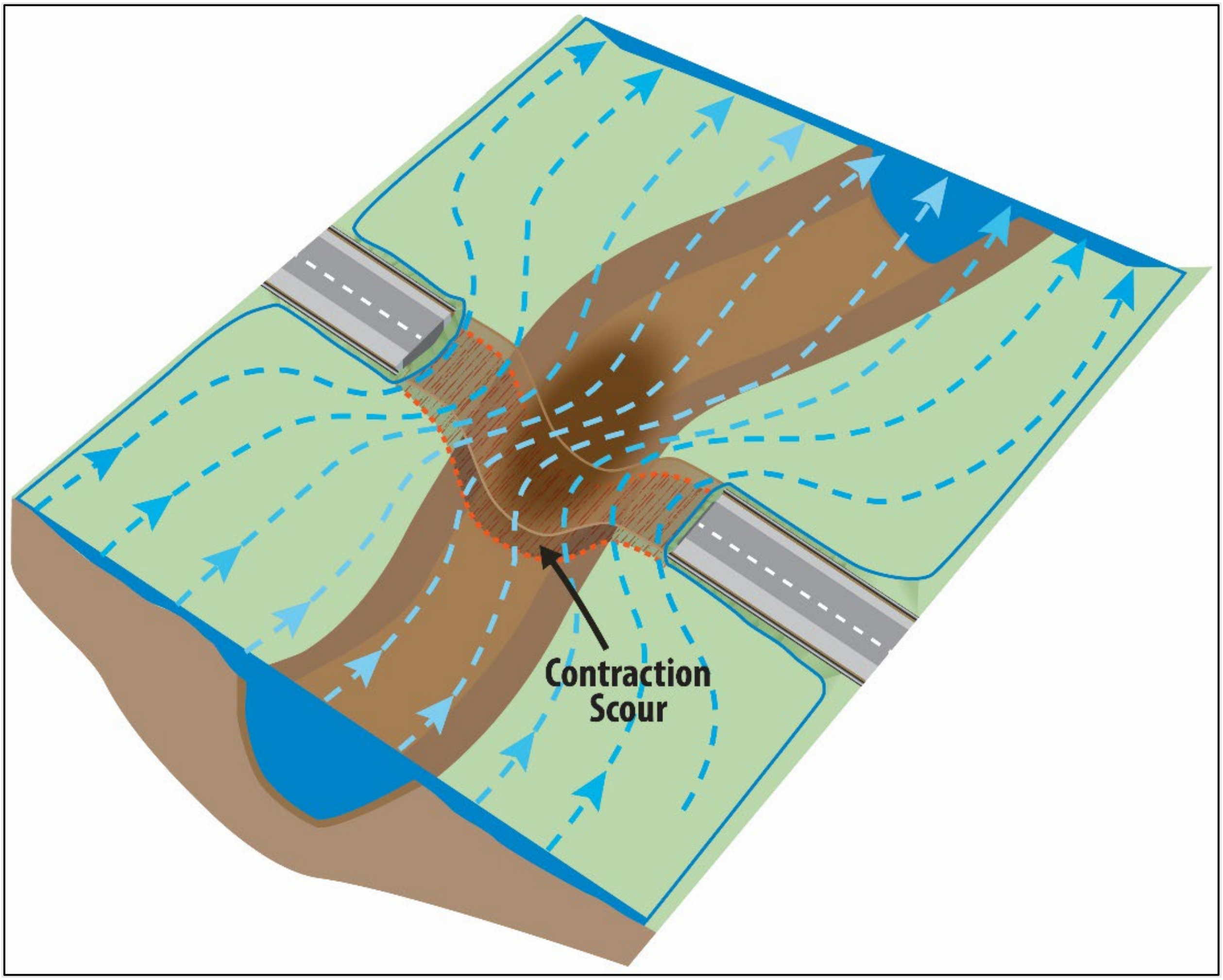


Figure 7.2. Constriction of flood flows causing contraction scour in a bridge opening.

7.1.2 Types of Load

Depending on the context, analysts typically think about the components of total sediment load in a variety of ways: 1) by source of sediment, 2) by type of movement, and 3) by method of measurement. The first framework for considering the components of the total load is by the source of sediment, where the source is either the channel bed or other sources, typically from watershed erosion and stream bank erosion (Figure 7.1). Bed material load is coarser material eroded from and deposited on the channel boundary (primarily the channel bed, but also bars and shoals). Material from other sources that is finer than the bed material is referred to as wash load. Factors affecting the supply of wash load include watershed geology, seasonal variation in location and type of precipitation, land use and vegetation cover (agricultural, urban, forested, shrubs, grassland, etc.), and stream bank stability. Wash load is transported through a river reach without appreciable interaction with the channel bed and is often transported in suspension although it can move along the bed and over the bed surface. The important distinction is that wash load movement is not dependent on mobilization of the bed material. Silts and clays are nearly always considered wash load because these sizes do not readily settle on the bed. Usually, the flow has the capacity to transport greater amounts of wash load than is supplied by the watershed, the exception being when so much wash load is available that it becomes a hyper-concentrated, or mud flow (see Chapter 8). Figure 7.3 describes the distinction of materials by source.

The second framework for considering components of total load is by type of movement (Simons and Şentürk 1976, Julien 2010). Bed material that moves along the bed of the channel is called bed load while the bed material that is entrained in the water column is the suspended bed material load, as shown in Figure 7.3. Bed load moves primarily by rolling, sliding, creeping, and saltation. Suspended bed material load moves in the water column, being lifted and mixed by turbulence.

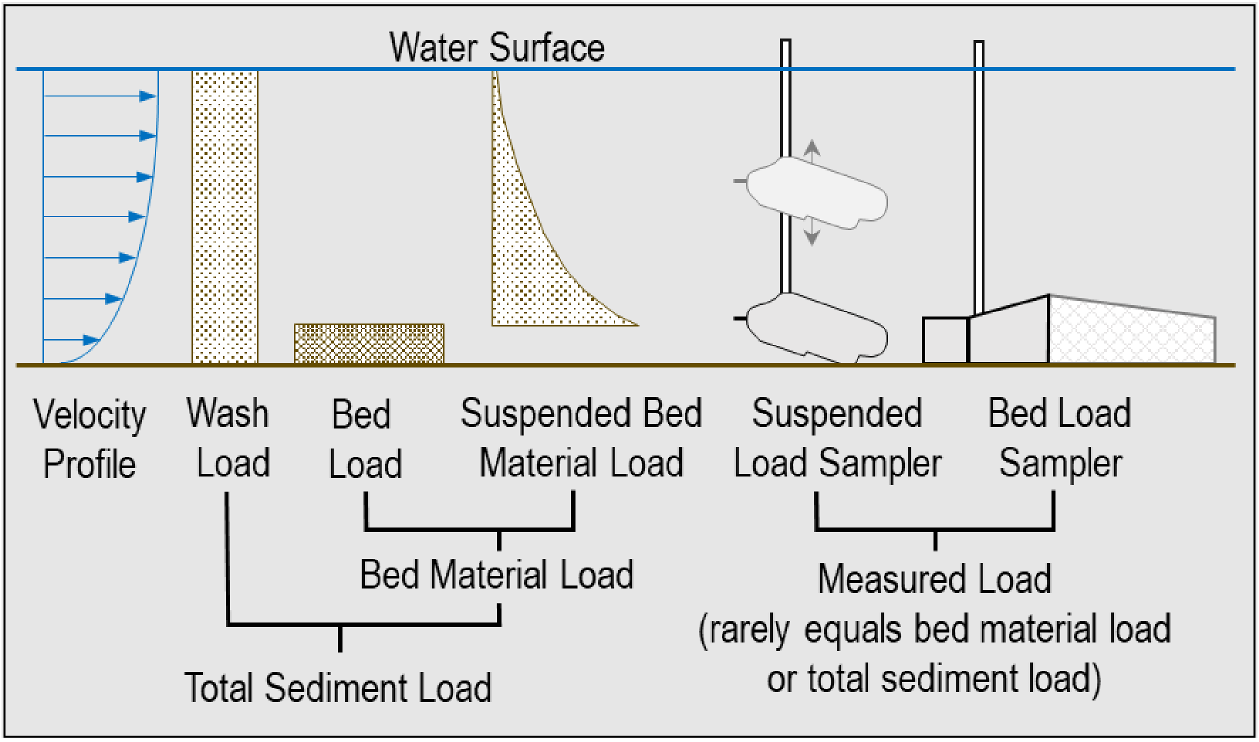


Figure 7.3. Sediment load components and measurement.

The third framework for breaking total load into components is by the method of measurement, as shown in Figure 7.3. The suspended load (suspended wash load and suspended bed material load) can be measured from the water surface to a height of about 3 to 4 inches above the bed, depending on the type of suspended load sampler. If an accompanying bed load measurement is not collected, the suspended load is referred to as the measured load. The unmeasured load is the sediment transported below the suspended sediment sampler, which includes the bed load and the "near-bed" portion of the suspended load. Bed load samplers (sometimes referred to as "unmeasured load samplers") measure that portion of load, so that the measured load becomes the suspended load plus the bed load, although near-bed suspended load can be missed if it passes through the mesh bag of the bed load sampler. Section 7.1.3 provides additional information on sediment transport measurement.

The amount of bed material load is limited by the capacity of the flow to move this relatively coarse material. A common rule of thumb is that the finest 10 percent of the bed surface gradation is wash load and the other 90 percent is bed material load (Einstein et al. 1940). However, many practitioners assume wash load is material finer than 0.0625 mm, which is the boundary between silt and sand (FHWA 2012a). An example of coarser wash load is the transport of sand and gravel sizes over an unmoving bed of cobbles. In a cobble-bed stream sand and gravel may be considered wash load because there is significant capacity to move these sizes, but the actual amount transported is limited by the supply. In most rivers, the bed material becomes finer with distance downstream, so that sizes that are considered wash load in upstream reaches become part of the bed material load further downstream.

7.1.3 Sediment Transport Measurements

Sediment transport measurements are often performed to provide calibration and validation data for sediment transport and modeling studies. Although measurement performed during low flows can provide information on wash loads, measurements during moderate and high flows represent full mobilization of the bed, providing data to test and select applicable sediment transport formulas (see section 7.3). As shown in Figure 7.3, samplers can be divided into suspended load samplers and bed load samplers. Suspended load samplers collect water and sediment, including suspended wash load and most of the suspended bed material load. Bed load samplers are available for the direct measurement of bed load and suspended sediment transported near the bed. The Federal Interagency Sediment Project includes a comprehensive list of sediment samplers (Davis 2005). The following sections describe several common sampler types.

7.1.3.1 Suspended Load Samplers

Suspended load samplers include depth-integrating samplers and point samplers (Julien 2010). Depth-integrating samplers collect water and sediment as the sampler is lowered and raised through the water column. As illustrated in Figure 7.3, velocity and suspended sediment concentration vary with depth below the water surface. Water and sediment enter the nozzle at the flow velocity, so the concentration of the sediment water mixture is integrated, and the bottle contains the mean concentration of the sediment. Depth-integrating samplers have been developed for use in rivers and streams of various sizes.

Point samplers are lowered to a specific depth to measure a sediment concentration. Multiple point samples are used to measure the sediment concentration profile over the flow depth. Figure 7.4 shows a depth-integrating sampler with the mouth open, ready to empty out the collected sample for laboratory analysis.

Tips from the Field

Sample Collection

Multiple samples are typically collected across the channel and combined to obtain a mean sediment concentration, with each sample bottle containing a similar volume of the water-sediment mixture. By adjusting the rate of lowering and raising the bottle, the user can avoid over- or underfilling it.

Bed Load Samplers

When using bed load samplers, ensure that the mesh size for the bag collecting the sediment is sufficiently large to avoid becoming clogged with fine particles. It is important to avoid digging the mouth of the sampler into the bed and collecting material that is not in motion. Missing material that is too large to enter the sampler and missing fine material that passes through the mesh bag are also potential issues.

Figure 7.4. D-74 suspended sediment sampler open and ready to empty sample of water-sediment mixture in the Rio Grande at the New Mexico 147 bridge. Image used by permission of Tetra Tech, Inc.

7.1.3.2 Bed Load Samplers

Bed load samplers for direct measurement of the bed load collect a volume or weight of sediment over a determined amount of time. Bunte et al. (2004) provide a detailed review of bed load measurement techniques in coarse bed streams. Bed load samplers, such as the Helley-Smith sampler (Figure 7.5) and other similar samplers, are used to estimate total weight and size distribution of the sediment particles collected.

7.1.4 Sediment Load and Concentration Relationships

There are several ways of expressing sediment loads and concentrations; volumetric, weight or mass, and concentration. Some are more common for sediment load measurements while others are used for computer models. This section provides mathematical relations for each method and relationships to convert between them. These relationships are useful for evaluating sediment transport data, performing sediment transport calculations, developing model input files, and for evaluating model output.

Discharge, Q, is the rate of flow of water expressed in cubic-feet per second (cfs) or cubic-meters per second (cms) for hydraulic modeling. Other disciplines find it useful to express water flow in other terms, such as acre-feet per year for water supply.

Figure 7.5. Helley-Smith bed load sampler used to measure near-bed sediment load in the Rio Grande at the New Mexico Highway 147 bridge. Image used by permission of Tetra Tech, Inc.

Sediment discharge, Q_s, is the volumetric rate of sediment movement expressed in the same units as water, cfs or cms. It is often useful to express sediment discharge as a “load” in terms of weight or mass, such as tons per day or metric-tons per day. Sediment concentration describes the relative amounts of sediment in the mixture of water and sediment and can be expressed volumetrically or by weight.

The following equations convert sediment transport from load (weight or mass) to volumetric rates. Sediment transport rates are expressed volumetrically unless otherwise specified.

$$Q_{s\text{-}tpd} = 43.2\,\gamma_s\,Q_s \tag{7.1}$$

where:

$Q_{s\text{-}tpd}$ = sediment load in tons/day

γ_s = unit weight of sediment in lb/ft^3

Q_s = sediment discharge in ft^3/s

$$Q_{s\text{-}mtpd} = 86.4\,\rho_s\,Q_s \tag{7.2}$$

where:

$Q_{s\text{-}mtpd}$ = sediment load in metric-tons/day

ρ_s = unit mass of sediment in kg/m^3

Q_s = sediment discharge in m^3/s

Sediment concentration is the ratio of mass or volume of sediment to the mass or volume of the mixture of water and sediment. Concentrations are often expressed as parts per million by multiplying the decimal value by one million. A common unit for expressing sediment concentration is milligrams per liter, which is the ratio of mass of sediment in milligrams to the volume of the water-sediment mixture in liters. The relationships for expressing concentration by volume and weight follow.

Concentration by volume:

$$C_v = Q_s/(Q + Q_s) = C_w/[S_g - (S_g - 1)\, C_w] \tag{7.3}$$

where:

C_v = concentration by volume (sediment volume/total volume)
Q_s = sediment discharge in ft^3/s
Q = water discharge in ft^3/s
C_w = concentration by weight (sediment weight/total weight)
S_g = sediment specific gravity

Concentration by weight:

$$C_w = S_g\, Q_s/(Q + S_g\, Q_s) = C_v\, S_g/[1 + (S_g - 1)\, C_v] \tag{7.4}$$

Concentration in parts per million by volume (not common):

$$C_{ppm\text{-}v} = 10^6\, C_v \tag{7.5}$$

where:

$C_{ppm\text{-}v}$ = concentration in parts per million by volume

Concentration in parts per million by weight:

$$C_{ppm\text{-}wt} = 10^6\, C_w \tag{7.6}$$

where:

$C_{ppm\text{-}wt}$ = concentration in parts per million by weight

Concentration in milligrams per liter:

$$C_{mg/l} = 10^6\, C_v\, S_g \tag{7.7}$$

where:

$C_{mg/l}$ = concentration in milligrams per liter

Conversions from concentration to volumetric rates of sediment transport are:

$$Q_s = C_v\, Q/(1 - C_v) = C_w\, Q/[S_g\, (1 - C_w)] \tag{7.8}$$

When sediment is eroded or deposited, the volume includes the void spaces between the sediment particles. Porosity is the ratio of voids to the total volume and typically ranges from 35 to 45 percent (0.35 to 0.45). The volume of eroded or deposited material for a time interval is:

$$\text{Volume} = Q_s \times \Delta t/(1 - \eta) \tag{7.9}$$

where:

Q_s = volumetric rate of excess (or deficit) sediment transport
Δt = time interval
η = decimal value of porosity of the eroded or deposited material

7.1.5 Sensitivity to Velocity

Experienced sediment transport analysts recognize that sediment transport is highly sensitive to one controlling variable – velocity – and to a lesser degree to depth. The relationship between sediment transport and the hydraulic variables (velocity and depth) is given in a power function equation for sediment transport capacity (Simons and Şentürk 1976, FHWA 2012a):

$$q_s = a\, V^b\, Y^c \tag{7.10}$$

where:

q_s = sediment discharge per unit width
V = velocity
Y = depth
a = an empirical coefficient
b = empirical velocity exponent
c = empirical depth exponent

In practice, the velocity exponent “b” ranges from 3 to 6, indicating a high level of sensitivity, and the depth exponent ranges from -1 to +1, indicating relatively low sensitivity. These levels of sensitivity are common to the range of sediment transport relationships even if velocity is not directly included in the relationship. This commonality of high sensitivity to velocity remains true for recent sediment transport formulations (FHWA 2012a). Table 7.1 illustrates the sensitivity of bed shear stress and sediment transport capacity to changing velocity. This type of sediment transport assessment is an example of a Level 1 concept.

The high sensitivity of sediment transport to velocity creates practical drawbacks in many situations but can also be a benefit. The main drawback is the need for accurate hydraulic information when calculating sediment transport, performing sediment transport analyses, or developing sediment transport models. If the calculated velocity underestimates the actual velocity by 20 percent, then the sediment transport calculation underestimates the actual sediment transport capacity of the flow by more than 50 percent. If the calculated velocity is 20 percent high, then the sediment transport calculation over-estimates the actual transport capacity by 70 percent or more.

Early Research Showed High Sensitivity to Velocity

The Meyer-Peter Muller (1948) bed load equation relates sediment transport capacity to excess shear stress to the power of 1.5, which gives a “b” value of approximately 3 for fully mobilized bed conditions. Similarly, Colby (1964) developed graphical relationships for sand transport that correspond to “b” exponents of 3 to 6 for velocity.

Table 7.1. Approximate changes in sediment transport capacity resulting from a change in velocity and the velocity exponent “b”.

Percent Change in Velocity	Percent Change in Sediment Transport Capacity		
	b = 3	b = 4	b = 5
-50	-88	-94	-97
-40	-78	-87	-92
-30	-66	-76	-83
-20	-49	-59	-67
-10	-27	-34	-41
10	33	46	61
20	73	107	149
30	120	186	271
40	174	284	438
50	238	406	659

Consecutive stream reaches with differing velocities are likely to have considerably different sediment transport capacities. If the velocity difference stems from small measurement errors in model input parameters, this may incorrectly produce aggradation or degradation in model-based computations of channel change. Alternatively, if the difference in velocity is real, such as upstream and downstream of a culvert or bridge, the computed aggradation or degradation are just as real. Therefore, survey data and representative hydraulic roughness estimates that cover the entire study area substantially improve the reliability of sediment transport calculations when evaluating differences and trends of channel change. Therefore, hydraulic model calibration/validation is a key step in the modeling process. As discussed in Section 7.2.2, sediment supply is often determined using hydraulics computed for an upstream supply cross-section or supply reach and project design depends on these calculations being representative of actual conditions.

A potential benefit of the high sensitivity of sediment transport to velocity comes in mobile-boundary sediment transport modeling and, in some respects, for actual channel stability. A small change in velocity resulting from a small change in depth (scour or fill) can create a larger change in sediment transport that can bring a cross-section or river reach into sediment balance. Therefore, a project design that makes adequate allowance for adjustments in depth, width, and slope does not rely as heavily on precise sediment supply estimates.

7.2 Modeling Sediment Transport

Sediment transport modeling is used to address a wide range of conditions and specific questions at transportation facilities. This section provides background information common to several readily available sediment transport models and information on selecting an appropriate model for specific applications. Modelers select an appropriate tool based on many criteria including model capabilities, strengths, and limitations. They also consider dimensionality (one-dimensional (1D) or two-dimensional (2D)), availability, documentation, computer hardware limitations, and personal experience with the model all to match the right tool with the pertinent sediment transport assessment objectives (see Section 5.3).

7.2.1 1D and 2D Sediment Transport and Morphological Modeling

Sediment transport modeling is an extension of hydraulic modeling, and the results of sediment transport calculations are sensitive to the hydraulic model calculations. The quality of the hydraulic model results, as discussed in *Two-Dimensional Hydraulic Modeling for Highways in the River Environment: Reference Document* (FHWA 2019a), directly influences the quality of the sediment transport model. This is true for both 1D and 2D models. Technical reference document HDS 7 (FHWA 2012c) provides information on selecting 1D versus 2D models. The primary advantage of using 2D models is their ability to better simulate hydraulic, sediment transport, and morphological complexity. The primary advantage of 1D models is their ability to efficiently evaluate large river systems, although this advantage is likely to diminish as computers become faster and more powerful. 2D models are generally better suited for:

- Multiple channels (braided, anabranching, or anastomosing).
- Highly sinuous channels.
- Complex hydraulics in bends and at confluences.
- Channels with multi-stage (compound) cross-sections or connected floodplains.
- Highly variable floodplain roughness and topography.
- Moderate to highly skewed crossing alignments.
- Multiple embankment openings (relief bridges or culverts).
- Detailed representation of velocity distributions at bridges.
- Substantial road overtopping.
- Upstream controls on flow distribution.
- Highly variable sediment sizes and erodibility.
- Countermeasure designs.

Another consideration is the level of effort in developing and running 1D versus 2D models. When detailed topographic and bathymetric data are available, a modeler familiar with the model software can develop either model efficiently. For many geometrically complex problems, it can be more practical to develop the 2D model because a 1D model may have to include interconnected reaches, junctions, and lateral flow splits, which are intrinsically part of the 2D model framework. As complexity increases, a 1D model may become difficult to calibrate and run. In some cases, modelers use both 2D and 1D models, such as a 2D model for bridge hydraulic design and a 1D model for floodplain permitting. When used together, the 2D model can provide valuable insights to inform the development of the 1D model.

Recognizing that sediment transport is a hydraulically unsteady process, modelers also consider the type of analysis involved and limitations on available computing power in selecting between a 1D and 2D model. The realm of 1D sediment transport models includes large-scale models of tens to hundreds of miles and simulating many years to decades. 2D models have detailed geometric resolution so short time steps are used to maintain model stability. This can result in extremely long computer run times.

1D and 2D sediment transport models compute aggradation and degradation by simulating the interaction between sediment transport and flow hydraulics. To simulate bed elevation changes, the models compare bed-material transport capacity at cross-sections (for 1D models) or for each element in a 2D model mesh covering the bed, based on the flow hydraulics and bed material characteristics. The model compares the estimated transport capacity with the sediment inflow and adjusts bed elevations to account for the difference between the sediment supply and transport capacity (i.e., the net addition or loss of bed material for the cross-section or element).

Interrelated hydraulic and sediment processes create several types of feedback simulated in the model. For example, changes in bed elevation alter local values of depth, velocity, and shear stress, leading to wider changes in flow distribution. As the bed aggrades and degrades and sediment is moved through the model, the surface bed material gradation may change, which in turn affects grain mobility, flow resistance, and ultimately, local sediment transport capacity.

3D Future

Some 3D models have sediment transport capabilities, but are currently better suited for highly localized analyses, such as scour around a pier or other obstructions. Researchers are working to make 3D models more available and usable by practitioners.

1D models represent lateral channel and floodplain geometry using cross-sections. Cross-section spacing represents the topography longitudinally. A limitation of 1D sediment transport models is that the cross-section geometry is often simplified to promote numerical stability. Simplifications include:

- Reducing the variation in the channel bed elevations to lessen irregular aggradation and deposition, particularly under low flow conditions.
- Removing structures (bridges, culverts) and representing them using blocked areas.

Figure 7.6 shows a cross-section from a 1D sediment transport model and demonstrates a problem that can occur when too much detail is included. At very low flows only a few points in the cross-section are actively conveying water and sediment potentially resulting in unnaturally focused degradation. One practice for addressing this issue is to filter the points and smooth the boundary. Because sediment transport is highly non-linear and sensitive to velocity, filtering is used to maintain the depth-area properties of the channel. Another practice is to set a lower limit on discharges that are included in the simulation, either by eliminating low flows from the flow record or by setting a minimum discharge for bed material motion. These approaches, however, can under- or overemphasize the influence of low flows.

Figure 7.7 shows a perspective plot of mesh elements in a 2D model with the arrows indicating flow direction within the channel. The layout of the elements and their corner (node) elevations represent the geometry of the channel, the floodplain, and the road embankment crossing the floodplain. Figure 7.8 shows a perspective plot of the topography of a larger portion of this model, including a relief bridge though the embankment on the floodplain (note the apparent remnant contraction scour in the relief bridge opening). This level of hydraulic complexity warrants the selection of a 2D model for performing scour calculations. Contraction scour can be computed within any sediment transport model. However, given the hydraulic complexities of a road crossing, simulating contraction scour in this situation generally calls for a 2D model. 2D models can be used to simulate contraction scour in both the main channel and at flood relief bridges.

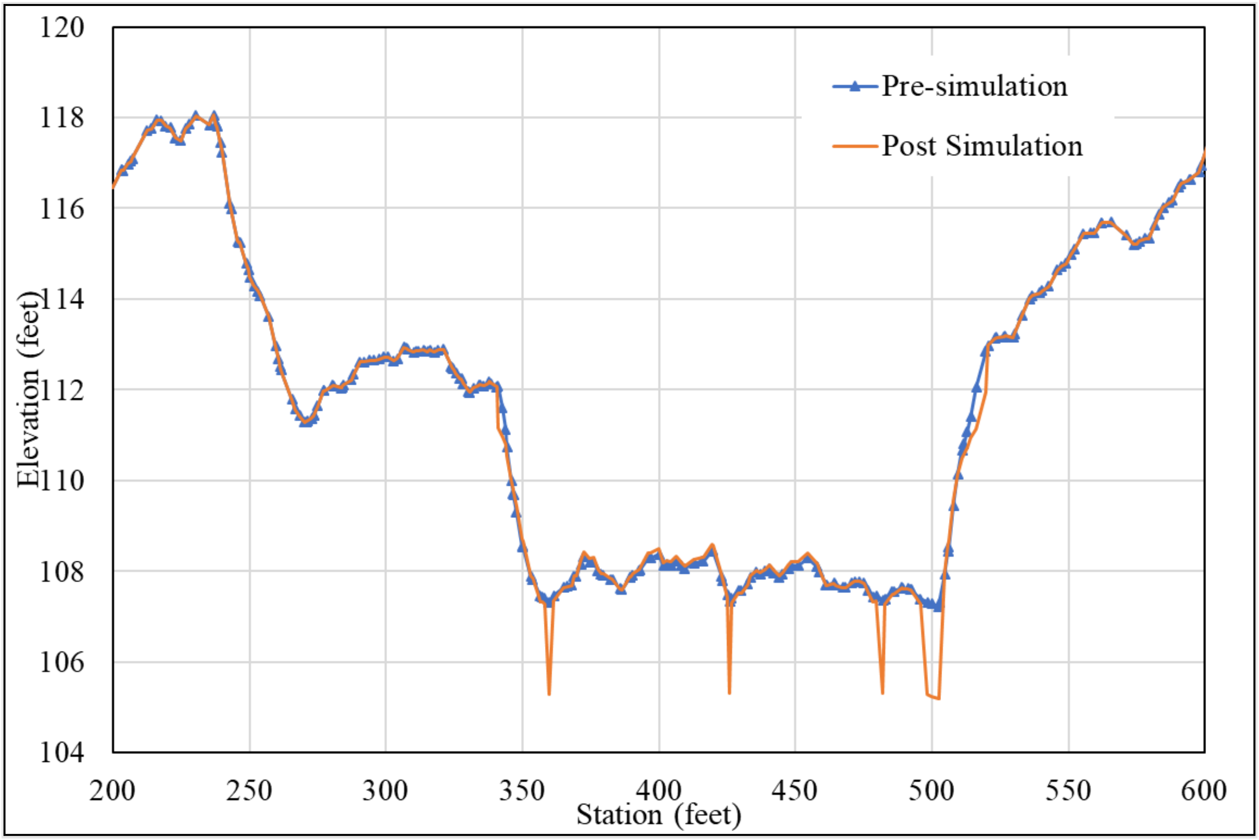


Figure 7.6. Pre- and post-mobile bed model cross-sections showing potential consequences of not filtering the cross-section points before a sediment transport simulation.

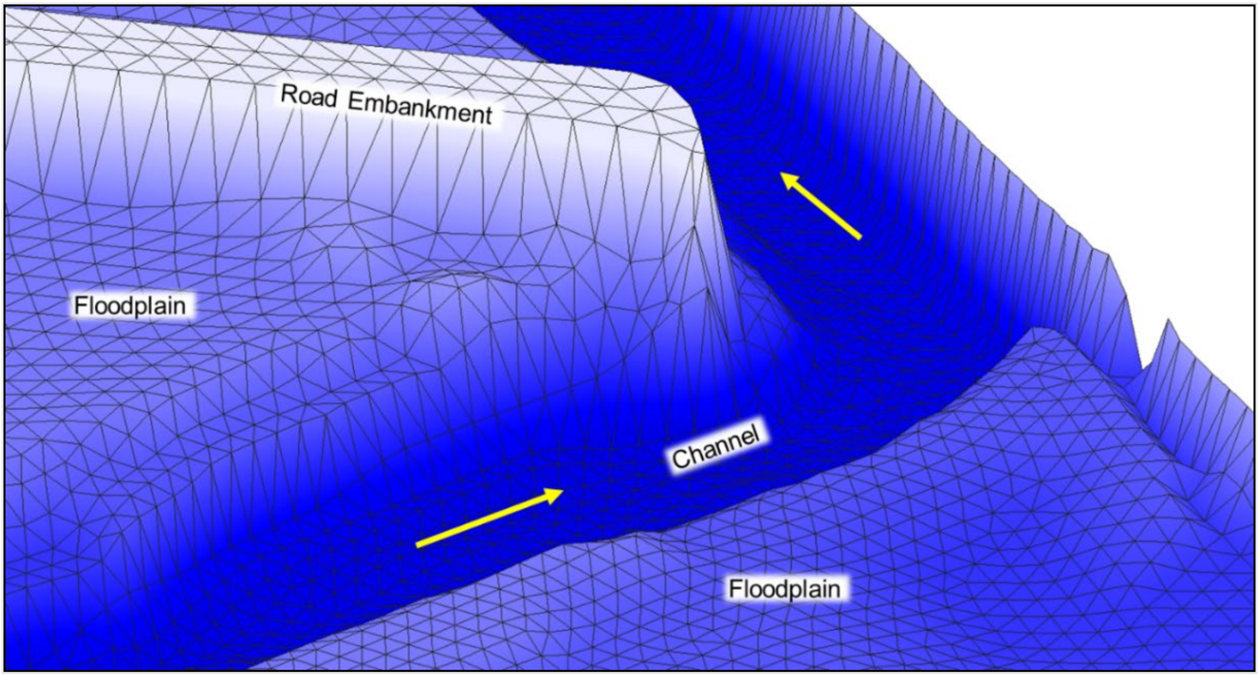


Figure 7.7. Perspective view of a 2D model mesh.

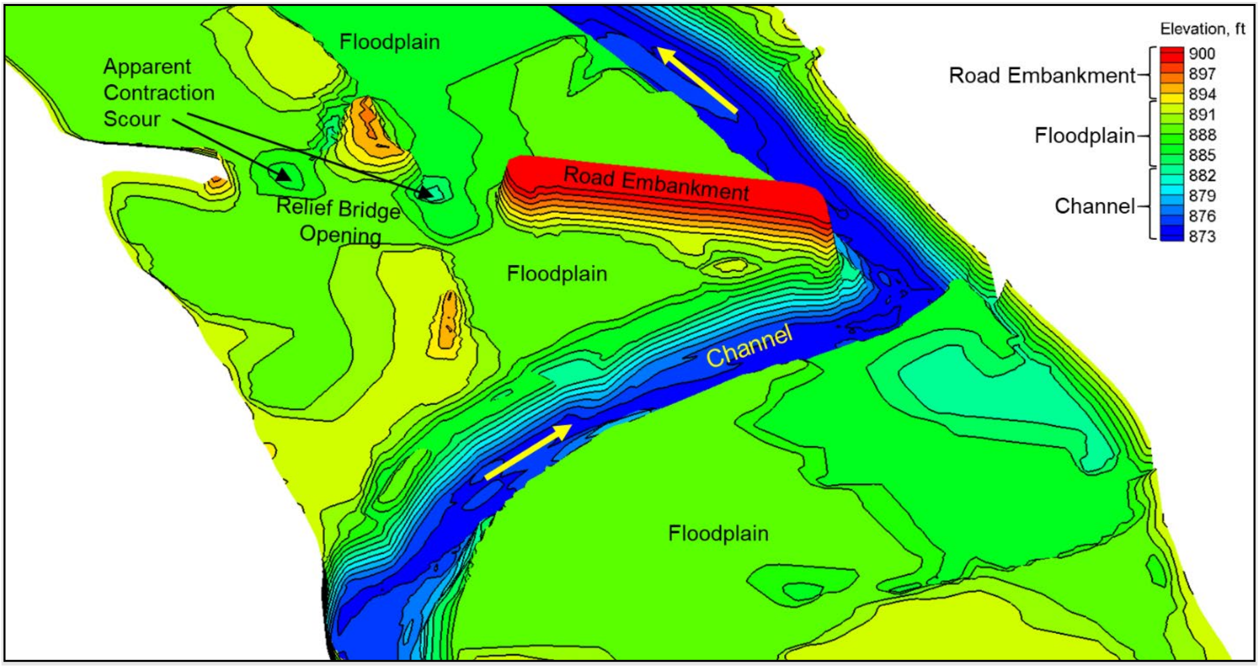


Figure 7.8. Perspective view of a 2D model surface with channel, floodplain, road embankment, and bridge openings.

Some 1D and 2D models are capable of simulating bank erosion and lateral channel migration. These capabilities can be as simple as projecting a stable slope from the bank toe into the adjacent floodplain when the channel lowers. More rigorous geotechnical representations of bank stability are included in some models. Sediment yield from bank erosion is included as another sediment source in these models.

Ideally, modelers select models based on project goals and model functionality, although available computer resources can dictate the choice of a 1D or 2D model. Models that use a single central processing unit (CPU) are the least efficient so many models use multiple CPUs. Some models are programmed to use graphics processing units (GPUs) that can achieve high levels of computation power. Because of these and other advances, computational power is becoming less of a limitation.

7.2.2 Model Extents and Input Data

Modelers create models of a location depending on hydraulic and sediment transport conditions, and other modeling objectives. This includes defining the area that the model represents known as the model extents or domain. It also includes input data that physically describes the site as well as flow and sediment data. A modeler invests substantial effort to develop accurate model geometry, meaningful flow resistance parameters, hydrology, boundary conditions, bed material gradations and layers, inflowing sediment loads and gradations, estimates of other sediment sources and sinks, and other parameters related to sediment transport simulations.

7.2.2.1 Model Extents

One important consideration is establishing the upstream and downstream model extents (see FHWA 2012c and 2019a). Modelers often set model boundaries so that the boundary conditions do not overly affect the study area. To do this, they focus the model geometry domain on the study area while extending the model sufficiently upstream and downstream to buffer influence of the boundary conditions. It is also important that the lateral extent of the model includes areas conveying the highest discharges that are to be simulated.

Hydraulic models of culvert and bridge crossings often include only short distances upstream and downstream, where flows are assumed to be fully expanded in the floodplain. As a rule of thumb, the upstream and downstream boundaries are set at least two floodplain widths upstream and downstream of a bridge crossing for a 2D hydraulic model or further, so flow is fully expanded into the floodplain and approximately one-dimensional (FHWA 2012c). While these upstream and downstream extents may be adequate for hydraulic modeling, sediment transport models often perform better if they include longer distances upstream and downstream.

Selecting the location for the upstream and downstream boundaries for a sediment transport model depends on the purpose of the model. A sediment transport model intended to evaluate contraction scour can have much closer upstream and downstream boundaries than a model developed to evaluate long-term aggradation or degradation. Contraction scour is a localized phenomenon that results from increased transport capacity in a contracted bridge opening or other flow constriction compared to that upstream. Because contraction scour excludes long-term aggradation or degradation, contraction scour simulations are also run for much briefer periods, such as a single event, which further allows for closer boundaries.

Modelers locate the upstream and downstream boundaries for long-term channel response, including reach or river system evaluations, to establish representative sediment inflows, hydraulic controls and, in some cases, geologic or structural base-level controls. Therefore, it is important for modelers to select boundaries either where hydraulic and channel stability conditions are well understood or are far enough from the area of interest to not overly influence the results. Subsequent sections discuss three types of analyses and boundary constraints relevant to modelling highways in the river environment in the contexts of: contraction scour (Section 7.3.1), channel response to culvert replacement (Section 7.3.2), and long-term bed change (Section 7.3.3).

7.2.2.2 Input Data

Modelers select and assign data inputs to calculate hydraulic parameters and sediment transport values. Similar inputs are used for most available hydraulic and sediment transport models. These inputs include:

Geometric Data and Flow Resistance Parameters: Accurate channel and floodplain geometries are important for hydraulic modeling and essential for sediment transport modeling. Because red LiDAR does not penetrate the water, hydraulic model geometry developed solely with LiDAR can exclude below-water areas, which can lead to a model with accurate floodplain elevations but with a portion of the channel excluded. It is important to remember that small changes in velocity can result in large changes in computed sediment transport rates. If a model is calibrated to observed water surface elevations but with incorrect bed elevations, both the calibrated flow resistance parameter and the computed velocities would be incorrect. If, however, the correct flow resistance is used, water depths and velocities may be more representative, but water surface elevations would not be correct. At higher discharges, the channel and floodplain flow distributions would also be incorrect. Modelers often select flow resistance parameters to produce conservative water surface elevations, especially for flood insurance studies but also for some hydraulic structure designs. This practice can lead to less representative sediment transport models. Therefore, to create representative sediment transport models, it is important to obtain accurate channel and floodplain surveys that cover the entire area of interest, and to calibrate/validate the model for in-channel flows and, if possible, flood flows.

Hydrology and Hydraulics: Sediment transport models are inherently hydraulically unsteady (changing depth and velocity with time). Sediment transport models developed to evaluate contraction scour may use a flood event hydrograph (unsteady) or a constant peak discharge (steady) from the flood event. However, changing bed elevations produced by contraction scour result in unsteady hydraulic conditions even with constant discharge. Long-term bed change studies depend on flow series data over the duration of the simulation, which can be many years and often decades.

Bed Sediment: Sediment transport models use information on bed sediment gradations and layers. Section 6.1 discusses methods for sampling surface and subsurface bed sediments. A long model domain may benefit from multiple bed material samples to represent bed gradations that change with along the channel. Tributary samples may also be used in large-domain, drainage network models.

The volume of deposited sediment includes the void spaces between the sediment particles. The porosity of the sediment body (the ratio of void volume to the total volume) is another important bed property. To avoid having to include porosity as an input variable, models often use the dry bulk density of the deposited sediment in lb/ft^3 or kg/m^3.

Sediment Inflows: Modelers include sediment sources and sinks relevant for the type of sediment transport analysis and the characteristics of the location. A sediment transport model developed to address long-term aggradation and degradation potential may include any or all the sources and sinks identified in Figure 7.1. All sediment transport analyses include the upstream channel sediment inflow. For many analyses, such as for small-scale stream restoration projects and contraction scour assessments, upstream channel sediment inflow may be the only sediment source considered. In some cases, such as when the upstream boundary of the model is the outlet of a reservoir, upstream channel sediment inflow may be very low. Three methods of assigning a sediment inflow are common to all sediment transport models: 1) equilibrium load, 2) rating curve, and 3) time series.

Equilibrium load is the simplest method for establishing inflow sediment load. For this method, models compute the transport capacity of each size fraction of the bed material based on the boundary geometry and hydraulic conditions and use the computed amounts as the supply. This method is commonly used when a relatively stable alluvial cross-section or channel reach can be identified at the upstream limit of the model. An advantage of this method is that the upstream sediment supply is likely to be consistent with the transport formula selected for the rest of the model. However, if the upstream boundary (cross-section in a 1D model or boundary elements in a 2D model) is not hydraulically representative, this type of upstream boundary can create a sediment imbalance within the model, resulting in unrealistic downstream aggradation and degradation.

A potential consequence of using equilibrium load is that the upstream cross-section geometry is fixed and static. If aggradation or degradation occurs near the boundary, the hydraulic conditions (velocity and depth) can become unrealistic, resulting in unrealistic sediment input. If this occurs, extending the model upstream to a location that is representative for sediment supply can reduce or eliminate this problem.

The ***rating curve*** method establishes the variation of the sediment transport rate for each sediment size class at the upstream model boundary over a range of flows. The input is a table of rating curves that describe sediment inflows for each size class as a function of water discharges. Figure 7.9 depicts a graphical example of a set of sediment rating curves. Using a reservoir outlet as an example, the rating curve may have zero sediment outflow for low-flow conditions with progressively larger size classes being scoured and transported as flow increases.

If sediment flushing or sluicing is part of the reservoir operations, this can be included in the rating curves.

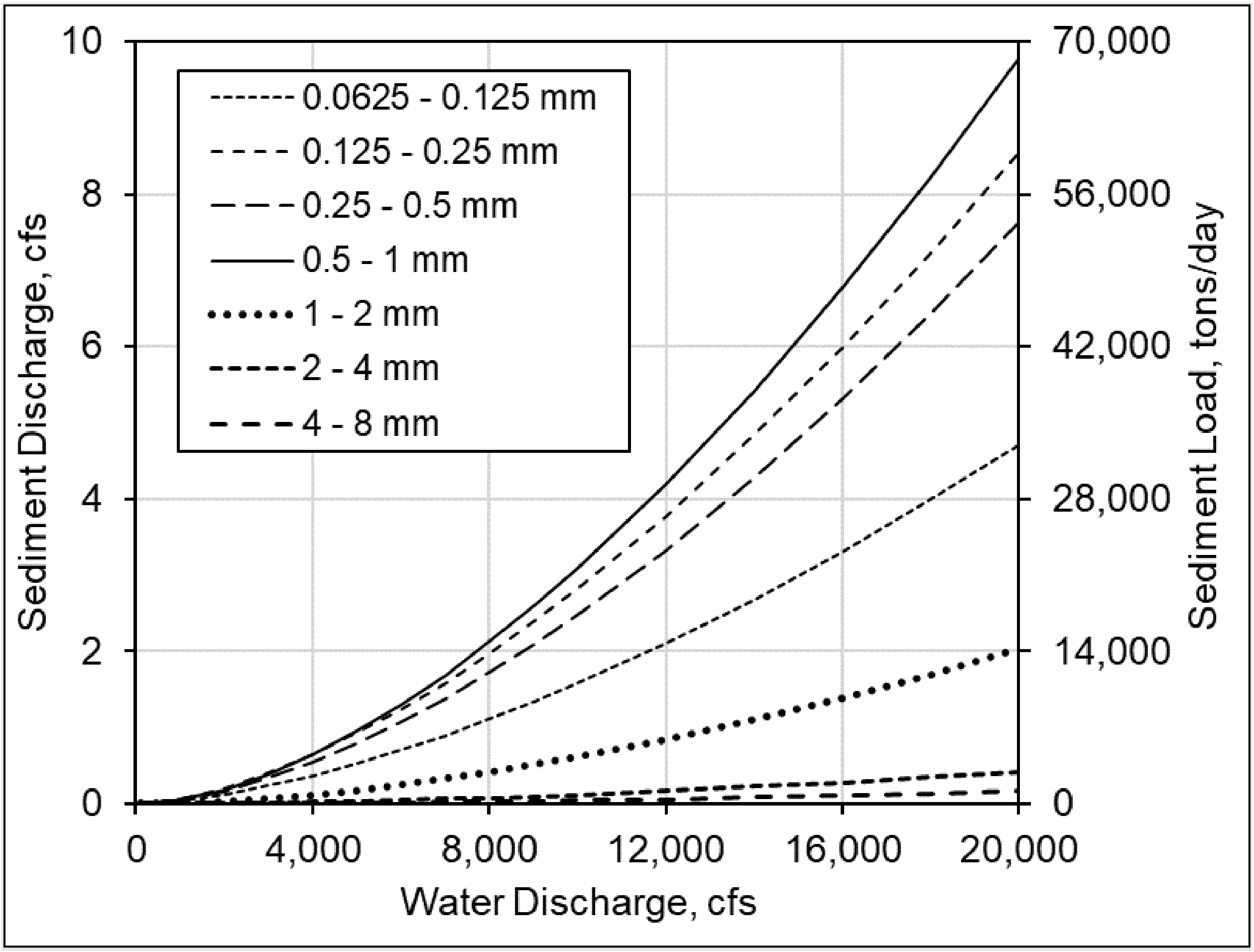


Figure 7.9 Example sediment rating curves by size fraction.

If rating curves are based on measured loads or some other field data, the inflowing sediment transport rate can be incompatible with transport capacities computed throughout the rest of the model. This is because the empirical functions used in the model may not fully represent the measured conditions (see Section 7.4). Therefore, it is beneficial to evaluate the selected transport function and model results to identify if an artificial imbalance is being created between the upstream boundary condition and the selected transport equation.

With the ***time series*** method, the modeler assigns sediment transport inflows for each time step in the model. This approach can incorporate seasonality into the simulation, such as: 1) higher sediment inflow in the spring than the rest of the year, 2) a period of high sediment supply in the flow record, or 3) changing basin conditions through time. As with the rating curve method, the modeler may find incompatibilities between the inflowing loads and the available transport formulae.

These methods are not only useful for setting the upstream sediment boundary condition on the mainstem but can also be used to set sediment inflows provided by tributary streams. The equilibrium load method uses the hydraulic conditions and bed material gradation at any inflow boundary, so a tributary can be included as a representative supply reach. The rating curve and time series methods can be used as direct sediment inflows (paired with water inflows) without including the tributary as a reach in the model. The dynamics of the tributary storing or releasing additional sediment are not included when sediment and water discharges are input directly.

With site-specific information and sound judgment, the modeler can identify and estimate the yields and losses associated with other sediment sources and sinks shown in Figure 7.1. The modeler can use a suitable bank erosion function to simulate local and upstream channel widening as an additional sediment source. Even if the channel width does not change, lateral migration can create both a wash load source (through erosion of fine, floodplain sediment at the retreating bank) and a bed material load sink (as coarse sediment is deposited on the point bar opposite). Although the model is unlikely to be able to simulate lateral channel migration, the modeler can estimate yields and losses associated with banks and bars for inclusion in the simulation.

Other Considerations: The input data described above are commonly used for sediment transport modeling. The modeler selects the sediment transport formula appropriate for the simulation. Transport formulae vary between modeling platforms and are discussed in Section 7.4. The models discussed in Section 7.4 also include methods for simulating erosion and transport of cohesive sediment. Each model includes a range of other parameters to represent sediment transport processes.

Modeling Tip: Restart Files

One technique is to start a sediment transport model from the results of a hydraulic model, i.e., using a "restart" file. The restart file is the converged solution of the hydraulic model for the same discharge as the starting flow rate in the unsteady sediment transport model. This practice avoids the occurrence of unwanted and potentially numerically unstable sediment transport results (bed change, transport rates, aborted runs) as the model attempts to converge on an initial solution. Even if the model remains stable, the potentially erroneous initial results can corrupt the subsequent results of the simulation.

7.3 Sediment Transport Applications

Although not modeled for typical bridge and culvert design, sediment transport contributes to a range of issues that can affect bridges, culverts, and roads. The applications discussed in this section involve computer modeling approaches tailored to address specific conditions or questions. In some cases, a project team may evaluate whether or how an observed trend, such as channel degradation or migration, might continue. In other cases, modelers evaluate design alternatives to mitigate issues, such as contraction scour or channel instability arising from culvert and bridge replacements, or whether sediment balance is maintained through the culvert, bridge, or restoration reach.

Although models are based on representations of physical processes, they are simplified versions of those processes. How well the processes are represented is important, but the input data, parameters, and overall model extent also determine the usefulness of the results. Regardless of whether the model is simple or complex, placing too much confidence in one model result can be as risky as discounting another model result. Therefore, it is important to critically evaluate the range of results and sensitivity of the results to varying inputs for each application.

7.3.1 Contraction Scour

Scour—the erosion of the soil, sediment, and other materials—is a concern when it occurs around bridge foundations, embankment footings and culverts. Contraction scour occurs when upstream flow contracts and accelerates to pass through a relatively narrow bridge opening or culvert. This is primarily an issue at bridges and culverts that are narrower than the channel. It is also an issue during floods when upstream flow fills the channel and spills onto the floodplains and the bridge opening or culvert span constricts the flow area. When the flow velocity in the contraction is higher than upstream, the bed scours and lowers. The lowering bed increases the flow area and eventually lowers the local velocity, and the contraction scour stabilizes.

Contraction scour is a sediment transport process resulting from an imbalance between the upstream supply of sediment and the higher sediment transport capacity within the bridge or culvert. HEC-18 (FHWA 2012b) provides relationships for evaluating contraction scour and HDS 7 (FHWA 2012c) provides discussion of scour considerations for bridge design. These documents describe the use of sediment transport modeling to estimate contraction scour at highway crossings and inform engineering interpretation of each of the assumptions inherent to the HEC-18 contraction scour equations. Stream simulation design (see FHWA 2010a) addresses contraction scour issues at culverts. As a means for evaluating potential contraction scour, sediment transport modeling is a level 3 approach applicable to complex hydraulic conditions and to highly unsteady flow conditions where the HEC-18 equations may be less applicable.

Live-Bed and Clear-Water Contraction Scour

Contraction scour occurs as either live-bed or clear-water sediment transport conditions. Live-bed scour occurs when there is bed material sediment movement in the upstream channel, that is, there is a sediment supply into the scour area. Clear-water scour occurs when the upstream flow velocity or shear stress is insufficient to transport bed material to the bridge or culvert, but there is sufficient velocity or shear stress to erode the material in the bridge/culvert. Although the name implies that no sediment is being transported, this is rarely the case. Silts and clays are commonly transported in suspension but have little interaction with the bed through the bridge or culvert. Therefore, "clear-water" references non-transporting conditions of bed material sands and coarser sediments. Channels typically have live-bed conditions during floods and floodplain areas are typically clear-water.

Contraction scour equations presented in HEC-18 are based on work by Laursen (1960, 1963). Laursen developed a live-bed contraction scour equation by comparing upstream sediment transport capacity, as the sediment supply, to the sediment transport capacity within the crossing. From this analysis, Laursen determined the amount of bed lowering that would balance these rates. Application of Laursen's live-bed equation involves the selection of an appropriate, noncontracted upstream cross-section representative of the sediment supply to the crossing. For clear-water conditions, where there is no bed material supply from upstream, Laursen developed an equation based on the amount of scour capable of reducing velocity to a non-eroding condition.

In addition to particle size or critical shear stress, engineers use discharges, velocities, widths, and depths from 1D or 2D hydraulic models to estimate contraction scour based on Laursen's equations. The calculations assume that the shear stresses act for a sufficiently long time for the maximum (or ultimate) scour to occur, that the scour does not appreciably alter the distribution of flow within the crossing, and that the bed material does not change in size or erodibility with depth.

These assumptions do not hold for all crossings. For example, the duration of a single flood or series of floods may be too short to reach ultimate contraction scour. In addition, the hydraulic conditions may evolve during a flood event such that a backwater effect at the crossing is decreased because of the contraction scour creating feedback between contraction scour and upstream backwater. Contraction scour can lower upstream water surfaces, increase upstream velocities, and increase upstream sediment transport. There is also the potential for the flow to encounter layers of more or less erodible material as scour progresses, which can increase or decrease scour. When project conditions depart from the equation's assumptions this may lead to either underestimates or overestimates of contraction scour.

Many practitioners seek to account for these additional factors, and sediment transport calculation can be a tool with which to address them. To address the influence of flow duration on scour in alluvial channels, the modeler can compare the model runs from simulations using a flood hydrograph to those from a long-term steady state flow. For scour in erosion-resistant materials, long term hydrographs are used. For the flood hydrograph simulation, the contraction scour starts as soon as sediment transport capacity in the crossing exceeds the upstream supply, and the overall hydrograph may not have a sufficient duration to reach an ultimate scour condition. For the steady state simulation, the model is set up with a constant discharge equal to the design discharge and run until ultimate scour is reached. These two scenarios combined (long-term unsteady- and steady-state flows) may provide the design team with information on the time it takes to reach various degrees of scour. The same model scenarios can also address the question of whether contraction scour reduces upstream backwater sufficiently to limit the expected scour, compared to the HEC-18 equations. Some sediment transport models have the capability to set up multiple sediment layers to address the effects of scour through successive sediment layers with different erodibilities.

Given the challenges and uncertainties of estimating contraction scour using sediment transport models, running several scenarios to test the sensitivity of the results to varying input parameters, or selecting input parameter values that produce more conservative results for crossing design may be helpful. These scenarios can include:

- Using a range of durations for input flood hydrographs.
- Including runs with different sediment transport formulas from the set of formulas applicable for the bed material and hydraulic conditions.
- Using a thicker mobile layer that allows more scour by delaying armoring (if the model includes armoring as an input variable) to be conservative.

2D sediment transport models are likely better suited for contraction scour applications because the hydraulic results, especially through the crossing, are more realistic. 1D models are well suited for less complex hydraulic situations but where the development of scour over time is being investigated. 1D models apportion flow between channel and floodplains based on the relative conveyance and assume the same energy slope in each sub-area. This simplifying assumption is used at all cross-sections in a 1D model, including bridge/culvert cross-sections. 2D models do not have these limiting assumptions and simulate sediment transport processes throughout the model domain, including channel and floodplain areas. 1D models typically only simulate sediment transport in the channel. Therefore, clear-water scour that often occurs in relief openings (and can occur in the area between the channel and abutment toe) can be simulated in a 2D sediment transport model but not in a 1D sediment transport model.

Figure 7.10 shows the results of a 2D sediment transport model used to compute contraction scour at a main channel and relief bridge for the Interstate 35 crossing of the Cimarron River channel and floodplain in Oklahoma. The model was run at a constant discharge for 12 hours. Live-bed contraction scour of up to 14 feet was calculated for the main channel bridge and clear-water scour of up to 4 and 6 feet was calculated near the north and south ends of the relief bridge, respectively.

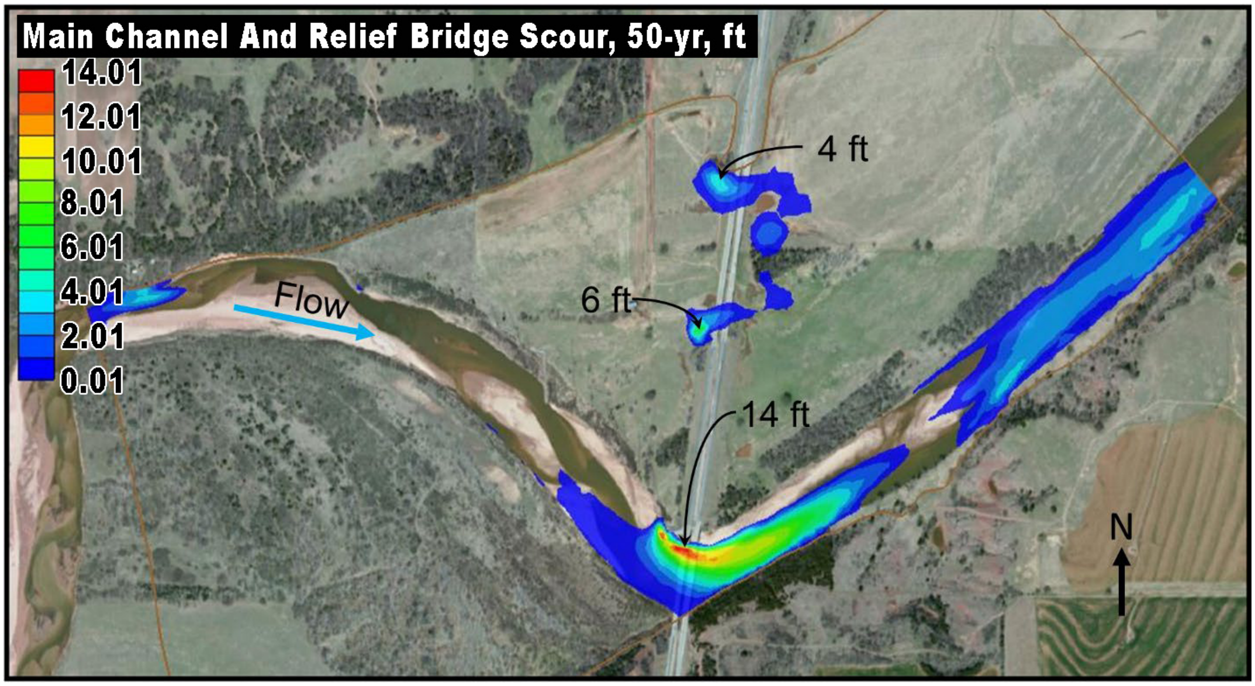


Figure 7.10. Contraction scour simulated with a 2D sediment transport model (Cimarron River, Oklahoma).

Figure 7.11 illustrates that contraction scour at the main bridge is deepest near the left bank, with almost no scour along the right bank. Figure 7.12 shows that contraction scour has not reached the ultimate condition within the 12-hour simulation period, particularly for the main channel, since the plot of scour depth with time has not leveled off.

In contrast to the information a 2D model produces as shown in Figure 7.11, 1D models provide an average value of contraction scour over the channel bed because sediment transport is averaged over the channel width. 2D models compute hydraulics and sediment transport on an element (see Section 7.2.1) basis representing variations in flow and scour.

3D Models for Contraction Scour

3D models provide more detailed representation of sediment and flow in the vertical direction in addition to the longitudinal and transverse directions. The added computational resources for the spatial and temporal components of contraction scour analyses in 3D models are currently impractical for most projects.

Whether the model is 1D or 2D, the upstream sediment supply boundary condition is typically prescribed using the equilibrium load method described in Section 7.2.2. This is a reasonable assumption consistent with the use of the HEC-18 contraction scour equations. Also, as the model is being used to evaluate contraction scour rather than long-term aggradation or degradation, assigning a different supply could mask or accentuate the estimated contraction scour. If a constant upstream flow discharge is simulated, the downstream water surface elevation boundary would be set at an applicable constant value. If a flood hydrograph is simulated, then the downstream water surface boundary reflects the range of flows, based on a prescribed rating curve, or an applicable normal depth or energy slope condition.

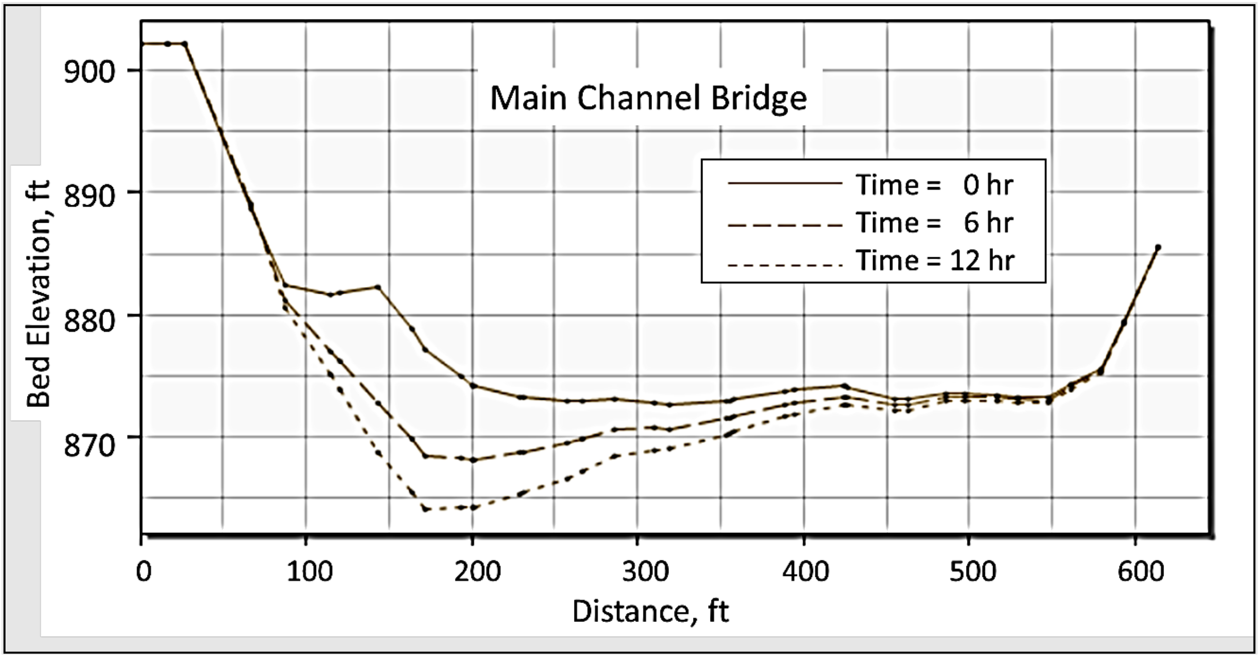


Figure 7.11. Simulated contraction scour in the main channel bridge opening (Cimarron River).

Figure 7.12. Simulated contraction scour development with time (Cimarron River).

7.3.2 Culvert Replacement

Depending on their design, culverts may alter the sediment transport balance and create new sediment transport conditions. Similarly, culvert replacement, whether to remedy structural issues, increase flow capacity, or to provide for aquatic organism passage (AOP), may result in new hydraulic and sediment transport conditions in the upstream and downstream channel reaches. Therefore, sediment transport analysis can be useful for evaluating the effects of culvert replacement. The FHWA provides two culvert analysis and design documents that discuss the importance of considering geomorphic characteristics, processes, and responses in the culvert design process and that can be used for evaluating culvert replacement:

- *Hydraulic Design of Highway Culverts (HDS 5)* (FHWA 2012d) provides general information on the hydraulic design of culverts.
- *Culvert Design for Aquatic Organism Passage (HEC-26)* (FHWA 2010a) describes the use of stream simulation to size bed material within a culvert that mimics conditions in the natural channel, facilitates sediment continuity, and provides for AOP.

Figure 7.13 shows a common condition observed at culverts where sediment deposition occurs upstream and erosion downstream. This condition could also occur at bridges where the channel bottom has been lined with concrete or riprap. Based only on the profile in the figure, it is conjecture whether the erosion or deposition is localized or extends well upstream or downstream of the crossing. Possible conditions that may be present given this limited information include:

- Upstream channel aggradation is localized because of lack of culvert capacity. The channel further upstream is unaffected by the culvert and is reasonably stable.
- The upstream channel has aggraded for a long distance upstream because of the higher bed level near the culvert inlet.
- Downstream degradation is localized due to outlet scour or due to reduced supply from upstream but is not widespread.
- The channel downstream has widespread degradation due to substantially reduced sediment supply from upstream.
- The channel downstream has widespread degradation due to downstream base level lowering that has resulted in a headcut or knickpoint migrating upstream to the culvert outlet. The culvert is acting as an unintended grade control for upstream bed levels.

Because culvert hydraulic analyses often include minimal upstream and downstream surveys, additional field evidence and analyses are useful for understanding sediment transport implications of culvert replacement. Determining the likely cause and effect for this channel and culvert crossing starts with stream reconnaissance and interpretation. This culvert creates a discontinuity in hydraulics and sediment transport making it possible that either of the upstream conditions can occur with any of the downstream conditions, depending on the dominant processes. For example, a downstream headcut could be the cause of downstream degradation and the upstream aggradation could be either localized or system wide.

Figure 7.14 illustrates the results from sediment transport modeling of replacement of the culvert in Figure 7.13 with a culvert that: 1) has the hydraulic capacity to reduce backwater effects and 2) is embedded into the channel bed relative to the downstream bed. The modeling allows evaluation of a range of potential responses in the channel and water surface profiles and potential channel responses which include:

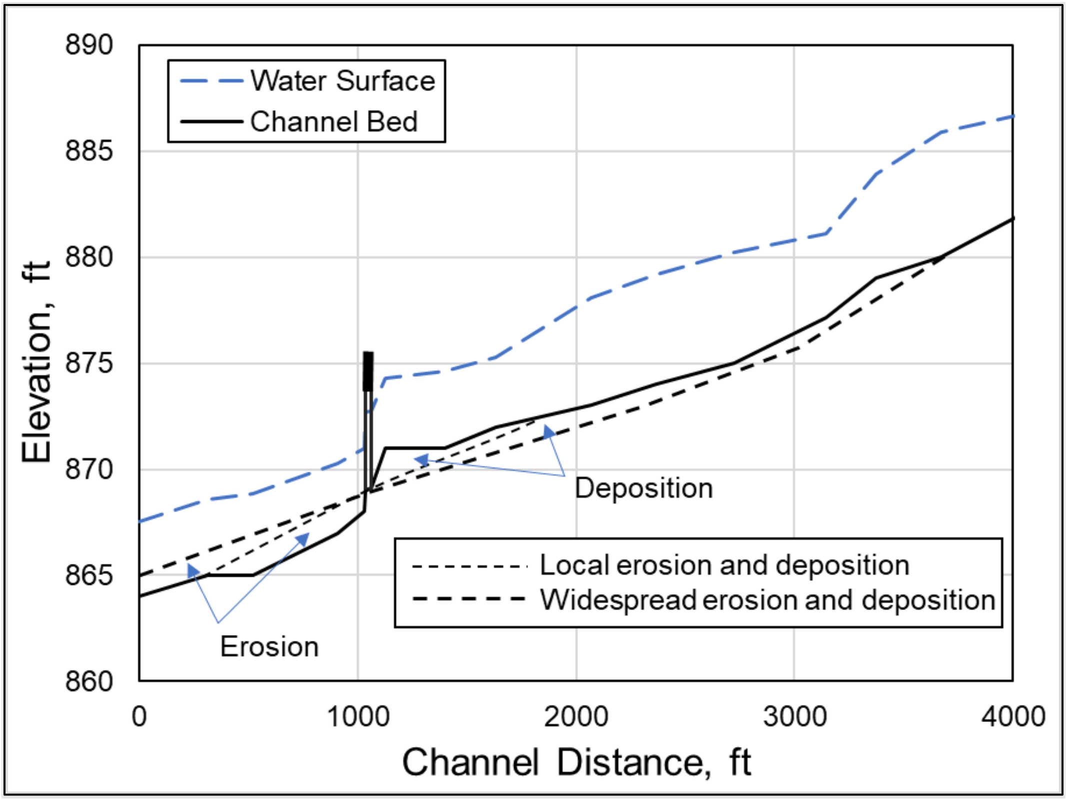


Figure 7.13. Long-stream channel bed and water surface profiles for a culvert with deposition upstream and erosion downstream.

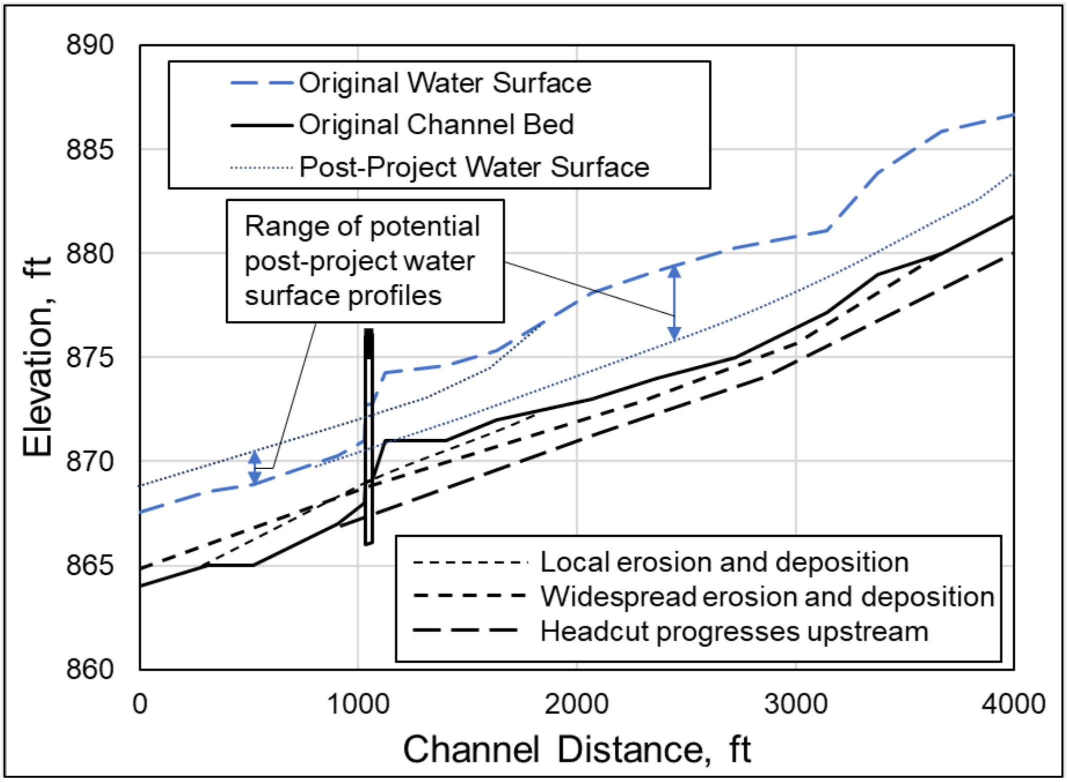


Figure 7.14. Potential channel and water surface response to culvert replacement.

Consider Looking Beyond the Right-of-Way

Culvert hydraulics computations are often performed with very short upstream and downstream reaches. Looking further up- and downstream to identify channel conditions and including stream profile information can enhance hydraulic (and sediment transport) analysis and may result in a final design that is more efficient and safer.

- The erosion and deposition were localized. The channel adjusts through the reach by transporting the excess material from upstream and depositing it into the downstream, previously scoured reach. The downstream water surface is minimally affected, but the upstream water surface is much lower because hydraulic capacity of the culvert is now larger and approach bed elevations are no longer artificially elevated above grade.
- The erosion and deposition were widespread. The new culvert lowers the base level and the channel bed lowers for thousands of feet upstream. If bed lowering is the only new source of coarse sediment, downstream deposition is limited. However, the bed lowering may be sufficient to destabilize the channel banks, producing a new source of fine sediment and substantially increasing deposition further downstream. As a result, aggradation my raise the water surface downstream and degradation may lower the upstream water surface over a longer distance.
- The downstream erosion was the result of a lower base level and a headcut or knickpoint that reached the original culvert outlet. The new culvert removes this control and headcut or knickpoint progresses upstream. Upstream bed lowering could be similar to, or more extensive than in the previous scenario. The eroded sediment may pass further downstream so that the downstream water surface is relatively unaffected (that is, morphologically, the reach downstream acts as a hinge zone). Alternatively, that reach may aggrade and experience higher water surface elevations because of the over-supply of coarse sediment from the degrading reach upstream.
- Although not depicted in Figure 7.14, removal of the unintended grade control function provided by the old culvert could allow additional headcuts or knickpoints generated by continued base level lowering from further downstream to progress through this system with similar, though greater, effects on the channel bed and water surface elevations.

Sediment transport modeling can be used to evaluate the probability of each of these post-replacement scenarios. To reduce the effects of boundary conditions on modeling results, it is important for the modeler to include sufficient upstream and downstream extents. If the boundaries are too close to the culvert, this may prevent the model from correctly simulating the full range of potential channel responses upstream or downstream. It is also important for the modeler to use representative bed material gradations and thicknesses, as well as representative hydrology, sediment supply, hydraulic controls, and bed level controls.

7.3.3 Long-Term Bed Changes

Long-term bed changes are often caused by sediment imbalances affecting river reaches or even entire fluvial systems. They can result from upstream basin changes in water or sediment supply, climate change, or from progressive changes in the downstream base level propagating upstream through head-cutting or knickpoint migration. Garcia (2008) indicates that 1D sediment transport models are most often applied to simulations involving extended river reaches and extended time periods, often to determine the long-term response of a river to natural or anthropogenic changes.

This is because of the lower computational demands of 1D models compared to 2D models. Currently, large-scale simulations covering hundreds of miles and decades of simulation time are generally the realm of 1D models, but 2D models are used for river sections of several miles and up to several years of simulation time.

Simulating long-term bed change can be complex considering the full range of sediment sources and sinks presented in Figure 7.1. Although a model may not simulate the processes involved explicitly, the modeler can estimate sediment inputs and losses associated with a variety of other sources and sinks and include them in the model. As illustrated below, long-term bed changes can be evaluated using a range of methods and may only involve extending over a relatively short river reach.

Long-Term Bed Change

Levels of analysis vary based on project risk, and can include:

- Bridge inspection cross-sections.
- Channel profiles.
- Equilibrium slope calculations.
- Gage records.
- Sediment transport.

Las Vegas Wash Example

One example of a long-term bed change study addressed channel degradation in Las Vegas Wash, originating in Las Vegas, Nevada and draining to Lake Mead. Historically, flow in the wash was ephemeral, but became perennial with increasing wastewater discharges. The increased flows, low sediment supply, and lowered water levels in Lake Mead combined to cause severe bed degradation.

Routine inspections of the State Route 147 bridge crossing Las Vegas Wash revealed substantial channel lowering of approximately 30 feet between 1970 to 1999. Other evidence of severe degradation came from graffiti observed high above the channel bed as shown in Figure 7.15. The FHWA evaluated long-term lowering potential using simple equilibrium slope calculations as described in HEC-20 Section 6.4, which indicated that an additional 40 feet of lowering was possible from then-current 1999 conditions. Equilibrium slope calculations determine the channel slope that produces a sediment transport capacity equal to the sediment supply. Although these calculations provide an estimate of a future channel slope, they do not indicate the rate of channel adjustment to a new equilibrium condition.

With the simpler equilibrium slope approach generating an extreme result, the project team developed a sediment transport model to provide an independent estimate of the degradation potential and the time to reach equilibrium. The model extent was 2.4 miles from Lake Las Vegas into the pool of Lake Mead. The project team measured bed material gradations and estimated sediment loads based on the amount of sediment removal during a repair of the flow and sediment bypass tunnel around Lake Las Vegas. They developed a long-term hydrograph with a constant base flow and several historical flood events. As shown in Figure 7.16, the model indicated more than 30 feet of bed lowering at the bridge in about 10 years (1999 to 2010), at which point the channel profile would stabilize. To prevent this outcome and protect the bridge, the FHWA designed and built grade control structures on Las Vegas Wash.

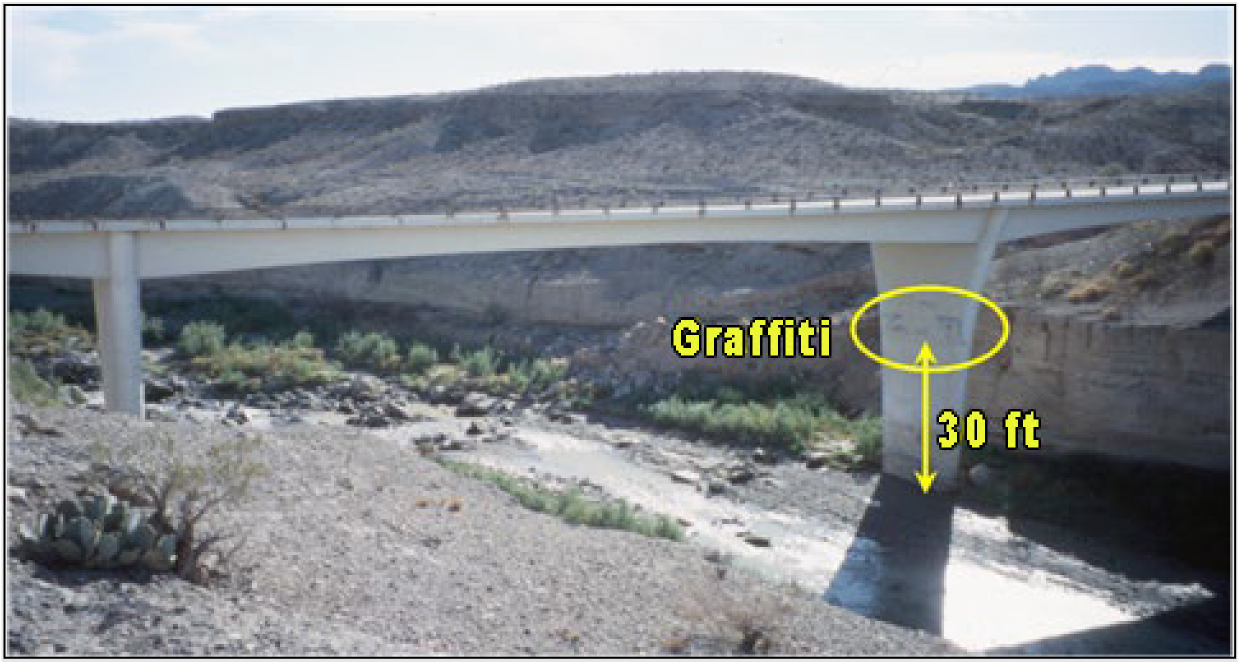


Figure 7.15. Degradation at State Route 147 over Las Vegas Wash, Nevada in 1999.

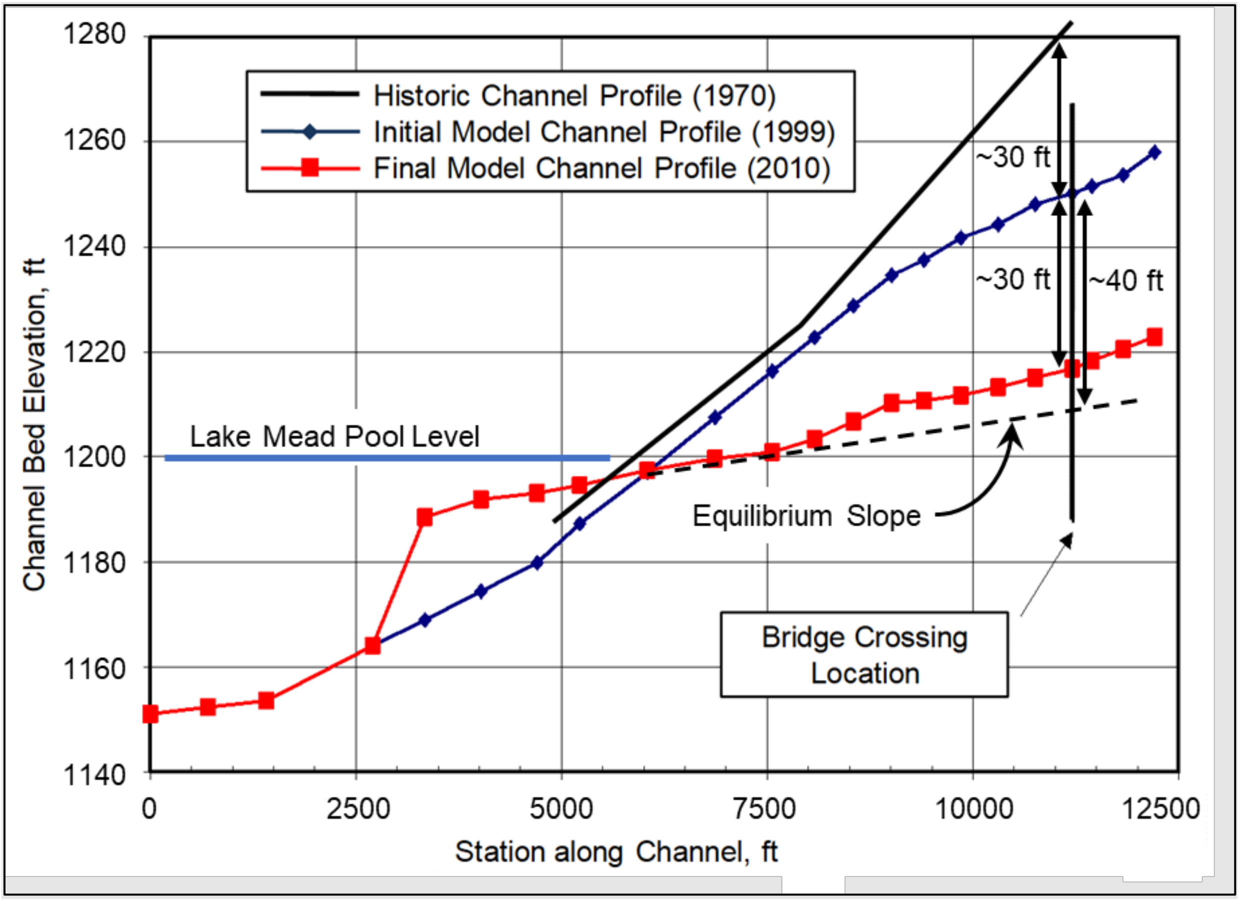


Figure 7.16. Channel profiles from a sediment transport model of Las Vegas Wash, Nevada.

Although the grade control structures achieved their objective of protecting the bridge, channel degradation downstream of the grade control structures eventually exceeded the earlier estimates. This was likely caused by decreasing water levels of Lake Mead, which continued to lower the base level. The project team addressed this degradation with additional grade control, further illustrating the value of ongoing bridge and project monitoring. Had the continued lowering of water levels in Lake Mead been anticipated, the sediment transport modeling likely would have shown that additional structures would eventually be warranted. Collectively, the range of analyses identified that future degradation posed a serious risk to the bridge and continued monitoring is now used to identify whether additional actions are justified.

7.3.4 Dynamic Stability

In their natural state, rivers are self-formed, and their dimensions, cross-sectional shape, and planform pattern are adjusted to current flow and sediment regimes, plus key biological processes. As described in Section 2.2.2 this state can be described as dynamic equilibrium or dynamic stability. Compared with a static channel, dynamic stability accommodates frequent, local changes in hydrology, sediment transport, and biology that provide habitat diversity and ecosystem resilience.

Stream restoration is an important application where “the hydraulic design of a stream restoration project should provide for a channel that is in dynamic equilibrium with its sediment load” (Copeland et al. 2001). In addition, providing opportunities for the river to maintain dynamic equilibrium by allowing channel properties to adjust to maintain overall flow and sediment continuity is beneficial at highway crossings by reducing long-term maintenance costs (refer to Figure 2.16).

Simulating dynamic stability in sediment transport and morphological models can be a difficult task. Ideally, these models include:

- Detailed geometry to capture the potential range of channel variability.
- Long-duration simulation to capture the range of flows and flow sequencing.
- Short time steps to capture flow variability and local channel adjustments.
- Other physical and biological processes that enable or resist channel change.

Although 1D models can be developed with great geometric detail, they rely on hydraulic averaging within a cross-section and other simplifying assumptions. These simplifications mask localized effects that may be important. Therefore, modelers often rely on 2D models for simulating dynamic stability.

Because of the complexity of dynamic equilibrium and the difficulty of capturing this complexity in computer models, simplified methods have been developed. Soar and Thorne (2001) describe two simplified concepts for maintaining or enhancing river functions: 1) balancing the sediment supply with the local sediment transport capacity and 2) allowing the channel space to adjust.

While the concept of working with a single, dominant discharge is attractive, it neglects the geomorphic role of the range of flows in forming and maintaining dynamic stability (Soar et al. 2013). To consider a wider range of flows, Soar and Thorne (2001) proposed the Capacity Supply Ratio (CSR) and Bledsoe et al. (2017) developed a spreadsheet design-support tool implementing CSR. The CSR is the ratio of the total bed material load transported by the historic sequence of flows in the design reach compared to that in the sediment supply reach immediately upstream, i.e., dynamic stability. A CSR equal to one indicates long-term sediment balance, even if the amount of sediment transported by any individual discharge may not be in balance. While individual flows result in local and temporary deposition or erosion, over the range of flows sediment input and capacity are balanced and the reach neither aggrades nor degrades. When the supply reach and design reach have the same properties (channel dimensions, shape, slope, sinuosity, and floodplain characteristics), the CSR equals one, but other channel configurations may also result in a CSR equal to one.

The CSR, a Level 2 spreadsheet tool (Bledsoe et al. 2017), uses simplified trapezoidal cross-sections, uniform valley slopes, and normal-depth hydraulics for the channel and floodplain to calculate sediment transport capacity over the flow record. The steps in the spreadsheet are:

1. Calculate the total sediment transport for the supply reach.
2. Develop alternative sets of theoretically stable channel widths in the design (project) reach (i.e., with the same total sediment transport capacity as the supply reach) by varying channel slope.
3. Select a suitable, dynamically stable channel width, based on constraints and preferences in the project reach. These can include available right-of-way, existing or planned infrastructure, valley slope and desired values for channel slope, width, depth, sinuosity, or meander belt width.

Table 7.2 presents a summary of the properties for an example supply reach and two possible solutions for the project reach downstream. The median sediment size is 0.5 mm. In this example, the supply reach has a depth of 8.6 feet and the design reach has a depth of 5 feet. The supply reach has a width of 103 feet width and a slope of 0.00054 while the two solutions have about the same slope, but narrower widths. The spreadsheet tool also provides information on the effective discharge and the discharges below which 50 percent and 75 percent of the sediment is transported (Q-s50 and Q-s75).

Table 7.2. Summary of reach properties with CSR = 1.

Reach	Supply	36-ft Solution	88-ft Solution
Channel Depth (ft)	8.6	5.0	5.0
Channel Width (ft)	103	36	88
Channel Slope	0.00054	0.00057	0.00052
Channel Sinuosity	Unspecified	1.15	1.24
Q-effective (ft^3/s)	1750	700	1750
Q-s50 (ft^3/s)	1590	1200	1570
Q-s75 (ft^3/s)	2573	1900	2430

Figure 7.17 shows an example of the application of the CSR spreadsheet tool over a range of combinations of channel width and slope that result in a CSR equal to one including the two in Table 7.2. As shown in the figure, it is theoretically possible to design a channel less than 20 feet wide to balance upstream sediment supply provided the design channel slope is greater than 0.0008. However, if a slope is greater than the valley slope, then this design solution is not feasible. Channel design slopes flatter than the valley slope in the project reach indicate the sinuosity to be specified in the design (i.e., channel sinuosity equals the valley slope divided by the design slope). Each of the channel combinations in Figure 7.17 have the potential to provide sediment continuity through the reach, provided space is allowed for the stream to adjust and accommodate variability in flow and sediment inputs.

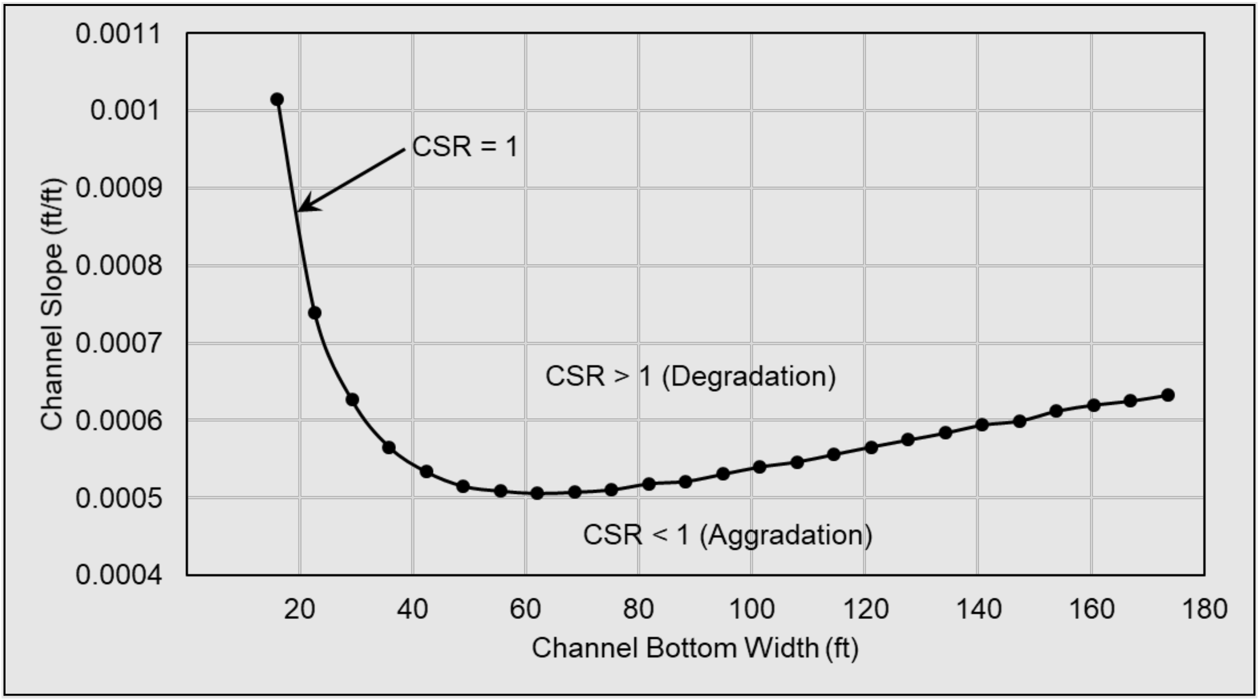


Figure 7.17. Example of dynamically stable widths and slope combinations generated using the CSR design tool.

Each of the channel alternatives depicted in Figure 7.17 has the potential to convey the sediment supply over the long term. However, the long term could include periods of aggradation or degradation as shown in Figure 7.18. The 36-ft channel has a substantially lower effective discharge and lower 50 percent and 75 percent quantile sediment transport flows than the supply reach as was summarized in Table 7.2. The effective discharge for a design width of 36 feet in the project reach is 700 ft^3/s, compared to an effective discharge of 1750 ft^3/s for both the supply reach and an 88-ft wide design reach. Sediment transport effectiveness is determined by the quantity of sediment transported by a designated range of flows. Figure 7.18 shows that for the 36-ft channel, flows less than 1800 ft^3/s are much more effective in transporting sediment than larger flows. Although the larger flows have higher sediment transport rates, the lower flows have much longer durations.

The CSR method allows for different channel widths in the design and supply reaches, to account for other project constraints. Although the CSR theoretically equals one for the 36-ft wide channel, Figure 7.18 shows that bed scour associated with the relatively high transport capacity of the 36-ft wide channel during low flows is balanced by net sediment deposition during high flows. Therefore, this design solution would likely create substantial seasonal variability in bed elevations that may be unacceptable in the vicinity of a highway crossing. The 88-ft wide alternative, which more closely matches the supply reach width of 103 feet, might make it the preferred option. When selecting the preferred option, the designer seeks to meet all the constraints and preferences, while allowing the channel to adjust and evolve over time within its band of dynamic stability.

Although the CSR spreadsheet is a useful tool, the simplified representation of the supply and design channels may not adequately represent hydraulic conditions. Since sediment transport is sensitive to minor misrepresentations of flow hydraulics, especially velocity, more detailed hydraulic modeling may be warranted. Consequently, supply reach hydraulics can be improved by averaging conditions based on several cross-sections from a hydraulic model of the study reach and developing a single, representative cross-section to mimic the reach-average results. However, a design channel from the CSR analysis is just the starting point, from which it is expected that the cross-sectional geometry, slope, and sinuosity can adjust and evolve within a dynamically stable band (see Figure 2.16). Vegetation plantings and nature-based solutions like those discussed in Section 4.6.1 can be used to minimize lateral shifting, while not attempting to fix the bank lines or constrict the channel planform.

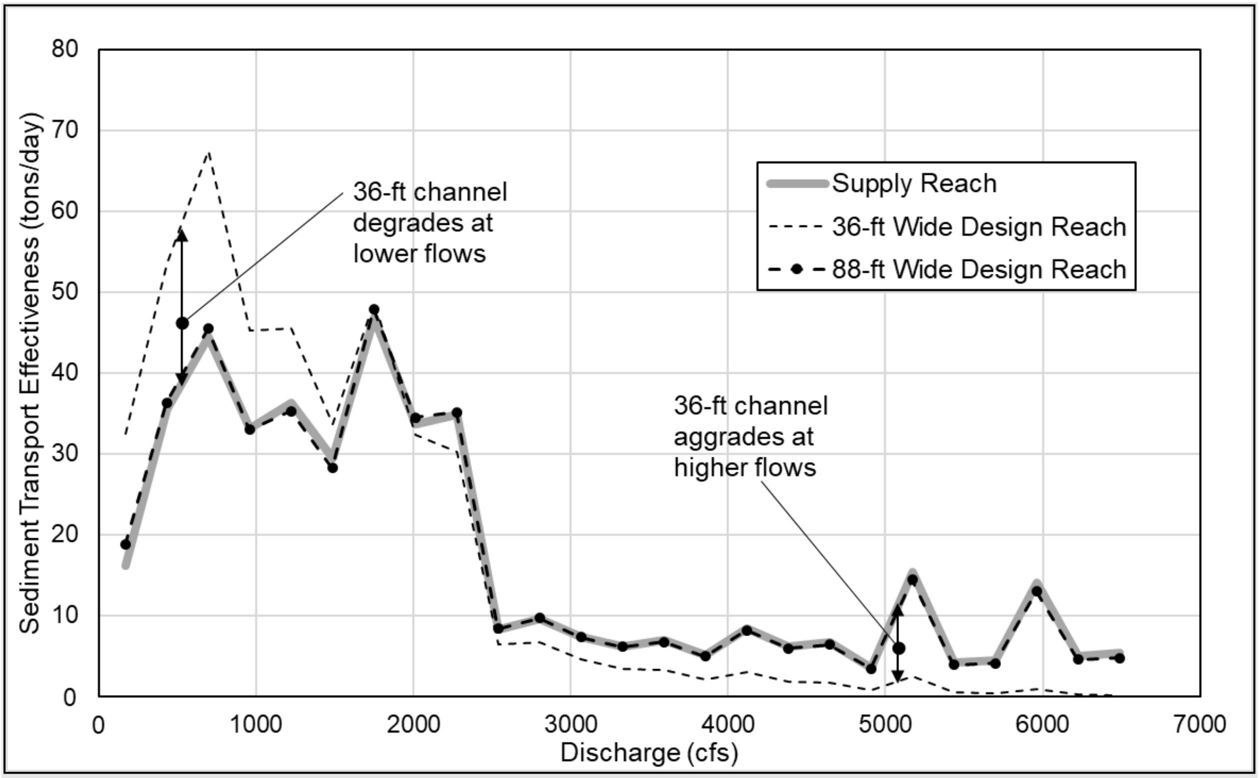


Figure 7.18. Sediment transport effectiveness for supply reach and two design reach solutions using the CSR design tool.

7.3.5 Planform Evolution and Metamorphosis

Section 6.3 describes qualitative methods for performing lateral migration analyses including meander belt delineation and identifying the channel migration zone. Although these methods do not predict when a channel is likely to migrate to a specific location in the floodplain, they provide information on areas recently occupied by the channel and areas that could be occupied in the future. A more quantitative approach for making predictions of channel migration is through map and aerial photo comparisons based on the approach developed by Lagasse et al. (2004) and discussed in Section 6.3 and HEC-20 Section 6.3 (FHWA 2012a).

The approach identifies past channel migration trends using overlays of historical channel locations, to extrapolate future rates of migration and channel alignments assuming historical stream hydrology, erosion processes, and bank properties persist into the future. The approach can be tested by using earlier images, say 1950 and 1980 aerial photos, to predict a more recent condition, such as 2015. With this validation, all the images can be used to extrapolate future conditions.

However, just as bed aggradation and degradation affect hydraulic variables, channel migration can change channel sinuosity, producing feedback that affects hydraulic variables related to sediment transport and bank erosion. This feedback is not accounted for in the overlay method nor are the effects of land-use change or climate change. For example, increased discharge increases stream power, which would be expected to increase the channel migration rate.

To address these limitations, researchers have developed equations and software to simulate channel migration. Examples include the RVR Meander Toolbox (Amad and Garcia 2006) and MEANDER (Briaud et al. 2007, Briaud et al. 2014). These programs simulate meander migration based on solution of the hydraulic equations that drive bank erosion. The erodibility of the material is characterized by an empirical erodibility coefficient or function. Different flow rates or long-term hydrographs can also be simulated. The MEANDER program does not make a deterministic prediction of future bank line coordinates, but produces a probability function of bank line locations as illustrated in Figure 7.19.

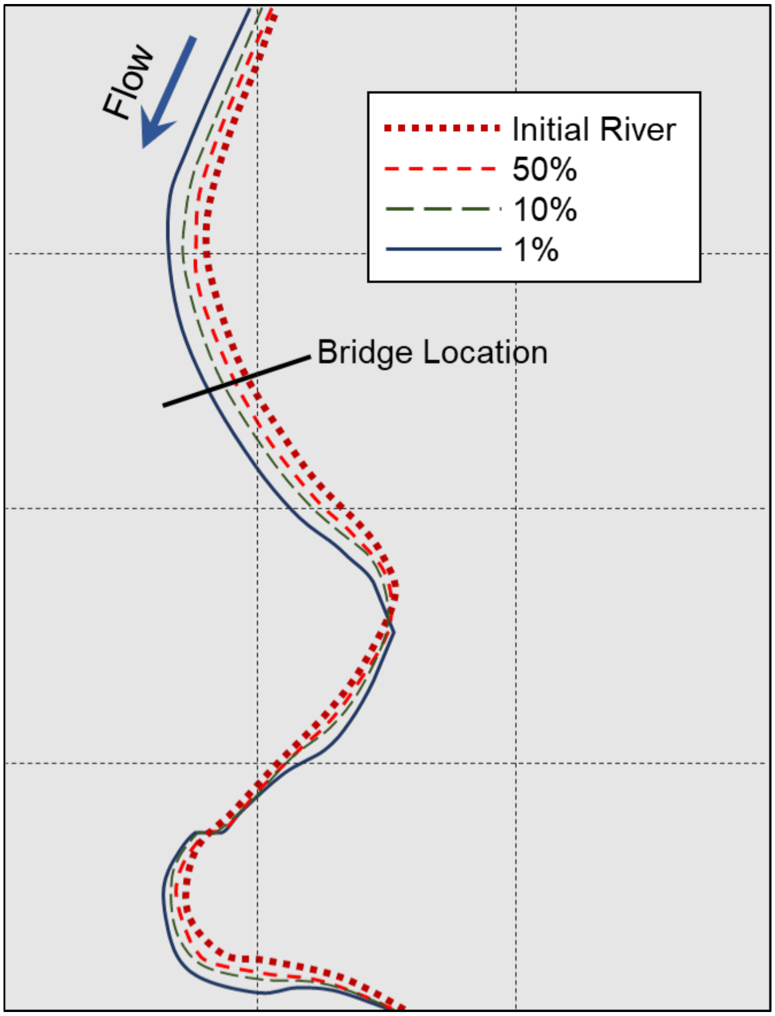


Figure 7.19. Future outside bank line probabilities from MEANDER program. Adapted from Briaud et al. (2007).

These models make several simplifying assumptions. RVR Meander (Abad and Garcia 2006) assumes a constant channel width, a single set of sediment characteristics, and a single, constant "channel-forming" discharge, and includes no formulation for channel cutoffs. MEANDER (Briaud et al. 2007) uses a long-term flow series that can accommodate the addition of extreme events. In both cases the channel migration process is treated primarily as an erosion process. Bank erosion is often related to geotechnical failure of unstable banks resulting from toe erosion, channel incision, and soil saturation. Once the bank collapses, the material is removed and transported downstream. The newly exposed bank material likely has different erodibility than the original bank material. The erodibility parameters for MEANDER can be determined from material erodibility testing and calibrated based on historical migration rates (Briaud et al 2014) and are assumed to be spatially consistent.

River meander shifting is an important consideration for transportation planning and design, so these types of analyses can provide valuable information to transportation projects, although not all channel change is gradual or incremental. Channels can also change dramatically in response to extreme loads or a change in planform type, such as from meandering to braided (termed planform metamorphosis). Sudden shifts may be triggered by changing flows, sediment loads, and upstream cutoffs, especially on alluvial fans. Section 5.5 of HEC-20 (FHWA 2012a) includes information on conditions that can transform a channel from one type of planform to another.

7.4 Sediment Transport Functions and Models

As explained in Section 2.1.2, the mobilization and transport of an individual sediment particle by a stream depends on a multitude of factors and the complex interactions between them. Mobilization and transport are further complicated by the sediment materials with varied particle sizes and size distributions; particle sources; variabilities in the near-bed, micro-scale hydraulics; and environmental factors. These complexities quickly make numerical solution of the relevant force-balance equations unmanageable even for powerful computers. For this reason, there is no single, unifying theory of bed sediment mobilization and transport that can be applied in all situations.

Nevertheless, mobilization and transport of an individual particle contributed from the stream bed are customarily expressed as a simple function that balances motivating forces applied to the particle by the flow, against the resisting forces as illustrated in Figure 2.6. Researchers have developed empirically based relationships based on physical processes to predict bed mobilization and bed material transport rates reasonably well when applied in specific situations. To be successful in sediment modeling the modeler selects the sediment transport equation(s) for the size and characteristics of the stream and bed material. Many resources are available to support the modeler making this selection (e.g., Copeland et al. 2002).

Software developers usually incorporate multiple bed material mobilization and transport functions into hydraulic and sediment models, providing users with a range of powerful analytical tools from which to choose wisely. Different equations often produce substantially different sediment transport rates for the same hydraulic and sediment conditions. To produce sediment movement rates and morphological model results that are well founded and reasonable it is important for the modeler to understand some of the details of the different transport equations and limitations on the stream and sediment contexts for which they may be reliably implemented. This section provides background and context for some common transport equations and model platforms to help users make more informed decisions when performing sediment transport analysis.

7.4.1 Computer Models

Table 7.3 summarizes widely used non-proprietary computer models capable of simulating sediment transport and associated bed elevation changes. These models (termed platforms) were developed by non-profits and governmental agencies and are free to use and suitable for both practical and research applications. The FHWA (2019a) provides general information on 2D hydraulic modeling. Other models and platforms have been developed by commercial companies and are proprietary.

Table 7.3. Non-proprietary sediment model platforms.

Platform	Developer	Sediment Modeling Capability	Reference
HEC-RAS	USACE	1D	www.hec.usace.army.mil
SRH2D	USBR	2D	www.usbr.gov/tsc
AdH	USACE	2D	www.erdc.usace.army.mil

The U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center "River Analysis System" (HEC-RAS) can simulate quasi-unsteady and unsteady sediment transport in 1D. Most modelers are familiar with the interface and extensive reference information is available for the sediment transport functions. HEC-RAS provides the user access to some input parameters used in the sediment calculations.

The U.S. Bureau of Reclamation (USBR) Sediment and River Hydraulics – Two-Dimension (SRH2D) model supports 2D sediment modeling. While this model is freely available, it is often used with an interface called the Surface-Water Modeling System (SMS) for setting up inputs and viewing results. SRH2D has the capacity to simulate river hydraulics at infrastructure including culverts, bridges, and gates. Sediment functionality at other structures is in development.

The U.S. Army Engineer Research and Development Center (ERDC) in Vicksburg MS (formerly the Waterways Experiment Station) has developed the Adaptive Hydraulics Modeling System (AdH). This powerful platform has yet to be applied widely in designing highway crossings and transportation-related river training works.

7.4.2 Transport Functions

Sediment is transported as bed load, suspended bed material load, or wash load. However, not all these transport mechanisms are equally important or even included in available transport functions. The importance of some transport mechanisms is illustrated by considering that in transport reaches and response reaches with laterally connected floodplains, wash load moves through the channel but does not deposit there. In these circumstances, lack of appreciable interaction between wash load and channel form means wash load can be frequently omitted when using numerical modeling to assess geomorphic change or to predict morphological response to construction or upgrading of a highway. Conversely, in response reaches that are artificially disconnected from their floodplains, wash load (usually 80 to 90 percent of the total sediment load) that is prevented from depositing in and being stored on the floodplain may accumulate in the channel, especially during the falling limb of the flood hydrograph. Under these circumstances, simulating wash load dynamics may be warranted if a crossing creates recirculating dead zones or creates upstream backwater reducing velocities. Fine-grained sediment that would typically be treated as wash load is also modeled in situations where it may be present in hyper concentrations.

Cohesive Material Erosion and Transport

Sediment particles smaller than 0.0625 mm, commonly referred to as silt and clay, are often treated as cohesive. Particles this small are generally transported as wash load and can frequently be ignored in riverine systems. Additionally, most transport functions were not developed to consider cohesive particles. Cohesive sediment erosion can be simulated, however, and is done commonly based on the approaches developed by Krone (1962), Partheniades (1965), and Briaud et al. (2011). The erodibility of cohesive soils varies considerably so material testing is recommended (Briaud et al. 2011, FHWA, 2012b). Platform-specific reference material provides details on specific input parameters.

The bed material load usually makes up only 10 to 20 percent of the total load, but it is disproportionately important to channel morphology and response to disturbance. When evaluating the bed material load, the relative contribution of bed load to suspended bed material load is an important criterion for selecting a transport function. Most transport functions predict either the total bed material load (bed load plus suspended bed material load) or just the bed load (see Figure 7.3). In this discussion of transport functions, total load and bed material load are treated as equivalent because the wash load is not included.

Table 7.4 lists ten total load functions and four bed load functions available in the most widely used computer platforms. Together, the functions represent decades of research and development that continues today. Most of the total load functions are intended for sand bed rivers where the majority of bed material transport is in suspension. Bed load functions are generally intended for gravel/cobble-bed systems where channel morphology and change are mostly influenced by the movement of particles too large to move in suspension. Functions for rivers that transport a mixture of sand and gravel/cobble also exist, though these functions are still classified as predicting the total load or only the bed load. Special transport equations are used for steep, boulder-bed streams, where the size of the bed material is on the scale of the depth of flow and the bed shear stress theory that underpins most transport functions is not applicable.

The selection of the most appropriate transport function for a sediment transport analysis is constrained by the preferred modeling platform as not all functions are available on all platforms. With the platform determined, the modeler considers the composition of the sediment transported and the channel size to select the appropriate function. Table 7.5 presents a summary of the data used in the development of the available functions. In many cases, several functions appear appropriate for a specific application and there is rarely an obvious choice. In selecting a function, modelers therefore refer to the manuals that accompany each modeling platform and when warranted, to cited publications for more information.

After determining an appropriate transport function, the modeler may benefit from becoming familiar with its characteristics to be aware of how any inherent shortcomings may lead to unreasonable results. It may also be helpful to consider how adjusting the parameters associated with each function may affect results. Sediment functions cannot account for factors such as the effects of vegetation, biological processes, and seasonality that are known to influence transport behavior in natural streams (Johnson et al. 2011, Rice et al. 2016). Brief descriptions of each function follow.

Table 7.4. Commonly available sediment transport functions.

Transport Function	Model Platform	Transport Type*	Optimal Sediment Size
Ackers and White (1973)	HEC-RAS	Total Load	Mixed
Engelund and Hansen (1967)	HEC-RAS/SRH2D	Total Load	Sand
Garcia-Parker (1991)	AdH	Total Load	Sand
Laursen-Copeland (1989)	HEC-RAS	Total Load	Mixed
MPM (1948)	HEC-RAS/AdH	Bed load	Gravel
MPM-Wong and Parker (2006)	HEC-RAS/SRH2D/AdH	Bed load	Gravel
Parker (1990)	SRH2D	Bed load	Gravel
Toffaleti (1968)	HEC-RAS	Total Load	Sand
Wilcock-Crowe (2003)	HEC-RAS/SRH2D/AdH	Bed load	Mixed
Wright-Parker (2004)	AdH	Total Load	Sand
Wu et al (2000)	SRH2D	Total Load	Sand
Van Rijn (1984)	AdH	Total Load	Sand
Yang (1973 and 1984 combined)	HEC-RAS/SRH2D	Total Load	Mixed
Yang (1979)	SRH2D/AdH	Total Load	Sand

*Total load is a contraction of “total bed material load,” – i.e., the sum of the suspended bed material load and the bed load.

Ackers and White (1973) is a total load function that was derived theoretically by using dimensional analysis and then verified with flume experiments. Values for Threshold Mobility (A) and transport formula coefficient (C) and exponent (m) were fit based on experiments incorporating dunes, ripples, and plane bed conditions. Updates to the coefficients by HR Wallingford (1990) and the original author Ackers (1993) were made as additional data from natural channels became available. HEC-RAS provides the ability to change these values.

Engelund-Hansen (1967) is a total load function that was developed for sand-bed streams. It is based on average velocity, slope, depth, and median grain size and does not incorporate a critical value for incipient motion resulting in transport under all conditions. It is best used for small to medium sized rivers (e.g., Niobrara River, NE; Rio Grande, NM), as it tends to over-predict transport for large rivers with high flows (e.g., lower Mississippi River, MS/LA).

Garcia-Parker (1991) is a total load function developed from data from small to medium-sized sand-bed streams where suspended sediment is the dominant form of transport. It was developed based on uniform sediment in flume experiments and then generalized using field data to include a hiding function to handle a mixture of sediment sizes. It is not recommended for large rivers.

Table 7.5. Hydraulic and sediment data used in transport function development.

Transport Function	Size range (mm)	Velocity (ft/s)	Depth (ft)	Slope
Ackers and White (1973)	0.04 – 7.0	0.07-7.1	0.01-1.4	0.00006 – 0.037
Engelund and Hansen (1967)	0.19-2.5	0.65-6.18	0.30 – 1.13	0.00007- 0.00102
Garcia-Parker (1991)	0.009 – 0.217	0.6 – 6.4	0.1 – 2.6	0.00061 – 0.01487
Laursen-Copeland (1989)	0.011 – 29	0.068-9.4	0.03 – 54	0.0000021-0.025
MPM (1948) and MPM-Wong and Parker (2006)	0.4 – 29	1.2 – 9.4	0.03 – 3.9	0.0004 – 0.02
Parker (1990)	2 – 203	n/a	0.036 – 1.46	0.0083 – 0.01
Toffaleti (1968)	0.062 – 4	0.7 – 7.8	0.07 – 56.7	0.000002 – 0.019
Wilcock-Crowe (2003)	0.21 – 64	0.8 – 4.1	0.29 – 0.40	0.00059 – 0.0204
Wright-Parker (2004)	0.062 – 4	0.7 – 7.8	0.07 – 56.7	0.000002 – 0.019
Wu et al (2000)	0.05 – 60	1.6 – 2.5	0.6 – 1.7	0.00449 – 0.00693
Van Rijn (1984)	0.32 – 1.5	1.0 – 4.2	0.33 – 3.3	n/a
Yang (1973) Sand	0.15 – 1.7	0.8 – 6.4	0.04 – 50	0.000043 – 0.028
Yang (1984) Gravel	2.5 – 7.0	1.4 – 5.1	0.08 – 0.72	0.0012 – 0.029
Yang 1979 (total load)	0.15 – 1.7	0.8 – 6.4	0.04 – 50	0.000043 – 0.028

Laursen-Copeland (1989) is a total load function of excess shear and the ratio of shear velocity to fall velocity. Laursen’s (1958) original work was based on data from sand-bed streams and flumes. Later work by Copeland generalized the function to include gravels up to a median size of 29 mm. Like the original Laursen (1958) function, the Laursen-Copeland function works well for silt-sized particles as well as sand and gravel. Copeland and Thomas added a hiding function that reduces shear that can mobilize coarser particles and increases the critical shear stress for mobilization of finer particles.

Meyer-Peter Müller (MPM) (1948) is a foundational bed load function that works well for particles larger than sand. It was derived empirically from flume data and calculates transport based on the difference between the shear stress applied to the bed and the shear stress capable of full mobilization (i.e., the excess shear). This results in no transport under low flow conditions and a rapid increase once mobilization begins. Implementations of this function for transport by size fraction that exclude a hiding function can produce excessive transport of finer fractions and limited transport of coarser fractions. The function works best for systems with large width-depth ratios. In the most recent published update, Wong and Parker (W-P) reanalyzed the same dataset, deriving alternative coefficients that assumed plane-bed conditions (2006).

In HEC-RAS, the default is to implement the original MPM coefficients with a correction to partition out shear stress due to form drag (to be consistent with earlier USACE modeling). HEC-RAS allows the modeler to use the W-P coefficients and remove the shear partitioning. SRH2D implements only the W-P values with no shear partitioning and includes the ability to choose a hiding function from 0.0 to 0.9 to approximate the effect sand has on the mobilization of larger particles. AdH allows for either the original MPM or W-P values. MPM is generally considered to underestimate transport of fine material.

Parker (1990) is a bed load function for gravel bed streams specifically developed to be used with sediment size data collected from the bed surface, as opposed to the subsurface. It has traditionally only been used when there is no sand (< 2 mm) in the bed surface, or the sand is excluded from the bed surface gradation for calculations. The function expands the excess shear concept introduced by MPM (1948) and introduces an empirically derived criterion for incipient motion and a hiding function to account for the difference in relative shear stress experienced by large and small particles distributed within a coarser matrix. SRH2D recommends Parker (1990) as suitable for sand and gravel mixed-bed systems.

Toffaleti (1968) is a total load function developed primarily for sand sized particles and is frequently applied to large rivers. As a simplification to Einstein's (1950) total load function, this formulation segments the water column into three sections (lower, middle, and upper) and computes the suspended load for each section. Bed load is calculated separately as a function of the lower zone suspended load, and it is combined with suspended load to determine the total load. For systems with a significant amount of gravel, Toffaleti's bed load relationship may not perform well. HEC-RAS provides the capacity to couple the suspended load functionality of Toffaleti with the MPM (1948) bed load function, which may work well for coarse-bed rivers.

Wilcock-Crowe (2003) is one of the most used bed load functions for systems with mixed sand and gravel. It was developed for use with surface-sampled sediment. The function is based on a series of flume observations and is a function like Parker (1990). It accounts for the observation that as the sand content in the bed increases, the critical shear stress that mobilizes the larger particles decreases. For this reason, the results are sensitive to the sand content in the bed.

Particles Hide? The Hiding Function

In streams with a wide range of sediment sizes, it may be appropriate to consider a transport function that incorporates a hiding function. A hiding function modifies the shear stress that can mobilize a particle size based on the prevalence of larger and smaller sizes in the bed. Distinct from bed sorting, which refers to the movement of sediment through the bed layers, hiding functions account for the fact that smaller particles are more likely to be embedded among larger particles and their critical shear stress for mobilization is increased. Conversely, larger particles can be more easily moved when surrounded by smaller particles that may act as "ball-bearings." Hiding functions have been incorporated in equations such as Parker (1990), Wilcock-Crowe (2003) and Garcia-Parker (1991).

Wright-Parker (2004) is a total load function developed for sand-bed systems. It is a re-evaluation of the original approach proposed by Engelund-Hansen (1967). It incorporates the Froude number and is appropriate for application from small to large rivers.

Wu et al. (2000) is a total load function that may be used for sand, small gravel, or a mixed bed. It calculates bed load and suspended load separately and incorporates a probability based hiding function to accommodate non-uniform sediment. SRH2D provides users with the option to adjust the critical Shields parameter from the default value of 0.03.

Van Rijn (1984) is a total load function composed of functions for computing bed load and suspended load of sand-bed systems. The bed load functionality was analytically derived based on the saltation height, particle velocity and bed load concentration of sediment and then calibrated against experimental data. The bed load serves as a reference for computing suspended load concentrations.

Yang (1973 and 1984) are total load transport functions that together are suitable for sand and gravel mixtures finer than 10 mm. Rather than relying on shear stress (i.e., the product of flow depth and energy slope) as the primary driver of sediment transport, Yang's functions use stream power (i.e., the product of velocity and energy slope) as the dominant independent variable. These functions have been shown to match well with field data from small to large rivers with high amounts of fine sediment. The gravel (1984) function may not produce reliable results for sediment coarser than fine gravel when appreciable amounts are present in the modeled river.

Yang (1979) is a total load transport function for sand-bed streams. This stream power-based function is like Yang (1973), but it does not include a criterion for incipient motion. Yang contends an incipient motion criterion is unnecessary once a minimum level of sediment transport is achieved. This function is therefore applicable to fine-grained streams where full mobilization is expected, and sediment concentrations are greater than 100 ppm by weight.

Bed Sorting: The Changing Nature of the Channel Bed

It is understood that deposition and erosion of sediment to and from the channel changes the elevation of the bed. What is less obvious is that these same processes also affect the composition of the surface and sub-surface layers which determine how much of each particle size class is available for transport at any instant in time. Bed sorting refers to the method of accounting for the exchange of sediment between the bed layers and the material being transported in the water column. The development of an armor layer, where a layer of larger particles shields the exposure of smaller particles underneath, is an observable example of bed sorting. Reference material for each model platform provides details of available approaches to represent this process.

Chapter 8 - Special and Regional Topics

Previous chapters in this manual provide nationally applicable information useful for understanding, assessing, and addressing interactions between river functions, river processes, and transportation infrastructure. This chapter addresses special or regionally relevant topics regarding hydrologic, hydraulic, sediment transport, and biogeomorphic processes associated with sustainable, resilient, and reliable transportation infrastructure in river environments with unique characteristics and challenges.

8.1 Coincident Flows at Confluences

Confluent waterways pose unique challenges. Roads may be affected by events in either one of the waterways, or by the combined effects of events in both the confluent waterways. Differences in hydrology, size, terrain, shape, and degree/type of human development between the contributing drainage basins may create several design challenges. For example, they complicate assessment of flows, hydraulics, and sediment dynamics not only at the confluence, but also for some distance upstream and downstream. Specifically, the magnitude, duration, and timing of runoff hydrographs may not coincide, creating challenges for establishing hydrologic design conditions. Tributary-mainstem interactions center on the confluence but their influences and effects extend along both the mainstem and the tributary waterway. Figure 8.1 illustrates an example confluence where the smaller Clackamas River joins the much larger Willamette River in Oregon.

Figure 8.1. Complexity at the Willamette River-Clackamas River confluence, Oregon.

A significant interaction may include a high flow event in the mainstem river creating a backwater condition in the tributary that slows velocities and reduces sediment transport capacity in the tributary channel. Conversely, a flood in the tributary when the mainstem channel is at base flow removes any backwater affecting the tributary, accelerating velocities and boosting sediment transport capacity in the tributary approaching the confluence. Imbalances between flows, velocities and sediment loads in the tributary and mainstem channels create conditions of local scour or deposition in the vicinity of the confluence, which can affect the stability of transportation infrastructure along either channel.

Coincident floods at a confluence create a different problem in that water levels in both the mainstem and tributary may greatly exceed those associated with the design flood calculated for either watercourse in isolation, and may result in less predictable patterns of inundation, scour, deposition, or bank erosion. It follows that complex hydraulics, sediment imbalances, and morphological changes at confluences can heighten risks to nearby transportation infrastructure.

Big Sioux River I-29 Bridge Failure

In 1962, one of the twin bridges carrying Interstate 29 over the Big Sioux River just upstream of its confluence with the Missouri River in Iowa collapsed. The failure occurred when a flood in the Big Sioux (55,000 ft^3/s) coincided with a low flow in the Missouri (5,000 ft^3/s). The large difference between flows in the tributary and mainstem rivers caused previously unrecorded velocities and bed scour in the vicinity of the bridge that led to failure of the piers. The bridge, which had been built in 1959, was closed to traffic when it collapsed.

A clear example of sediment deposition near a river confluence is shown in Figure 8.2. In this case, a flood on the Hood River deposited sediment and debris at the confluence with the much larger Columbia River. A large proportion of that sediment was deposited in the slow, deep flow in the mainstem backwatered by the Bonneville Dam, creating the extensive delta. The confluence delta extended some distance upstream along the Hood River, reducing conveyance capacity in the flood control channel and at bridges, leading to urgent dredging of the delta to restore acceptable conditions. Recognizing the potential range of coincident flow and sediment transport events at confluences and designing transportation infrastructure to accommodate potentially extreme impacts is key to developing resilient and sustainable transportation projects that encroach on tributary confluences.

8.1.1 Analysis Strategies

Planners and engineers apply a variety of strategies and tools to evaluate the potential interactions between tributary confluences and transportation infrastructure. The process begins by identifying the potential impact of flow interactions at a confluence on new or modified transportation infrastructure. If available, the engineer can review existing flood profile and elevation information, such as that provided by FEMA, to make an initial assessment of the potential extent of hydraulic influence of the confluence. If warranted and feasible, confluence-related risks to new highways can be avoided by routing the road outside the zone of hydraulic influence. The design of bridges, culverts, and road embankments that encroach into the area of influence can consider the associated hydraulic, sediment and morphological risk factors.

Figure 8.2. Delta formed in 2018 by flooding at the Columbia River/Hood River confluence in Oregon.

8.1.1.1 Tributary and Mainstem Flow Distributions

Hydrologists can compare the magnitude of tributary frequency estimates to the mainstem frequency characteristics to understand the relative significance of each flow source. Small tributary flows may be insignificant to the flow conveyance capacity of the mainstem channel. Conversely, the magnitude of the mainstem channel flows may have great significance to the transportation infrastructure located on small tributaries.

Hydrologists can qualitatively and quantitatively assess the potential for coincident flows at confluences. Qualitative assessment considers rain and snowfall patterns and the shapes, terrains, flashiness, and relative sizes of the contributing drainage basins. Similar basins affected by the same weather patterns may have comparable flow regimes and a high potential for coincident flows. If available, historic flow gaging records can be examined to identify the relative magnitude and time of peak flows along mainstem and tributary streams. Practical procedures for estimating the probability of coincident events are available for planning and designing highway projects at stream confluences (Kilgore et al. 2013).

8.1.1.2 Hydraulic Analysis

Engineers can model a series of scenarios made up of plausible combinations of coincident flow conditions to evaluate a range of potential situations that inform resilient design of transportation infrastructure near a confluence. Table 8.1 summarizes an example set of scenarios and the anticipated effects on sediment transport and geomorphology. Depending on the characteristics of the site, the engineer may focus on a subset of these that are of concern for the site or develop additional scenarios. The range of possible scenarios illustrate a diverse range of circumstances that can be important to consider in project development, whether it is planning to accommodate future land use conditions in confluent watersheds or consideration of flow regulation influences in conducting maintenance activities.

Table 8.1. Summary of possible confluence analysis scenarios.

Analysis Scenario	Mainstem Hydraulic Condition	Tributary Hydraulic Condition	Potential Geomorphic Conditions of Confluence
1	Low flow/Low stage	Low flow/Low stage	Mainstem and tributary: low velocity, low sediment transport, low deposition potential
2	Low flow/Low stage	High flow/High stage	Mainstem: low velocity, low sediment transport, high deposition potential Tributary: high velocity, high sediment transport conditions
3*	Low flow/High stage	High flow/High stage	Mainstem: low velocity, low sediment transport, high deposition potential Tributary: high sediment transport
4	High flow/High stage	Low flow/High stage	Mainstem: high velocity, high sediment transport Tributary: high deposition potential
5	High flow/High stage	High flow/High stage	Mainstem and tributary: high velocity, high sediment transport, ow deposition potential

*Special case of backwater effect on the mainstem caused by a downstream hydraulic control such as a dam.

8.1.2 Geomorphic Effects

As described in Table 8.1, the hydraulic effects of various coincident flows in mainstem and tributary channels directly influence the dynamics of sediment in the vicinity of the confluence. While confluences can be centers of long-term sediment deposition (in some cases in the form of alluvial fans), they may also be prone to incremental or episodic scour or bank erosion. In general, high sediment fluxes are associated with out of bank flows, but bankfull flows can drive rapid planform adjustments. The number of possible combinations of flood flows, sediment transport events, and morphological responses makes it difficult to anticipate and mitigate all potentially adverse impacts on transportation infrastructure near a confluence. Tributaries can also supply much coarser bed material that the mainstem can only mobilize infrequently. The resulting fan at the tributary mouth can direct mainstem flows to the opposite side of the mainstem river causing bank erosion.

When high flows are coincident, the general expectation is that sediment transport capacities and fluxes are high in both the mainstem and tributary channels, resulting in sediment moving through the confluence area with little deposition. When mainstem flow is high but tributary flow is low, backwater effects translate up the tributary. The likely result is deposition of some of the mainstem sediment load in the mouth of the tributary, with the finer fraction of that load (sand, silt, clay) predominant. The tributary is unlikely to contribute significantly to that deposition, however, as under this flood scenario it is not delivering much sediment to the confluence. When tributary flows are high and mainstem flows are low, velocities and sediment transport capacity along the tributary are maximized due to the absence of backwater effects from the mainstem flow, coupled with effective lowering of the base level for the tributary. Local bed scour and bank erosion in the lowermost reach of the tributary may add to the sediment load input from upstream, driving deposition of a tributary bar or even a delta in the mainstem as shown in Figure 8.2.

The precise timings, rates, amounts, and distributions of scour, deposition, bank erosion, and instability at a confluence are site specific, vary with discharge, and evolve (Riley et al. 2015). Local sediment dynamics and channel changes around confluences may pose significant hazards to the integrity and safe operation of nearby highway infrastructure.

A generalized understanding of sediment dynamics and channel changes at confluences can be acquired from available literature, for example Best and Rhoads (2008) and Rhoads (2020). These sources explain why confluences in alluvial rivers are often hot spots of sediment storage/release and associated channel adjustments. There are two main reasons for this. First, the sum of the sediment capacities of the two streams approaching a confluence is rarely the same as the capacity of the combined flow in the trunk stream downstream of the confluence. Second, sediment inputs from the confluent streams are often unsynchronized. For example, a big flood in one branch may flush sediment into the confluence, which remains there until the occurrence of a sufficiently large flood to move the deposited material downstream. While stored at the confluence, deposited sediment may cause local bank erosion and channel shifting at rates not experienced away from the confluence.

For example, Figure 8.3 illustrates how unsynchronized sediment inputs from the North and South Forks of the Toutle River, Washington, between 2009 and 2018 drove very high rates of bank erosion and channel evolution that shifted the entire confluence about a third of a mile upstream. Following the 1980 eruption of Mount St. Helens upstream, WSDOT located its highways and crossings outside the hydraulic zone of influence. This reduced risks to road users and transportation infrastructure related to confluence shifting. It also reduced expenditure on erosion countermeasures and maintenance that would otherwise have been incurred.

8.1.3 Habitats and Ecosystems

Confluences serve an important role in the ecology of a river network and the wider watershed. They are critical for long-stream connectivity in the river and tributary system and are often biologically active locations (Benda et al. 2004). For example, confluences provide opportunities for anadromous fish species to drift downstream to the ocean and navigate back to their natal streams, for migratory species to transit between winter and summer foraging areas, and for resident species to make use of a wide range of heterogeneous habitats within a relatively small area.

At confluences, tributary streams provide varied habitats and generate locally beneficial variations in temperature, water chemistry, nutrients, turbidity, sediment characteristics, and bed morphology that diversify habitats beyond those available in the mainstem. Conversely, tributaries can have detrimental effects on the mainstem by contributing dissolved or sediment borne pollutants (Blettler et al. 2016).

Many roads pass near confluences for good reason. In these situations, planners and engineers can avoid, minimize, or mitigate any unavoidable environmental impacts by recognizing the significance of habitats and ecosystems at confluences. Confluences also offer opportunities to restore valued river functions that have been damaged or lost through the unintended consequences of previous development and river management, including past highway projects.

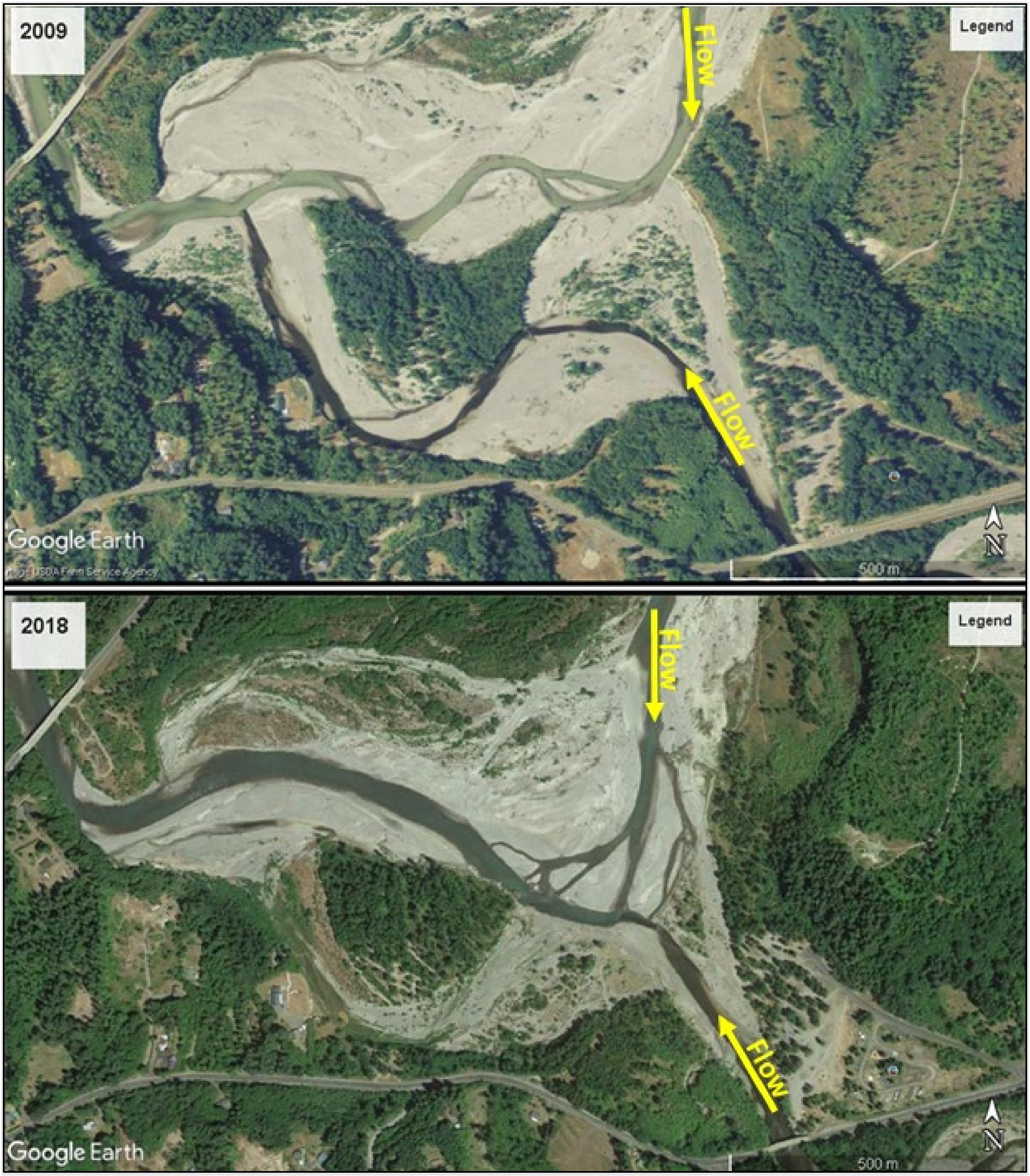


Figure 8.3. Bank erosion and shifting of the confluence of the North and South Forks of the Toutle River, WA. Highway crossings on both the mainstem Toutle and South Fork are just outside the confluence's zone of influence, avoiding confluence-related risks and the cost of erosion countermeasures.

8.2 Ice

Regions of the northern United States, generally latitudes above about 35 degrees, experience at least one month when the average air temperature is below freezing. The effects of lower temperatures may include the formation of ice on many rivers, during winter and breakup during spring. An example of an ice-covered river at a bridge crossing is shown in Figure 8.4.

Many bridges have failed due to the adverse impacts of ice (Cook 2014). Ice effects can manifest themselves through static loading (ice forces created by pressures of ice buildup on or against structures), dynamic loading (surges of water, ice, and debris released when cover or jams break up abruptly), or uplift caused by ice adhering to the structure and fluctuating water levels. As described in HEC-18, ice can also induce pressure flow conditions through a bridge that increase scour potential (FHWA 2012b).

Figure 8.4 Looking upstream along the ice covered Conococheague Creek at a bridge crossing in Williamsport, Pennsylvania. Source: J. Coleman (RK&K) and used by permission.

Figure 8.5 shows destruction of a bridge because of the buildup and movement of river ice. The presence of ice can sometimes block or divert river or stream flow creating flood hazards. The northern latitudes can also experience weather patterns that fluctuate markedly in air temperature and precipitation, thereby potentially creating icing and associated problems for road users.

Figure 8.5. In 2019, ice floes destroyed the Highway 281 bridge over the Niobrara River in Nebraska. Image used by permission of T. Miles (© 2019).

8.2.1 Direction of Flow

Most of the main watersheds of the contiguous United States (e.g., the Mississippi River), drain from north to south. Some watersheds drain north, east-west, or west-east, and some follow somewhat circuitous alignments, reflecting the underlying geology and terrain. For example, the upper tributaries of the Missouri River include rivers that approximately follow a line of latitude or veer northward. By contrast, practically all the major rivers of Siberia (e.g., the Ob and the Yenesi Rivers) flow northward because mountain ranges preclude other directions, and this is also the case for rivers like the Colville and Kuparuk in Alaska. River alignment is significant because it influences the character of ice-related processes, though not always in a consistent manner owing to fluctuating weather patterns. This is because latitude-orientation affects the nature of ice-cover breakup and the occurrence of ice-related surges that can flood communities in floodplains. Generally, North American rivers flowing north experience more ice-related problems than ones flowing south because breakup can occur upstream while frozen reaches still exist downstream leading to damming/jamming and backwater impacts. A well-documented example of this condition occurs in the community of Grand Forks, on the Red River (of the North) in North Dakota (Scully 2020). The Red River at Grand Forks flows north toward Lake Winnipeg, Canada.

8.2.2 Hydraulic Influence and Forms of River Ice

The seasonal appearance of river ice and freeze-up expands and modifies the relationship between flow, bed-material transport, and channel morphology over a range of scales in space and time, and its influence varies with the dimensions of the river channel. The flow of water in larger channels is less affected by the presence of ice cover. A relatively long, level ice cover, for instance, increases the wetted perimeter of flow in a channel, and thereby significantly increases the boundary resistance exerted on the flow. The relative increase of wetted perimeter diminishes as flow depth increases.

Locally, ice accumulated as an ice jam during spring breakup increases flow resistance by blocking and constricting flow. Increased flow resistance, by local constriction or increased wetted perimeter, increases flow depth (creating a backwater profile of gradually varied flow), alters velocity distributions, and modifies drag on the bed. For a given channel, the influence of ice on the bed and banks becomes more significant as water discharge increases. Increased discharge also accelerates the velocity of moving ice and increases the possibility of flooding. These factors usually invalidate stage-discharge relationships developed without consideration of ice for gaged river transects.

River-ice influences become more significant when water discharge fluctuates appreciably. The potential for additional adverse ice influences increases in a common cycle: 1) ice-cover breakup provides an opportunity for ice jamming that can dam the river and 2) the ice jam eventually releases causing a surge of water downstream and rapid drawdown upstream. Flow blockage and redirection caused by ice can result in scour of the channel bed (especially at bridges) and it may generate bank erosion along rivers formed in erodible sediments. Figure 8.6 depicts bank erosion and provides an example of ice abrasion where the ice has scarred the tree located near the top of bank along this channel. Erosion of channel or bank materials also can be caused by the physical abrasion of ice on the channel boundary during breakup and movement.

Anchor Ice

Anchor ice is attached or "anchored" to the channel bottom. Its presence changes the hydraulic properties of the channel because it usually lowers the hydraulic roughness of the bed and raises the effective bed surface elevation. These changes illustrate how the formation of ice, in general, complicates the hydraulic evaluation of river flows in the presence of ice.

8.2.2.1 Ice Runs

The term "ice run" is loosely used to describe the downstream drift of individual pieces of ice or pieces of ice that are jumbled together as "ice rubble." The former type of ice run may involve ice floes (relatively large, remnant pieces of ice cover). Drifting ice slush and ice pans may also be called ice runs and occur when ice cover first forms.

Severe ice runs result from the dynamic breakup of ice cover, and are associated with increased water discharge, because breakup usually occurs in response to increased discharge. Conversely, thermal breakup occurs when solar radiation and rising temperatures weaken ice. The severity of an ice run depends on several factors, including:

- The magnitude of water-discharge increase.
- The rate of increasing air-temperature relative to the rate of water-discharge increase.
- Ice-cover strength.

- The resulting sizes of ice rubble and ice floes relative to channel width.
- A channel's geographic orientation relative to latitude.

Figure 8.6. Photograph demonstrating the effects of ice abrasion. Image used by permission of Tetra Tech, Inc.

Channel geometry plays an important role in conveyance of ice rubble and floes moving along rivers as ice runs. Laboratory flume experiments and numerical simulations have established that the ratio of ice-piece width to channel width limits ice run conveyance. Conveyance decreases rapidly when the planform dimensions of an ice floe or rubble-mass exceed about 1/8 of the width of the flow passage (Lucie et al. 2017, Osada et al. 2020). Also, the presence of a shallow bar or crossing areas susceptible to ice grounding can reduce ice conveyance. Larger pieces of drifting ice rubble (ice floes) usually involve larger magnitudes of momentum, and therefore larger pieces or drifting masses of ice rubble are more likely to be jammed at sharp turns and bifurcations (around islands or bars) in channels.

In rivers with bridge crossings, ice-piece length is governed by the minimum span between bridge abutments or piers. The piers of multi-span bridges may slow or impede an ice run resulting from ice-cover breakup, as ice rubble and floes. They frequently lodge and accumulate against piers, and potentially form an arch of accumulated rubble and floes that entirely prevent ice from moving through the opening. Large ice floes can also significantly affect bars, banks, vegetation, and infrastructure in and along rivers (including highway encroachments) by applying significant shearing or impact forces. Riprap abutment protection and bank protection under ice conditions is much larger than is used based on open water conditions and may involve more frequent maintenance.

8.2.2.2 Ice Jams

Ice jams form at locations where runs of ice floes or rubble congest, accumulate, and stop moving. Ice jam locations depend on the typical dimensions and strength of the ice pieces/rubble and the effective width and morphology of the channel. Bridge openings that are significantly narrower than natural width of the channel and its functional floodplain can promote jam formation. In the case of multi-span bridges, the presence of bridge piers increases the likelihood of ice jam formation. Where pier-bound jams occur, bridge piles are likely to be subject to additional loading as they support the downstream end (toe) of the jam. Channel morphology may also facilitate ice jam formation where the local channel planform (e.g., presence of bends, shallow bars, or bifurcations at islands) promotes the formation of ice cover and runs. North-flowing rivers experience more severe ice jams because, as the weather warms, spring melting and ice runs both progress from south to north. Northward running ice from southern reaches runs into the still-intact ice cover further north, increasing the probability of jam formation, bridge blockages, damage to the channel bed and banks, and ice-related flooding.

8.2.3 Managing Ice-Related Risks at Road Crossings

As described in the previous section, road crossings that reduce channel capacity tend to reduce ice conveyance capacity because of approach roadway embankments, abutments, and piers and may be vulnerable to ice runs and ice jams. Road crossings with culverts are also vulnerable to ice jams because of reduced conveyance. Even bridges that do not significantly narrow the natural capacity of the river to convey ice runs may be susceptible to damage when impacted by significant volumes of ice moving at appreciable velocities as illustrated in Figure 8.5. In design locations where ice cover, runs, or jams have occurred in the past or could occur in the future, it is important for transportation project teams to consider:

- Ice loading (static and dynamic).
- Scour resulting from ice constriction. Blockages and flow confinement caused by ice can influence local scour and contraction scour conditions. The FHWA’s HEC-18 (2012b) provides detailed discussion of scour calculation procedures and approaches to considering ice in this process.
- Additional freeboard on bridge structures to compensate for reduced water conveyance capacity due to partial blockage by ice.
- Ice effects on riprap bank erosion protection including increasing the elevation of riprap extent to account for potential ice thickness above the design flow water surface.
- Potential effects on bioengineered riverbank protection structures. Karle (2007) found that bioengineered structures such as root wads would be damaged if subjected to direct impacts from large ice floes, but well-established willow brush layers work well in protecting the upper bank from ice damage on steep banks and are resilient in recovering from ice jam damage.

8.3 Wood in Rivers

As discussed in Section 2.1.3, wood in the river environment, especially in large pieces or logjams, provides a wide range of beneficial hydrologic, hydraulic, sediment, and ecological functions (Maser and Sedell 1994, Nagayama and Nakamura 2010, Roni et al. 2014, Whiteway et al. 2010, USBR and ERDC 2016). However, adverse interactions between large wood and highway infrastructure can result in unacceptable risks to people and property. HEC-9 presents methods for evaluating and mitigating the potential for wood to accumulate at bridges and culverts (FHWA 2005). There is no national consensus on how best to manage wood in rivers. First, natural wood loadings, as well as typical sizes and material properties of wood pieces, vary widely between ecoregions (Wohl et al. 2017). Second, the ways wood, flow processes, and channel forms interact vary between the headwater, middle-course, and lowland reaches (Kramer and Wohl 2017). Finally, perceptions of wood in rivers vary regionally (Chin et al. 2014). In-depth treatment of wood and its management is available in other references such as the *National Large Wood Manual* (USBR and ERDC 2016).

Regional differences in stream functions that are either provided or promoted by wood relate to the age (and size) of wood available in the landscape, connectivity between wood sources and streams, and wood mobility in the drainage network. Tree species composition and the characteristics of the riparian corridor dictate the numbers, sizes, and volumes of wood supplied to the channel. However, wood distribution within the channel, and its tendency to form natural logjams, mostly depends on the length of the largest pieces relative to the width of the channel (Fox 2003). For example, in narrow, coarse-bedded, headwater streams, relatively large trees act as “key pieces” to create channel-spanning underflow and dam-type jams that strongly influence channel form, slope, bed grain size, roughness, and stability as shown in Figure 8.7. Key pieces are also a factor for bridge design as span lengths can be set to reduce formation of woody debris spanning adjacent piers (FHWA 2012a, 2012b). Conversely, further downstream in large, gravel and sand-bedded watercourses wood forms deflector, bar-head, and flow-parallel jams, while natural wood cribs may form at the channel margins also shown in Figure 8.7. When large wood lodges and forms jams in these locations, it provides little grade control, but it does increase flow resistance and morphological diversity while reducing sediment mobility and retaining organic material. Lowland wood and jams can also alter channel planform, influence lateral stability, and increase channel-floodplain connectivity.

Wood enters river and floodplains in many ways that are continuous (e.g., individual tree mortality, incremental bank retreat, beaver activity) or episodic (e.g., severe weather and blow down floods, fires, landslides, snow avalanches, and debris flows). As a result, rates of wood supply vary. For instance, in the southern and eastern regions of the country, large quantities of wood can suddenly be delivered to a river during a hurricane, while in the West, high wood loadings may persist for years following a forest fire or major infestation. Landslides, snow avalanches, and debris flows can put huge numbers of trees into rivers in areas with high altitudes, steep terrain, and well-connected channel-slope systems.

Watershed development and resulting land-use changes affect wood loadings in multiple ways. Clearing old-growth or mature, second growth forest reduces wood sizes. Depending on State permitting and local practices, forestry and tree-farming activities can limit encroachment into riparian corridors. Both can reduce the overall volume of wood supplied to the drainage system. Hydromodification from urbanization or other land-use changes affects runoff volume, duration, and peak flows, which can accelerate the transport of wood through the river system. Similarly, channel modification for flood control, stabilization, or navigation can promote greater wood mobility through increasing channel uniformity, dimension, and velocity.

Watershed and riparian land development and bank armoring reduce opportunities for wood recruitment. Development of extensive road networks reduces forested area and typically introduces numerous stream crossings that trap wood and consequently reduce downstream wood supply and frequently generate maintenance tasks. Historically, wood was cleared from river channels for a variety of reasons, ranging from flood control and navigation safety, to a-quatic organism passage and aesthetics, and production of lumber. While operations and maintenance procedures still routinely involve wood removal in many regions, best management practices (BMPs) and restoration science have shown that placing large wood in streams considered deficient in this functional resource can be beneficial. Figure 8.8 provides an example of the use of an engineered logjam that both adds wood and deflects flow.

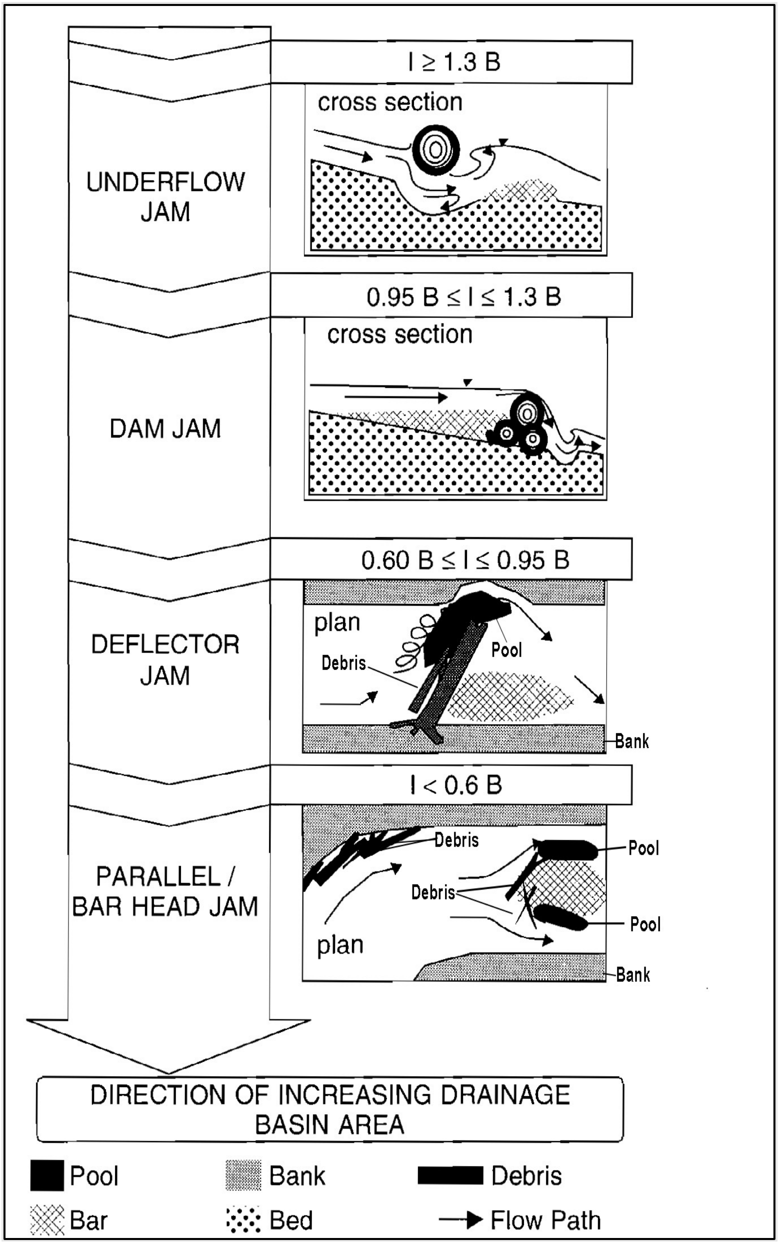


Figure 8.7. Large wood and wood jam type classification (L = length of key wood piece, B = channel width). Source: N.P. Wallerstein and used by permission.

Both naturally occurring and placed wood can be mobilized by the river and moved downstream, with the potential for adverse interactions with crossings (e.g., bridges and culverts) and encroaching highways (Wohl et al. 2016). Extensive research has been conducted regarding the risk large wood poses at bridges, with specific concern for: 1) possible reduction in the capacity of the structure to convey flood flows and 2) enhanced contraction and pier scour resulting from partial blockage (Diehl 1997, Lagasse et al. 2010, FHWA 2012b).

Figure 8.8. Engineered logjam (ELJ) built in 2018 to deflect flow into a side channel of the Sandy River, Oregon. Note excavator and people circled for scale. Image used by permission of Wolf Water Resources Inc.

Including an initial qualitative risk assessment for wood passage in the planning and design of new highway encroachments or crossings in the river environment is of critical importance. Such an assessment considers the results of office and field studies of the types detailed in Section 6.1 (Data Collection) and Section 6.6 (Stream Interpretation). Wood-specific assessments may include:

- Office-based review of inspection, monitoring, and maintenance records for the site and nearby sites to identify past wood-related issues.
- Office-based assessment of other readily available information regarding surrounding development, potential wood sources at and upstream of the project site, and characteristic maximum heights of local tree species.
- Inspection of available aerial photographs or satellite images of the contributing watershed to assess the percent forested and connected to the stream network.
- Field reconnaissance and site visits to ascertain the likelihood of wood delivery to the project reach either as individual pieces or in rafts generated by the break-up of natural or engineered logjams upstream.

Project planners and designers can make a qualitative risk assessment based on the general scope of the project, the abundance of wood at and upstream of the site, history of maintenance activities related to wood accumulation, and past or potential consequences of wood blockage on conveyance, scour, and flooding. If the qualitative assessment identifies potentially unacceptable risks, the project team undertakes a quantitative wood risk evaluation. This involves estimating the probability of a significant blockage occurring multiplied by its potential consequences, such as raising flood lines, damage to the structure, or bank erosion (for details see De Cicco et al. 2018). By comparing wood-related risks for different project alternatives (as part of a feasibility analysis and appraisal of project alternatives), the team can identify and select a design option that avoids unacceptable wood-related risk.

For existing highways in the river environment, managing wood-related risks at crossings and encroachment structures may be part of an inspection and maintenance program. This may involve removing or relocating either wood that has accumulated at the crossing or in a location where it may cause flooding or erosion of an encroaching highway, or wood in the channel upstream that may cause a problem in the future (FHWA 2012a). Given the cascading problems that can be caused by impaired river function, maintenance and wood management actions are likely to be most effective when they retain the environmental benefits of wood in the stream while reducing current and potential risks to acceptable levels. An added benefit of this approach of balancing the benefits and risks of wood in rivers is to minimize future operation and maintenance actions, and generally develop sustainable infrastructure (FHWA 2005, Lagasse et al. 2010). In some circumstances, it may be beneficial to reintroduce wood downstream of a bridge where it has collected, especially if there are not vulnerable structures nearby. However, careful consideration of potential risks created by such actions is prudent.

Crossings structures may be adjusted to better accommodate wood transport by: 1) allowing sufficient freeboard to pass floating wood above the design flood water surface elevation, 2) ensuring that the bridge span or culvert area is large enough to pass the largest pieces of wood likely to be delivered by the flow, and 3) locating bridge piers outside the main channel. As discussed in Section 4.5 (Impact Mitigation) use of bridge and culvert designs that span the functional floodplain allows wood functions to continue unimpeded and facilitate diversity, sustainability, and resilience in the road-stream-floodplain system. In some cases, spanning the functional floodplain does not increase the capital cost of the project (ODOT 2004, Cummings and Pyles 2013). In other cases, capital costs may increase, but maintenance costs removing trapped wood and the damage it may cause may be reduced. In other cases, it may simply be impractical to span the functional floodplain for reasons other than capital construction costs.

8.4 Human-Generated Debris

Human-generated debris enters the fluvial system from multiple origins in a watershed, some point sources, and others diffuse sources. This debris causes environmental and aesthetic degradation, distress to wildlife, nuisance to riparian landowners, and maintenance for operators of infrastructure, highways, and other assets in the river environment. The composition of human-derived debris is abundantly diverse, including both inorganic and organic materials as shown in Figure 8.9 and Figure 8.10. The quantity and volume of debris also ranges widely, from remains of buildings and infrastructure damaged or destroyed by floods to common litter. Common constituents of human-derived debris sampled from aquatic ecosystems include plastic, metal, glass, lumber, and paper (Hoellein et al. 2014, McCormick and Hoellein 2016, van Emmerik and Schwarz 2019).

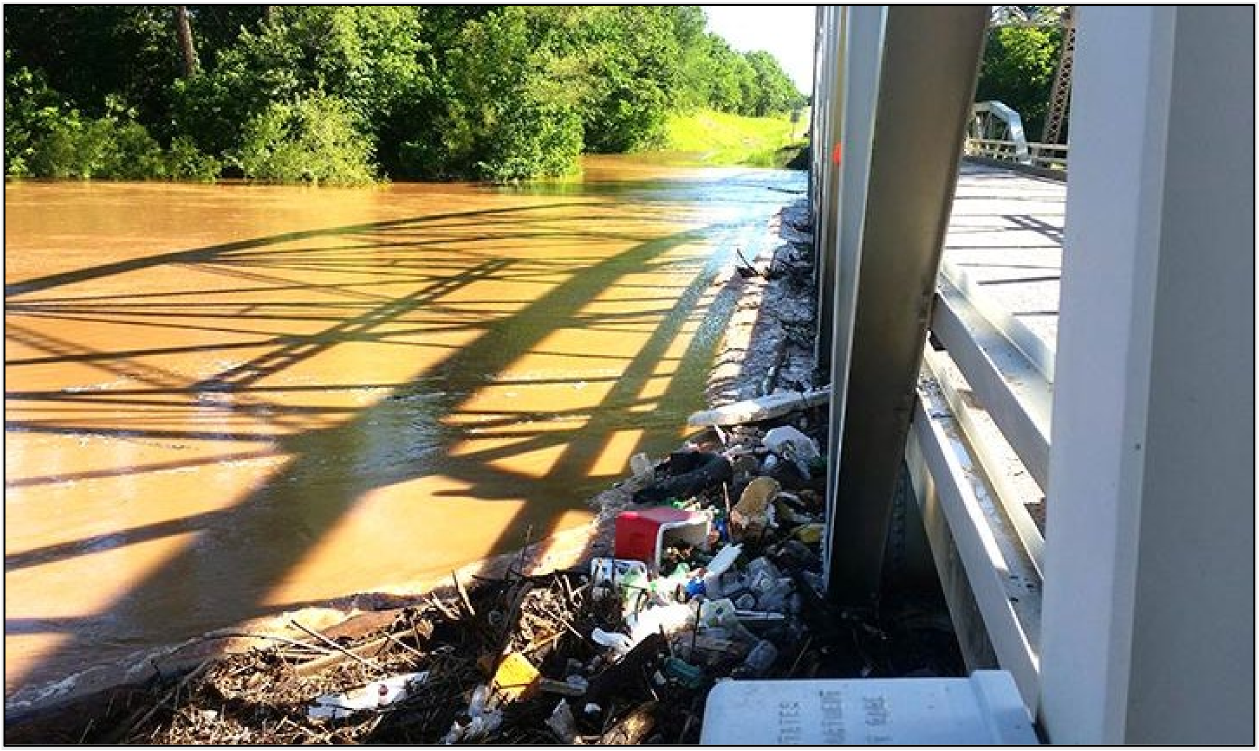


Figure 8.9. Litter and trash accumulation (SH-99 Washita River Bridge, Oklahoma). Image used by permission of the Oklahoma Department of Transportation.

Figure 8.10. Trash floating in the backwater area of a woody debris jam (Mt. Scott Creek, Clackamas, OR).

Transportation infrastructure often provides easy access to watercourses with abundant opportunities for illegal dumping of debris adjacent to, or directly into, watercourses. Furthermore, the proximity of roads and watercourses often allows debris to be blown directly or carried by stormwater into streams. Stormwater drainage outfall connections from transportation infrastructure to watercourses are common. Littering is a significant source of trash in rivers, with plastic cups, bottles, and wrappers finding their way into watercourses from nearby facilities such as parking lots, pedestrian trails, and sidewalks as shown in Figure 8.11. Uncovered or improperly secured loads on vehicles supply additional debris. As a result, some debris enters rivers from transportation infrastructure daily, with considerably more entering rivers during flood events (González et al. 2016, van Emmerik and Schwarz 2019).

Common Types of Human-Generated Riverine Debris

Tires

Plastics*

Cans*

Bottles

Lumber

Cigarette butts*

Food packaging*

Plastic bags*

(USBR 2016)

*The five most common things found at river cleanups (American Rivers 2019)

Figure 8.11. Debris (under the bridge) that may soon be in the waterway.

Given the many problems and risks associated with human-derived debris in rivers, it is important to consider techniques for avoiding, controlling, or mitigating the introduction of trash and other human-generated debris when planning, designing, or constructing new or modified transportation infrastructure. The FHWA's HEC-9 provides information on the selection of debris control countermeasures (FHWA 2005). Common techniques include:

- Planning alignments for transportation infrastructure that maximize separation from rivers.
- Design of physical barriers to debris such as fences or trash racks along drainage routes to the river.
- Design of crossings that can accommodate the presence of debris in rivers.

The construction phase of a transportation infrastructure project poses unique challenges for debris and pollutant management in the river environment. These challenges include accidental discharge, leakage or spill of fuels and oils from construction equipment, and inadequate management of debris created by demolition activities. To reduce trash entering rivers, maintenance and operations professionals can employ good site-keeping practices, provide opportunities for appropriate public waste disposal, install and maintain appropriate signage, enforce littering and waste disposal laws, and conduct public awareness campaigns. Maintenance and operations programs may offer opportunities for stakeholder engagement and collaboration with other government agencies, non-profits, landowners, and the local community to develop a planned, coordinated, comprehensive approach to litter and related issues.

8.5 Water Quality

Highways and bridges in the river environment can be a substantial source of sediment and dissolved water-quality constituents that may adversely affect the habitat and ecology of receiving streams (FHWA 2003, FHWA 2009c, NCHRP 2002, Wagner et al. 2011, NASEM 2014, Smith et al. 2018, Granato 2019; USGS 2020). For example, concentrations of suspended solids in available data range from 0.4 to 5,440 mg/L and concentrations of suspended sediments range from 1 to 142,000 mg/L (Granato 2019).

Ecological studies show that sediment deposits may accumulate near highway and urban outfalls and, in turn, sediment associated contaminants can have adverse effects on aquatic ecology in such areas (FHWA 2003). The FHWA in cooperation with the USGS developed the highway runoff database (HRDB) and the Stochastic Empirical Loading and Dilution Model (SELDM) to provide data, tools, and techniques to estimate and simulate stormflow volumes, concentrations, and loads of highway and urban runoff constituents (2009cc, Granato 2013, USGS 2020). These tools and techniques are designed to transform complex scientific data into meaningful information about the risk of adverse effects of runoff on receiving waters, the potential need for mitigation measures, and the potential effectiveness of such management measures for reducing these risks (Granato 2013, Granato 2014, Granato and Jones 2019).

8.6 Invasive Species

Invasive species are non-native organisms that cause ecological and economic damage. Hundreds of species of invasive plants, insects, pathogens, terrestrial animals, and aquatic organisms have been introduced (deliberately or accidentally) into rivers and ecosystems. Typical examples include kudzu (*Pueraria lobata*), reed canary grass (*Phalaris arundinacea*), bullfrogs in the western United States (*Lithobates catesbeianus*), and zebra mussels (*Dreissena polymorpha*). Invasive species change the dynamics of the system and have negative consequences on the environment including displacement of native plant and animal species.

When performing work in or near a watercourse, biosecurity is vital to avoid inadvertently spreading invasive species. Highway projects may also offer opportunities for eradicating invasive species at a site or reach-scale.

This section identifies invasive species impacts and transportation infrastructure project actions that can introduce or spread noxious weeds or undesirable animals. While measures involved in reducing the risk of spreading invasive species at project sites are region-specific and species-specific, some useful principles and BMPs are outlined.

Calculating Invasive Species Impacts

For those damages that can be expressed in monetary terms, damages from invasive species are estimated to be as high as $138 billion per year.

Up to 70 percent of 20th century extinctions of native aquatic species may have involved invasive species.

42 percent of current endangered species are impacted significantly by invasive species.

(USEPA 2016b)

8.6.1 Hazards of Invasive Species

In riverine and other habitats, plant and animal species have coevolved such that they often maintain a balanced ecosystem. Invasive species can disrupt the balance when there are no natural checks and are one of the greatest challenges for managers of sport species, habitat, and wildlife. Introduction of invasive species sometimes results in adverse effects to native species to the extent that they are classified as a “state species of concern” or being Federally listed as “threatened or endangered” under the Endangered Species Act (ESA).

Planning and timely management of invasive species can reduce or eliminate impacts. Without appropriate management, costs associated with invasive species can escalate rapidly. Long-term invasive species management is best achieved when coordinated with, and incorporated into, routine inspection and maintenance operations.

Figure 8.12 depicts a sequence for thinking about invasive plants, insects, or animals: 1) prevention, 2) eradication, 3) containment, and 4) management. While prevention is preferred, even the best prevention efforts are unlikely to stop all invasive species. Once prevention has failed, the next option is eradication. The difficulty of achieving eradication increases rapidly, until it is no longer feasible. It is therefore important that invasive species control plans include early detection and rapid response. If eradication is unlikely or infeasible, then containment to prevent further spreading is desirable. If the species is detected too late or containment is ineffective, then ongoing, long-term, coordinated, and costly investment becomes the only approach available.

Agencies Involved with Invasive Animal Species

USDA’s Animal and Plant Health Inspection Service, (APHIS) Wildlife Services.

US Fish and Wildlife Service.

State Departments of Natural Resources.

State Departments of Fish and Wildlife.

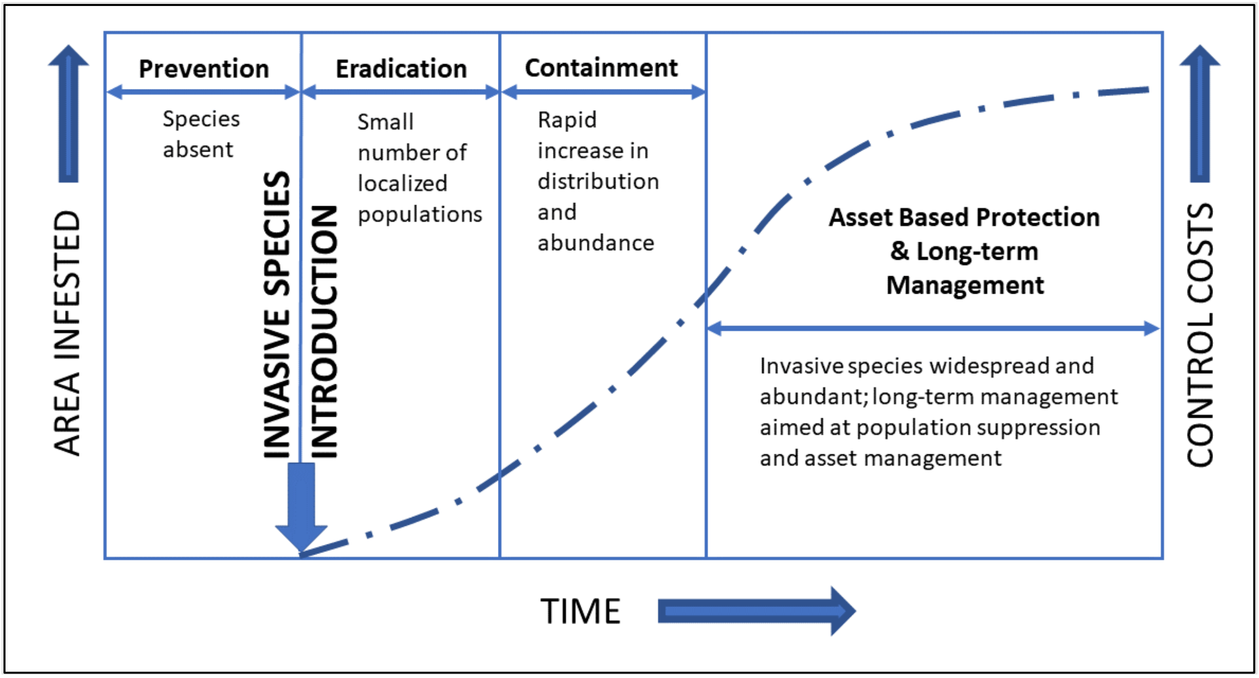


Figure 8.12. The invasion curve. Source: USACE.

Executive Order 13112 (64 FR 6183 (Feb. 8, 1999)) defines an invasive species as “a species that is non-native to the ecosystem under consideration and whose introduction causes, or is likely to cause, economic or environmental harm or harm to human health.” The Executive Order created the National Invasive Species Council (NISC), which includes the Secretary of Transportation, to facilitate use of relevant programs to prevent the introduction and to control/manage invasive species that have already been introduced (NISC 2016). The NISC also maintains a directory of State and regional invasive species lists at https://www.invasivespeciesinfo.gov/subject/lists.

As a result of EO 13112, invasive species control efforts have increased, particularly through coordination of Cooperative Weed Management Areas (CWMAs). Each CWMA is a partnership between Federal, Tribal, State, and local government agencies, individuals, and other interest groups that manages invasive plants in a specific area. CWMAs provide education, regulatory direction, professional technical assistance, and environmental awareness to preserve and protect natural resources from the degrading impacts of invasive terrestrial and aquatic vegetation (CWMA 2020). Local CWMAs can supply maps, data and other information useful to highway planners, designers and managers. Some of these resources can be accessed at https://www.naisn.org/cwmamap/.

Departments of transportation and the facilities they oversee may also be adversely impacted by invasive species in ways including:

- Increased operation and maintenance costs for control of invasive species.
- Risk and expense of using herbicides to control invasive plant species.
- Increased wildfire and flood risks.
- Reduction of infrastructure integrity (especially embankments) from the rooting and burrowing activities of invasive animals such as hogs and nutria (Vissichelli 2018).

8.6.2 Invasive Species at Transportation Project Sites

Several activities inherent to transportation infrastructure projects have the potential to introduce or spread invasive species. For example, moving construction equipment (whether for on-land or in-water work) from a contaminated site to an invasive-free site can transport invasive species, their eggs, larvae, or seeds. Even if a native species is inadvertently transferred, individual specimens may carry invasive parasites, diseases, pathogens, or toxins. During site clearance, it is important to avoid propagating invasive species by, for example, using a brush hog. This is because every fragment of an invasive plant has the potential to be carried downstream to another location where it may start a new colony. Similarly, when clearing invasive grasses, the seed bank in the topsoil remains viable unless the soil is deeply buried or hot composted.

DOTs Get Greedy Goats for Invasive Plant Control

Departments of Transportation in several states including California, Delaware, Hawaii, Nebraska, and Washington have started deploying herds of goats in place of herbicides as a more sustainable and often lower cost approach to control invasive non-native weeds (AASHTO 2020, NIFA 2011, MauiWatch 2017, Yowell 2015, Florip 2015). Not only do goats preferentially eat such weeds, but goats sterilize the weeds through their digestive process slowing the return of invasive vegetation. Compounding the benefits of these programs, goat grazing for invasive plant management increases organic matter in the soil, aerates the soil with the goat hooves, decreases erosion, and increases desired plant species diversity (MauiWatch 2017).

Revegetation efforts, including use of live plantings or plant materials from off-site in nature-based solutions (NBS), may also inadvertently introduce invasive species to a project site. Examples might include inadvertent use of hybrid species or large wood colonized by invasive insects, microbes, or fungi. Such risks can be reduced by using local plant suppliers recommended by knowledgeable, local stakeholders. During site maintenance, use of contaminated mulch or topsoil, as well as movement of invasive-contaminated equipment without thorough inspection and cleaning, are also risk factors for introducing and spreading invasive species (Venner 2006). Guidelines for equipment inspection and cleansing procedures have been developed by the U.S. National Park and Forest Services. It is also a common procedure for project teams to remind contractors of their obligation to inspect and clean their equipment.

Practices that help prevent the spread of invasive species include:

- Transporting all residual plant parts to an appropriate safe disposal site.
- Avoiding the transport of hay, gravel, loam, and fill from infected sites to other locations.
- Recognizing that germination rates of invasive plant seeds are likely higher on humid, bare soil.
- Cleaning all equipment used to cut or mow invasive species on-site, to prevent the transport of seeds and fragments. High pressure air, a portable wash station with a runoff container, or brushing and brooming (without water) are safe cleaning methods.
- Prominently displaying equipment cleaning and management protocols.

Example Invasive Species Protocols and Practices Resources

New Hampshire Department of Transportation 2008 Best Management Practices Guide for Roadsides Invasive Plants:

www.nh.gov/dot/org/projectdevelopment/environment/documents/BMPsforRoadsideInvasivePlants.pdf

The California Invasive Plant Council's Preventing the Spread of Invasive Plants: Best Management Practices for Transportation and Utility Corridors:

www.cal-ipc.org/resources/library/publications/landmanagers/

The Ontario Invasive Species Council's Clean Equipment Protocol for Industry:

www.ontarioinvasiveplants.ca/wp-content/uploads/2016/07/Clean-Equipment-Protocol_June2016_D3_WEB-1.pdf

The Wisconsin Council on Forestry series of BMP guides, including the Invasive Species Best Management Practices For Transportation and Utility Rights-of-Way:

councilonforestry.wi.gov/Documents/InvasiveSpecies/ROW-Manual.pdf

Details on practices for managing invasive species t:

www.greatlakesphragmites.net/management/roadsides/

Wetland mitigation projects that support transportation infrastructure projects are vulnerable to invasive species and may present unique project challenges. For example, projects may be expected to meet specific performance criteria for presence of invasive species (e.g., 10 percent or less), which may be difficult and costly to achieve in cases where invasive species are already established (ICF International 2010). Recognizing this difficulty, project planners may take this factor into account when selecting a mitigation site, potentially limiting the impact of the project (ICF International 2010).

State Spotlight: The Penn State Vegetation Management Project

Since 1985, the Pennsylvania Department of Transportation has partnered with Pennsylvania State University in the Penn State Vegetation Management Project. The university assists PennDoT with ongoing development of an evidence-based roadside vegetation management program. In addition to evaluating and documenting emerging vegetation management technologies generally, the project takes an Integrated Vegetation Management (IVM) approach. The objective of IVM is to use available resources as effectively as possible to conserve desirable vegetation, minimize undesirable vegetation, and maintain aesthetics preferred by residents and road users (Pennsylvania State University 2020). For more information on the project and IVM, see:

plantscience.psu.edu/research/projects/vegetative-management

8.6.3 Invasive Species Passage through Barrier Removal

Connectivity between the aquatic, riparian, floodplain, and catchment ecosystems is a vital river function (see Section 2.4). There is an ideal degree of connectivity in any stream system and it is neither completely connected, nor completely disconnected. This manual has emphasized that river realignments resulting from road encroachment can impact river functions including organism passage along the river corridor. Retrofitting encroachments, the process of realigning existing roads or modifying existing crossings (bridges, culverts) and embankments to restore river connectivity, may mitigate some negative impacts. The purpose is to restore or enhance river functions valued by stakeholders and society (including aquatic and terrestrial organism passage and sediment continuity).

Conversely, just as the passage of native and beneficially introduced species is facilitated by this form of retrofit, so is passage of invasive species. Because each site and situation have unique characteristics, there are no strategies that are universally effective.

8.7 Beaver Activity

As discussed in Chapter 2, prior to near extirpation by settlers, beavers (*Castor canadensis*) were prolific throughout nearly all North America. Through construction of millions of dams, they had radical and pervasive impacts on flows and morphologies of streams and rivers (Pollock et al. 2018). By the end of the 18th century, beavers had largely disappeared from substantial portions of the United States, and rivers that were formerly multi-channel-wetland-floodplain complexes (beaver meadows) had metamorphosed into incised, single-thread streams or been replaced by drainage ditches and prismatic channels. Because of the reintroduction of beavers across the United States over the last century, beavers have reoccupied most of their former range (Naiman et al. 1988). Where that occurs in urban or farmed areas, conflicts between beaver activity and people are common and costly to solve through lethal trapping. At the same time, the public have growing appreciation of the benefits of beaver activity (Goldfarb 2018). Research (e.g., Puttock et al. 2017, McCreesh et al. 2019, Wohl 2019) shows that beavers enhance all four river functions described in Chapter 2: 1) conveyance and storage, 2) river evolution, 3) habitat, and 4) connectivity.

The Beaver Restoration Guidebook (Pollock et al. 2018) developed by the USFWS, NOAA, USFS, and others highlights numerous potential beneficial outcomes on river functions from beaver activity:

- Increased water retention during dry periods and more consistent base flows.
- Decreased peak flows, at least for frequent floods with moderate magnitudes and short return intervals.
- Expansion of aquatic and riparian habitat area, diversity, and complexity.
- Increased wetland area.
- Increased hyporheic exchange and groundwater recharge.
- Improved water quality (from sediment retention, temperature moderation, nutrient cycling, and bioprocessing of contaminants).
- Prevention of channel incision/faster recovery of degraded channels.

- Enhancement of long-stream connectivity for flow, sediment, fish, and other aquatic organisms (Burchsted at al. 2010).
- Enhancement and maintenance of stream/floodplain lateral connectivity.
- Carbon sequestration.

The impacts of beavers on river functions can have substantial regional variability. For instance, in semi-arid regions without a consistent supply of large wood, beaver dams may play a similar role to the large wood supplied by riparian forests of the Northwest and one that is as important to stream equilibrium (Cramer 2012).

Growing, science-based understanding, coupled with increased public appreciation for them, is inspiring new approaches to beaver conflict resolution. Modern solutions either accommodate beaver activity or capitalize on that activity in solving other river management problems (Hood et al. 2018, Bailey et al. 2019).

Beaver reintroduction is increasingly being used for watershed-scale restoration of self-sustaining stream corridor functions (Pollock et al. 2018). Efforts are now underway, largely led by river restorers in the Pacific Northwest, to re-introduce beavers to degraded streams and ditched meadows so that they can build dams and create ponds, with some notable successes in terms of biological and morphological recovery (Pollock et al. 2018, Goldfarb 2018).

Resources for Beaver Restoration

The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains

www.fws.gov/oregonfwo/Documents/2018BRGv.2.01.pdf

The Beaver Restoration Assessment Tool (BRAT): a planning tool for assessing the potential for beaver as a stream conservation and restoration agent over large regions and watersheds. This tool from Utah State University is free to download at:

brat.riverscapes.xyz

For multidisciplinary teams implementing and maintaining highway projects that include a stream restoration component, there are many resources for exploring the potential of beaver restoration as part of a nature-based solution (NBS) or as a means of mitigating road-related, river and environmental impacts. In addition to consulting *The Beaver Restoration Guidebook*, transportation teams may assess their sites' beaver-supporting and beaver restoration potential by using *The Beaver Restoration Assessment Tool (BRAT).* Transportation teams interested in beaver restoration are also likely to benefit greatly by pursuing collaborative relationships with relevant stakeholders, including government agencies, non-profits, landowners, and the local community. Because the process involved in beaver reintroduction may be complex, developing such relationships as early as possible in the project planning or design process is important.

Inappropriate reintroduction of beavers to parts of the United States may also lead to chronic conflicts with highway infrastructure that are costly when addressed through lethal trapping. The primary challenges are:

- Blocking of culverts that do not meet stream simulation design parameters.
- Flooding, including flash floods from beaver dam failures and from the removal of beaver dams by people attempting to address such issues as blocked culverts.
- Damage to vegetation, loss of foliage cover and increased wood loads, particularly in backyards, parks and areas of new plantings for landscaping, mitigation/restoration efforts, or green infrastructure.

In many states, the response to beaver/infrastructure conflicts is to deconstruct dams and use either lethal or non-lethal trapping to remove the beavers. Experience shows that beavers can return and rebuild, making these approaches to maintenance repetitive, costly, and ineffective (Pollock et al. 2018, Boyles and Savitzky 2008). Additionally, as Pollock et al. (2018) observe, removal of beavers and their dams, lodges, and channels, can create ancillary, sometimes irreversible, problems, including:

- Transformation of perennial streams into intermittent or ephemeral streams, with negative impacts on riparian landowners and water rights issues.
- Simplification of channel morphology, leading to increased flow velocities, local erosion, incision that migrates upstream, and a pulse of additional sediment delivered to the reach downstream. Resulting channel instability may raise local flood elevations and could potentially impact encroaching transportation infrastructure, necessitating countermeasures.
- Disturbance to wetlands equivalent to in-filling, groundwater withdrawal, clearance of native species and many other disturbances that may be inconsistent with the Federal Clean Water Act (1972) [33 U.S.C. §§ 1251-1387] or State regulations.
- Disruption to fish and invertebrate communities that likely outweigh any perceived thermal or passage benefits of beaver extirpation.
- Reduced water quality downstream due, for example, to increased phosphorus concentrations that may lead to eutrophication and stream colonization by noxious, invasive weeds and other nuisance species.

Project teams faced with a conflict beaver situation are likely to benefit from consulting a beaver management specialist.

8.8 Mud and Debris Flows

Mud and debris flows occur when streamflow picks up sufficiently large quantities of sediment, rock, wood, and other debris such that the flow becomes: 1) less predictable, 2) more destructive, and 3) more voluminous than water alone. Any of these alterations to flood flows can damage transportation infrastructure as shown in Figure 8.13. his section provides information and discussion on how to assess the risks posed to highways in the river environment, and how those risks can be reduced to acceptable levels.

Locations with a high potential for debris or mud flow hazards include (USGS 2005a, CGS 2019):

- At or near the foot of a steep slope, especially slopes of 26 degrees (1V:2H) or steeper.
- At or near the junctions of ravines with canyons.
- Near the apex of an alluvial fan.
- Within alluvial fans.
- Areas below recent high intensity burn zones.
- Areas with weak soils or rocks.

Mass movement (mass wasting) of rock, debris, or earth in the form of falls, slides, or flows can have a significant effect on sediment production in a watershed. The amount of sediment that can enter stream channels depends on the hydrologic and geologic conditions, as well as the degree of connectivity between the mass wasting site and the drainage network. Specific methods for mitigating the risks of mud and debris flow at alluvial fans are discussed in Section 8.9.

8.8.1 Sediment, Rock, Wood, and Debris in Water

Overland flow entering the drainage network may carry sediment, wood, and debris originating from within the watershed. Other organic and inorganic materials are added to the flow from the channel bed, banks, and connected floodplains and slopes. Under normal streamflow conditions, the concentrations of material carried by the flow are too low to significantly affect the physical properties of the flowing fluid. However, in steep, energetic watercourses with very high transport capacities and abundant inputs of sediment, wood, and debris, the fluid flow properties can change. When the flow carries abnormally high concentrations of solid particles (in other words, when it is hyperconcentrated) it may be described as a mud flow. When still more sediment, wood, and debris are incorporated into the flow, the fluid flow can be described as a debris flow or (in some regions of the United States) a debris torrent.

It is important to recognize that these hyperconcentrated flow types (mud flows and debris flows) have different basic fluid properties than normal streamflow. Basic fluid properties such as how much flow weighs by volume (density) and how easily it flows (viscosity) are affected by hyper-concentration. Increased fluid densities can even enable transport of large rocks and boulders, typically immobile by normal streamflow (see Figure 8.13). Fluid dynamics are governed by physics. The physics of water flow or water with lower concentrations of sediment is called Newtonian. The physics of flow of Newtonian fluids is well-understood. However, mud and debris flows are non-Newtonian fluids with very different and less predictable fluid properties. Specifically, mud and debris flows create a heterogeneous flow with temporally and spatially variable properties that make predicting their flow behavior more difficult.

What did Newton think about fluids?

When Newton's fluids (like water) flow, their ability to move does not change with how fast they are moving. Non-Newtonian fluids can move more easily once they begin to move. This makes mud and debris flows more dangerous because once they begin to move, they can accelerate.

A mud or debris flow can be triggered by a variety of flood types, including events generated by very intense/prolonged rainfall, breaching of a natural or artificial dam, a glacial outburst flood (jökulhlaup), melting of glaciers and ice fields by volcanic eruption (lahar), or flash flooding in a watershed recently ravaged by fire. Sources of hyperconcentrated sediments and debris typically include landslides, slope erosion, soil stripping, gullying, streambank erosion, glacial melting/outwash, mine tailings, and burned areas of watersheds. Mud and debris flows are common in alpine and arid regions with sparse natural vegetation, as well as in humid areas where the natural cover has been cleared for agriculture, forestry, mining, or other types of development. Mud and debris flow deposits are often found on alluvial fans that form at the interface between steep, confined, high-energy streams and a relatively flatter and more open plain or valley floor (see Section 8.9).

Figure 8.13. Impacts of a combined mud and debris flow on a highway bridge. Source: USFS.

The physics of flood flows vary significantly, depending on the concentration of sediment and organic materials in the moving fluid-solid mixture. Three types of sediment/water flow are typically referenced:

- Normal streamflow.
- Hyperconcentrated (mud) flow.
- Debris flow.

In the literature, researchers have generally distinguished between these flow types based on solids concentration by weight or volume. Although there are differences within the literature, Figure 8.14 presents a representative categorization. When sediment concentration is greater than 50 percent by volume the flow is generally considered a landslide.

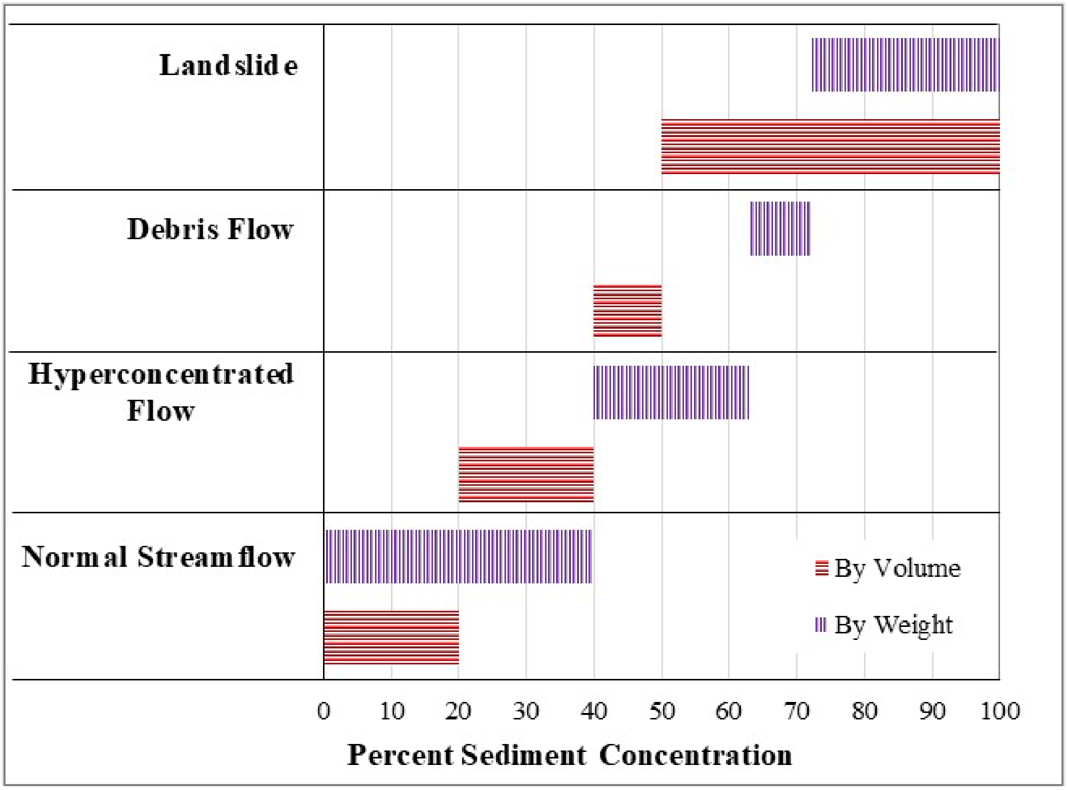


Figure 8.14. Classifications of flows by sediment concentration. Adapted from Bradley (1986).

For normal streamflow, the sediment load has a minimal impact on the hydraulic behavior of the fluid. Although sediment concentrations up to about 20 percent by volume are possible in normal streamflow, river flows typically have concentrations by volume less than 5 to 10 percent (USGS 2005b). Sediment is transported by normal streamflow as suspended load and bed load (see Section 7.1 and FHWA 2012a, 2012c).

Fluid properties and sediment transport characteristics change under hyperconcentrated flow (mud flow) conditions, as large volumes of sediment are distributed throughout the water column and the mixture no longer behaves strictly as a Newtonian fluid. Nevertheless, basic hydraulic and sediment transport equations and models are still generally applicable and produce acceptable results when used to analyze and predict the behavior of hyperconcentrated flows. The approximate upper limit for a hyperconcentrated flow is 40 percent sediment concentration by volume, above which the properties and behavior of the flow increasingly resemble those of a debris flow.

The properties and behavior of a debris flow are quite different from those of normal streamflow, or even hyperconcentrated flow. A key distinction is that the flow behavior of a debris flow is primarily controlled by the sediment and the composition of the sediment/debris mixture (Krone and Bradley 1990). The amount of clay has a major impact on the ability of the mixture to flow. A 50 percent sediment concentration by volume is the approximate upper limit for debris flows, above which such mass movements are classified as landslides or debris avalanches.

As described by O'Brien (2006), flow characteristics change over the course of a debris flow event. During typical debris flow events, clear-water flows arrive first from basin rainfall-runoff. These clear-water flows are followed by a surge, or "frontal wave," of sediment and debris (40 to 50 percent sediment/debris concentration by volume). When the peak water discharge arrives, the average sediment concentration typically drops to the range of 30 to 40 percent by volume.

However, surges of higher sediment concentration may recur during the falling limb of the event hydrograph.

Because of the large volume of water associated with extreme floods, such as the 100-year return period event, these floods do not generally generate debris flows. Even though they may contain large quantities of sediment and debris, the dilution is likely to keep the concentration below the level that would classify it as debris flow. Therefore, smaller flood events (e.g., 10-year or 25-year return period floods) may have a higher likelihood of generating a debris flow.

8.8.2 Wildfires and Mud/Debris Flows

Wildfires present a unique hazard that contributes to mud and debris flow occurrence because of the sudden removal of vegetation combined with the alteration of runoff characteristics caused by fire. Post-fire mud and debris flows are generally triggered by one of two processes:

- Surface erosion caused by overland flow (surface runoff).
- Landslides caused by ground saturation from rainfall infiltration.

Runoff-dominated processes are by far the most common after wildfires because typically fire reduces the infiltration capacity of soils while also making soil particles resistant to wetting (hydrophobic). Both conditions increase surface runoff and erosion (USGS 2005b). Interagency Burned Area Emergency Response (BAER) teams often produce post-fire reports that provide valuable information about the extent of fires and the degree of burning experienced, which has a direct impact on hydrologic soil properties. The USGS conducts post-fire debris-flow hazard assessments for select fires in the Western United States using geospatial data related to basin drainage area and slopes, burn severity, soil properties, and rainfall characteristics. These assessments are used to estimate the probability and volume of mud and debris flows that may occur in response to a design storm event. Further details may be found at: www.usgs.gov/natural-hazards/landslide-hazards/science/emergency-assessment-post-fire-debris-flow-hazards?qt-science_center_objects=0#qt-science_center_objects.

8.8.3 Mud and Debris Flow Bulking

Mud and debris flows transport such large volumes of solid material that they significantly increase the volume of the flowing liquid/solid mixture. This phenomenon is referred to as “bulking.” To account for this bulking, hydraulic engineers increase the water discharge in their designs by a “bulking factor” (BF) (Richardson et al. 2001). Because of bulking, mud and debris flows commonly overwhelm the flow conveyance capacities of transportation infrastructure designed to handle only normal streamflow. For teams designing transportation infrastructure in areas prone to very high sediment and debris concentrations, the use of a bulking factor provides a means to estimate the additional conveyance capacity to pass mud and debris flows.

For a watershed where the entire area contributes sediment and debris, the bulked peak flow is the sum of the peak clear-water discharge and the volumetric sediment/debris discharge. The BF is then the ratio of the bulked discharge to the clear-water discharge. Volumetric sediment discharge can be back calculated for a known water discharge and a selected BF. In the case where only part of a watershed supplies sediment and debris, or if an upstream debris-control structure reduces the amount of sediment available for transport, the bulking factor can be applied on a proportional basis.

The risk of a mud or debris flow damaging a bridge, culvert, or conveyance channel can be reduced by designing transportation infrastructure using an appropriate bulking factor. The sediment and debris load or concentration can only be estimated with significant uncertainty. The

BF is generally applied to the peak flow to obtain the total (bulked) peak flow and the engineer also introduces a safety factor into the hydraulic design (Hamilton and Fan 1996).

Engineers typically select the BF and safety factor based on evaluation of watershed data and sound engineering judgment. The evaluation may include field reconnaissance, data collection, and consultation with local, State, and Federal agencies. By considering the uncertainty and potential safety factors, the engineer strives to reduce the risk posed to the structure by a mud or debris flow to a level that is acceptable, or at least tolerable, always considering public safety. For hydraulic design, the bulked flows are used when computing adequate bridge span and freeboard, culvert size, or conveyance channel dimensions.

The equation for bulking factor is:

$$BF = (Q + Q_s)/Q = 1 + C_v/(1 - C_v) = 1 + C_w/[S_g\,(1 - C_w)] \tag{8.1}$$

where:

BF = bulking factor
Q = water discharge in ft^3/s
Q_s = sediment discharge in ft^3/s
C_v = concentration by volume (sediment volume/total volume)
S_g = sediment specific gravity
C_w = concentration by weight (sediment weight/total weight)

The upper limit of concentrations in a typical water flood is about 200,000 ppm by volume, 410,000 ppm by weight, or a bulking factor of 1.25. Figure 8.15 shows the relationship between total sediment concentration and bulking factor.

Example: Bulking Factor Application

In San Bernardino, California, engineers developed designs for the replacement of two adjacent bridges over City Creek, Boulder Avenue, and Base Line Street. Both bridges were designed to accommodate a 100-year discharge of 10,470 ft^3/s. Since the bridges are located in an area prone to high sediment concentration and there is a history of bridges washing out in the reach, the design discharge was adjusted by a bulking factor to account for the potential for the increased flow volume that would be caused by the sediment loading. A bulking factor of 1.5 was used, consistent with the sediment concentration reflecting a mud flood as shown in Figure 8.15. This resulted in a 100-year bulked discharge equal to 10,470 ft^3/s x 1.5 = 15,705 ft^3/s.

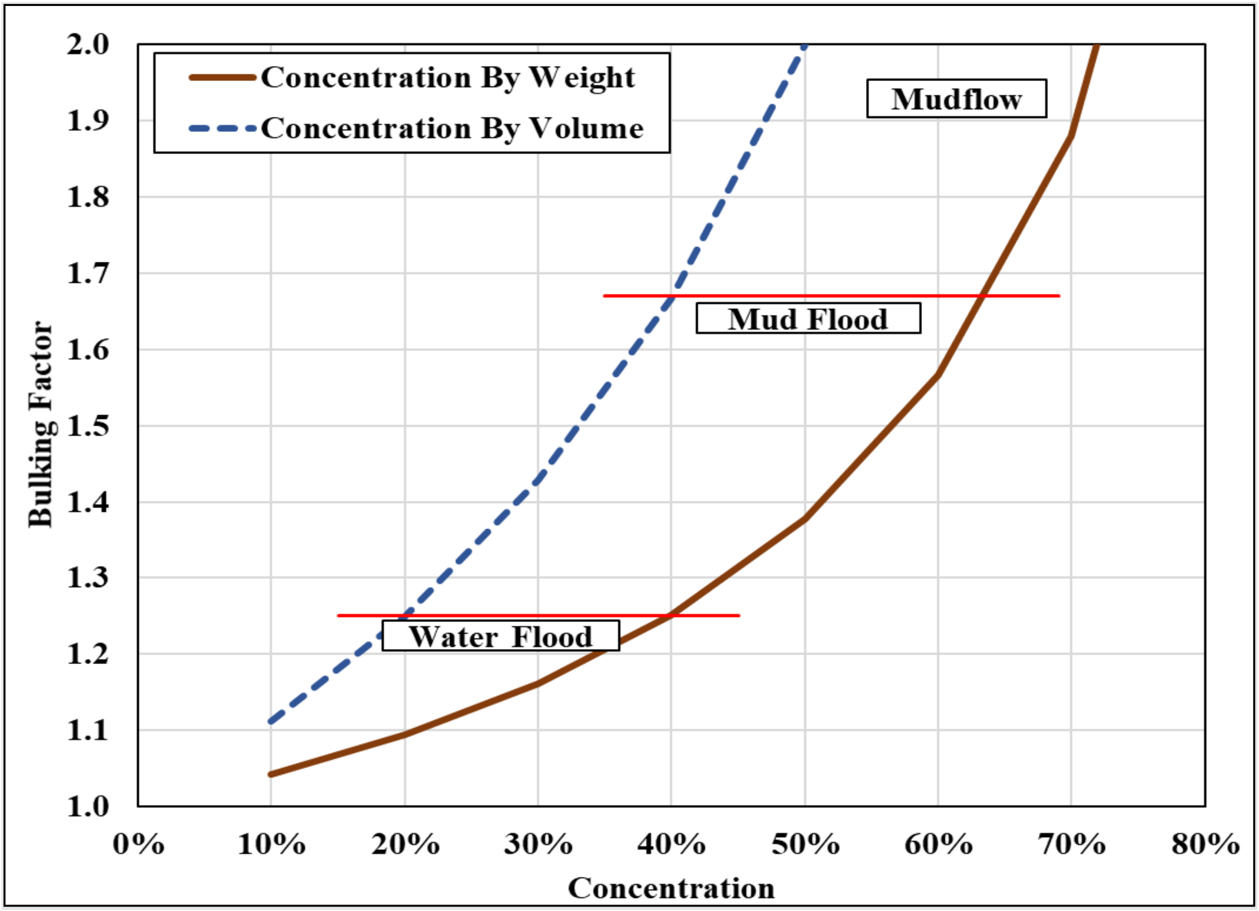


Figure 8.15. Relationship between total sediment concentration and bulking factor.

8.9 Alluvial Fans

An alluvial fan is a depositional landform with the shape of a cone or fan as shown in Figure 8.16. A fan may form in a single, sediment-rich stream where it leaves an upland area and enters a wide plain or a large valley. A fan may also form where a steep, high-energy tributary stream drains into the valley of a larger river. Sediments (ranging in size from boulders to silt) eroded from the high-energy, upland watershed accumulate on the flatter terrain to build a fan shaped deposit when viewed from above.

The dynamic behavior of alluvial fans presents significant hazards to highway infrastructure due to rapid in-channel sediment deposition or scour, channel avulsion, overtopping, by-passing, flanking, debris flows, and burial. The risks posed to highways crossing alluvial fans present a variety of design considerations for transportation infrastructure including:

- Potential for mud and debris flows.
- Episodic deposition of sediment and debris along channels and on the fan surface.
- Potential for sudden channel relocations due to sediment blockages and avulsions.
- Sediment deposition, loss of conveyance, blockage, and bypass of hydraulic structures.
- Scour in channels or overbank areas at/adjacent to hydraulic structures.

While fans are predominantly depositional features, channels crossing them are usually unstable. For example, the downstream third of the main channel crossing the fan in Figure 8.16 has areas of deep incision.

During high discharges, flow characteristically spreads out across the fan, forming areas of sheet flow and multiple, small, divergent channels carrying heavy loads of sediment and debris. During floods, flow paths form, aggrade, and shift frequently through a combination of rapid lateral migration and sudden, unpredictable relocations to other portions of the fan. Sediment and debris concentrations in these fast-moving streams may generate mud and debris flows. However, during high, in-bank flows, streams may scour the loose, freshly deposited sediment to incise deeply into the fan surface, as has happened in Figure 8.16.

Not all alluvial fans are as apparent as that shown in Figure 8.16. They form and persist over thousands of years and, in humid environments, may be difficult to identify on the ground or in aerial images because of their subtle slopes or because they are obscured by forest or other vegetation. Alluvial fans are found in both arid and humid climates.

Figure 8.16. Alluvial fan formed where Wineglass Canyon enters Death Valley, California. Image used by permission of M.B. Miller (© 1998).

Alluvial fans are highly dynamic fluvial features that change and evolve constantly as sediment, wood, and debris conveyed by floods and mud/debris flows is deposited, re-entrained, and either re-distributed across the fan or flushed downstream. Change may be gradual or episodic (sporadic and unexpected). For example, in a channel avulsion, the stream may suddenly switch from one side of the fan to the other because of the transport and deposition of large volumes of sediment, wood, and debris blocking the earlier channel. Given this dynamic behavior, the alignment of active channels and the overall footprint of an alluvial fan are difficult to predict.

8.9.1 Analytical Methods

FEMA's *Guidelines for Determining Flood Hazards on Alluvial Fans* contains helpful information on recognizing alluvial fan landforms and methods for defining active and inactive areas (FEMA 2000). In most situations, the characteristic cone or fan shaped deposits of an alluvial fan can best be identified by examining maps of topography, soils, and surficial geology; inspecting aerial photographs; and making site visit observations. For example, the contour lines, stream planform, and road network in Figure 8.17 reveal the presence of an alluvial fan in southern California.

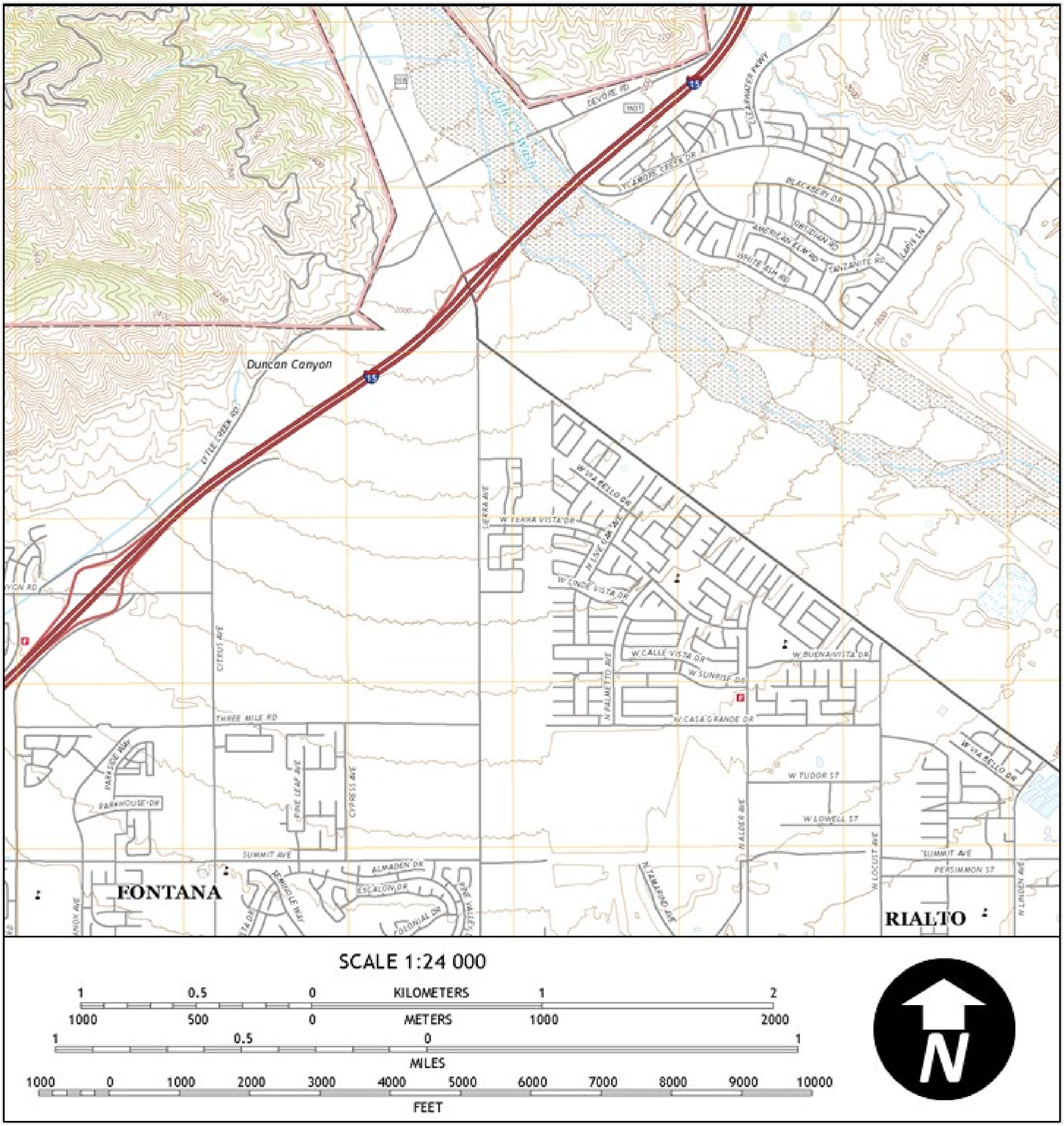


Figure 8.17. Topographic contours, stream planform, and road network on an alluvial fan in southern California.

The unconfined and dynamic nature of flows through and across alluvial fans makes delineating flood hazards for transportation project planning and design problematic. Historically, FEMA used probabilistic methods of hazard delineation (Dawdy 1979) for the National Flood Insurance Program (NFIP). More recently, 2D hydraulic models are used to identify flow paths and depths on alluvial fans. However, the highly variable and uncertain and dynamic nature of sediment supplied to the fan, shifting channel locations, and changing fan topography due to sediment deposition and erosion creates significant uncertainties in the results from such models. Furthermore, the variable hydraulic characteristics of density, viscosity, and hydraulic roughness associated with mud and debris flows introduce additional uncertainties for simulating processes on an alluvial fan using 2D hydraulic models. In view of these uncertainties, design teams often find it prudent to apply bulking factors or a factor of safety or both to allow for the impacts of mud and debris flows on alluvial fans compared with normal streamflow. Research work on the development of hydraulic models that account for the hydraulic effects of mud and debris flows is ongoing (O’Brien 2006, USACE 2020).

8.9.2 Hazard Mitigation Measures

Design teams responsible for transportation projects on alluvial fans have a range of potential approaches to mitigating hazards presented by alluvial fans. These include: 1) roadway alignment, 2) sediment control and conveyance, and 3) monitoring, operations, and maintenance.

8.9.2.1 Roadway Alignment

The alignment along which a highway traverses an active alluvial fan has direct bearing on the character and level of risk associated with crossing the fan. In addition to hydraulic and sediment dynamics, alignment selection may be influenced by highly diverse habitat that can be found on alluvial fans. Selecting a highway alignment that avoids an alluvial fan may eliminate the flood and geomorphic risks posed by a fan. If this is impossible or impractical, planners and designers may consider alignments that reduce the associated alluvial fan hazards to an acceptable, or at least tolerable level.

A road running along a large river valley may cross one or multiple alluvial fans that coalesce and interact. Figure 8.18 shows a sketch of three generalized alignments for crossing an alluvial fan. Alignment A is located as close as possible to the upstream apex of the fan. The channel at this location is confined by the natural topography, essentially avoiding fan dynamics and reducing uncertainty regarding the primary channel flow path. This alignment involves a single bridge or culvert crossing. However, the magnitude of flows, hydraulic forces, and sediment loads to be passed through a single structure would be maximized with alignment A, leading to a relatively large crossing and, probably, erosion countermeasures.

Alignment B follows a route midway between the apex and toe of the fan. This involves crossing multiple channels and potential flood flow paths, each of which is likely to pose risks to the highway and crossings due to cross-sectional instability, lateral shifting, or avulsion. In theory, dividing the primary flow into several branches means that potential flow magnitudes at each crossing are likely to be diminished. With this alignment crossing structures could be smaller, less heavily stabilized, and less expensive to construct. However, during the service life of the crossings, it is conceivable that any one of the channels might incise to capture and convey the entire primary flow. To allow for greater uncertainty regarding future discharges it would, therefore, be prudent to design each crossing to pass the entire primary flow. Generally, mid-fan alignments like B are not preferred because uncertainties, design challenges, and construction likely drive costs higher than for alignment A.

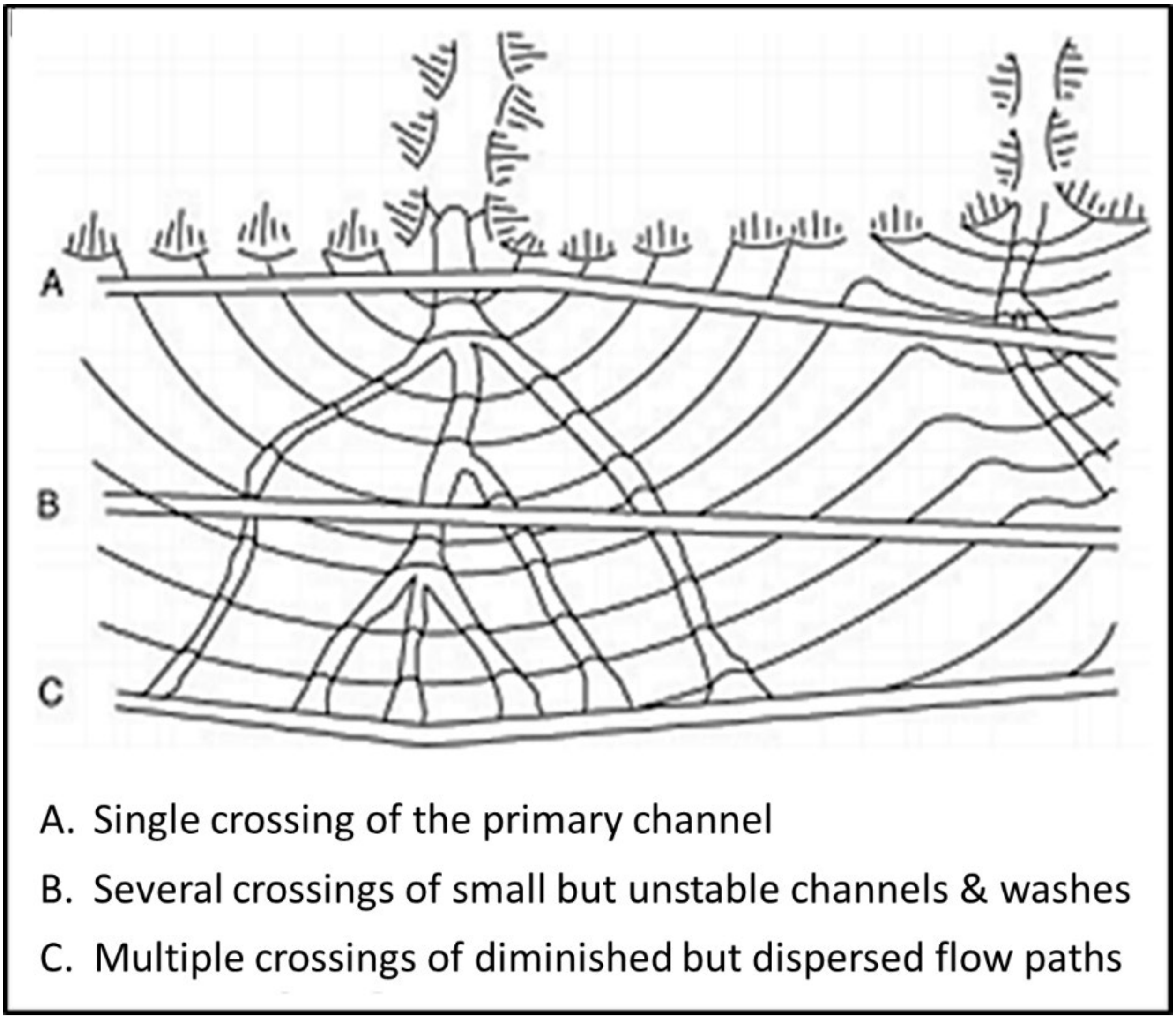


Figure 8.18. Potential road alignments on a fan. Adapted from Caltrans (2020) and used by permission with disclaimer noted in the acknowledgments.

Alignment C runs along the toe (or distal edge) of the fan. Here, uncertainty regarding the positions and magnitudes of flow crossing locations is highest, but flow magnitude at any given location is, in theory, minimized due to the increased potential for flow dispersion and infiltration over the fan. Due to its position close to the distal extent of the fan, it might be reasoned that alignment C would receive primarily water floods, as opposed to the heavily sediment/wood/debris laden flows experienced closer to the apex. This is the case because these loads are substantially depleted by deposition along channels and on the fan surface upstream. It may be assumed that alignment C may use more crossings to account for uncertainty regarding potential flow paths, but the hydraulic structures may be much smaller in size. Like alignment B, the risk with this assumption is that incision during high, in-bank discharges generates a head-cut in one flow path that migrates upstream and focuses water and, perhaps, debris flows into a single channel as previously shown in Figure 8.16. Generally, a distal-fan alignment like C is a viable alternative to alignment A, though it is not risk-free. Crossing inspection and stream monitoring is the best way to manage alluvial fan-related risks to crossing structures and road users.

8.9.2.2 Sediment Control and Conveyance

Instability of streams and rivers crossing alluvial fans relates to the supply of sediment from the watershed upstream and the deposition of that material along the channel(s). Source control—managing the watershed sediment supply—is one option for reducing the propensity for channels to aggrade, shift, or avulse on the fan. Watershed sediment supply can be minimized by prevention of widespread land disturbance activities and maintenance of well-vegetated contributing basins and riparian corridors. However, a variety of natural phenomena such as insect damage, wildfire, and mass wasting events can occur, greatly affecting watershed land cover and increasing sediment yields. Human activities in watershed areas, such as over-grazing, inappropriate forest management, and land development can also greatly affect watershed runoff and sediment supply to a fan.

In some circumstances, the risks to a highway crossing an alluvial fan may be sufficient to justify construction of structures to trap and retain sediment, wood, and debris. This involves building a dam, drop structure, sediment trap, or debris basin (Zech et al. 2014). One or more of these structures are placed upstream of the alluvial fan. The traps and basins are emptied periodically and after significant flood events. Long-term costs and societal and environmental impacts of operation, maintenance, and disposal of material collected by storage structures are significant considerations for road project sustainability (Zech et al. 2014). Figure 8.19 illustrates an example of a highly developed alluvial fan. This sediment control and conveyance system consists of a basin located at the apex of the fan and a lined channel conveying flows around the developed areas and under a bridge along the road at the toe of the fan.

Conveyance structures, such as armored channels and flumes, for controlled passage of flood and debris flows have been used at numerous alluvial fan locations. However, the variable density and viscosity properties associated with mud and debris flows create significant uncertainties regarding the effective hydraulic design of such facilities. Material transported to the downstream end of such conveyance facilities becomes an additional management priority. A commitment to long-term operation and maintenance is important for ongoing performance.

A variety of flow directing structures has been used to separate uncertain flow paths on alluvial fans from transportation infrastructure. Such structures include guide dikes, flood walls, and earthen berms that are typically used to concentrate and redirect flows toward a preferred path or designated highway crossing. By confining and directing flows on the fan, the number and sizes of crossing structures can be optimized.

Roadway embankment protection can reduce erosion when a roadway is exposed to a flow path on an alluvial fan. Since flow paths on a fan are transient and prone to unpredictable movement, it is important to consider protection against all potential flow conditions that may impact the embankment, including parallel, impinging, and overtopping flows. Figure 8.20 shows erosion damage to a road on an alluvial fan caused when flow left the active channel on the fan and instead followed the alignment of the road.

Figure 8.19 Aerial view of Magnesia Spring Canyon alluvial fan in Rancho Mirage, California.

8.9.2.3 Long-term Monitoring, Operations, and Maintenance

Alluvial fans are dynamic river landforms that evolve in response to variable inputs of water, sediment, wood, and debris supplied from the contributing watershed upstream. Flows on a fan range from highly erosive water floods capable of scouring loose, alluvial sediment and rapidly enlarging an existing channel, to mud and debris flows capable of burying a channel, bridge, or culvert in minutes. Given the unique and time-variant characteristics, placing transportation infrastructure on an alluvial fan involves a long-term commitment to inspection, monitoring, and maintenance to make the highway as safe, resilient, and reliable as possible. Depending on site-specific circumstances, effective long-term programs may include:

- Inspection of crossing structures for excessive degradation or aggradation.
- Assessment of hydraulic conveyance capacity of all crossing structures such as bridges and culverts.
- Assessment of the hydraulic conveyance and location of flow paths on the fan as they relate to the crossing structures.

- Inspection, cleaning, and repair sediment control and conveyance structures protecting the roadway corridor.

Figure 8.20. Road damage on an alluvial fan caused by locally concentrated overland flow.

8.10 Tidally Influenced and Tidally Dominated Rivers and Streams

The environment of a tidally influenced or tidally dominated river differs from those in purely fluvial watercourses. Tidally dominated rivers, like that shown in Figure 8.21, are subject to:

- Tidally driven changes in water level and reversals in flow direction.
- Weather-related wave action that varies daily, seasonally, and over decades (due to El Niño on the West Coast or North Atlantic Oscillation on the East Coast).
- Coastal flooding due to storm surges.

Tidally influenced rivers differ in that flow is mostly unidirectional, and normal tidal fluctuations reduce the magnitude of the flow rather than reverse it. However, tidally influenced rivers can also be subject to long-term, weather-related wave action and coastal flooding, leading to occasional flow reversals during these extreme events. These external forcing agents, in turn, drive hydrologic, hydraulic, sediment transport, and ecological conditions that differ distinctly from those experienced in fluvial streams. More specifically, the hydraulic forces associated with coastal storm induced water fluxes, currents, and waves are generally greater than those experienced in the fluvial reaches of a watercourse. It follows that bank protection, jetties, and piles constructed in tidally influenced reaches are heavier and more expensive. The FHWA developed references to assist planners and engineers addressing this context including HEC-25 *Highways in the Coastal Environment* (FHWA 2020) and *A Primer on Modeling in the Coastal Environment* (FHWA 2017c). The *Coastal Engineering Manual* is another authoritative source for coastal engineering (USACE 2002).

Figure 8.21. Tidally influenced Yaquina River at the Highway 101 bridge crossing near Newport, Oregon. Image used by permission of WEST Consultants, Inc.

This section describes how fluvial flows, tides, and extreme coastal events influence highways including:

- Hydrology and hydraulics.
- River geometry and gradient.
- Movement of fluvial and marine sediments.
- Ecological richness, diversity, and complexity.

8.10.1 Hydrology, Hydraulics, and Hydrodynamics

These coastal and riverine areas involve consideration of hydrology, hydraulics, and hydrodynamic conditions. For example, coastal hydrodynamics may describe tidal characteristics (temporal changes in heights or current location and magnitude) and further considers and distinguishes astronomic tides and other types of tides (e.g., storm tides, wind influenced tides, high and low-pressure systems, etc.) (NOAA 2020, FHWA 2020). Coastal practice Hydrology and hydraulics (H&H) within tidally influenced and tidally dominated rivers and streams are complex because river and tidal flows and forces are both significant and vary on daily, seasonal, and annual timescales (Sandbach et al. 2018, FHWA 2020). A characteristic of tidally dominated rivers is the inflow and outflow of water with these tides; referred to in literature as the tidal prism. All tidal conditions vary with location depending on the tidal range (difference between the average high and average low tides), the geometry of the portion of the river influenced by the tides and the proximity of the river to the coast. Climate, vegetation, wind and storm induced waves and surges, the scale of the river, inlets, current mean sea level elevation, and relative sea level rise (RSLR) also influence H&H characteristics.

Modern hydrodynamic computer models are capable of simulating various combinations of water levels, fluvial and tidal currents, surges, waves, sediment transport, salinity intrusion, stratification, and wave action in coastal rivers that result from tidal, meteorological, and density forcing. The following paragraphs discuss these topics. Table 8.2 summarizes publicly available sources of information. Detailed information about the development, calibration, and validation of the hydrodynamic modeling can be found in *Highways in the Coastal Environment* (FHWA 2020) and *A Primer on Modeling in the Coastal Environment* (FHWA 2017c).

Bathymetric data describe the underwater surface in the coastal and river areas involved in modeling. In addition to the sources listed in Table 8.2, data might be available from the USACE or the NOAA Electronic Navigational Chart (ENC) for water bodies with a navigation channel. The bathymetry of these areas can play an important role in the model (or actual site) behavior. For example, deeper versus shallower bathometry influences behavior of waves and wave propagation (FHWA 2018, FHWA 2020).

Table 8.2. Online data sources for coastal information.

Data Type	Data Source
Bathymetry	NOAA Bathymetry Data Viewer website: maps.ngdc.noaa.gov/viewers/bathymetry Land topography from USGS National Elevation Dataset website: www.usgs.gov/core-science-systems/national-geospatial-program/national-map United States Interagency Elevation Inventory: coast.noaa.gov/inventory
Tides and Currents	NOAA tides and currents: tidesandcurrents.noaa.gov/
Discharge	USGS: maps.waterdata.usgs.gov/mapper/
Salinity	USGS Coastal Salinity Index: www2.usgs.gov/water/southatlantic/projects/coastalsalinity/availability.php NASA satellite data: salinity.oceansciences.org/science-satellites.htm
Waves	NOAA National Data Buoy Center (NDBC): www.ndbc.noaa.gov
Wind and Pressure	NOAA NDBC website Meteorological data for weather gaging stations from the NOAA National Center for Climate Data (NCDC): www.ncdc.noaa.gov/cdo-web/

The tidal range is the difference between the water surface elevation at high and low tide. It can be determined using tidal records (a time series of water level measurements, usually from a station) or a set of tidal harmonics (derived from tidal records). A tide record includes both the astronomical tide and storm surges. Tidal records, as shown in Figure 8.22, are available from tide gages (sometimes described as “tide stations”) that are mostly installed and maintained by the National Oceanic and Atmospheric Administration (NOAA), although other organizations also have tide stations. Table 8.2 provides links to websites providing data on tides and tidal currents. The tide record represents the expected water levels based on astronomical influences (primarily moon and sun gravitational effects) with any surge height added to the astronomical tides. Factors including storms, wind, barometric pressure, river flows, and rainfall influence the height and duration of the surge which can be either negative or positive.

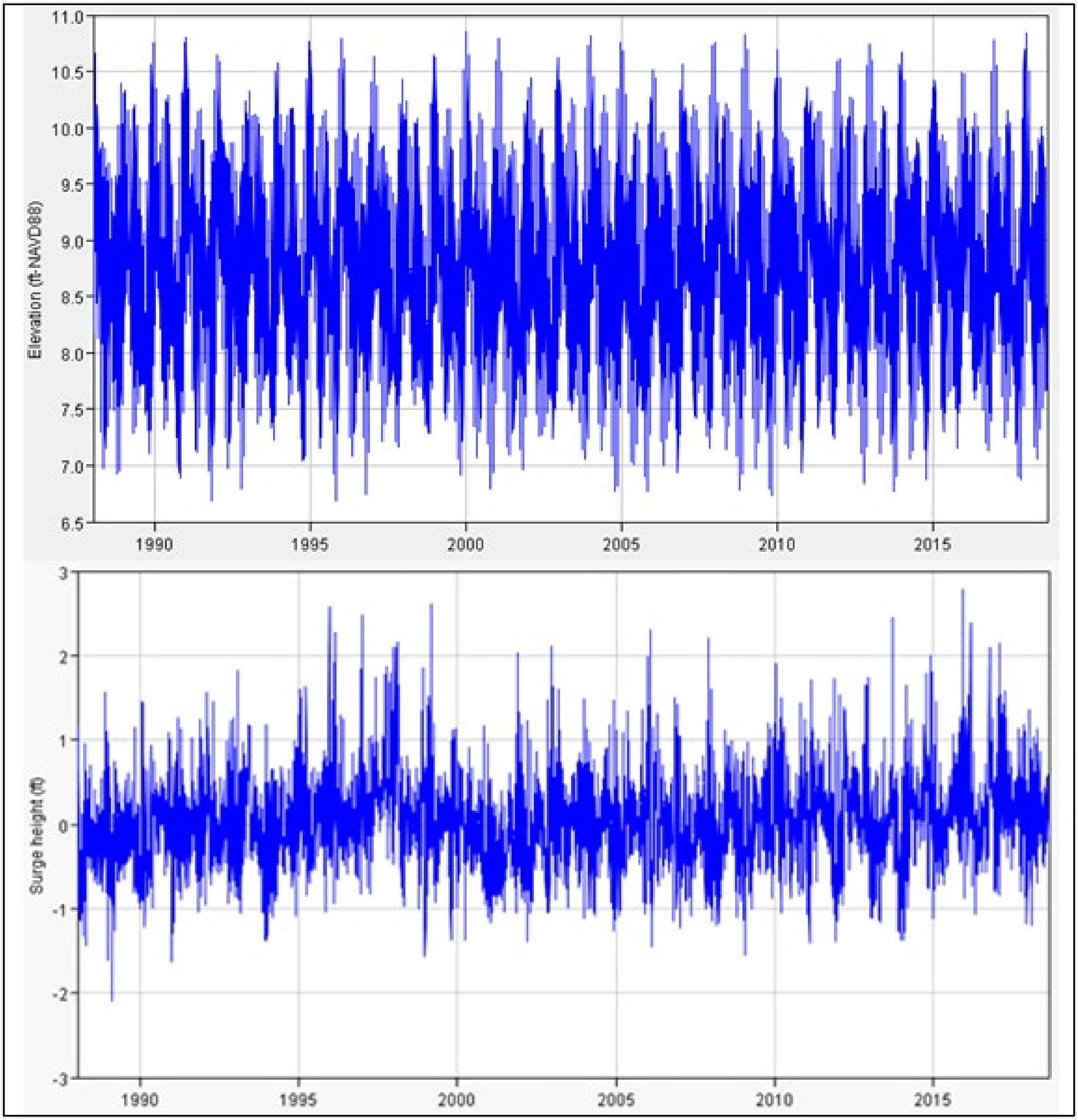


Figure 8.22. Long-term tidal and surge record.

Micro, Meso, or Macro?

Davies (1964) classifies tidal environments based on the tidal range as:

- Micro-tidal, tidal range less than 2 m.
- Meso-tidal, tidal range between 2 and 4 m.
- Macro-tidal, tidal range greater than 4 m.

Figure 8.22 represents a micro-tidal environment.

Tidal harmonics are the derived repeating wave characteristics, such as amplitude and period, extracted from the observed record or extrapolated from stations. When using a riverine model in a tidally influenced river, modelers establish downstream boundary conditions for evaluating the hydraulics using tidal records or these harmonics. The advantage of using tidal harmonics is they can simulate any time interval without inputting historic data or assuming future behavior. Temporary stage recorders can measure water levels near the area of interest. Likewise, a velocity meter or an Acoustic Doppler Current Profiler (ADCP) can be used to measure velocities and currents. FEMA or USACE established surge elevations or surge elevations determined through a project specific coastal hydrodynamic models could also be used to develop downstream boundary conditions for tidally influenced rivers (FHWA 2018, FHWA 2020). Modelers interested in tidally dominated streams would likely use coastal hydrodynamic modeling software to develop the downstream boundary conditions for any complimentary riverine models.

When designing a bridge or culvert, a challenge is determining an appropriate forcing function (e.g., design discharge or water surface elevations) at the model boundary. Water surface elevations are influenced by the downstream coastal process such as tidal fluctuations or surges. To further complicate this, there are times when extreme coastal surge occurs in tandem with extreme rainfall events. This is known as compound flooding (FHWA 2020). When these two events coincide, the high backwater from the surge and the additional volume of water from the rainfall can exceed rainfall or coastal design events considered separately (FHWA 2020). Understanding compound flooding involves considering the joint probability of both extreme coastal and rainfall events. These probabilities are not always independent because the drivers of these probabilities can be the same event (i.e., a single hurricane could lead to a large storm surge closely followed by heavy rainfall). Conservatively combining the worst-case scenarios may not always be practical or affordable as a design approach. Thus, it is important for practitioners to carefully consider risk in proposing an extreme rainfall event when analyzing compound flooding.

Knowledge of the driving processes (or forcing functions) of the river can help decide hydrologic input conditions. For example, in streams and small rivers, peak discharge from the tidal prism (tidal flows during flood or ebb tides) may be greater than the 100-year freshwater flood event. The analysis may determine river discharge to be a constant or variable stage or discharge hydrograph for locations where the river or creek enters the tidally influenced or tidally dominated reach. The analyses may also express salinity at these inflow boundaries to consider the effects of density. Available gaging station records or methods derived from Chapter 5 - may form the basis of hydrographs used in the analyses. The website in Table 8.2 provides available USGS discharge data for tidally influenced and tidally dominated streams.

Some hydrodynamic models can account for salinity at the ocean boundary as either a constant or varying value. Differences in density caused by changes in salinity influence water movement. Saltwater does not mix easily with the fresh water, typically leading to density and temperature stratification, with a wedge of saltwater driving upstream under the freshwater river flow. Factors that drive mixing include wind, tidal range, volume and rate of freshwater influx, and estuary shape. These factors change seasonally and are different in every watercourse. Seasonal influences include heavy spring rains or a shift in local wind directions (Sumich 1996). Publicly available data sources for salinity are provided in Table 8.2.

Wind driven waves influence the hydraulics of any large waterbody, including those in a tidally dominated river. Wave sizes for modeling or other analyses are typically identified by the entire range of waves observed by measurements. Measured wave data are available from NOAA National Data Buoy Center (NDBC) website in Table 8.2. Data available from the buoy network include wind direction and speed, significant wave height, dominant wave period, average wave period, sea level atmospheric pressures, air temperature, sea surface temperature, and dew point temperature.

Meteorological conditions affecting tidally dominated streams include wind stress and pressure fields. These can significantly alter tidal and river flows in the relatively shallow coastal environments and influence waves. They can be simulated as constant or variable in time and space. Data sources are summarized in Table 8.2.

Other important factors for characterizing and modeling of tidally dominated systems include:

- Consideration of predominant processes: i.e., simulation of tides and nearshore waves to accurately compute the water levels, currents, and density structures at the downstream boundary in estuaries with large mouths.
- Up-river model extents that capture the full tidal prism represented at the ocean boundary.
- Calibration and validation of the important forcing variables over a range sufficient to ensure that they are appropriately simulated in the model.

Development of a hydrodynamic model suitable for use in river crossing design involves the following steps:

1. Collection of available data (water levels, wave conditions, wind, and bathymetry).
2. Data collection for calibration, sensitivity testing, and validation (tidal currents, water levels, wave heights and long-term sediment transport trends when applicable).
3. Creation of a digital surface by merging bathymetric and land survey topography data.
4. Creation of a suitable computational mesh.
5. Model calibration.
6. Model validation.
7. Definition of baseline (without highway river crossing) conditions.

Tidally influenced rivers can be modeled using a 1D or 2D unsteady flow hydraulic model. The governing equations used in these models are the full dynamic equations (conservation of mass and momentum). These simpler models typically only simulate the tidal stage hydrograph at the coastal boundary and a river flow hydrograph at the upstream end of the boundary, though some include surface wind stress. The discharge within the tidally influenced area is influenced by the tidal prism, so model domains that encompass the tidal extent help to accurately reflect the discharge throughout the model.

The strong influence of coastal processes in tidally dominated rivers, may increase the complexity of modeling compared with riverine hydraulic models. Practitioners may account for this by using both coastal and riverine models with one providing boundary conditions to the other allowing consideration of potentially damaging processes to bridges and roadways such as scour or wave impacts. The worst-case scenario from either model can be taken to create more resilient structures.

Accounting for relative sea level rise in both tidally influenced and tidally dominated river models with bridges and culverts can improve the long-term resilience of these structures. More information about this can be found in NCHRP 15-61 *Applying Climate Change Information to Hydrologic and Hydraulic Design of Transportation Infrastructure* (Kilgore et al. 2019) and HEC-25 *Highways in the Coastal Environment Third Edition* (FHWA 2020). Additional information about the development and use of models in tidally influenced and tidally dominated areas is provided in *A Primer on Modeling in the Coastal Environment* (FHWA 2017c) and HEC-25 *Highways in the Coastal Environment Third Edition* (FHWA 2020).

Design of the hydraulic opening for a bridge or culvert is generally dependent on local, State, and Federal design criteria. Factors that can influence the design of the hydraulic opening include:

- Applicable State or Federal design standards.
- Average daily traffic volume (influences design flood frequency).
- Whether or not waterbody is navigable (influences which FHWA regulations and U.S. Coast Guard laws apply).
- Regional influences on design standards (e.g., design of bridges to withstand hurricanes, etc.).
- Location specific influences (e.g., different design loadings, depending on whether a bridge is exposed to, or sheltered from, ocean waves or long-fetch wind waves).

More information about the design of coastal bridges is provided in *Highways in the Coastal Environment* (FHWA 2020).

8.10.2 Sediment Transport and Scour

Because of the numerous temporally and spatially varied hydrodynamic and sedimentation factors affecting tidally influenced rivers, estimating their sediment transport capacity is particularly complicated (Dalrymple and Choi 1978). Sediment transport estimates are typically made using the same empirically based equations derived from field and laboratory measurements for fluvial conditions described in Section 7.4.2.

In a tidal environment, entrainment and transport of both cohesive and noncohesive particles are influenced by:

- Physical processes (tides, waves, river velocity).
- Biochemistry (flocculation of very fine sands, silts, and clays when fresh river water mixes with salt water).
- Biology (vegetation effects on roughness, turbulence, and trapping of muddy sediments).

In these environments, finer cohesive and noncohesive sediments are typically transported as either suspended bed material load or wash load. Deposition of the fine material occurs predominantly under low velocity conditions when the tide turns, forming mudflats with elevations at and around the high tide limit. Coarser, noncohesive sands and gravels are transported as bed load that form various types of bedforms and bars, both in the estuary and the nearshore (littoral) zone. Different transport equations apply to cohesive and noncohesive particles.

Sediment transport rate is a non-linear relationship that results in a net transport of sediment in the direction with the higher average velocity during the tidal cycle. Marine sediments may be deposited in the tidal zone, as well as terrestrial sediments delivered by the river. There is a lag in scour and settling of sediment in many tidal environments resulting from the difference between the critical shear stresses for entrainment and deposition, and because of the slow settling velocity of fine, unflocculated sediments. This results in a landward-fining trend in bed sediment grain size. The tidal cycle results in bi-directional sediment transport and intermittent episodes of sand or gravel transport during flood and ebb tides (mid-point between high and low tide) where the currents are sufficiently strong to transport sediment, alternating with periods of fines deposition on mud flats during slack water conditions.

Other factors that influence sediment transport include winds, waves, currents, longshore sediment transport rates, and density currents (Wang and Andutta 1978). For example, wind-blown sediment could be introduced into a tidally influenced river during strong on-shore winds that erode coastal sand dunes or re-suspend sediments previously deposited by coastal or fluvial processes. Wind transport can influence the formation and migration of both ripple and dune bedforms. Longshore sediment transport is driven by near-shore currents and waves. It is an important component on the evolution of the shoreline, especially around river mouths. The longshore shore sediment can be influenced by changes in sediment supply from large rivers, wind direction, large storm events, coastal landforms, and coastal infrastructure. Longshore sediment transport is seasonal and can cause partial or complete blockage of the river by a spit or bar during summer months. An example of this phenomena is illustrated in Figure 8.23, where longshore sediment transport has blocked the mouth of the San Luis Rey River in California.

Figure 8.23 Effect of longshore sediment transport at the mouth of the San Luis Rey River, California.

Waves create turbulence, shear forces, and circulations that can entrain sediment into the water column. Waves may influence deposition patterns, or cause bank erosion that can introduce additional sediment into the system. Density currents are fluids kept in motion by the action of gravity acting on fluid density differences. Density currents can be created by differences in temperature, salinity, or suspended sediment concentrations and they are especially important in low energy rivers, where layers of salt and fresh water may become stratified. These currents can influence the transport and deposition of sediment.

Uncertainty in Sediment Transport Modeling

A variety of uncertainties exist in sediment transport modeling due to limitations of available data, understanding of the involved phenomena, and the tools available to represent sediment transport. To maximize confidence in modeling results, models are calibrated and validated to observed conditions. Further, analysis of model results against changes in important model parameters are undertaken to understand the sensitivity of the model output.

The factors affecting sediment transport also affect scour and they are considered when determining the boundary conditions for a scour analysis related to a compound flood event (FHWA 2012, AASHTO 2014, FHWA 2020). For example, a heavy rainfall event that coincides with a high storm surge may lead to high backwater effects that reduce velocities through the bridge. Considering this scenario as a worst-case condition might result in an underestimate of scour because it may not be the defining design condition. Conditions during the falling limb of the surge event might instead generate larger scour estimates and be applicable for design.

The topic of scour in coastal and tidal rivers is complex and largely beyond the scope of this manual. Practitioners working in coastal rivers may wish to consult other references including FHWA (2012), AASHTO (2014), and FHWA (2020).

8.10.3 Ecology

Among the considerations for those implementing transportation infrastructure projects in tidal areas is the natural biological richness of these areas. Tides and corresponding tidal flows transport nutrients, moderate temperatures, and influence conditions in numerous ecosystems from intertidal zones, estuaries, coastal wetlands, and riparian lands.

Regulations and Permitting Considerations in the Coastal Environment

In addition to the Federal and State regulations and permits discussed in Chapter 3, transportation infrastructure projects in coastal environments may be subject to the Federal Coastal Zone Management Act (CZMA), Nationwide Permit 27 (Aquatic Habitat Restoration, Enhancement, and Establishment Activities), Nationwide Permit 54 (Living Shorelines), and others (FHWA 2019b).

For more information, see The National Coastal Zone Management Program at:

coast.noaa.gov/czm/

Figure 8.24 and Figure 8.25 show aerial views of two tidally influenced rivers, with both demonstrating the diverse biological conditions in an estuary and the proximity of human development, including transportation infrastructure. In Figure 8.24, roads border much of the riparian area in this estuary, and a major highway bridge crosses the waterway near its mouth. Because of its proximity to ecologically vulnerable areas in this estuary, development and maintenance of transportation infrastructure has the potential to adversely affect the functions of intertidal zones, wetlands, and riparian areas, particularly when road-related environmental pressures combine with those from jetties, revetments and other infrastructure. The infrastructure is also exposed to potentially adverse effects from high energy waves and boat wakes, high tides, storm surges, and tsunamis. The following subsections provide descriptions of the varied ecological areas commonly associated with tidally dominated and tidally influenced rivers and streams.

8.10.3.1 Intertidal Zones

The intertidal zone lies between the mean low tide elevation and the mean high tide elevation. It may include various habitats including extensive mudflats, sandy beaches, and rocky environments ranging from tidal pools to steep cliffs. Frequent, regular switching between aquatic and subaerial conditions results in unique habitats to which various organisms have adapted, including marsh grasses, kelp, bivalves, shrimp, fish, burrowing worms, snails, and shore birds.

8.10.3.2 Estuaries

An estuary is a sheltered coastal waterbody with one or more rivers, streams, or creeks flowing into it. Estuaries support some of the most biodiverse and productive ecosystems. These attributes stem from mixing of fresh and salt water to produce spatially and temporally variable brackish habitats (Underwood and Kromkamp 1999). Topography, wind, waves, tidal influxes, and estuary size influence salinity, which can range from freshwater to ocean concentrations. Seasonal variations reflect fluctuations in the balance between coastal wave energy and river discharge. Short-term variations result from extreme events (storms, surges, floods, droughts) as well as normal tidal cycles.

Estuaries are typically relatively shallow, allowing for strong interaction between the bed and the water column. Ecological processes and biogeochemical cycles in an estuary are influenced by estuarine circulation, river and groundwater discharge, tidal flooding, sediment resuspension events, and exchange flow with adjacent marsh systems. They host complex ecosystems of marine organisms that provide a rich food source for a variety of fish, shrimp, crabs, bivalves, and aquatic birds.

8.10.3.3 Coastal Wetlands

Coastal wetlands can be found in or around estuaries and tidal rivers, often extending many miles inland. They can be tidal, tidally influenced (via a groundwater link), or non-tidal and contain salty, fresh, or brackish water. Coastal wetlands habitats include saltmarsh, freshwater marsh, bottomland hardwood swamps, mangrove swamps, cypress swamps, and shrubby depressions that support an abundance of marine, coastal, and other species. They improve water quality and provide fish spawning areas as well as feeding grounds. Some birds depend on coastal wetlands for breeding, nesting, feeding, and shelter during their annual cycles. They are also important to a variety of migratory birds, such as ducks, shorebirds, gulls, terns, and flamingos.

Figure 8.24. Aerial view of Yaquina River estuary near Newport, Oregon.

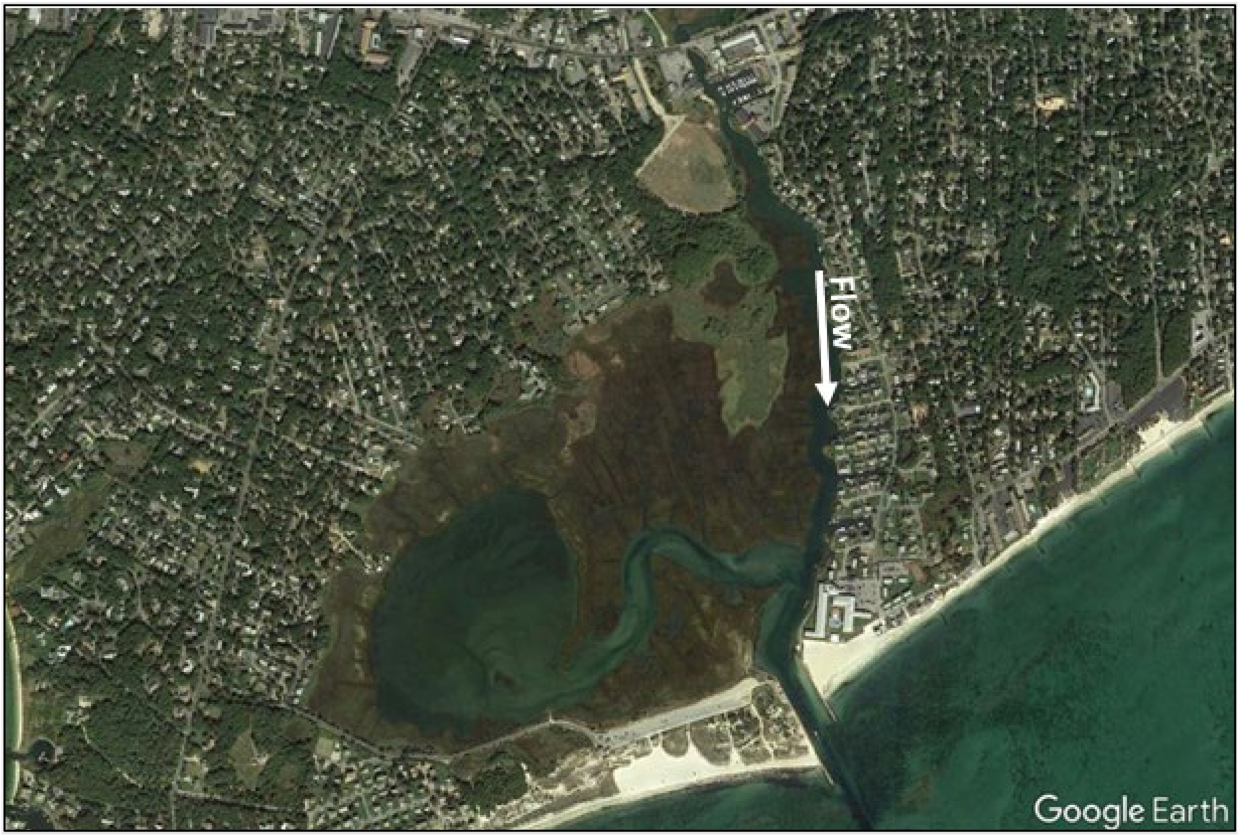


Figure 8.25. Tidally influenced Parkers River in West Yarmouth, Massachusetts.

8.10.3.4 Riparian Lands

Riparian areas near tidally influenced streams have many of the same characteristics as those along any other watercourse. They are also important transitional zones between aquatic and floodplain plant ecosystems. Because the association with adjacent waters is an intrinsic component of the function and structure of riparian areas, the characteristics of tidally influenced streams provide for soil and vegetation characteristics in the riparian corridor that are distinctly different from surrounding lands and are strongly influenced by the presence of water. These transition zones are extremely productive and sustain broadly-based food webs that help support diverse assemblages of fish and wildlife.

8.10.4 Connectivity

Long-stream connectivity maintenance presents a challenge of building transportation infrastructure in the vicinity of tidally influenced watercourses. Historically, long-stream disconnection resulting from construction of restrictive hydraulic openings and roadway embankments across the tidally influenced floodplain and channels has caused significant impacts to ecological conditions along coastal wetlands and intertidal areas. Impacts to water and sediment movement caused by transportation infrastructure have had significant impacts to the processes involved in the natural creation and maintenance of habitat in an otherwise biologically rich environment. Figure 8.26 shows an interstate highway crossing an estuary and broad tidal flats. The roadway embankment and limited hydraulic openings of the two bridges constrict the conveyance of water, sediment, and wood to the intertidal zones and wetlands located downstream of the highway. Highways can also present tidal restrictions limiting connectivity of tidal waters upstream of the roadway.

Figure 8.26. Interstate 5 crossing of the Nisqually River delta, Washington State.

Transportation project teams recognize the importance of maintaining long-stream connectivity in tidally influenced river environments. A USEPA resource summarizes the state of knowledge of tidal restrictions and their potential effects on the coastal environment and provides recommendations for tidal restriction avoidance and removal when practicable (USEPA 2020). When project teams minimize conveyance restrictions for flows in both the flood and ebb directions, they minimize potential environmental effects. This could involve increasing hydraulic connections by maximizing the hydraulic openings of bridges, reducing roadway embankment encroachment where possible, and establishing additional relief conveyance structures in floodplain areas.

8.11 Inspection and Monitoring

This manual describes the importance of roads, rivers, and floodplains to society and provides information for understanding rivers and floodplains and for designing roadways so that they compatibly co-exist. Because all three are dynamic, inspection and monitoring are important practices.

8.11.1 Value Added from Inspection and Monitoring

Bridges and culverts with spans greater than 20 feet are inspected on a recurring basis as discussed in Section 6.5. Other elements of the transportation infrastructure are also inspected in some locales depending on the needs, maintenance experience, and budgets. For example, Maryland DOT inspects such spans less than 20 ft every 4 years. Many states have initiated or maintain inventories of these assets to better prioritize expenditures of maintenance budgets. These programs identify performance issues early and allow implementation of maintenance and corrective actions.

Inspection and monitoring also adds value where transportation infrastructure longitudinally encroaches into riverine and floodplain environments. As with bridges and culverts, inspection and monitoring can identify problems that could degrade valuable environmental functions and detect risks posed by adverse environmental hazards.

For highways in the river environment, value-added inspection and monitoring applies not only to the transportation infrastructure itself (i.e., bridges, approach embankments/cuts, the channel immediately up- and downstream, etc.), but also to the river environment more generally (i.e., reach-scale channel stability/change, fish passage, mitigation measures, etc.). Value-added inspection facilitates an understanding of how transportation assets affect the stream.

A possible approach is to leverage existing inspection of transportation assets to include a monitoring component. This may be achieved if value-added monitoring is performed in partnership with specialists from other agencies and organizations that have interests in the stream corridor and project site. Opportunities for partnerships to monitor these assets are growing because of the shared interests of Federal, Tribal, State, County agencies and private landowners in stream functions, biodiversity, key/game species, and environmental quality.

8.11.2 Purpose and Procedures

Routine inspections are performed by highway agencies. Value-added inspection and monitoring are not routinely performed but can be undertaken to detect undesirable environmental changes or trends before they:

- Pose a risk to the safety or property of road users and the wider public.
- Reduce the integrity and operational efficiency of a highway or crossing.

- Cause adverse environmental impacts or reduce the effectiveness of mitigation to an extent that poses unacceptable risks to sport, game, or protected species.

Early and proactive identification of potential problems usually saves time, effort, and cost as issues can be addressed efficiently through scheduled maintenance or adaptive management. When the results of inspection and monitoring are fed back into planning and design, practical experience informs and improves highway technologies, practices, and outcomes.

As summarized in Figure 8.27, inspection and monitoring provide data for assessment of asset performance. Assessment involves systematic review of inspection and monitoring procedures and results, and then checking that the design objectives are being fulfilled, by comparing outcomes against project targets.

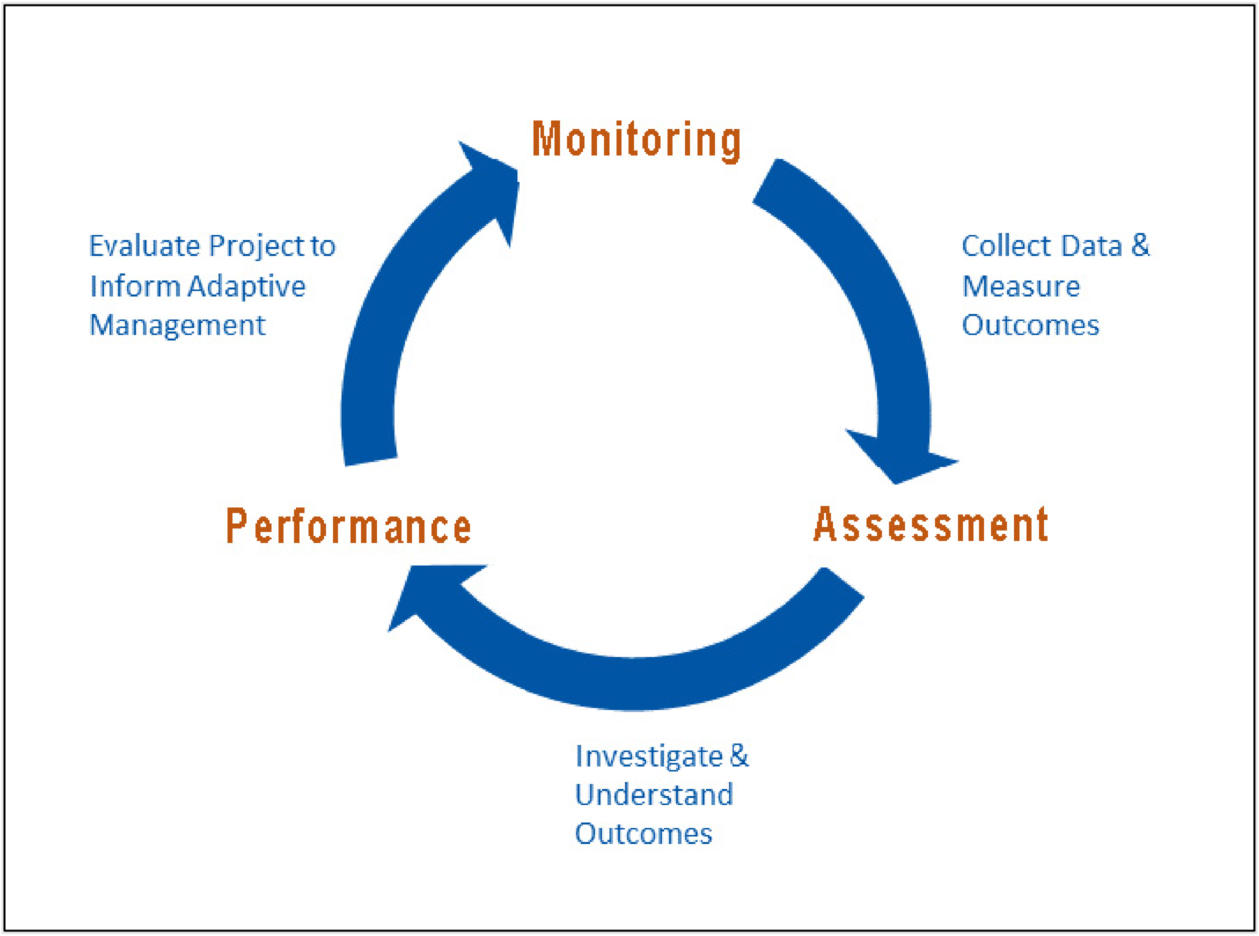


Figure 8.27. Monitoring-assessment-performance cycle.

Even without performance appraisal and assessment, inspection and monitoring may be divided into four elements: 1) pre-project surveys, 2) implementation surveys, 3) effectiveness surveys, and 4) maintenance inspection.

Pre-project surveys establish baseline environmental conditions and determine their sensitivity to potential environmental impacts of alternative project designs. They are also used to assess the river and its environment, delineate wetlands, and identify the presence of species known to be sensitive to disturbance or are covered by Section 7 of the ESA.

Implementation surveys occur during and immediately following construction. The designated personnel verify BMP implementation, oversee variations from the final design, and establish the as-built dimensions and environmental features of the channel, riparian corridor, riverine wetlands, and floodplain. Environmental implementation surveys (together with engineering as-built surveys of the highway and crossings) are important because they provide a post-construction baseline against which future changes in conditions can be compared (Coleman and Nichols 2016). Increasingly, organizations employ unmanned aerial systems and internet-connected web cameras to provide efficient and comprehensive photographic documentation as part of implementation surveys.

Effectiveness surveys are undertaken periodically following implementation to verify that the project site and stream (upstream and downstream) are recovering from disturbance as intended, and that post-project environmental quality targets are achieved (Coleman and Nichols 2016). Effectiveness surveys may be as simple as visiting the site periodically to visually check that environmental impacts generated by post-project responses in the river and floodplain are acceptable. This type of environmental monitoring can usually be incorporated into scheduled safety inspections of bridges, culverts, and roads.

In some cases, regulatory and permitting agencies may stipulate more specific monitoring actions, for example, maximum late-summer water temperatures or fish passage minimum depths, maximum velocities, or jump heights (Coleman and Nichols 2016). Environmental monitoring to address specific State or Federal requirements may involve installation of sensors or visits by specialists, for example, fish passage engineers or aquatic biologists. Specialist monitoring to determine what river functions and species are being supported, can be complex. Often, this type of monitoring is best designed and conducted in cooperation with a State or Federal environmental agency, a university, or a non-profit organization, such as a Watershed Council or Land Trust.

Inspections detect problems and inform scheduling of maintenance work so that the infrastructure operates as intended throughout its service life. Maintenance inspections typically include:

- Roadbed.
- Embankments/cuts.
- Protective structures (e.g., revetments, bioengineering).
- Crossings (bridges/culverts)
- Assessment of “channel condition.”

Assessment of channel condition is imprecisely understood resulting in variable information from this element of an inspection. Locating the highway outside of the active river corridor and designing crossings to meet minimum environmental and fluvial performance standards avoids many interactions between highway and river. In such cases, the importance of a precise understanding of channel condition is reduced.

Even in situations where the design intent was avoidance of road and river interaction, there may be occasions where adaptive management is appropriate to halt or reverse an unintended road-river interaction. Even when the circumstances were not anticipated when the project was designed, interaction between a stream and a highway can lead to unacceptable risks to both road users and the stream environment. Early detection based on a suitable inspection and monitoring program avoids disruption and supports efficient solutions through routine maintenance or adaptive management.

Any maintenance or adaptive management action has the potential to generate further stream responses. Before maintenance or adaptive management is initiated, the team is likely to benefit from considering whether the environmental impact being addressed is:

- Unacceptable to one or more stakeholders, environmental agencies, or organizations.
- Unlikely to be time-limited and recover naturally given the recuperative capacity of the river and its ecosystem.
- Sufficiently serious that the added environmental risks associated with potential unintended consequences of the proposed adaptive management action are acceptable.

8.11.3 Closure: Integration of Road, River, and Floodplain with Inspection, Monitoring, and Adaptive Management

This manual illustrates that the river environment is a complex, multi-functional space comprising the channel (or channels) that convey water, sediment, and wood at normal flows, as well as the river corridor, channel migration zone, and floodplain inundated during high flows. The river environment operates through an array of physical and chemical processes, providing habitat to a wide range of aquatic, riparian, and floodplain species. The life of the river not only influences physical forms and processes; it also provides society with a range of highly valued ecosystem services.

The objective for a highway in the river environment is to provide society with transportation benefits that satisfy basic social and economic needs while protecting river functions, making responsible use of natural resources, and maintaining or improving the well-being of the environment. In this way, transportation projects balance and satisfy social, environmental, and economic values, creating sustainable infrastructure. Inspection and monitoring add value to design, maintenance, and adaptive management of highways in the river environment by establishing how well the project and any environmental mitigations function over the long-term. Inspection and monitoring also adds value to the safety of road users while identifying deficiencies and facilitating timely adaptive management.

Rivers, wetlands, and floodplains are multi-functional assets. Ensuring long-term sustainability and resilience of the river environment is best achieved in collaboration with all relevant stakeholders. When a road encroaches into the river environment, the highway owner/operator becomes a key stakeholder in the river environment and its stewardship.

The river corridor is a space that is shared and valued by multiple users. Integrated inspection, monitoring, performance appraisal, and assessment brings specialists together to develop a common understanding of how the river functions as a whole system. A broad, multi-disciplinary multi-entity approach to monitoring builds appreciation of the complexity and inter-connectedness of the road and the river environment. This appreciation provides a firm foundation for sustainable design, construction, and management of highways in the river environment.

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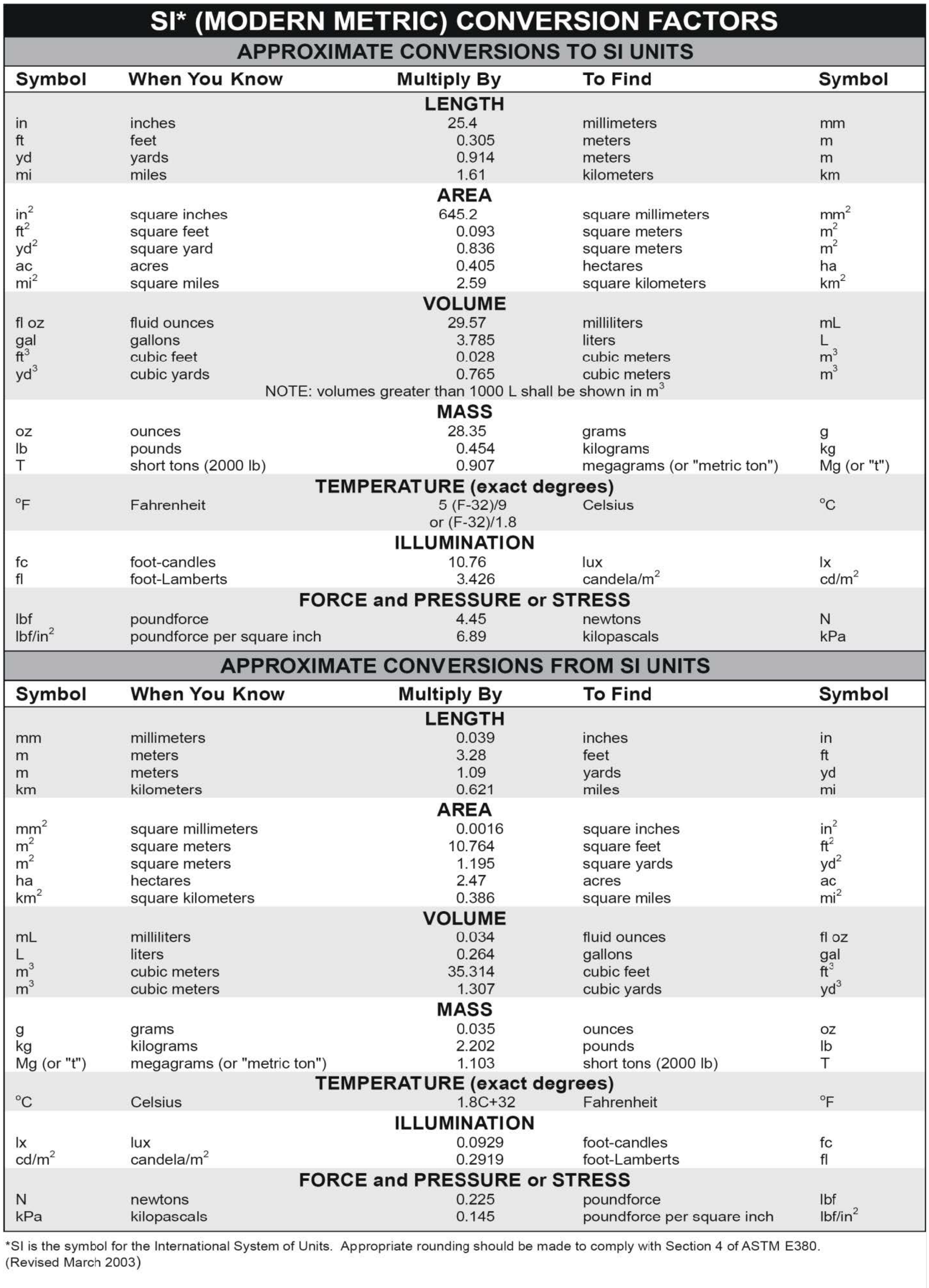
Appendix – Units



SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)