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Third Edition

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16. This document provides guidelines for identifying stream instability problems at highway stream crossings. It is a dual unit update of the second edition published in 1995. The HEC-20 manual covers geomorphic and hydraulic factors that affect stream stability and provides a step-by-step analysis procedure for evaluation of stream stability problems. Stream channel classification, stream reconnaissance techniques, and rapid assessment methods for channel stability are summarized. Quantitative techniques for channel stability analysis, including degradation analysis, are provided, and channel restoration concepts are introduced.

In addition to minor editorial revisions, the following substantive changes have been made in this revised edition of HEC-20: corrected definition of density of water, ρ, (p. xi); revised definition of grain roughness k_s, for gravel and coarse bed material (p. 6.15) and corrected multiplier for kinematic viscosity in Appendix A (Table A.7).

17. Key Words

bridge design, bridge stability, channel classification, stream reconnaissance, quantitative techniques, highway structures, scour, hydraulics, sediment, stream geomorphology, stream stability, channel restoration

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LIST OF SYMBOLS

A	=	Cross-sectional flow area, m^2 (ft^2)
A_m	=	Meander amplitude, m (ft)
a, b, c	=	Coefficients
b	=	Length of the bridge opening, m (ft)
C	=	Conveyance, m^3/s (ft^3/s)
C_d	=	Coefficient of drag
C_t	=	Sediment concentration in parts per million by weight
c	=	Bank material cohesion, Pa or N/m^2 (lbs/ft^2)
D_c	=	Diameter of sediment particle at incipient motion conditions, mm or m (in or ft)
D_i	=	The i^{th} percentile size of bed material finer than a given size, mm or m (in or ft)
D_{50}	=	Median sediment size, mm or m (in or ft)
Fr	=	Froude Number
FS	=	Factor of safety
g	=	Acceleration of gravity, m/s^2 (ft/s^2)
h_L	=	Energy loss m (ft)
H	=	Depth of submergence, m (ft)
K	=	Conveyance, m^3/s (ft^3/s)
K_u	=	Conversion constant (SI/English units)
K_s	=	Shield's Parameter
k_s	=	Grain roughness
L	=	Distance upstream of base level control, m (ft)
L	=	Reach length, m (ft)
M	=	Mass of the debris, kg (slugs or lbs)
M	=	Weighted silt-clay index
MR	=	Migration rate, m/yr (ft/yr)
MD_5	=	5-year migration distance, m (ft)
m	=	Roughness correction factor for sinuosity of the channel
n	=	Manning's roughness coefficient
n_b	=	Base value for straight, uniform channel
n_1	=	Value for surface irregularities in the cross section
n_2	=	Value for variations in shape and size of the channel
n_3	=	Value for obstructions
n_4	=	Value for vegetation and flow conditions

LIST OF SYMBOLS (continued)

P	=	Planform sinuosity
P	=	Wetted perimeter, boundary), m (ft)
P_c	=	Decimal fraction of material coarser than the armoring size
Q	=	Discharge, total discharge, m^3/s (ft^3/s)
Q_r	=	Radial stress, N/m^2 (lbs/ft^2)
Q_s	=	Sediment discharge, m^3/s (ft^3/s)
q	=	Discharge per unit width, $m^3/s/m$ or m^2/s ($ft^3/s/ft$)
q_s	=	Sediment discharge per unit width, $m^3/s/m$ or m^2/s ($ft^3/s/ft$)
R	=	Hydraulic radius (ratio of flow area to wetted perimeter), m (ft)
R_c	=	Radius of the center of the stream, m (ft)
R_i	=	Radius of the inside bank, m (ft)
R_o	=	Radius of the outside bank at the bend, m (ft)
S	=	Stopping distance, m (ft)
S	=	Energy slope or channel slope, m/m (ft/ft)
S_{eq}	=	Equilibrium channel slope, m/m (ft/ft)
S_{ex}	=	Existing channel slope, m/m (ft/ft)
s	=	Shear strength, Pa or N/m^2 (lbs/ft^2)
U_*	=	Shear velocity, m/s (ft/sec)
V	=	Velocity or average velocity of flow, m/s (ft/s)
V_{cr}	=	Critical velocity, m/s (ft/s)
$V_{s\ (inflow)}$	=	Volume of sediment supplied, m^3 (ft^3)
$V_{s\ (outflow)}$	=	Volume of sediment transport, m^3 (ft^3)
W	=	Width, m (ft)
W_D	=	Width under dominant discharge, m (ft)
x	=	Sinusoidal function of distance
Y	=	Depth, m (ft)
Y	=	Depth of tension cracking, m (ft)
Y_a	=	Thickness of the armoring layer, m (ft)
Y_s	=	Depth of scour, m (ft)
Y_s	=	Ultimate degradation amount, m (ft)
Z	=	Bed elevation referenced to a common datum, m (ft)
z_o	=	Depth of tensile stress, m (ft)
β	=	Angle of bank failure plane relative to horizontal

LIST OF SYMBOLS (continued)

γ	=	Specific weight of water, N/m^3 (lbs/ft^3)
γ_s	=	Specific weight of sediment, N/m^3 (lbs/ft^3)
Δt	=	Time increment, s
ΔV	=	Volume of sediment stored or eroded, m^3 (ft^3)
ΔW	=	Lateral erosion distance, m (ft)
ΔZ	=	Change in bed elevation, m (ft)
ΔZ	=	Difference in water surface elevation between the concave and convex banks, m (ft)
Δ_{max}	=	Maximum lateral (migration) erosion distance, m (ft)
η	=	Porosity of bed material
θ	=	Bank slope angle
θ	=	Channel direction
θ	=	Shields parameter
λ	=	Meander wavelength, m (ft)
μ	=	Pore water pressure, Pa or N/m^2 (lbs/ft^2)
ν	=	Kinematic viscosity, m^2/s (ft^2/s)
ρ	=	Density of water, kg/m^3 ($slugs/ft^3$)
σ	=	Normal stress, Pa or N/m^2 (lbs/ft^2)
τ_o	=	Average boundary shear stress, Pa or N/m^2 (lbs/ft^2)
τ_c	=	Critical shear stress, Pa or N/m^2 (lbs/ft^2)
τ_e	=	Shear stress ratio, τ_o/τ_c
ϕ	=	Bank material friction angle
ϕ'	=	Apparent angle of internal friction
ω	=	Maximum angle between a channel segment and the mean downvalley axis
ω	=	Fall velocity of sediment, m/s (ft/s)

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GLOSSARY

abrasion: Removal of streambank material due to entrained sediment, ice, or debris rubbing against the bank.

aggradation: General and progressive buildup of the longitudinal profile of a channel bed due to sediment deposition.

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 which 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 whose flow is divided at normal and lower stages by large islands or, more rarely, by large bars; individual islands or bars are wider than about three times water width; channels are more widely and distinctly separated than in a braided stream.

anastomosing stream: An anabranched stream.

angle of repose: The maximum angle (as measured from the horizontal) at which gravel or sand particles can stand.

annual flood: The maximum flow in one year (may be daily or instantaneous).

apron: Protective material placed on a streambed to resist scour.

apron, launching: An apron designed to settle and protect the side slopes of a scour hole after settlement.

armor (armoring): Surfacing of channel bed, banks, or embankment slope to resist erosion and scour. (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; (b) placement of a covering to resist erosion.

articulated concrete mattress: Rigid concrete slabs which can move without separating as scour occurs; usually hinged together with corrosion-resistant cable fasteners; primarily placed for lower bank protection.

average velocity: Velocity at a given 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 a catastrophic event.

backfill: The material used to refill a ditch or other excavation, or the process of doing so.

backwater: The increase in water surface elevation relative to the elevation occurring under natural channel and floodplain conditions. It is 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 sides of a channel between which the flow is normally confined.

bank, left (right): The side of a channel as viewed in a downstream direction.

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 floodplain: The floodplain associated with the flood with a 100-year recurrence interval.

bed: The bottom of a channel bounded by banks.

bed form: A recognizable relief feature on the bed of a channel, such as a ripple, dune, plane bed, antidune, or bar. Bed forms are a consequence of the interaction between hydraulic forces (boundary shear stress) and the bed sediment.

bed layer: A flow layer, several grain diameters thick (usually two) immediately above the bed.

bed load:	Sediment that is transported in a stream by rolling, sliding, or skipping along the bed or very close to it; considered to be within the bed layer (contact load).
bed load discharge (or 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).
bedrock:	The solid 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 and is equal to the transport capability of the flow.
bed shear (tractive force):	The force per unit area exerted by a fluid flowing past a stationary boundary.
bed slope:	The inclination of the channel bottom.
blanket:	Material covering all or a portion of a streambank to prevent erosion.
boulder:	A rock fragment whose diameter is greater than 250 mm.
braid:	A subordinate channel of a braided stream.
braided stream:	A stream whose flow is divided at normal stage by small mid-channel bars or small islands; 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 within which are subordinate channels.
bridge opening:	The cross-sectional area beneath a bridge that is available for conveyance of water.
bridge waterway:	The area of a bridge opening available for flow, as measured below a specified stage and normal to the principal direction of flow.
bulk density:	Density of the water sediment mixture (mass per unit volume), including both water and sediment.
bulkhead:	A vertical, or near vertical, wall that supports a bank or an embankment; also may serve to protect against erosion.
bulking:	Increasing the water discharge to account for high concentrations of sediment in the flow.
catchment:	See drainage basin.

causeway: Rock or earth embankment carrying a roadway across water.

caving: The collapse of a bank caused by undermining due to the action of flowing water.

cellular-block mattress: Interconnected concrete blocks with regular cavities placed directly on a streambank or filter to resist erosion. The cavities can permit bank drainage and the growth of vegetation where synthetic filter fabric is not used between the bank and mattress.

channel: The bed and banks that confine the surface flow of a stream.

channelization: Straightening or deepening of a natural channel by artificial cutoffs, grading, flow-control measures, or diversion of flow into an engineered channel.

channel diversion: The removal of flows by natural or artificial means from a natural length of channel.

channel pattern: The aspect of a stream channel in plan view, with particular reference to the degree of sinuosity, braiding, and anabranching.

channel process: Behavior of a channel with respect to shifting, erosion and sedimentation.

check dam: A low dam or weir across a channel used to control stage or degradation.

choking (of flow): Excessive constriction of flow which may cause severe backwater effect.

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 at a pier or abutment (or contraction scour) when there is no movement of the bed material upstream of the bridge crossing at the flow causing bridge scour.

cobble: A fragment of rock whose diameter is in the range of 64 to 250 mm.

concrete revetment: Unreinforced or reinforced concrete slabs placed on the channel bed or banks to protect it from erosion.

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: Contraction scour, in a natural channel or at a bridge crossing, involves 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. The contraction can be caused by the bridge or from a natural narrowing of the stream channel.

Coriolis force: The inertial force caused by the Earth's rotation that deflects a moving body to the right in the Northern Hemisphere.

countermeasure: A measure intended to prevent, delay or reduce the severity of hydraulic problems.

crib: A frame structure filled with earth or stone ballast, designed to reduce energy and to deflect streamflow away from a bank or embankment.

critical shear stress: The minimum amount of shear stress required to initiate soil particle motion.

crossing: The relatively short and shallow reach of a stream between bends; also crossover or riffle.

cross section: A section normal to the trend of a channel or flow.

current: Water flowing through a channel.

current meter: An instrument used to measure flow velocity.

cut bank: The concave wall of a meandering stream.

cutoff: (a) 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; (b) 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, vegetation, or trash, transported by a stream.

degradation (bed): A general and progressive (long-term) lowering of the channel bed due to erosion, over a relatively long channel length.

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.

dike: An impermeable linear structure for the control or containment of overbank flow. A dike-trending parallel with a streambank differs from a levee in that it extends for a much shorter distance along the bank, and it may be surrounded by water during floods.

dike (groin, spur, jetty): A structure extending from a bank into a channel that is designed to: (a) reduce the stream velocity as the current passes through the dike, thus encouraging sediment deposition along the bank (permeable dike); or (b) deflect erosive current away from the streambank (impermeable dike).

discharge: Volume of water passing through a channel during a given time.

dominant discharge: (a) 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; (b) That discharge which determines the principal dimensions and characteristics of a natural channel. The dominant formative discharge depends on the maximum and mean discharge, duration of flow, and flood frequency. For hydraulic geometry relationships, it is taken to be the bankfull discharge which has a return period of approximately 1.5 years in many natural channels.

drainage basin: An area confined by drainage divides, often having only one outlet for discharge (catchment, watershed).

drift: Alternative term for vegetative "debris."

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.

entrenched stream: Stream cut into bedrock or consolidated deposits.

ephemeral stream: A stream or reach of stream that does not flow for parts of the year. As used here, the term includes intermittent streams with flow less than perennial.

equilibrium scour: Scour depth in sand-bed stream with dune bed about which live bed pier scour level fluctuates due to variability in bed material transport in the approach flow.

erosion: Displacement of soil particles due to water or wind action.

erosion control matting: Fibrous matting (e.g., jute, paper, etc.) placed or sprayed on a stream- bank for the purpose of resisting erosion or providing temporary stabilization until vegetation is established.

fabric mattress: Grout-filled mattress used for streambank protection.

fall velocity: The velocity at which a sediment particle falls through a column of still water.

fascine: A matrix of willow or other natural material woven in bundles and used as a filter. Also, a streambank protection technique consisting of wire mesh or timber attached to a series of posts, sometimes in double rows; the space between the rows may be filled with rock, brush, or other materials.

fetch: The area in which waves are generated by wind having a rather constant direction and speed; sometimes used synonymously with fetch length.

fetch length: The horizontal distance (in the direction of the wind) over which wind generates waves and wind setup.

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.

filter: Layer of fabric (geotextile) or granular material (sand, gravel, or graded rock) placed between bank revetment (or bed protection) and soil for the following purposes: (1) to prevent the soil from moving through the revetment by piping, extrusion, or erosion; (2) to prevent the revetment from sinking into the soil; and (3) to permit natural seepage from the streambank, thus preventing the buildup of excessive hydrostatic pressure.

filter blanket: A layer of graded sand and gravel laid between fine-grained material and riprap to serve as a filter.

filter fabric (cloth): Geosynthetic fabric that serves the same purpose as a granular filter blanket.

fine sediment load: That part of the total sediment load that is composed of particle sizes
finer than those represented in the bed (wash load). Normally, the 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.

flanking: Erosion around the landward end of a stream stabilization countermeasure.

flashy stream: Stream characterized by rapidly rising and falling stages, as indicated by a sharply peaked hydrograph. Typically associated with mountain streams or highly disturbed urbanized catchments. Most flashy streams are ephemeral, but some are perennial.

flood-frequency curve: A graph indicating the probability that the annual flood discharge will exceed a given magnitude, or the recurrence interval corresponding to a given magnitude.

floodplain: A nearly flat, alluvial lowland bordering a stream, that is subject to frequent inundation by floods.

flow-control structure:	A structure either within or outside a channel that acts as a countermeasure by controlling the direction, depth, or velocity of flowing water.
flow hazard:	Flow characteristics (discharge, stage, velocity, or duration) that are associated with a hydraulic problem or that can reasonably be considered of sufficient magnitude to cause a hydraulic problem or to test the effectiveness of a countermeasure.
flow slide:	Saturated soil materials which 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 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 distance above a design stage that is allowed for waves, surges, drift, and other contingencies.
Froude Number:	A dimensionless number that represents the ratio of inertial to gravitational forces in open channel flow.
gabion:	A basket or compartmented rectangular container made of wire mesh. When filled with cobbles or other rock of suitable size, the gabion becomes a flexible and permeable unit with which flow- and erosion-control structures can be built.
general scour:	General scour is a lowering of the streambed across the stream or waterway at the bridge. This lowering may be uniform across the bed or non-uniform. That is, the depth of scour may be deeper in some parts of the cross section. General scour may result from contraction of the flow or other general scour conditions such as flow around a bend.
geomorphology/ morphology:	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.
grade-control structure (sill, check dam):	Structure placed bank to bank across a stream channel (usually with its central axis perpendicular to flow) for the purpose of controlling bed slope and preventing scour or headcutting.
graded stream:	A geomorphic term used 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.

groin: A structure built from the bank of a stream in a direction transverse to the current to redirect the flow or reduce flow velocity. Many names are given to this structure, the most common being "spur," "spur dike," "transverse dike," "jetty," etc. Groins may be permeable, semi-permeable, or impermeable.

grout: A fluid mixture of cement and water or of cement, sand, and water used to fill joints and voids.

guide bank: A dike extending upstream from the approach embankment at either or both sides of the bridge opening to direct the flow through the opening. Some guidebanks extend downstream from the bridge (also spur dike).

hardpoint: A streambank protection structure whereby "soft" or erodible materials are removed from a bank and replaced by stone or compacted clay. Some hard points protrude a short distance into the channel to direct erosive currents away from the bank. Hard points also occur naturally along streambanks as passing currents remove erodible materials leaving nonerodible materials exposed.

headcutting: Channel degradation associated with abrupt changes in the bed elevation (headcut) that generally migrates in an upstream direction.

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.

hydraulics: The applied science concerned with the behavior and flow of liquids, especially in pipes, channels, structures, and the ground.

hydraulic model: A small-scale physical or mathematical representation of a flow situation.

hydraulic problem: An effect of streamflow, tidal flow, or wave action such that the integrity of the highway facility is destroyed, damaged, or endangered.

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.

hydrograph: The graph of stage or discharge against time.

hydrology: The science concerned with the occurrence, distribution, and circulation of water on the earth.

imbricated: In reference to stream bed sediment particles, having an overlapping or shingled pattern.

icing: Masses or sheets of ice formed on the frozen surface of a river or floodplain. When shoals in the river are frozen to the bottom or otherwise dammed, water under hydrostatic pressure is forced to the surface where it freezes.

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.

invert: The lowest point in the channel cross section or at flow control devices such as weirs, culverts, or dams.

island: A permanently vegetated area, emergent at normal stage, that divides the flow of a stream. Islands originate by establishment of vegetation on a bar, by channel avulsion, or at the junction of minor tributary with a larger stream.

jack: A device for flow control and protection of banks against lateral erosion consisting of three mutually perpendicular arms rigidly fixed at the center. Kellner jacks are made of steel struts strung with wire, and concrete jacks are made of reinforced concrete beams.

jack field: Rows of jacks tied together with cables, some rows generally parallel with the banks and some perpendicular thereto or at an angle. Jack fields may be placed outside or within a channel.

jetty: (a) An obstruction built of piles, rock, or other material extending from a bank into a stream, so placed as to induce bank building, or to protect against erosion; (b) A similar obstruction to influence stream, lake, or tidal currents, or to protect a harbor (also spur).

lateral erosion: Erosion in which the removal of material is extended horizontally as contrasted with degradation and scour in a vertical direction.

launching: Release of undercut material (stone riprap, rubble, slag, etc.) downslope or into a scoured area.

levee: An embankment, generally landward of top bank, that confines flow during high-water periods, thus preventing overflow into lowlands.

live-bed scour: Scour at a pier or abutment (or contraction 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 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.
lower bank:	That portion of a streambank having an elevation less than the mean water level of the stream.
mathematical model:	A numerical representation of a flow situation using mathematical equations (also computer model).
mattress:	A blanket or revetment of materials interwoven or otherwise lashed together and placed to cover an area subject to scour.
meander or full meander:	A meander in a river consists of two consecutive loops, one flowing clockwise and the other counter-clockwise.
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 ($D_{50.}$)

mid-channel bar: A bar lacking permanent vegetal cover that divides the flow in a channel at normal stage.

middle bank: The portion of a streambank having an elevation approximately the same as that of the mean water level of the stream.

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.

natural levee: A low ridge that slopes gently away from the channel banks that is formed along streambanks during floods by deposition.

nominal diameter: Equivalent spherical 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.

overbank flow: Water movement that overtops the bank either due to stream stage or to 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 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).

peaked stone dike: Riprap placed parallel to the toe of a streambank (at the natural angle of repose of the stone) to prevent erosion of the toe and induce sediment deposition behind the dike.

perennial stream: A stream or reach of a stream that flows continuously for all or most of the year.

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 component of a river-training structure.

pile dike: A type of permeable structure for the protection of banks against caving; consists of a cluster of piles driven into the stream, braced and lashed together.

piping:	Removal of soil material through subsurface flow of seepage water that develops channels or "pipes" within the soil bank.
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.
poised stream:	A stream which, as a whole, maintains its slope, depths, and channel dimensions without any noticeable raising or lowering of its bed (stable stream). Such condition may be temporary from a geological point of view, but for practical engineering purposes, the stream may be considered stable.
probable maximum flood:	A very rare flood discharge value computed by hydrometeorological methods, usually in connection with major hydraulic structures.
quarry-run stone:	Stone as received from a quarry without regard to gradation requirements.
railbank protection:	A type of countermeasure composed of rock-filled wire fabric supported by steel rails or posts driven into streambed.
rapid drawdown:	Lowering the water against a bank more quickly than the bank can drain without becoming unstable.
reach:	A segment of stream length that is arbitrarily bounded for purposes of study.
recurrence interval:	The reciprocal of the annual probability of exceedance of a hydrologic event (also return period, exceedance interval).
regime:	The condition of a stream or its channel with regard to stability. A stream is in regime if its channel has reached an equilibrium form as a result of 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, more or less, a state of equilibrium with respect to erosion and deposition.
regime formula:	A formula relating stable alluvial channel dimensions or slope to discharge and sediment characteristics.
reinforced-earth bulkhead:	A retaining structure consisting of vertical panels and attached to reinforcing elements embedded in compacted backfill for supporting a streambank.

reinforced revetment:	A streambank protection method consisting of a continuous stone toe-fill along the base of a bank slope with intermittent fillets of stone placed perpendicular to the toe and extending back into the natural bank.
relief bridge:	An opening in an embankment on a floodplain to permit passage of overbank flow.
retard (retarder structure):	A permeable or impermeable linear structure in a channel parallel with the bank and usually at the toe of the bank, intended to reduce flow velocity, induce deposition, or deflect flow from the bank.
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.
riparian:	Pertaining to anything connected with or adjacent to the banks of a stream (corridor, vegetation, zone, etc.).
riprap:	Layer or facing of rock or broken concrete dumped or placed to protect a structure or embankment from erosion; also the rock or broken concrete suitable for such use. Riprap has also been applied to almost all kinds of armor, including wire-enclosed riprap, grouted riprap, sacked concrete, and concrete slabs.
river training:	Engineering works with or without the construction of embankment, built along a stream or reach of stream to direct or to lead the flow into a prescribed channel. Also, any structure configuration constructed in a stream or placed on, adjacent to, or in the vicinity of a streambank that is intended to deflect currents, induce sediment deposition, induce scour, or in some other way alter the flow and sediment regimes of the stream.
rock-and-wire mattress:	A flat wire cage or basket filled with stone or other suitable material and placed as protection against erosion.
roughness coefficient:	Numerical measure of the frictional resistance to flow in a channel, as in the Manning's or Chezy's 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:	That part of precipitation which appears in surface streams 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 load:	Sediment bounced along the streambed by energy and turbulence of flow, and by other moving particles.
sand:	A rock fragment 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, 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 yield:	The total sediment outflow from a watershed or a drainage area at a point of reference and in a specified time period. This outflow is equal to the sediment discharge from the drainage area.
seepage:	The slow movement of water through small cracks and pores of the bank material.
shear stress:	See unit shear force.
shoal:	A relatively shallow submerged bank or bar in a body of water.
sill:	(a) A structure built under water, across the deep pools of a stream with the aim of changing the depth of the stream; (b) A low structure built across an effluent stream, diversion channel or outlet to reduce flow 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.
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.
slope-area method:	A method of estimating unmeasured flood discharges in a uniform channel reach using observed high-water levels.

slump: A sudden slip or collapse of a bank, generally in the vertical direction and confined to a short distance, probably due to the substratum being washed out or having become unable to bear the weight above it.

soil-cement: A designed mixture of soil and Portland cement compacted at a proper water content to form a blanket or structure that can resist erosion.

sorting: Progressive reduction of size (or weight) of particles of the sediment load carried down a stream.

spill-through abutment: A bridge abutment having a fill slope on the streamward side. The term originally referred to the "spill-through" of fill at an open abutment but is now applied to any abutment having such a slope.

spread footing: A pier or abutment footing that transfers load directly to the earth.

spur: A permeable or impermeable linear structure that projects into a channel from the bank to alter flow direction, induce deposition, or reduce flow velocity along the bank.

spur dike: See guide bank.

stability: A condition of a channel when, though it may change slightly at different times of the year as the result of varying conditions of flow and sediment charge, there is no appreciable change from year to year; that is, accretion balances erosion over the years.

stable channel: A condition that exists when a stream has a bed slope and cross section which allows its channel to transport the water and sediment delivered from the upstream watershed without aggradation, degradation, or bank erosion (a graded stream).

stage: Water-surface elevation of a stream with respect to a reference elevation.

stone riprap: Natural cobbles, boulders, or rock dumped or placed as protection against erosion.

stream: A body of water that may range in size from a large river to a small rill flowing in a channel. By extension, the term is sometimes applied to a natural channel or drainage course formed by flowing water whether it is occupied by water or not.

streambank erosion: Removal of soil particles or a mass of particles from a bank surface due primarily to water action. Other factors such as weathering, ice and debris abrasion, chemical reactions, and land use changes may also directly or indirectly lead to bank erosion.

streambank failure: Sudden collapse of a bank due to an unstable condition such as removal of material at the toe of the bank by scour.

streambank protection:	Any technique used to prevent erosion or failure of a streambank.
suspended sediment discharge:	The quantity of sediment passing through a stream cross section above the bed layer in a unit of time suspended by the turbulence of flow (suspended load).
sub-bed material:	Material underlying that portion of the streambed which is subject to direct action of the flow. Also, substrate.
subcritical, supercritical flow:	Open channel flow conditions with Froude Number less than and greater than unity, respectively.
tetrahedron:	Component of river-training works made of six steel or concrete struts fabricated in the shape of a pyramid.
tetrapod:	Bank protection component of precast concrete consisting of four legs joined at a central joint, with each leg making an angle of 109.5° with the other three.
thalweg:	The line extending down a channel that follows the lowest elevation of the bed.
tieback:	Structure placed between revetment and bank to prevent flanking.
timber or brush mattress:	A revetment made of brush, poles, logs, or lumber interwoven or otherwise lashed together. The completed mattress is then placed on the bank of a stream and weighted with ballast.
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.
toe protection:	Loose stones laid or dumped at the toe of an embankment, groin, etc., or masonry or concrete wall built at the junction of the bank and the bed in channels or at extremities of hydraulic structures to counteract erosion.
total scour:	The sum of long-term degradation, general (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).
tractive force:	The drag or shear on a streambed or bank caused by passing water which tends to move soil particles along with the streamflow.
trench-fill revetment:	Stone, concrete, or masonry material placed in a trench dug behind and parallel to an eroding streambank. When the erosive action of the stream reaches the trench, the material placed in the trench armors the bank and thus retards further erosion.

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.

ultimate scour: The maximum depth of scour attained for a given flow condition. May require multiple flow events and in cemented or cohesive soils may be achieved over a long time period.

uniform flow: Flow of constant cross section and velocity through a reach of channel at a given time. Both the energy slope and the water slope are equal to the bed slope under conditions of uniform flow.

unit discharge: Discharge per unit width (may be average 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. Usually in units of stress, Pa (N/m^2) or (lb/ft^2).

unsteady flow: Flow of variable discharge and velocity through a cross section with respect to time.

upper bank: The portion of a streambank having an elevation greater than the average water level of the stream.

velocity: The time rate of flow usually expressed in m/s (ft/sec). The average 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.

vortex: Turbulent eddy in the flow generally caused by an obstruction such as a bridge pier or abutment (e.g., horseshoe vortex).

wandering channel: A channel exhibiting a more or less non-systematic process of channel shifting, erosion and deposition, with no definite meanders or braided pattern.

wandering thalweg: A thalweg whose position in the channel shifts during floods and typically serves as an inset channel that conveys all or most of the stream flow at normal or lower stages.

wash load: Suspended material of very small size (generally clays and colloids) originating primarily from erosion on the land slopes of the drainage area and present to a negligible degree in the bed itself.

watershed: See drainage basin.

waterway opening width (area): Width (area) of bridge opening at (below) a specified stage, measured normal to the principal direction of flow.

weephole: A hole in an impermeable wall or revetment to relieve the neutral stress or pore pressure in the soil.

windrow revetment: A row of stone placed landward of the top of an eroding streambank. As the windrow is undercut, the stone is launched downslope, thus armoring the bank.

wire mesh: Wire woven to form a mesh; where used as an integral part of a countermeasure, openings are of suitable size and shape to enclose rock or broken concrete or to function on fence-like spurs and retards.

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CHAPTER 1

INTRODUCTION

1.1 PURPOSE

The purpose of this document is to provide guidelines for identifying stream instability problems at highway-stream crossings. Techniques for stream channel classification and reconnaissance, as well as rapid assessment methods for channel instability are summarized. Qualitative and quantitative geomorphic and engineering techniques useful in stream channel stability analysis are presented.

1.2 BACKGROUND

Approximately 83 percent of the 583 000 bridges in the National Bridge Inventory (NBI) are built over streams. A large proportion of these bridges span alluvial streams that are continually adjusting their beds and banks. Many, especially those on more active streams, will experience problems with aggradation, degradation, bank erosion, and lateral channel shift during their useful life. The magnitude of these problems is demonstrated by the average annual flood damage repair costs of approximately $50 million for highways on the Federal-aid system.

1.3 COMPREHENSIVE ANALYSIS

This manual is part of a set of Hydraulic Engineering Circulars (HEC) issued by the Federal Highway Administration (FHWA) to provide guidance for bridge scour and stream stability analyses. The three manuals in this set are:

HEC-18 Evaluating Scour at Bridges[1]
HEC-20 Stream Stability at Highway Structures
HEC-23 Bridge Scour and Stream Instability Countermeasures[2]

The Flow Chart shown in Figure 1.1 illustrates the interrelationship between these three documents and emphasizes that they should be used as a set. A comprehensive scour analysis or stability evaluation must be based on information presented in all three documents.

While the flow chart does not attempt to present every detail of a complete stream stability and scour evaluation, it has sufficient detail to show the major elements in a complete analysis, the logical flow of a typical analysis or evaluation, and the most common decision points and feedback loops. It clearly shows how the three documents tie together, and recognizes the differences between design of a new bridge and evaluation of an existing bridge.

The HEC-20 block of the flow chart outlines initial data collection and site reconnaissance activities leading to an understanding of the problem, evaluation of river system stability and potential future response. The HEC-20 procedures include both qualitative and quantitative geomorphic and engineering analysis techniques which help establish the level of analysis necessary to solve the stream instability and scour problem for design of a new bridge, or for the evaluation of an existing bridge that may require rehabilitation or countermeasures.

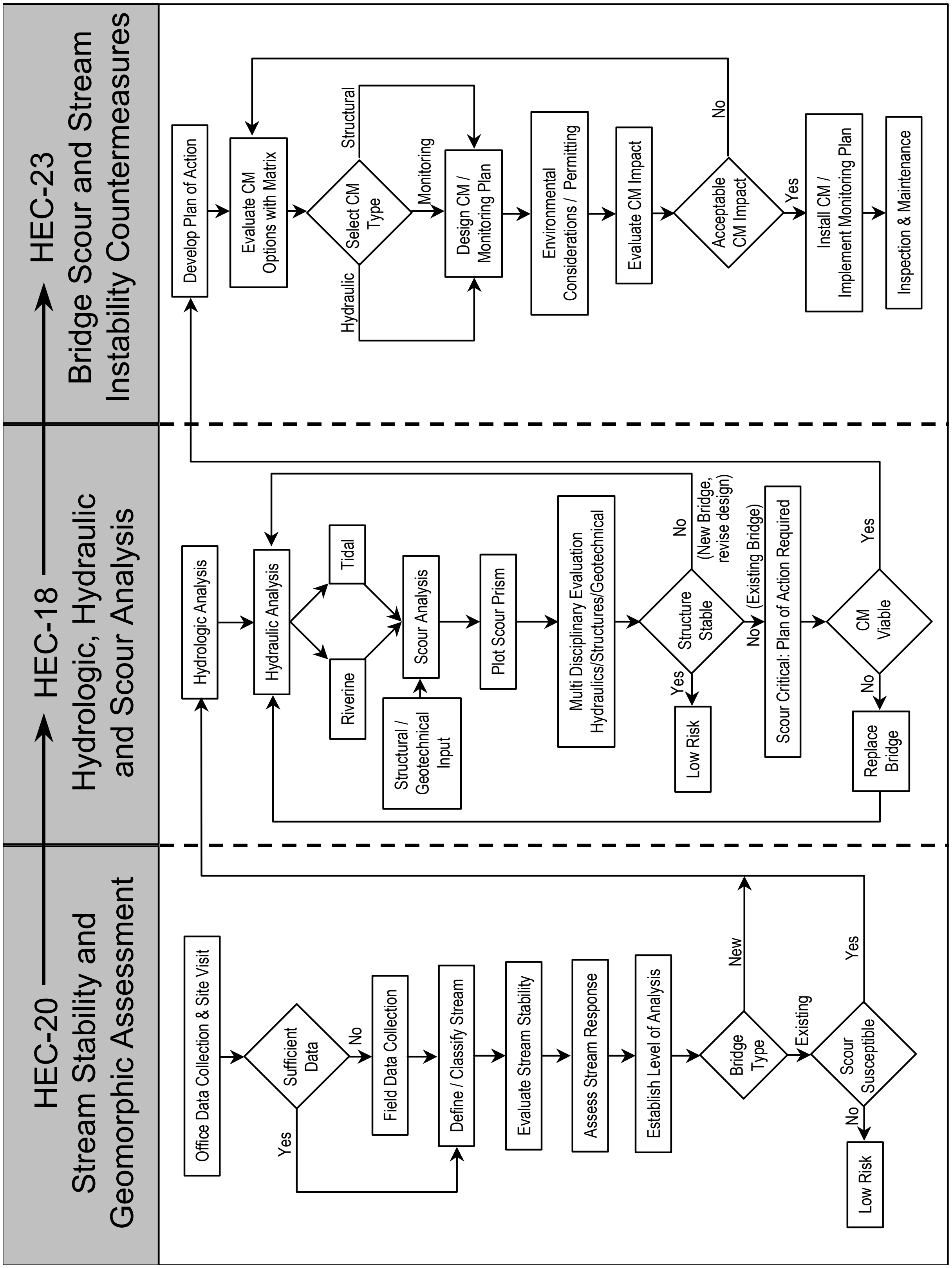


Figure 1.1. Flow chart for scour and stream stability analysis and evaluation.

The "Classify Stream," "Evaluate Stream Stability," and "Assess Stream Response" portions of the HEC-20 block are expanded in Chapter 3 into a six-step Level 1 and an eight-step Level 2 analysis procedure. In some cases, the HEC-20 analysis may be sufficient to determine that stream instability and/or scour problems do not exist, i.e., the bridge has a "low risk" of failure regarding scour susceptibility.

In most cases, the analysis or evaluation will progress to the HEC-18 block of the flow chart. Here more detailed hydrologic and hydraulic data are developed, with the specific approach determined by the level of complexity of the problem and waterway characteristics (e.g., tidal or riverine). The "Scour Analysis" portion of the HEC-18 block encompasses a seven-step specific design approach which includes evaluation of the components of total scour.

Since bridge scour evaluation requires multidisciplinary inputs, it is often advisable for the hydraulic engineer to involve structural and geotechnical engineers at this stage of the analysis. **Once the total scour prism is plotted, then all three disciplines must be involved in a determination of the structural stability of the bridge foundation**.

For a new bridge design, if the structure is stable the design process can proceed to consideration of environmental impacts, cost, constructability, and maintainability or if the bridge is unstable, revise the design and repeat the analysis. For an existing bridge, a finding of structural stability at this stage will result in a "low risk" evaluation, with no further action required. However, a Plan of Action should be developed for an unstable existing bridge (scour critical) to correct the problem as referenced in HEC-18[1] and HEC-23.[2]

The scour problem may be so serious that installing countermeasures would not provide a viable solution and a replacement or substantial bridge rehabilitation would be required. If countermeasures would correct the stream instability or scour problem at a reasonable cost and with acceptable environmental impacts, the analysis would progress to the HEC-23 block of the flow chart.

Hydraulic Engineering Circular 23 provides a range of resources to support bridge scour and stream instability countermeasure selection and design. A countermeasure matrix in HEC-23 presents a variety of countermeasures that have been used by State departments of transportation (DOTs) to control scour and stream instability at bridges. The matrix is organized to highlight the various groups of countermeasures and identifies distinctive characteristics of each countermeasure. The matrix identifies most countermeasures used and lists information on their functional applicability to a particular problem, their suitability to specific river environments, the general level of maintenance resources required, and which DOTs have experience with specific countermeasures. Finally, a reference source for design guidelines is noted.

HEC-23 includes specific design guidelines for the most common (and some uncommon) countermeasures used by DOTs, or references to sources of design guidance. Inherent in the design of any countermeasure are an evaluation of potential environmental impacts, permitting for countermeasure installation, and redesign, if necessary, to meet environmental requirements. As shown in the flow chart, to be effective most countermeasures will require a monitoring plan, inspection, and maintenance.

1.4 FACTORS THAT AFFECT STREAM STABILITY

Factors that affect stream stability and, potentially, bridge stability at highway stream crossings can be classified as geomorphic factors and hydraulic factors. Rapid and unexpected changes can occur in streams in response to human activities in the watershed and/or natural disturbances of the fluvial system, making it important to anticipate changes in channel geomorphology, location and behavior. Geomorphic characteristics of particular interest to the highway engineer are the alignment, geometry, and form of the stream channel. The behavior of a stream at a highway crossing depends not only on the apparent stability of the stream at the bridge, but also on the behavior of the stream system of which it is a part. Upstream and downstream changes may affect future stability at the site. Natural disturbances such as floods, drought, earthquakes, landslides, forest fires, etc., may result in large changes in sediment load in a stream and major changes in the stream channel. These changes can be reflected in aggradation, degradation, or lateral migration of the stream channel.

Geomorphic factors that can influence stream stability include stream size, flow habit (i.e., ephemeral or perennial) and the characteristics of channel boundaries. The bed material of a stream can be a cohesive material, sand, gravel, cobbles, boulders, or bedrock. Bank material is also composed of these materials and may be dissimilar from the bed material. Obviously, the stability and the rate of change in a stream is dependent on the material in the bed and banks. Other natural factors such as the stream's relationship to its valley, floodplain and planform characteristics, and features such as natural levees, incision, and riparian vegetation are important indicators of stream stability (or instability).

Human-induced changes in the drainage basin and the stream channel, such as alteration of vegetative cover and changes in pervious (or impervious) area can alter the hydrology of a stream, sediment yield, and channel geometry. Channelization, stream channel straightening, streamside levees and dikes, bridges and culverts, reservoirs, gravel mining, and changes in land use can have major effects on streamflow, sediment transport, and channel geometry and location. Geomorphic factors are discussed in detail in Chapter 2.

1.5 IDENTIFICATION AND ANALYSIS OF STREAM STABILITY PROBLEMS

Identification of the geomorphic factors that can affect channel stability in the bridge reach provides a useful first step in detecting existing or potential channel instability and scour problems at highway bridges. Consideration of fundamental geomorphic principles can lead to a qualitative prediction, in terms of trends, of the most likely direction of channel response to natural and human-induced change in the watershed and river system. However, more general methods of river classification can also provide insight on potential instability problems common to a given stream type.

A necessary first step in any channel classification or stability analysis is a field site visit. Geomorphologists have developed stream reconnaissance guidelines and specific techniques, including geomorphic assessment checklists, which can be useful to the highway engineer during a site visit. In addition, a rapid assessment methodology using both geomorphic and hydraulic factors could help identify the most likely sources of stability problems in a stream reach. Guidance for reconnaissance, classification, and rapid assessment techniques, as well as qualitative techniques for evaluating channel response, are presented in Chapter 4.

Hydraulic factors which affect stream channel and bridge stability are numerous and include bed forms and their effects on sediment transport, resistance to flow, flow velocities and flow depths. They also include the magnitude and frequency of floods; characteristics of floods, (i.e., duration, time to peak, and time of recession); flow classification (e.g., unsteady, nonuniform, turbulent, supercritical or subcritical); ice and other floating debris in the flow; and flow constrictions. Other factors are bridge length, location, orientation, span lengths, pier location and design; superstructure elevation and design; the location and design of countermeasures; and the effects of natural and human-induced changes which affect the hydrology and hydraulic flow conditions of the stream. In the bridge reach, bridge design and orientation can induce contraction scour and local scour at piers and abutments. Hydraulic factors are discussed in Chapter 5.

In analyzing stream stability problems, it may be necessary to go beyond a qualitative trends analysis, particularly if remedial action or countermeasures are required. Quantitative geomorphic and engineering techniques are available for analyzing bank stability and lateral and vertical channel stability. In addition, quantitative techniques may be necessary when channel stability or river restoration design are components of a highway project. Chapter 6 provides an introduction to quantitative geomorphic and engineering techniques useful for stream stability analyses. Many of these techniques can be applied to the restoration and rehabilitation of environmentally degraded stream channels. Chapter 7 provides an introduction to currently available channel restoration guidelines.

1.6 ANALYSIS METHODOLOGY

The evaluation and design of a highway stream crossing or encroachment should begin with a qualitative assessment of stream stability. This involves application of geomorphic concepts to identify potential problems and alternative solutions. This analysis should be followed with quantitative analyses using basic hydrologic, hydraulic and sediment transport engineering concepts. Such analyses could include evaluation of flood history, channel hydraulic conditions (up to and including, for example, water surface profile analysis) and basic sediment transport analyses such as evaluation of watershed sediment yield, incipient motion analysis and scour calculations. This analysis can be considered adequate for many locations if the problems are resolved and the relationships among different factors affecting stability are adequately explained. If not, a more complex quantitative analysis based on detailed mathematical modeling and/or physical hydraulic models should be considered. A step-wise methodology for analyzing stream stability problems is presented in Chapter 3.

In general, the solution procedure for analyzing stream stability could involve the following three levels of analysis:

Level 1: Application of Simple Geomorphic Concepts and other Qualitative Analyses
Level 2: Application of Basic Hydrologic, Hydraulic and Sediment Transport Engineering Concepts
Level 3: Application of Mathematical or Physical Modeling Studies

1.7 MANUAL ORGANIZATION

This manual is organized to:

- Familiarize the user with the important geomorphic factors which are indicators of and contributors to potential and existing stream and bridge stability problems (Chapter 2)
- Provide a procedure for the analysis of potential and existing stability problems (Chapter 3)
- Provide guidance for stream channel reconnaissance and classification, an introduction to qualitative methods for evaluating channel response, and reference to rapid assessment techniques (Chapter 4)
- Provide a summary of hydraulic factors that can affect stream stability and quantitative geomorphic and engineering techniques to assess river channel stability (Chapters 5 and 6)
- Provide an introduction to channel restoration concepts (Chapter 7)
- Provide selected references (Chapter 8)

1.8 DUAL SYSTEM OF UNITS

This edition of HEC-20 uses dual units (SI metric and English). The "English" system of units as used throughout this manual refers to U.S. Customary units. **In Appendix A, the metric (SI) unit of measurement is explained. The conversion factors, physical properties of water in the SI and English systems of units, sediment particle size grade scale, and some common equivalent hydraulic units are also given.** This edition uses for the unit of length the meter (m) or foot (ft); of mass the kilogram (kg) or slug; of weight/force the newton (N) or pound (lb); of pressure the Pascal (Pa, N/m^2) or (lb/ft^2); and of temperature the degree centigrade (°C) or Fahrenheit (°F). The unit of time is the same in SI as in English system (seconds, s). Sediment particle size is given in millimeters (mm), but in calculations the decimal equivalent of millimeters in meters is used (1 mm = 0.001 m) or for the English system feet (ft). The value of some hydraulic engineering terms used in the text in SI units and their equivalent English units are given in Table 1.1.

Table 1.1. Commonly Used Engineering Terms in SI and English Units.

Term	SI Units	English Units
Length	1 m	3.28 ft
Volume	1 m^3	35.31 ft^3
Discharge	1 m^3/s	35.31 ft^3/s
Acceleration of Gravity	9.81 m/s^2	32.2 ft/s^2
Unit Weight of Water	9800 N/m^3	62.4 lb/ft^3
Density of Water	1000 kg/m^3	1.94 $slugs/ft^3$
Density of Quartz	2647 kg/m^3	5.14 $slugs/ft^3$
Specific Gravity of Quartz	2.65	2.65
Specific Gravity of Water	1	1
Temperature	°C = 5/9 (°F - 32)	°F

CHAPTER 2

GEOMORPHIC FACTORS AND PRINCIPLES

2.1 INTRODUCTION

Most streams that highways cross or encroach upon are alluvial; that is, the streams are formed in materials that have been and can be transported by the stream. In alluvial stream systems, it is the rule rather than the exception that banks will erode; sediments will be deposited; and floodplains, islands and side channels will undergo modification with time. Alluvial channels continually change position and shape as a consequence of hydraulic forces exerted on the bed and banks. These changes may be gradual or rapid and may be the result of natural causes or human activities.

Some streams are not alluvial. The bed and bank material is very coarse, and except at extreme flood events, does not erode. These streams are classified as sediment supply deficient, i.e., the transport capacity of the streamflow is greater than the availability of bed material for transport. The bed and bank material of these streams may consist of cobbles, boulders or even bedrock. In general these streams are stable, but should be carefully analyzed for stability at large flows.

A study of the plan and profile of a stream is very useful in understanding stream morphology. Plan view appearances of streams are varied and result from many interacting variables. Small changes in a variable can change the plan view and profile of a stream, adversely affecting a highway crossing or encroachment. This is particularly true for alluvial streams. Conversely, a highway crossing or encroachment can inadvertently change a variable, adversely affecting the stream.

This chapter presents an overview of general landform and channel evolutionary processes to illustrate the dynamics of alluvial channel systems. A checklist of geomorphic properties of interest to the highway engineer is presented as a framework for identifying and understanding river channel dynamics. Finally, factors affecting bed elevation changes and the sediment continuity principle provide an introduction to alluvial channel response to natural and human-induced change.

2.2 LANDFORM EVOLUTION

Earth scientists (geomorphologists) have historically concerned themselves with documenting and explaining the changing morphology of the landscape through time. For example, Figure 2.1 illustrates the changing character of a landscape during a million years of geologic time. Initially, this type of evolution of landforms would appear to be of no interest to the highway or bridge engineer, but it serves as an alert that change can be expected at the scale of individual landforms (hillslopes, channels), and the change can be sufficiently rapid to cause problems.

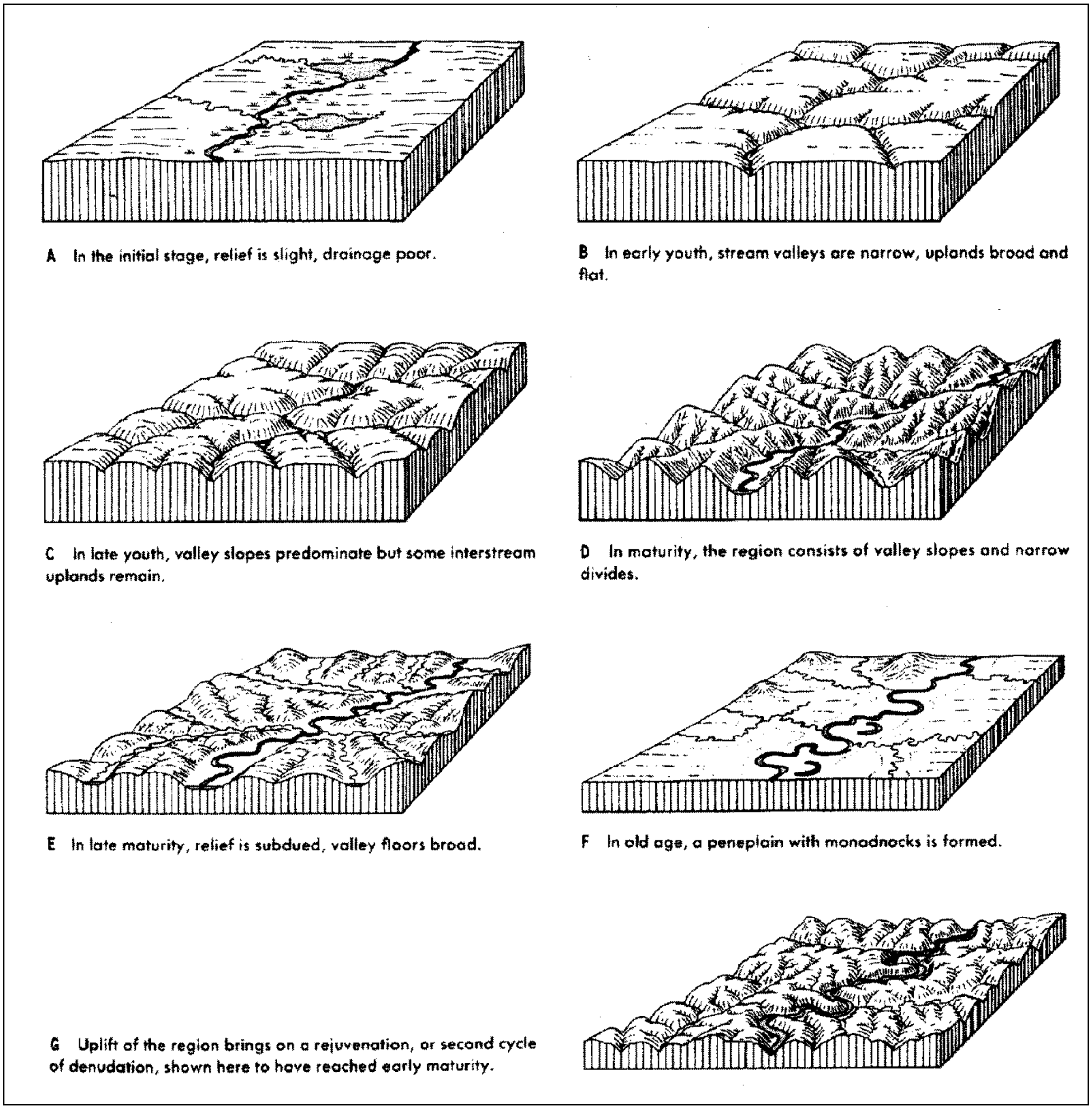


Figure 2.1. The cycle of erosion, proposed by W.M. Davis, drawn by E. Raisz.[3]

In the extreme case of incised channels (gullies, arroyos) rapid incision is followed by channel adjustment (deepening, widening) to a new condition of relative stability as erosion decreases, sediment storage increases and a floodplain develops (Figure 2.2). Simon[4] obtained data on the sediment loads transported through incised channels in Tennessee (Figure 2.3A). The stages of channel evolution shown in Figure 2.2 are reflected in the changing sediment loads of Figure 2.3A. Note that there is an apparent increase of sediment load at stage E (Figure 2.3A) as some stored sediment is remobilized.

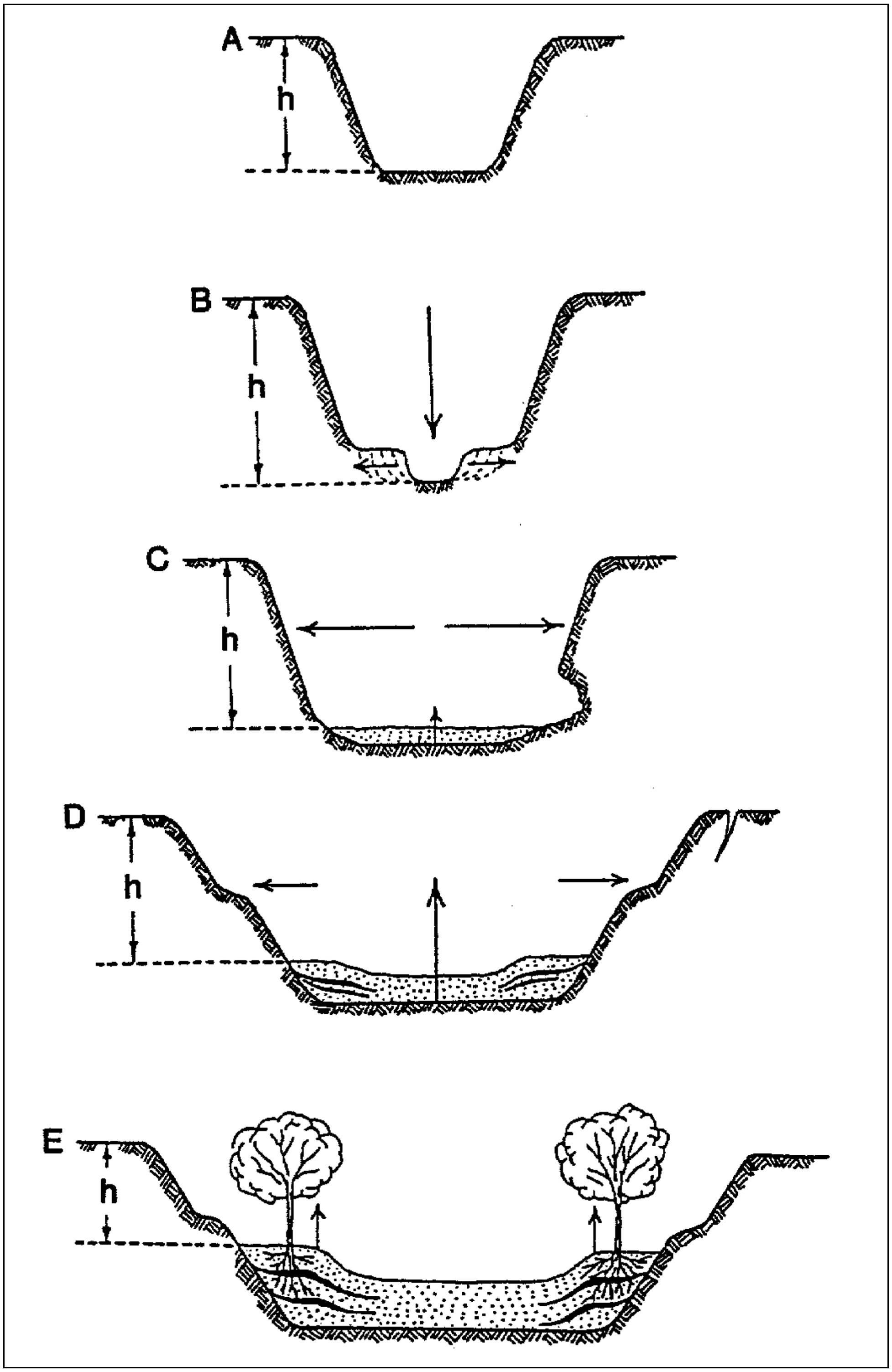


Figure 2.2. Evolution of incised channel from initial incision (A, B) and widening (C, D) to aggradation (D, E) and eventual relative stability; h is bank height.[7]

Field investigations in the upper Colorado River basin have also revealed that the large arroyos formed by incision of valley-floor alluvium in the latter part of the nineteenth century are at present storing sediment in newly developed floodplains.[5] Daily sediment-load data were collected starting in 1930. In 1963, upstream dams trapped much of sediment and the post-1963 record was not used. These incised channels are also behaving as illustrated in Figure 2.2. At the later stages of adjustment, they are eroding less sediment and storing large amounts of sediment. As a result, sediment loads at the Grand Canyon gaging station have decreased, during the period of record, prior to closure of Glen Canyon Dam and other upstream dams in 1963 (Figure 2.3B). In addition, sediment deposition in Lake Powell between 1963 and 1986 is only 43 percent of that estimated prior to dam construction,[6] which indicates that the channel adjustment process is occurring throughout the upper Colorado River basin, in a manner similar to that in the incised channels of the southeast (Figure 2.3A).

Because of climatic differences, the evolutionary changes involved in the complex response of Figure 2.2 require about 100 years in the southwest but only about 40 years in the southeast. Additional discussion of complex response of fluvial systems is provided in Section 4.4.

As the cross section of an incised channel (Figure 2.2) changes through time, the pattern can also evolve from straight to sinuous (Figure 2.4). In fact, a river that straightens naturally by meander cutoffs will also evolve to restore the meandering pattern (Figure 2.4, 2.5A). The downstream shift of meanders (Figure 2.5A) and the cutoff and regrowth of meanders (Figure 2.5A, B) are all part of the natural evolution of channel patterns through time.

Although the landscape as a whole may appear unchanging except over vast periods of time (Figure 2.1), components of the landscape can evolve or adjust to human activities (Figures 2.2, 2.3) and hydrologic variations (Figures 2.3, 2.4) during relative short periods of time and can pose serious problems for the highway engineer.

2.3 GEOMORPHIC FACTORS AFFECTING STREAM STABILITY

2.3.1 Overview

Figure 2.6 introduces a set of geomorphic factors that can affect stream stability. Each of the geomorphic properties listed in the left column of Figure 2.6 could be used as the basis of a valid stream characterization at a bridge site. The approach presented here is based on stream properties observed on aerial photographs and in the field. Its major purpose is to facilitate the assessment of streams for engineering purposes, particularly regarding lateral stability of a stream. Common stream types are described and their engineering significance discussed. Data and observations are derived from a study of case histories of 224 bridge sites in the United States and Canada.[10, 11]

This section is organized according to Figure 2.6. No particular significance is assigned to the order of the figure, and association of characteristics should not be inferred with descriptions above or below in the figure. Chapter 4 contains an introduction to more general stream channel classification systems.

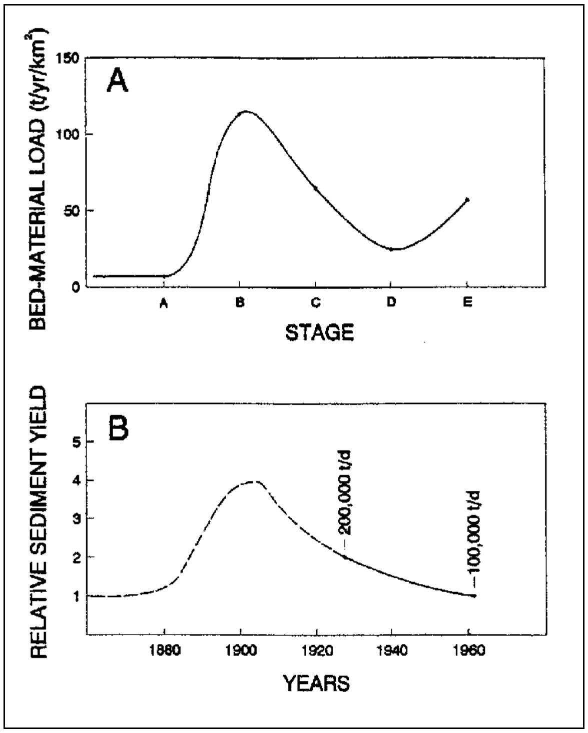


Figure 2.3. Sediment loads following channel incision: (A) Bed-material load transported by incised Tennessee streams for each stage of incised-channel evolution (Figure 2.2), (B) Hypothetical (dashed line) and measured (solid line) sediment volumes transported through Grand Canyon.

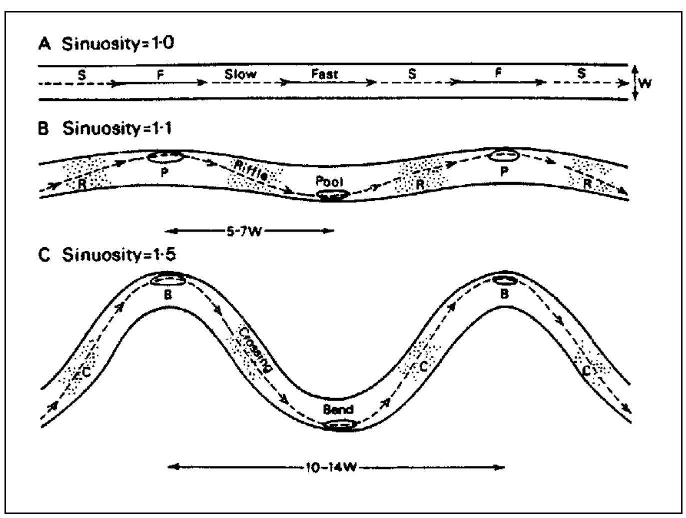


Figure 2.4. Three possible stages in the development of a meandering reach: (A) Reaches of faster and slower eddy flow at bankfull discharge, (B) Development of pools and riffles with spacing of 5-7 channel widths, (C) Development of meanders with a wavelength of 10-14 channel widths.[8]

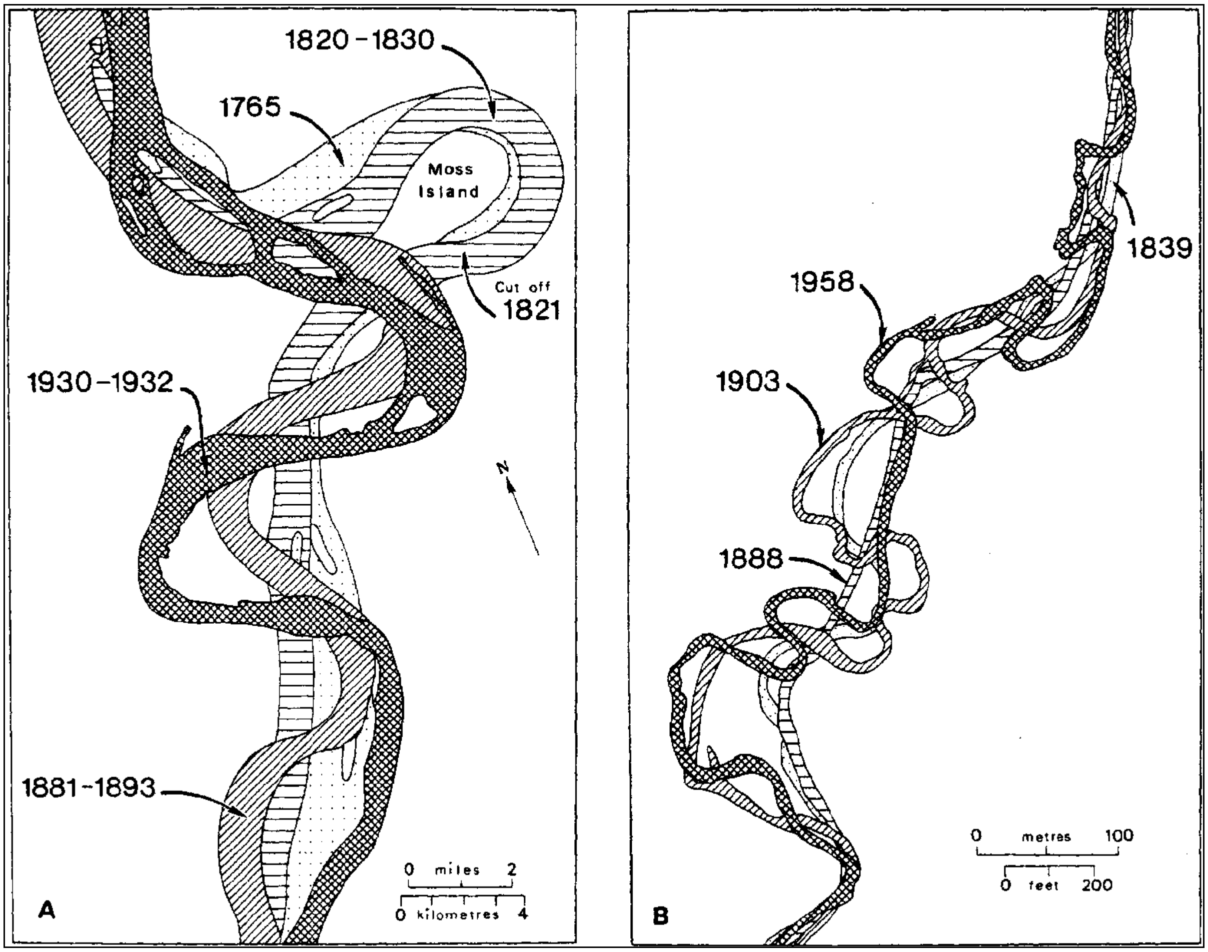


Figure 2.5. Surveys showing changes of course for two meandering rivers: (A) Mississippi River in northern Tennessee during the period 1765-1932,[3] (B) River Sid in east Devon during the period 1839-1958.[9]

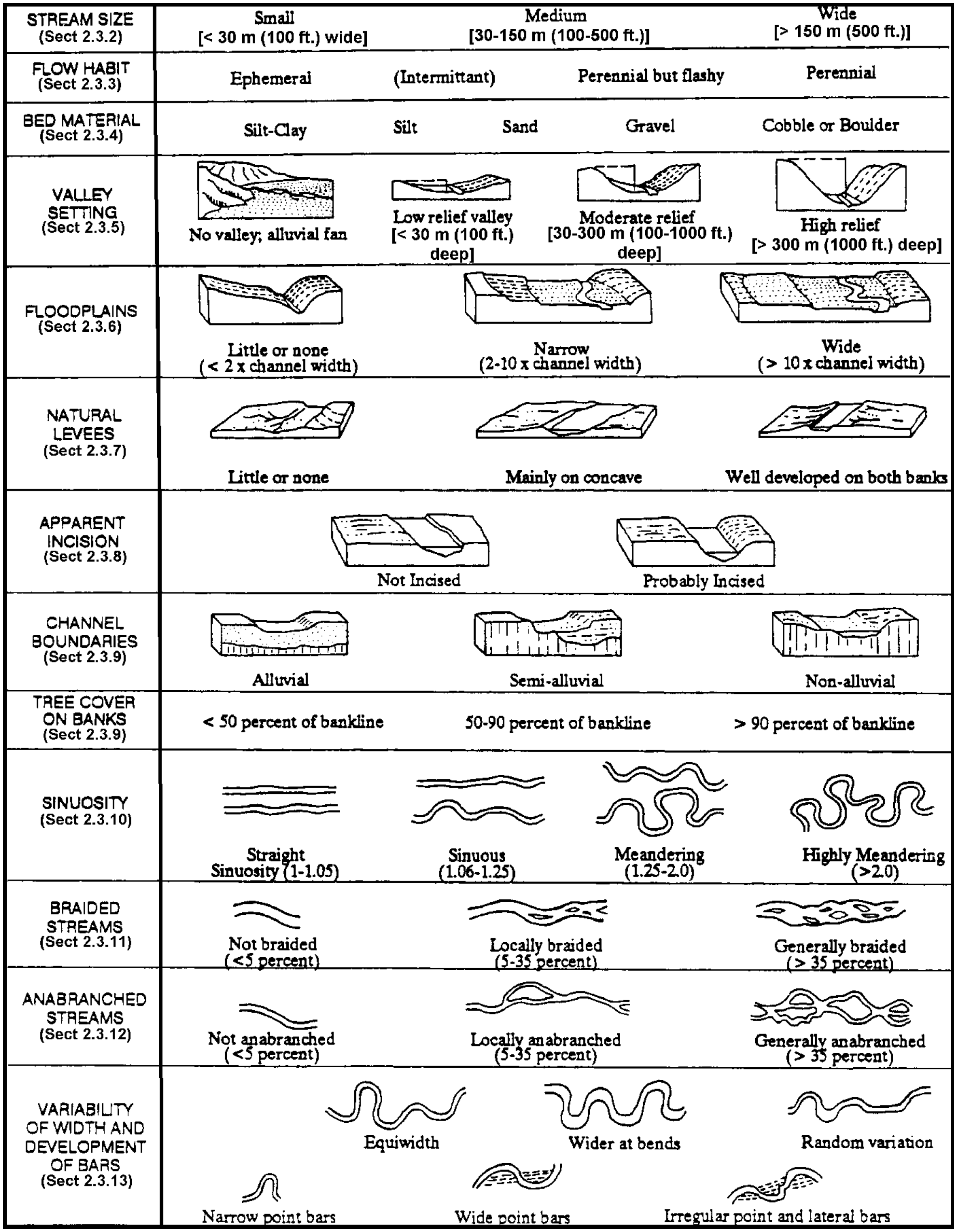


Figure 2.6. Geomorphic factors that affect stream stability (adapted from Brice and Blodgett).[10]

2.3.2 Stream Size

Stream depth tends to increase with size, and potential for scour increases with depth. Thus, potential depth of scour increases with increasing stream size.

The potential for lateral erosion also increases with stream size. This fact may be less fully appreciated than the increased potential for deep scour. Brice et al., cite as examples the lower Mississippi River, with a width of about 1500 m (5,000 ft), which may shift laterally 30 m (100 ft) or more in a single major flood; the Sacramento River, where the width is about 300 m (1,000 ft), is unlikely to shift more than 8 m (25 ft) in a single flood; and streams whose width is about 30 m (100 ft) are unlikely to shift more than 3 m (10 ft) in a single flood.(10) Except for the fact that the potential for lateral migration increases with stream size, no generalization is currently possible regarding migration rates.

The size of a stream can be indicated by discharge, drainage area, or some measure of channel dimensions, such as width or cross-sectional area. No single measure of size is satisfactory because of the diversity of stream types. For purposes of stream classification (Figure 2.6), bank-to-bank channel width is chosen as the most generally useful measure of size, and streams are arbitrarily divided into three size categories on the basis of width. The width of the stream does not include the width of the floodplain, but floodplain width is an important factor in bridge design if significant overbank flow occurs.

Bank-to-bank width is sometimes difficult to define for purposes of measurement when one of the banks is indefinite. This is particularly true at bends, where the outside bank is likely to be vertical and sharply defined but the inside bank slopes gradually up to floodplain level. The position of the line of permanent vegetation on the inside bank is the best available indicator of the bank line, and it tends to be rather sharply defined along many rivers in humid regions. The width of a stream is measured along a perpendicular line drawn between its opposing banks, which are defined either by their form or as the riverward edge of a line of permanent vegetation. For sinuous or meandering streams, width is measured at straight reaches or at the inflections between bends, where it tends to be most consistent. For multiple channel streams, width is the sum of the widths of individual, unvegetated channels.

The National Mapping Division of the U.S. Geological Survey (USGS) uses, insofar as possible, the so-called "normal" stage or the stage prevailing during the greater part of the year for representing streams on topographic maps. They find that the "normal" stage for a perennial river usually corresponds to the water level filling the channel to the line of permanent vegetation along its banks. Normal stage is also adopted here to define channel width.

2.3.3 Flow Habit

The flow habit of a stream may be ephemeral, perennial but flashy, or perennial. An ephemeral stream flows briefly in direct response to precipitation, and as used here, includes intermittent streams. A perennial stream flows all or most of the year, and a perennial but flashy stream responds to precipitation by rapid changes in stage and discharge. Perennial streams may be relatively stable or unstable, depending on other factors such as channel boundaries and bed material.

In arid regions, ephemeral streams may be relatively large and unstable. They may pose problems in determining the stage-discharge relationship and in estimating the depth of scour. A thalweg that shifts with stage and channel degradation by headcutting may also cause problems. In humid regions, ephemeral streams are likely to be small and pose few problems of instability.

2.3.4 Bed Material

Streams are classified, according to the dominant size of the sediment on their beds, as silt-clay bed, sand bed, gravel bed, and cobble or boulder bed. Accurate determination of the particle size distribution of bed material requires careful sampling and analysis, particularly for coarse bed material, but for most of the bed material designations, rough approximations can be derived from visual observation.

The greatest depths of scour are usually found on streams having sand or sand-silt beds. The general conclusion is that scour problems are as common on streams having coarse bed material as on streams having fine bed material. However, very deep scour is more probable in fine bed material.(10) In general, sand-bed alluvial streams are less stable than streams with coarse or cohesive bed and bank material.

2.3.5 Valley Setting

Valley relief is used as a means of indicating whether the surrounding terrain is generally flat, hilly, or mountainous. For a particular site, relief is measured (usually on a topographic map) from the valley bottom to the top of the highest adjacent divide. Relief greater than 300 m (1,000 ft) is regarded as mountainous, and relief in the range of 30 to 300 m (100 to 1,000 ft) as hilly. Streams in mountainous regions are likely to have steep slopes, coarse bed materials, narrow floodplains and be nonalluvial, i.e., supply-limited sediment transport rates. In many regions, channel slope increases as the steepness of valley side slopes increases. Brice et al., reported no specific hydraulic problems at bridges at 23 study sites in mountainous terrain, at which all have beds of gravel or cobble-boulder.(11) Streams in regions of lower relief are usually alluvial and exhibit more problems because of lateral erosion in the channels.

Streams on alluvial fans or on piedmont slopes in arid regions pose special problems. A piedmont slope is a broad slope along a mountain front, and streams issuing from the mountain front may have shifting courses and poorly defined channels, as on an alluvial fan. Alluvial fans are among the few naturally occurring cases of aggradation problems at transverse highway crossing. They occur wherever there is a change from a steep to a flat gradient. As the bed material and water reaches the flatter section of the stream, the coarser bed materials are deposited because of the sudden reduction in both slope and velocity. Consequently, a cone or fan builds out as the material is dropped with the steep side of the fan facing the floodplain. Although typically viewed as a depositional zone, alluvial fans are also characterized by unstable channel geometries and rapid lateral movement. Deposition tends to be episodic, being interrupted by periods of fan trenching and sediment reworking.

The occurrence of deposition versus fan trenching on an alluvial fan surface are important factors in the assessment of stream stability at bridge crossings (Figure 2.7). On an untrenched fan, the sediment depositional zone will be nearer the mountain front, possibly creating more channel instability on the upper fan surface than on the lower fan surface. In contrast, a fan that is trenched will promote sediment movement across the fan and move the depositional zone closer to the toe of the fan, suggesting that the upper fan surface will be more stable than the lower fan surface. However, the general instability of fan channels and their tendency for rapid changes during large floods, and the possible channel avulsion created by deposition near the fan head, suggest that any location of an alluvial fan surface is, or could easily become, an area where channel stability is a serious concern to bridge safety.(12, 13)

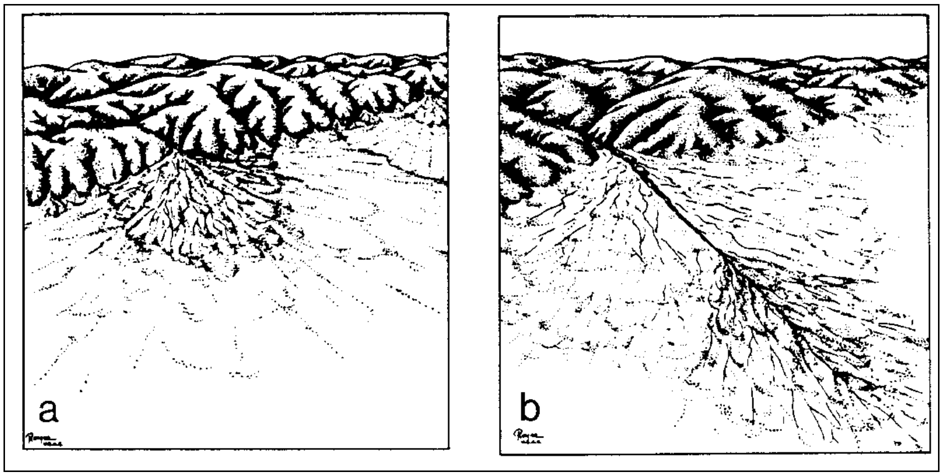


Figure 2.7. Diverse morphology of alluvial fans: (a) area of deposition at fan head, (b) fan-head trench with deposition at fan toe (after Bull).(14)

There is considerable similarity between deltas and alluvial fans. Both result from reductions in slope and velocity, have steep slopes at their outer edges and tend to reduce upstream slopes. Deposits very similar to a delta develop where a steep tributary enters a larger stream. The steep channel tends to drop part of its sediment load in the main channel building out into the main stream. In some instances, drastic changes can occur in the main stream channel as a result of deposition from the tributary stream. Channels on both alluvial fans and deltaic deposits commonly change through avulsion, a sudden change in channel course that occurs when a stream breaks through its banks.

2.3.6 Floodplains

Floodplains are described as the nearly flat alluvial lowlands bordering a stream that are subject to inundation by floods. Many geomorphologists prefer to define a floodplain as the surface presently under construction by the stream, which is flooded with a frequency of about 1.5 years (excluding incised channels, see Section 2.3.8). According to this definition, surfaces flooded less frequently are terraces, abandoned floodplains, or flood-prone areas. However, flood-prone areas are considered herein as part of the floodplain. Vegetative cover, land use, and flow depth on the floodplain are also significant factors in stream channel stability. In Figure 2.6, floodplains are categorized according to floodplain width relative to channel width.

Over time, the highlands of an area are worn down, streams erode their banks, and the material that is eroded is utilized farther downstream to build banks and bars. Streams move laterally, pushing the highlands back. Low, flat valley land and floodplains are formed. As streams transport sediment to areas of flatter slopes and, in particular, to bodies of water where the velocity and turbulence are too small to sustain transport of the material, the material is deposited forming deltas. As deltas build outward, the upstream portion of the channel is elevated through deposition and becomes part of the floodplain. Also, the stream channel is lengthened and the slope is further reduced. The upstream streambed is filled in and average flood elevations are increased. As the stream works across the stream valley, deposition causes the total floodplain to raise in elevation. Hence, even old streams are far from static. Old rivers meander, and they are affected by changes in sea level, influenced by movements of the earth's crust, changed by delta formations or glaciation, and subject to modifications due to climatological changes and as a consequence of man's development.

2.3.7 Natural Levees

Natural levees form during floods as the stream stage exceeds bankfull conditions. Sediment is then deposited on the floodplain due to the reduced velocity and transporting capacity of the flood in these overbank areas. The natural levees formed near the stream are rather steep because coarse material drops out quickly as the overbank velocity is smaller than the stream velocity. Farther from the stream, the gradients are flatter and finer materials drop out. Swamp areas are found beyond the levees.

Classification based on natural levees is illustrated in Figure 2.6. Streams with well-developed natural levees tend to be of constant width and have low rates of lateral migration. Well-developed levees usually occur along the lower courses of streams or where the floodplain is submerged for several weeks or months a year. If the levee is breached, the stream course may change through the breach. Areas between natural levees and the valley sides may drain, but slowly. Streams tributary to streams with well-developed natural levees may flow approximately parallel with the larger stream for long distances before entering the larger stream.

2.3.8 Apparent Incision

The apparent incision of a stream channel is judged from the height of its banks at normal stage relative to its width. For a stream whose width is about 30 m (100 ft), bank heights in the range of 1.8 to 3.0 m (6 to 10 ft) are about average, and higher banks indicate probable incision. For a stream whose width is about 300 m (1,000 ft), bank heights in the range of 3.0 to 5.0 m (10-15 ft) are about average, and higher banks indicate probable incision. Incised streams tend to be fixed in position and are not likely to bypass a bridge or to shift in alignment at a bridge. Lateral erosion rates are likely to be slow, except for western arroyos with high, vertical, and clearly unstable banks.

2.3.9 Channel Boundaries and Vegetation

Although no precise definitions can be given for alluvial, semi-alluvial, or non-alluvial streams, some distinction with regard to the erosional resistance of the earth material in channel boundaries is needed. In geology, bedrock is distinguished from alluvium and other surficial materials mainly on the basis of age, rather than on resistance to erosion. A compact alluvial clay is likely to be more resistant than a weakly cemented sandstone that is much older. Nevertheless, the term "bedrock" does carry a connotation of greater resistance to erosion, and it is used here in that sense. An alluvial channel is in alluvium, a non-alluvial channel is in bedrock or in very large material (cobbles and boulders) that do not move except at very large flows, and a semi-alluvial channel has both bedrock and alluvium in its boundaries. The bedrock of non-alluvial channels may be wholly or partly covered with sediment at low stages, but is likely to be exposed by scour during floods.

Most highway stream crossings are over alluvial streams which are susceptible to more hydraulic problems than non-alluvial streams. However, the security of a foundation in bedrock depends on the quality of the bedrock[1] and the care with which foundation is set. Serious problems and failures have developed at bridges with foundations on shale, sandstone, limestone, glacial till, and other erodible rock. The New York State Thruway Schoharie Creek bridge failure is a catastrophic example of such a failure. Bed material at the bridge site was highly cemented glacial till which scoured, undermining spread footings.[15]

Changes in channel geometry with time are particularly significant during periods when alluvial channels are subjected to high flows, and few changes occur during relatively dry periods. Erosive forces during high-flow periods may have a capacity as much as 100 times greater than those forces acting during periods of intermediate and low-flow rates. When considering the stability of alluvial streams, in most instances it can be shown that approximately 90 percent of all changes occur during that small percentage of the time when the flow equals or exceeds dominant discharge. A discussion of dominant discharge may be found in Hydraulic Design Series No. 6, but the bankfull flow condition is recommended for use where a detailed analysis of dominant discharge is not feasible.[13]

The most significant property of materials of which channel boundaries are comprised is particle size. It is the most readily measured property, and, in general, represents a sufficiently complete description of the sediment particle for many practical purposes. Other properties such as shape and fall velocity tend to vary with size in a roughly predictable manner.

In general, sediments have been classified into boulders, cobbles, gravel, sands, silts, and clays on the basis of their nominal or sieve diameters. The size range in each general class is given in Table 2.1. Note that even when the English system of units is used, sand size particles and smaller are typically described in millimeters. Noncohesive material generally consists of silt (0.004 - 0.062 mm), sand (0.062 - 2.0 mm), gravel (2.0 - 64 mm), or cobbles (64 - 250 mm).

The appearance of the streambank is a good indication of relative stability. A field inspection of a channel will help to identify characteristics which are associated with erosion rates:

- Unstable banks with moderate to high erosion rates usually have slopes which exceed 30 percent, and a cover of woody vegetation is rarely present. At a bend, the point bar opposite an unstable cut bank is likely to be bare at normal stage, but it may be covered with annual vegetation and low woody vegetation, especially willows. Where very rapid erosion is occurring, the bank may have irregular indentations. Fissures, which represent the boundaries of actual or potential slump blocks along the bank line indicate the potential for very rapid bank erosion.

- Unstable banks with slow to moderate erosion rates may be partly reshaped to a stable slope. The degree of instability is difficult to assess, and reliance is placed mainly on vegetation. The reshaping of a bank typically begins with the accumulation of slumped material at the base such that a slope is formed, and progresses by smoothing of the slope and the establishment of vegetation.

Table 2.1. Sediment Grade Scale.					
Size			Approximate Sieve Mesh Openings (per inch)		Class
Millimeters	Microns	Inches	Tyler	U.S. Standard	
4000-2000	---	180-160	---	---	Very large boulders
2000-1000	---	80-40	---	---	Large boulders
1000-500	---	40-20	---	---	Medium boulders
500-250	---	20-10	---	---	Small boulders
250-130	---	10-5	---	---	Large cobbles
130-64	---	5-2.5	---	---	Small cobbles
64-32	---	2.5-1.3	---	---	Very coarse gravel
32-16	---	1.3-0.6	---	---	Coarse gravel
16-8	---	0.6-0.3	2.5	---	Medium gravel
8-4	---	0.3-0.16	5	5	Fine gravel
4-2	---	0.16-0.08	9	10	Very fine gravel
2.00-1.00	2000-1000	---	16	18	Very coarse sand
1.00-0.50	1000-500	---	32	35	Coarse sand
0.50-0.25	500-250	---	60	60	Medium sand
0.25-0.125	250-125	---	115	120	Fine sand
0.125-0.062	125-62	---	250	230	Very fine sand
0.062-0.031	62-31	---			Coarse silt
0.031-0.016	31-16	---			Medium silt
0.016-0.008	16-8	---			Fine silt
0.008-0.004	8-4	---			Very fine silt
0.004-0.0020	4-2	---			Coarse clay
0.0020-0.0010	2-1	---			Medium clay
0.0010-0.0005	1-0.5	---			Fine clay
0.0005-0.0002	0.5-0.24	---			Very fine clay

- Eroding banks are a source of debris when trees fall as they are undermined. Therefore, debris can be a sign of unstable banks and of great concern due to potential blockage of bridge openings.

- Stable banks with very slow erosion rates tend to be graded to a smooth slope of less than about 30 percent. Mature trees on a graded bank slope are convincing evidence of bank stability. In most regions of the United States, the upper parts of stable banks are vegetated, but the lower part may be bare at normal stage, depending on bank height and flow regime of the stream. Where banks are low, dense vegetation may extend to the water's edge at normal stage. Where banks are high, occasional slumps may occur on even the most stable graded banks. Shallow mountain streams that transport coarse bed sediment tend to have stable banks.

Active bank erosion can be recognized by falling or fallen vegetation along the bank line, cracks along the bank surface, slump blocks, deflected flow patterns adjacent to the bank line, live vegetation in the flow, increased turbidity, fresh vertical faces, newly formed bars immediately downstream of the eroding area, and, in some locations, a deep scour pool adjacent to the toe of the bank. These indications of active bank erosion can be noted in the field and on stereoscopic pairs of aerial photographs. Color infrared photography is particularly useful in detecting most of the indicators listed above, especially differences in turbidity.(16) Figure 2.8 illustrates some of the features which indicate that a bank line is actively eroding.

Figure 2.8. Active bank erosion illustrated by vertical cut banks, slump blocks, and falling vegetation.

Bank Materials. Resistance of a streambank to erosion is closely related to several characteristics of the bank material. Bank material deposited in the stream can be broadly classified as cohesive, noncohesive, and composite. Typical bank failure surfaces of various materials are shown in Figure 2.9 and are described as follows:(17)

- Noncohesive bank material tends to be removed grain by grain from the bank. The rate of particle removal, and particle movement, and hence the rate of bank erosion, is affected by factors such as particle size, bank slope, the direction and magnitude of the velocity adjacent to the bank, turbulent velocity fluctuations, the magnitude of and fluctuations in the shear stress exerted on the banks, seepage force, piping, and wave forces. Figure 2.9(a) illustrates failure of banks of noncohesive material from flow slides resulting from a loss of shear strength because of saturation, and failure from sloughing resulting from the removal of materials in the lower portion of the bank.

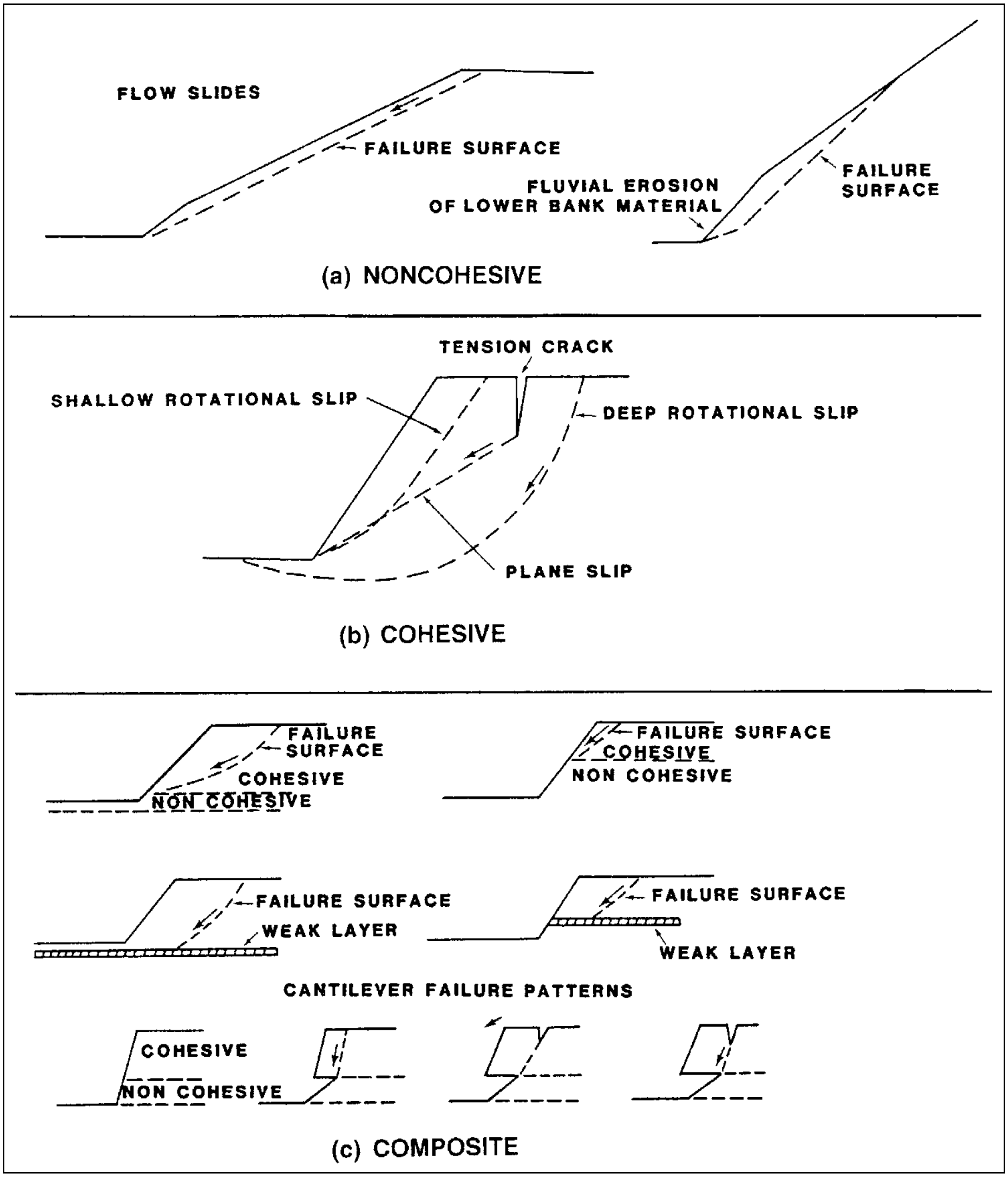


Figure 2.9. Typical bank failure surfaces: (a) noncohesive, (b) cohesive, and (c) composite (after Brown).[17]

- Cohesive material is more resistant to surface erosion and has low permeability, which reduces the effects of seepage, piping, frost heaving, and subsurface flow on the stability of the banks. However, when undercut and/or saturated, such banks are more likely to fail due to mass wasting processes. Failure mechanisms for cohesive banks are illustrated in Figure 2.9(b).

- Composite or stratified banks consist of layers of materials of various sizes, permeability, and cohesion. The layers of noncohesive material are subject to surface erosion, but may be partly protected by adjacent layers of cohesive material. This type of bank is also vulnerable to erosion and sliding as a consequence of subsurface flows and piping. Typical failure modes are illustrated in Figure 2.9(c).

<u>Piping</u>. Piping is a phenomenon common to alluvial streambanks. With stratified banks, flow is induced in more permeable layers by changes in stream stage and by waves. If flow through the permeable lenses is capable of dislodging and transporting particles, the material is slowly removed, forming "pipes" which undermine portions of the bank. Without this foundation material to support the overlying layers, a block of bank material drops down and results in the development of tension cracks as sketched in Figure 2.9(c). These cracks allow surface flows to enter, further reducing the stability of the affected block of bank material. Bank erosion may continue on a grain-by-grain basis or the block of bank material may ultimately slide downward and outward into the channel, with bank failure resulting from a combination of seepage forces, piping, and mass wasting.

<u>Mass Wasting</u>. Local mass wasting is another form of bank failure. If a bank becomes saturated and possibly undercut by flowing water, blocks of the bank may slump or slide into the channel. Mass wasting may be caused or aggravated by the construction of homes on river banks, operation of equipment adjacent to the banks, added gravitational force resulting from tree growth, location of roads that cause unfavorable drainage conditions, agricultural uses on adjacent floodplain, saturation of banks by leach fields from septic tanks, and increased infiltration of water into the floodplain as a result of changing land-use practices.

Various forces are involved in mass wasting. Landslides, the downslope movement of earth and organic materials, result from an imbalance of forces. These forces are associated with the downslope gravity component of the slope mass. Resisting these downslope forces are the shear strength of the materials and any contribution from vegetation via root strength or engineered slope reinforcement activities. When the toe of a slope is removed, as by a stream, the slope materials may move downward into the void in order to establish a new equilibrium. Often, this equilibrium is a slope configuration with less than original surface gradient. The toe of the failed mass then provides a new buttress against further movements. Erosion of the toe of the slope then begins the process over again.

<u>Bank Erosion and Failure</u>. The erosion, instability, and/or retreat of a stream bank is dependent on the processes responsible for the erosion of material from the bank and the mechanisms of failure resulting from the instability created by those processes. Bank retreat is often a combination of these processes and mechanisms operating at various timescales. While the detailed analysis of bank stability is, primarily, a geotechnical problem (see for example, FHWA publications on soil slope stability),[18,19] insight on the relationship between stream channel degradation and bank failure, for example, can be important to the hydraulic engineer concerned with bank instability. The processes responsible for bank erosion and bank failure mechanisms are discussed in more detail in Appendix B.

2.3.10 Sinuosity

Sinuosity is the ratio of the length of a stream reach measured along its centerline, to the length measured along the valley centerline or along a straight line connecting the ends of the reach. The valley centerline is preferable when the valley itself is curved. Sometimes, sinuosity is defined as the ratio of valley slope to stream slope or, more commonly, the ratio of the thalweg length to the valley length, where the thalweg is the trace of the deepest point in successive channel cross sections. Straight stream reaches have a sinuosity of one, and the maximum value of sinuosity for natural streams is about four.

A straight stream, or one that directly follows the valley centerline, sometimes has the same slope as the valley. As the sinuosity of the stream increases, its slope decreases in direct proportion. Similarly, if a sinuous channel is straightened, the slope increases in direct proportion to the change in length.

The size, form, and regularity of meander loops are aspects of sinuosity. Symmetrical meander loops are not very common, and a sequence of two or three identical symmetrical loops is even less common. In addition, meander loops are rarely of uniform size. The largest is commonly about twice the diameter of the smallest. Statistically, the size-frequency distribution of loop radii tends to have a normal distribution.

There is little relation between degree of sinuosity and lateral stream stability. A highly meandering stream may have a lower rate of lateral migration than a sinuous stream of similar size (Figure 2.6). Stability is largely dependent on other properties, especially bar development and the variability of channel width (see Section 2.3.13).

Streams are broadly classified as straight, meandering or braided. Any change imposed on a stream system may change its planform geometry.

Straight Streams. A straight stream has small sinuosity at bankfull stage. At low stage, the channel develops alternate sandbars, and the thalweg meanders around the sandbars in a sinuous fashion. Straight streams are considered a transitional stage to meandering, since straight channels are relatively stable only where sediment size and load are small, gradient, velocities, and flow variability are low, and the channel width-depth ratio is relatively low. Straight channel reaches of more than 10 channel widths are not common in nature.

Meandering Streams. Alluvial channels of all types deviate from a straight alignment. The thalweg oscillates transversely and initiates the formation of bends. In a straight stream, alternate bars and the thalweg are continually changing; thus, the current is not uniformly distributed through the cross section, but is deflected toward one bank and then the other. Sloughing of the banks, nonuniform deposition of bed load, debris such as trees, and the Coriolis force due to the Earth's rotation have been cited as causes for the meandering of streams. When the current is directed toward a bank, the bank is eroded in the area of impingement, and the current is deflected and impinges on the opposite bank farther downstream. The angle of deflection of the current is affected by the curvature formed in the eroding bank and the lateral depth of erosion. Figure 2.10 shows bars, pools, and crossings (riffles) typical of a meandering channel (see also Figures 2.4 and 2.5). A more detailed explanation of the meandering process and flow patterns through meanders is provided in Chapter 6.

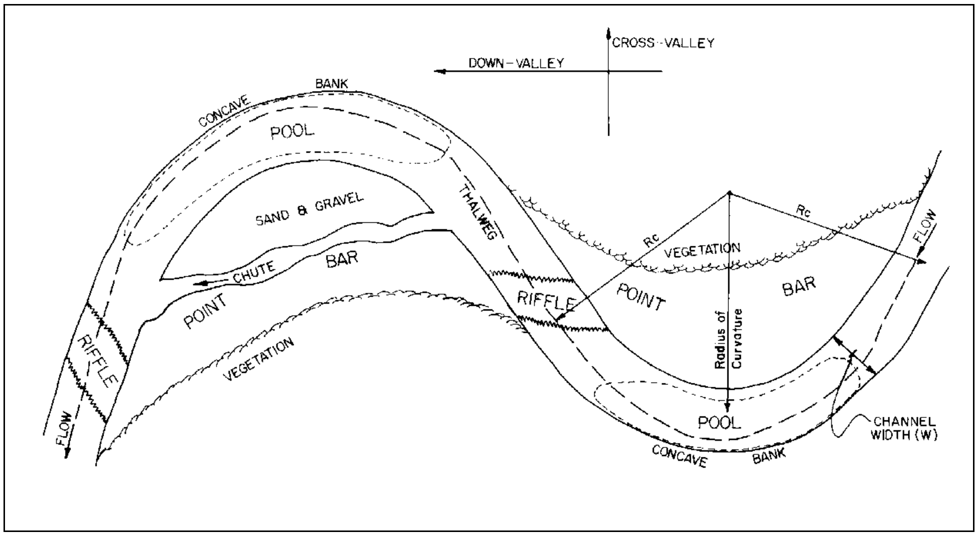


Figure 2.10. Plan view of a meandering stream.

Sinuous, meandering, and highly meandering streams have more or less regular inflections that are sinuous in plan view, consisting of a series of bends connected by crossings. In the bends, deep pools are carved adjacent to the concave bank by the relatively high velocities. Because velocities are lower on the inside of bends, sediments are deposited in this region, forming point bars. Also, the centrifugal force in the bend causes a transverse water surface slope and helicoidal flow with a bottom velocity away from the outer bank toward the point bar. These transverse velocities enhance point bar building by sweeping the heavier concentrations of bed load toward the convex bank where they are deposited to form the point bar. Some transverse currents have a magnitude of about 15 percent of the average channel velocity.

The bends in meandering streams are connected by crossings (short straight reaches) which are quite shallow compared to the pools in the bendways. At low flow, large sandbars form in the crossings if the channel is not well confined. Scour in the bend causes the bend to migrate downstream and sometimes laterally. Lateral movements as large as 750 m/yr (2,500 ft/yr) have been observed in large alluvial rivers. Much of the sediment eroded from the outside bank is deposited in the crossing and on the point bar in the next bend downstream. The variability of bank materials and the fact that the stream encounters and produces such features as clay plugs causes a wide variety of river forms. The meander belt formed is often fifteen to twenty times the channel width.

On a laterally unstable channel, or at actively migrating bends on an otherwise stable channel, point bars are usually wide and unvegetated and the opposite bank is cut and often scalloped by erosion. The crescent-shaped scars of slumping may be visible from place to place along the bank line. The presence of a cut bank opposite a point bar is evidence of instability. Sand or gravel on the bar appears as a light tone on aerial photographs. The unvegetated condition of the point bar is attributed to a rate of outbuilding that is too rapid for vegetation to become established. However, the establishment of vegetation on a point bar is dependent on factors other than the rate of growth of the point bar, such as climate and the timing of floods. Therefore, the presence of vegetation on a point bar is not conclusive evidence of stability. If the width of an unvegetated point bar is considered as part of the channel width, the channel tends to be wider at bends.

As a meandering stream system moves laterally and longitudinally, meander loops move at unequal rates because of unequal erodibility of the banks. This causes the channel to appear as a slowly developing bulb-form. Channel geometry depends upon the local slope, bank material, and the geometry of adjacent bends. Years may be required before a configuration characteristic of average conditions in the stream is attained.

If the proposed highway or highway stream crossing is located near a meander loop, it is useful to have some insight into the probable way in which the loop will migrate or develop, as well as its rate of growth. No two meanders will behave in exactly the same way, but the meanders on a particular stream reach tend to conform to one of the several modes of behavior illustrated in Figure 2.11, which is based on a study of about 200 sinuous or meandering stream reaches.[10]

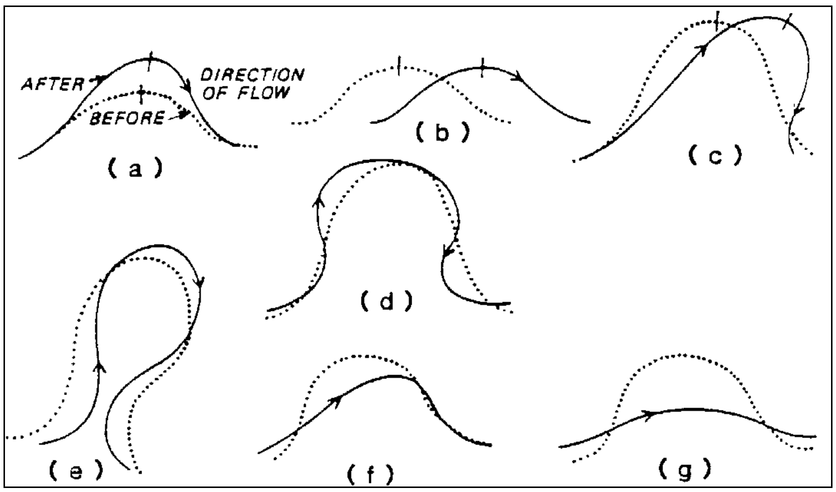


Figure 2.11. Modes of meander loop development: (a) extension, (b) translation, (c) rotation, (d) conversion to a compound loop, (e) neck cutoff by closure, (f) diagonal cutoff by chute, and (g) neck cutoff by chute (after Brice and Blodgett).[10]

Mode a (Figure 2.11) represents the typical development of a loop of low amplitude, which decreases in radius as it extends slightly in a downstream direction. Mode b rarely occurs unless meanders are confined by artificial levees or by valley sides on a narrow floodplain. Well developed meanders on streams that have moderately unstable banks are likely to follow Mode c. Mode d applies mainly to larger loops on meandering or highly meandering streams. The meander has become too large in relation to stream size and flow, and secondary meanders develop, converting it to a compound loop. Mode e also applies to meandering or highly meandering streams, usually of the equiwidth, point-bar type. The banks have been sufficiently stable for an elongated loop to form without being cut off, but the neck of the loop is gradually being closed and cutoff will eventually occur at the neck. Modes f and g apply mainly to locally braided, sinuous, or meandering streams having unstable banks. Loops are cut off by chutes that break diagonally or directly across the neck.

Oxbow lakes are formed by the cutoff of meander loops, which occurs either by gradual closure of the neck (neck cutoffs) or by a chute that cuts across the neck (chute cutoffs). Neck cutoffs are associated with relatively stable channels, and chute cutoffs with relatively unstable channels. Recently formed oxbow lakes along a channel are evidence of recent lateral migration. Commonly, a new meander loop soon forms at the point of cutoff and grows in the same direction as the previous meander. Cutoffs tend to induce rapid bank erosion at adjacent meander loops. The presence of abundant oxbow lakes on a floodplain does not necessarily indicate a rapid channel migration rate because an oxbow lake may persist for hundreds of years.

Usually the upstream end of the oxbow lake fills quickly to bank height. Overflow during floods and overland flow entering the oxbow lake carry fine materials into the oxbow lake area. The lower end of the oxbow remains open and drainage entering the system can flow out from the lower end. The oxbow gradually fills with fine silts and clays which are plastic and cohesive. As the stream channel meanders, old bendways filled with cohesive materials (referred to as clay plugs) are sufficiently resistant to erosion to serve as semipermanent geologic controls which can drastically affect planform geometry.

The local increase in channel slope due to cutoff usually results in an increase in the growth rate of adjoining meanders, and an increase in channel width at the point of cutoff. On a typical wide-bend point-bar stream, the effects of cutoff do not extend very far upstream or downstream. The consequences of cutoffs are an abruptly steeper stream gradient at the point of the cutoff, scour at the cutoff, and a propagation of the scour in an upstream direction. Downstream of a cutoff, the gradient of the channel is not changed and, therefore, the increased sediment load caused by upstream scour will usually be deposited at the site of the cutoff or below it, forming a large bar.

In summary, there is little relation between degree of sinuosity, as considered apart from other properties, and lateral stream stability.(10) A highly meandering stream may have a lower rate of lateral migration than a sinuous stream of similar size. Assessment of stability is based mainly on additional properties, especially on bar development and the variability of channel width. However, many hydraulic problems are associated with the location of highway crossings at a meander or bend. These include the shift of flow direction (angle of attack) at flood stage, shift of thalweg toward piers or abutments, development of point bars in the bridge reach, and lateral channel erosion at piers, abutments, or approaches.

In general, the most rapid bank erosion is generally at the outside of meanders, downstream from the apex of the loop. The cutoff of a meander, whether done artificially or naturally, causes a local increase in channel slope and a more rapid growth rate of adjoining meanders. Adjustment of the channel to increase in slope seems to be largely accomplished by increase in channel width (wetted perimeter) at and near the point of cutoff.

Some generalizations can be made, from knowledge of stream behavior, about the probable consequences of controlling or halting the development of a meander loop by the use of countermeasures. The most probable consequences relate to change in flow alignment (or lack of change, if the position of a naturally eroding bank is held constant). The development of a meander is affected by the alignment of the flow that enters it. Any artificial influence on flow alignment is likely to affect meander form. Downstream bank erosion rates are not likely to be increased, but the points at which bank erosion occurs are likely to be changed. In the case where flow is deflected directly at a bank, an increase in erosion rates would be expected. The failure of a major bridge on the Hatchie River near Covington, Tennessee has been attributed, in part, to lateral migration of the channel in the bridge reach.(20)

2.3.11 Braided Streams

A braided stream is one that consists of multiple and interlacing channels (Figure 2.6). In general, a braided channel has a large slope, a large bed-material load in comparison with its suspended load, and relatively small amounts of silts and clays in the bed and banks. The magnitude of the bed load is more important than its size. If the flow is overloaded with sediment, deposition occurs, the bed aggrades, and the slope of the channel increases in an effort to obtain a graded (equilibrium) condition. As the channel steepens, velocity increases, and multiple channels develop. Multiple channels are generally formed as bars of sediment and deposited within the main channel, causing the overall channel system to widen.

Multiple, mid-channel islands and bars are characteristic of streams that transport large bed loads. The presence of bars obstructs flow and scour occurs, either lateral erosion of banks on both sides of the bar, scour of the channels surrounding the bar, or both. This erosion will enlarge the channel and, with reduced water levels, an island may form at the site of a gravel or sand bar. The worst case will be where major bar or island forms at a bridge site. This can produce erosion of both banks of the stream and bed scour along both sides of the island. Reduction in the flow capacity beneath the bridge can result as a vegetated island forms under the bridge. An island or bar that forms upstream or downstream of a bridge can change flow alignment and create bank erosion or scour problems at the bridge site.

Island shift is easily identified because active erosion at one location and active deposition at another on the edge of an island can be recognized in the field. Also, the development or abandonment of flood channels and the joining together of islands can be detected by observing vegetation differences and patterns of erosion and deposition.

The degree of channel braiding is indicated by the percent of reach length that is divided by bars and islands, as shown in Figure 2.6. Braided streams tend to be common in arid and semiarid parts of the western United States and regions having active glaciers.

Braided streams may present difficulties for highway construction because they are unstable, change alignment rapidly, carry large quantities of sediment, are very wide and shallow even at flood flow and are, in general, unpredictable. Deep scour holes can develop downstream of a gravel bar or island where the flow from two channels comes together.

Braided streams generally require long bridges if the full channel width is crossed or effective flow-control measures if the channel is constricted. The banks are likely to be easily erodible, and unusual care must be taken to prevent lateral erosion at or near abutments. The position of braids is likely to shift during floods, resulting in unexpected velocities, angle of attack, and depths of flow at individual piers. Lateral migration of braided streams takes place by lateral shift of a braid against the bank, but available information indicates that lateral migration rates are generally less than for meandering streams. Along braided streams, however, migration is not confined to the outside of bends but can take place at any point by the lateral shift of individual braids.

2.3.12 Anabranched Streams

An anabranched stream differs from a braided stream in that the flow is divided by islands rather than bars, and the islands are large relative to channel width (also called an anastomosing stream). The anabranches, or individual channels, are more widely and distinctly separated and more fixed in position than the braids of a braided stream. An anabranch does not necessarily transmit flow at normal stage, but it is an active and well-defined channel, not blocked by vegetation. The degree of anabranching is arbitrarily categorized in Figure 2.6 in the same way as the degree of braiding was described.

Although the distinction between braiding and anabranching may seem academic, it has real significance for engineering purposes. Inasmuch as anabranches are relatively permanent channels that may convey substantial flow, diversion and confinement of an anabranched stream is likely to be more difficult than for a braided stream. Problems associated with crossings on anabranched streams can be avoided if a site where the channel is not anabranched can be chosen. If not, the designer may be faced with a choice of either building more than one bridge, building a long bridge, or diverting anabranches into a single channel. Problems with flow alignment may occur if a bridge is built at or near the junction of anabranches. Where anabranches are crossed by separate bridges, the design discharge for the bridges may be difficult to estimate. If one anabranch should become partly blocked, as by floating debris or ice, an unexpected amount of flow may be diverted to the other.

2.3.13 Variability of Width and Development of Bars

The variability of unvegetated channel width is a useful indication of the lateral stability of a channel. The visual impression of unvegetated channel width on aerial photographs depends on the relatively dark tones of vegetation as contrasted with the lighter tones of sediment or water. A channel is considered to be of uniform width (equiwidth) if the unvegetated width at bends is not more than 1.5 times the average width at the narrowest places.

The relationship between width variability and lateral stability is based on the rate of development of point bars and alternate bars. If the concave bank at a bend is eroding slowly, the point bar will grow slowly and vegetation will become established on it. The unvegetated part of the bar will appear as a narrow crescent. If the bank is eroding rapidly, the unvegetated part of the rapidly growing point bar will be wide and conspicuous. A point bar with an unvegetated width greater than the width of flowing water at the bend is considered to be wider than average. Lateral erosion rates are probably high in stream reaches where bare point bars tend to exceed average width. In areas where vegetation is quickly established, as in rainy southern climates, cut banks at bends may be a more reliable indication of instability than the unvegetated width of point bars.

Three categories of width variability are distinguished in Figure 2.6, but the relative lateral stability of these must be assessed in connection with bar development and other properties. In general, equiwidth streams having narrow point bars are the most stable laterally, and random-width streams having wide, irregular point bars are the least stable. Vertical stability, or the tendency to scour, cannot be assessed from these properties. Scour may occur in any alluvial channel. In fact, the greatest potential for deep scour might be expected in laterally stable equiwidth channels, which tend to have relatively deep and narrow cross sections and bed material in the size range of silt and sand.

2.4 AGGRADATION/DEGRADATION AND THE SEDIMENT CONTINUITY CONCEPT

2.4.1 Aggradation/Degradation

Aggradation and degradation are the vertical raising and lowering, respectively, of the streambed over relatively long distances and time frames. Such changes can be the result of both natural and man-induced changes in the watershed. The sediment continuity concept is the primary principle applied in both qualitative and quantitative analyses of bed elevation changes. After an introduction to the concept of sediment continuity, some factors causing a bed elevation change are reviewed.

2.4.2 Overview of the Sediment Continuity Concept

The amount of material transported, eroded, or deposited in an alluvial channel is a function of sediment supply and channel transport capacity. Sediment supply is provided from the tributary watershed and from any erosion occurring in the upstream channel. Sediment transport capacity is a function of the sediment size, the discharge of the stream, and the geometric and hydraulic properties of the channel. When the transport capacity (sediment outflow) equals sediment supply (sediment inflow), a state of equilibrium exists.

Application of the sediment continuity concept to a single channel reach illustrates the relationship between sediment supply and transport capacity. Technically, the sediment continuity concept states that the sediment inflow minus the sediment outflow equals the time rate of change of sediment volume in a given reach. More simply stated, during a given time period the amount of sediment coming into the reach minus the amount leaving the downstream end of the reach equals the change in the amount of sediment stored in that reach (Figure 2.12). The sediment inflow to a given reach is defined by the sediment supply from the watershed (upstream of the study reach plus any significant lateral input directly to the study reach). The transport capacity of the channel within the given reach defines the sediment outflow. Changes in the sediment volume within the reach occur when the total input to the reach (sediment supply) is not equal to the downstream output (sediment transport capacity). When the sediment supply is less than the transport capacity, erosion (degradation) will occur in the reach so that the transport capacity at the outlet is satisfied, unless controls exist that limit erosion. Conversely, when the sediment supply is greater than the transport capacity, deposition (aggradation) will occur in the reach.

Controls that limit erosion may either be human induced or natural. Human-induced controls included bank protection works, grade control structures, and stabilized bridge crossings. Natural controls can be geologic, such as outcroppings, or the presence of significant coarse sediment material in the channel. The presence of coarse material can result in the formation of a surface armor layer of larger sediments that are not transported by average flow conditions.

2.4.3 Factors Initiating Bed Elevation Changes

<u>Human-induced Changes</u>. Human activities are the major cause of streambed elevation changes. Very few bed elevation changes are due to natural causes, although some may be the result of both natural and human-induced causes. The most common activities which result in bed elevation changes caused by human activity are channel alterations, streambed mining, dams and reservoirs, and land-use changes. Highway construction, including the construction of bridges and channel alterations of limited extent, usually affect stream vertical stability only locally.

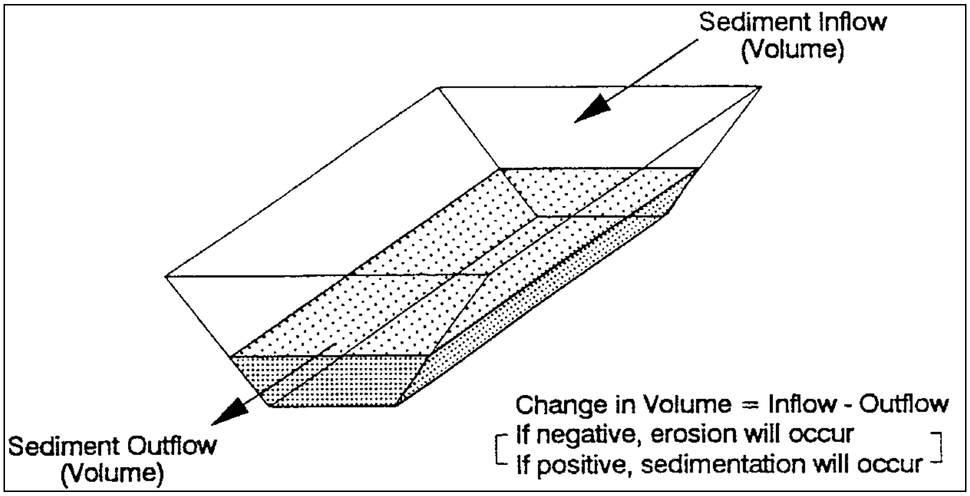


Figure 2.12. Definition sketch of sediment continuity concept applied to a given channel reach over a given time period.

Channel Alterations. Dredging, channelization, straightening, the construction of cutoffs to shorten the flow path of a stream, and clearing and snagging to increase channel capacity are the major causes of streambed elevation changes. An increase in slope resulting from a shorter flow path, or an increase in flow capacity results in increased velocities and a corresponding increase in sediment transport capacity. If the stream was previously in equilibrium (supply equal to transport capacity) the channel may adjust, either by increasing its length or by reducing its slope by degradation, in order to reestablish equilibrium. The most frequent response is a degrading streambed followed by bank erosion and a new meander pattern.

Constrictions in a stream channel, as in river control projects to maintain a navigation channel or highway crossings, also increase velocities and the sediment transport capacity in the constricted reach. The resulting degradation can be considered local, but it may extend through a considerable reach of stream, depending on the extent of the river control project. Constrictions may also cause local aggradation problems downstream.

The response to an increased sediment load in a stream that was near equilibrium conditions (i.e., supply now greater than transport capacity) is normally deposition in the channel downstream of the alteration. The result is an increase in flood stages and overbank flooding in downstream reaches. In time, the aggradation will progress both upstream and downstream of the end of the altered channel, and the stream reach may become locally braided as it seeks a new balance between sediment supply and sediment transport capacity.

Streambed Mining. Streambed mining for sand or gravel can be beneficial or detrimental, depending on the balance between sediment supply and transport capacity. Where the sediment supply exceeds the stream's transport capacity because of man's activities in the watershed or from natural causes, controlled removal of gravel bars and limited mining may enhance both lateral and vertical stability of the stream.

The usual result of streambed mining is an imbalance between sediment supply and transport capacity. Upstream of the operation, the water surface slope may be increased and bank erosion and headcutting or a nick point may result. The extent of the damage that can result is a function of the volume and depth of the sand and gravel pit relative to the size of the stream, bed material size, flood hydrographs, upstream sediment transport, and the location of the pit. If the size of the borrow pit is sufficiently large, a substantial quantity of the sediment inflow will be trapped in the pit and degradation will occur downstream. If bank erosion and headcutting upstream of the pit produce a sediment supply greater than the trap capacity of the pit and the transport capacity downstream, aggradation could occur. However, this circumstance is unlikely and streambed mining generally causes degradation upstream and downstream of the pit.

Dams and Reservoirs. Storage and flood control reservoirs produce a stream response both upstream and downstream of the reservoir. A stream flowing into a reservoir forms a delta as the sediment load is deposited in the ponded water. This deposition reduces the stream gradient upstream of the reservoir and causes aggradation in the channel. Aggradation can extend many kilometers upstream.

Downstream of reservoirs, stream channel stability is affected because of the changed flow characteristics and because flow releases are relatively sediment-free. Clear-water releases pick up a new sediment load and degradation can result. The stream channel and stream gradient that existed prior to the construction of the dam was the cumulative result of past floods of various sizes and subject to change with each flood. Post-construction flows are usually of lesser magnitude and longer duration, and the stream will establish a new balance in time consistent with the new flow characteristics.

It is possible for aggradation to occur downstream of a reservoir if flow releases are insufficient to transport the size or volume of sediment brought in by tributary streams. Streamflow regulation, which is an objective in dam construction and reservoir operation, is sometimes overlooked in assessing stream system response to this activity. The reduction in flood magnitude and stage downstream of dams as a result of reservoir operation can result in greatly increased hydraulic gradients and degradation in tributaries downstream of the dam. A notorious bridge failure on the Big Sioux River was, in part, attributable to such a condition.

Land Use Changes. Agricultural activities, urbanization, commercial development, and construction activities also contribute to bed elevation problems in streams. Clear cutting of forests, and the destruction of grasslands by overgrazing, burning and cultivation can accelerate erosion, causing streams draining these areas to become overloaded with sediment (i.e., excess sediment supply). As the overload persists, the stream system aggrades and increases its slope to increase its sediment transport capacity.

Construction and developing urban and commercial areas can affect stream gradient stability. Fully developed urban areas are low sediment producers because of impervious areas and lawns, but tend to increase the magnitude of runoff events and reduce their duration. The response of a small stream system to these changes is degradation, changes in planform (e.g., increased sinuosity), and channel widening downstream of the urbanized area. However, if the urbanized area is small relative to the basin of the stream in which it is located, the net effect will probably be small.

Natural Changes. Natural causes of stream gradient instability are primarily natural channel alterations, earthquakes, tectonic and volcanic activities, climatic change, fire, and channel bed and bank material erodibility.

Cutoffs and chute channel development (as a channel straightens) are the most common natural channel alterations. This results in a shorter flow path, a steeper channel gradient, and an increase in sediment transport capacity. Significant bank erosion and degradation progressing to an upstream control can result. Downstream of the cutoff, aggradation will occur.

Severe landslides, mud flows, uplifts and lateral shifts in terrain, and liquefaction of otherwise semi-stable materials are associated with earthquakes and tectonic activities. The response to these activities include channel changes, scour or deposition locally or system-wide, headcutting and bank instability.

Alluvial fans, discussed under Valley Setting, are among the most common naturally occurring cases of channel aggradation.[12]

CHAPTER 3

ANALYSIS PROCEDURES FOR STREAM INSTABILITY

3.1 INTRODUCTION

A stable stream does not change in size, form, or position with time; however, all alluvial channels change to some extent and are somewhat unstable. For highway engineering purposes, a stream channel can be considered unstable if the rate or magnitude of change is great enough that the planning, location, design, or maintenance considerations for a highway encroachment are significantly affected. The kinds of changes that are of concern are:

- Lateral bank erosion, including the erosion that occurs from meander migration
- Aggradation or degradation of the streambed that progresses with time
- Short-term fluctuations in streambed elevation that are usually associated with the passage of a flood (scour and fill)

These changes are associated with instability in a stream system or in an extensive reach of stream.

Local instability caused by the construction of a highway crossing or encroachment on a stream is also of concern. This includes scour caused by contraction of the flow, and local scour due to the disturbance of streamlines at an object in the flow, such as at a pier or an abutment. The purpose of this chapter is to outline the analysis procedures that may be utilized to evaluate stream instability. These analysis procedures provide details on many of the general analysis steps of the comprehensive analysis flow chart of Figure 1.1.

3.2 GENERAL SOLUTION PROCEDURE

The analysis of any complex problem should begin with an overview or general evaluation, including a qualitative assessment of the problem and its solution. This fundamental initial step should be directed towards providing insight and understanding of significant physical processes, without being too concerned with the specifics of any given component of the problem. The understanding generated from such analyses assures that subsequent detailed analyses are properly designed.

The progression to more detailed analyses should begin with application of basic principles, followed as required, with more complex solution techniques. This solution approach, beginning with qualitative analysis, proceeding through basic quantitative principles and then utilizing, as required, more complex or state-of-the-art solution procedures assures that accurate and reasonable results are obtained while minimizing the expenditure of time and effort.

The inherent complexities of a stream stability analysis, further complicated by highway stream crossings, require such a solution procedure. The evaluation and design of a highway stream crossing or encroachment should begin with a qualitative assessment of stream stability. This involves application of geomorphic concepts to identify potential problems and alternative solutions. This analysis should be followed with quantitative analyses using basic hydrologic, hydraulic and sediment transport engineering concepts. Such analyses could include evaluation of flood history, channel hydraulic conditions (up to and including, for example, water surface profile analysis) and basic sediment transport analyses such as evaluation of watershed sediment yield, incipient motion analysis and scour calculations. This analysis can be considered adequate for many locations if the problems are resolved and the relationships among different factors affecting stability are adequately explained. If not, a more complex quantitative analysis based on detailed mathematical modeling and/or physical hydraulic models should be considered.

In summary, the general solution procedure for analyzing stream stability could involve the following three levels of analysis:

Level 1: Application of Simple Geomorphic Concepts and other Qualitative Analyses
Level 2: Application of Basic Hydrologic, Hydraulic and Sediment Transport Engineering Concepts
Level 3: Application of Mathematical or Physical Modeling Studies

3.3 DATA NEEDS

The types and detail of data required to analyze a highway crossing or encroachment on a stream channel are highly dependent on the relative instability of the stream and the depth of study required to obtain adequate resolution of potential problems. More detailed data are needed where quantitative analyses are necessary, and data from an extensive reach of stream may be required to resolve problems in complex and high risk situations.

3.3.1 Data Needs for Level 1 Qualitative and Other Geomorphic Analyses

The data required for preliminary stability analyses include maps, aerial photographs, notes and photographs from field inspections, historic channel profile data, information on man's activities, and changes in stream hydrology and hydraulics over time.

The National Bridge Inspection Standards (NBIS) Program requires inspections on a two-year cycle of the 575 000 bridges on the National Bridge Inventory. The FHWA publication the "Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges" specifies the bridge and channel hydraulics and scour data that are evaluated and reported within the NBIS.(21) Item 60, substructure, Item 61, Channel and Channel Protection, Item 71, Waterway Adequacy, and Item 113, Scour Critical Bridges, are among the items reported in the NBIS. These items can be used to aid the highway engineer in generating data needed for analysis.

Typically, a cross section of the bridge waterway at the time of each inspection will provide a chronological picture of the bridge waterway. Area, vicinity, site, geologic, soils, and land use maps each provide essential information. Unstable stream systems upstream or downstream of the encroachment site can cause instability at the bridge site. Area maps are needed to locate unstable reaches of streams relative to the bridge site. Vicinity maps help to identify more localized problems. They should include a sufficient reach of stream to permit identification of stream characteristics, and to locate bars, braids, and channel controls. Site maps are needed to determine factors that influence local stability and flow alignment, such as bars and tributaries. Geologic maps provide information on deposits and rock formations and outcrops that control stream stability. Soils and land use maps provide information on soil types, vegetative cover, and land use which affect the character and availability of sediment supply.

Aerial photographs record much more ground detail than maps and are frequently available at five-year intervals. This permits measurement of the rate of progress of bend migration and other stream changes that cannot be measured from maps made less frequently. A highway agency should periodically obtain aerial photographs of actively unstable streams that threaten highway facilities, including immediately after major floods. However, aerial photographs taken after the passage of an ice jam or immediately after a major flood must be interpreted with care since they may provide misleading information regarding the rate of change.

Notes and photographs from field inspections are important to gain an understanding of stream stability problems, particularly local stability. Field inspections should be made during high- and low-flow periods to record the location of bank cutting or sloughing and deposition in the channel. Flow directions should be sketched, signs of aggradation or degradation noted, properties of bed and bank materials estimated or measured, and the locations and implications of impacting activities recorded.

If historic stream profile data are available, it will provide information on channel stability. Stage trends at stream gaging stations and comparisons of streambed elevations with elevations before construction at structures will provide information on changes in stream profile. As-built bridge data and cross sections are frequently useful. Structure-induced scour should be taken into consideration where such comparisons are made.

Human's activities in a watershed are frequently the cause of stream instability. Information on urbanization, land clearing, snagging in stream channels, channelization, bend cutoffs, streambed mining, dam construction, reservoir operations, navigation projects, and other activities, either existing or planned, are necessary to evaluate the impact on stream stability.

Data on changes in morphology are important because change in a stream rarely occurs at a constant rate. Stream instability can often be associated with an event, such as an extreme flood or a particular activity in the watershed or stream channel. If association is possible, the rate of change can be more accurately assessed. Similarly, information on changes in hydrology or hydraulics can sometimes be associated with activities that caused the change. Where changes in stream hydraulics are associated with an activity, changes in stream morphology are also likely to have occurred.

3.3.2 Data Needs for Level 2 Basic Engineering Analyses

Data requirements for basic hydrologic, hydraulic and sediment transport engineering analyses are dependent on the types of analyses that must be completed. Hydrologic data needs include dominant discharge (or bankfull flow), flow duration curves, and flow frequency curves. Discussion of hydrologic methods is beyond the scope of this manual; however, information can be obtained from the FHWA publication HDS 2 and Department of Transportation manuals.[(22)] Hydraulic data needs include cross sections, channel and bank roughness estimates, channel alignment, and other data for computing channel hydraulics, up to and including water surface profile calculations. Analysis of basic sediment transport conditions requires information on land use, soils, and geologic conditions, sediment sizes in the watershed and channel, and available measured sediment transport rates (e.g., from USGS gaging stations).

More detailed quantitative analyses require data on the properties of bed and bank materials and, at times, field data on bed-load and suspended-load transport rates. Properties of bed and bank materials that are important to a study of sediment transport include size, shape, fall velocity, cohesion, density, and angle of repose.

Chapter 4 outlines stream reconnaissance techniques and provides checklists that can assist in obtaining and organizing much of the data needed for Level 1 and Level 2 analyses. Chapter 4 also provides reference to rapid assessment procedures that will support a preliminary evaluation of potential scour and channel stability problems using limited site data. Chapters 5 and 6 contain additional quantitative techniques that will assist in determining the extent of lateral and vertical instability problems, and in channel stability analysis.

3.3.3 Data Needs for Level 3 Mathematical and Physical Model Studies

Application of mathematical and physical model studies requires the same basic data as a Level 2 analysis, but typically in much greater detail. For example, water and sediment routing by mathematical models (e.g., BRI-STARS or HEC-6), and construction of a physical model, would both require detailed channel cross-sectional data.[23,24] The more extensive data requirements for either mathematical or physical model studies, combined with the additional level of effort needed to complete such studies, results in a relatively large scope of work.

3.4 DATA SOURCES

Preliminary stability data may be available from government agencies such as the USACE, Natural Resources Conservation Service (formerly Soil Conservation Service, SCS), USGS, local river basin commissions, and local watershed districts. These agencies may have information on historic streambed profiles, stage-discharge relationships, and sediment load characteristics. They may also have information on past and planned activities that affect stream stability. Table 3.1 provides a list of sources for the various types of data needed to assess stream stability at a site.

3.5 LEVEL 1: QUALITATIVE GEOMORPHIC ANALYSES

A flow chart of the typical steps in qualitative geomorphic analyses is provided in Figure 3.1. The six steps are generally applicable to most stream stability problems. As shown on Figure 3.1, the qualitative evaluation leads to a conclusion regarding the need for more detailed (Level 2) analysis or a decision to complete a screening or evaluation based on the Level 1 analysis. A Level 1 qualitative analysis is a prerequisite for a Level 2 engineering analysis for bridge design or rehabilitation (see also Chapter 1, Figure 1.1).

Table 3.1. List of Data Sources (after FHWA).[13]	
Topographic Maps:	
(1)	Quadrangle maps - U.S. Department of the Interior, Geological Survey, Topographic Division; and U.S. Department of the Army, Army Map Service.
(2)	River plans and profiles - U.S. Department of the Interior, Geological Survey, Conservation Division.
(3)	National parks and monuments - U.S. Department of the Interior, National Park Service.
(4)	Federal reclamation project maps - U.S. Department of the Interior, Bureau of Reclamation.
(5)	Local areas - commercial aerial mapping firms.
(6)	American Society of Photogrammetry.
Planimetric Maps:	
(1)	Plats of public land surveys - U.S. Department of the Interior, Bureau of Land Management
(2)	National forest maps - U.S. Department of Agriculture, Forest Service.
(3)	County maps - State DOTs.
(4)	City plats - city or county recorder.
(5)	Federal reclamation project maps - U.S. Department of the Interior, Bureau of Reclamation.
(6)	American Society of Photogrammetry.
(7)	ASCE Journal - Surveying and Mapping Division.

Table continues

Table 3.1. List of Data Sources (after FHWA).[13] continued

Aerial Photographs:

(1) The following agencies have aerial photographs of portions of the United States: U.S. Department of the Interior, Geological Survey, Topographic Division; U.S. Department of Agriculture, Commodity Stabilization Service, Soil Conservation Service and Forest Service; U.S. Air Force; various state agencies; commercial aerial survey; National Oceanic and Atmospheric Administration; and mapping firms.

(2) American Society of Photogrammetry.

(3) Photogrammetric Engineering.

(4) Earth Resources Observation System (EROS) - Photographs from Gemini, Apollo, Earth Resources Technology Satellite (ERTS) and Skylab.

Transportation Maps:

(1) State DOTs

Triangulation and Benchmarks:

(1) State Engineer.

(2) State DOTs

Geologic Maps:

(1) U.S. Department of the Interior, Geological Survey, Geologic Division; and state geological surveys or departments. (Note - some regular quadrangle maps show geological data also).

Soils Data:

(1) County soil survey reports - U.S. Department of Agriculture, Soil Conservation Service.

(2) Land use capability surveys - U.S. Department of Agriculture, Soil Conservation Service.

(3) Land classification reports - U.S. Department of the Interior, Bureau of Reclamation.

(4) Hydraulic laboratory reports - U.S. Department of the Interior, Bureau of Reclamation.

Table continues

Table 3.1. List of Data Sources (after FHWA).[13] continued

Climatological Data:

(1) National Weather Service Data Center.

(2) Hydrologic bulletin - U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

(3) Technical papers - U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

(4) Hydro-meteorological reports - U.S. Department of Commerce, National Oceanic and Atmospheric Administration; and U.S. Department of the Army, Corps of Engineers.

(5) Cooperative study reports - U.S. Department of Commerce, National Oceanic and Atmospheric Administration; and U.S. Department of the Interior, Bureau of Reclamation.

Streamflow Data:

(1) Water supply papers - U.S. Department of the Interior; Geological Survey, Water Resources Division.

(2) Reports of state engineers.

(3) Annual reports - International Boundary and Water Commission, United States and Mexico.

(4) Annual reports - various interstate compact commissions.

(5) Hydraulic laboratory reports - U.S. Department of the Interior, Bureau of Reclamation.

(6) Bureau of Reclamation.

(7) U.S. Army Corps of Engineers, Flood control studies.

Sedimentation Data:

(1) Water supply papers - U.S. Department of the Interior, Geological Survey, Quality of Water Branch.

(2) Reports - U.S. Department of the Interior, Bureau of Reclamation; and U.S. Department of Agriculture, Soil Conservation Service.

(3) Geological Survey Circulars - U.S. Department of the Interior, Geological Survey.

Table continues

Table 3.1. List of Data Sources (after FHWA).[13] continued	
Quality of Water Reports:	
(1)	Water supply papers - U.S. Department of the Interior, Geological Survey, Quality of Water Branch.
(2)	Reports - U.S. Department of Health, Education, and Welfare, Public Health Service.
(3)	Reports - state public health departments
(4)	Water resources publications - U.S. Department of the Interior, Bureau of Reclamation.
(5)	Environmental Protection Agency, regional offices.
(6)	State water quality agency.
Irrigation and Drainage Data:	
(1)	Agriculture census reports - U.S. Department of Commerce, Bureau of the Census.
(2)	Agricultural statistics - U.S. Department of Agriculture, Agricultural Marketing Service.
(3)	Federal reclamation projects - U.S. Department of the Interior, Bureau of Reclamation.
(4)	Reports and progress reports - U.S. Department of the Interior, Bureau of Reclamation.
Power Data:	
(1)	Directory of Electric Utilities - McGraw Hill Publishing Co.
(2)	Directory of Electric and Gas Utilities in the United States - Federal Power Commission.
(3)	Reports - various power companies, public utilities, state power commissions, etc.
Basin and Project Reports and Special Reports	
(1)	U.S. Army Corps of Engineers.
(2)	U.S. Department of the Interior, Bureau of Land Management, Bureau of Mines, Bureau of Reclamation, Fish and Wildlife Service, and National Park Service.

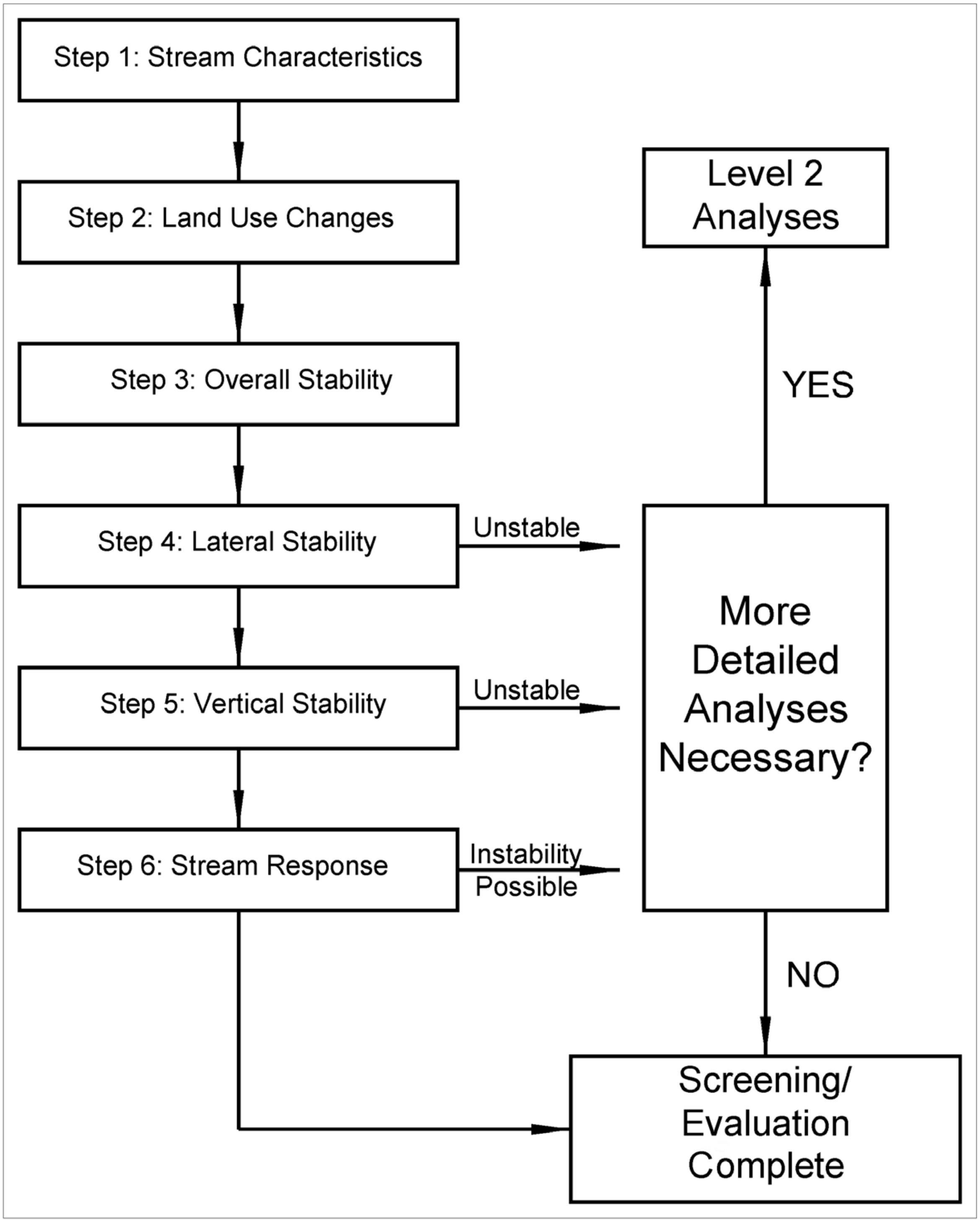


Figure 3.1. Flow chart for Level 1: Qualitative Geomorphic Analyses.

3.5.1 Step 1. Define Stream Characteristics

The first step in stability analysis is to identify stream characteristics according to the factors discussed in Chapter 2, Geomorphic Factors and Principles. Defining the various geomorphic characteristics of the stream provides insight into stream behavior and response (see Chapter 4 for additional stream channel reconnaissance and classification techniques).

3.5.2 Step 2. Evaluate Land Use Changes

Water and sediment yield from a watershed is a function of land-use practices. Thus, knowledge of the land use and historical changes in land use is essential to understanding conditions of stream stability and potential stream response to natural and human-induced changes.

The presence or absence of vegetative growth can have a significant influence on the runoff and erosional response of a fluvial system. Large scale changes in vegetation resulting from fire, logging, land conversion and urbanization can either increase or decrease the total water and sediment yield from a watershed. For example, fire and logging tend to increase water and sediment yield, while urbanization promotes increased water yield and peak flows, but decreased sediment yield from the watershed. Urbanization may increase sediment yield from the channel.

Information on land use history and trends can be found in Federal, State and Local government documents and reports (i.e., census information, zoning maps, future development plans, etc.). Additionally, analysis of historical aerial photographs can provide significant insight on land use changes. Land use change due to urbanization can be classified based on estimated changes in pervious and impervious cover. Changes in vegetative cover can be classified as simply as no change, vegetation increasing, vegetation damaged and vegetation destroyed. The relationship or correlation between changes in channel stability and land use changes can contribute to a qualitative understanding of system response mechanisms.

3.5.3 Step 3. Assess Overall Stream Stability

Table 3.2 summarizes possible channel stability interpretations according to stream characteristics discussed in Chapter 2 (Figure 2.6), as well as additional factors that commonly influence stream stability. Figure 3.2 is also useful in making a qualitative assessment of stream stability based on stream characteristics. It shows that straight channels are relatively stable only where flow velocities and sediment load are low. As these variables increase, flow meanders in the channel causing the formation of alternate bars and the initiation of a meandering channel pattern. Similarly, meandering channels are progressively less stable with increasing velocity and bed load. At high values of these variables, the channel becomes braided. The presence and size of point bars and middle bars are indications of the relative lateral stability of a stream channel.

Bed material transport is directly related to stream power, and relative stability decreases as stream power increases as shown by Figure 3.2. Stream power is the product of shear stress at the bed and the average velocity in the channel section. Shear stress can be determined from the average shear stress equation (γRS). See Section 6.3.2 or HDS 6[13] for further discussion.

Table 3.2. Interpretation of Observed Data (after Keefer et al.).[25]

Observed Condition	Channel Response			
	Stable	Unstable	Degrading	Aggrading
Alluvial Fan[1]				
Upstream		X		X
Downstream		X	X	
Dam and Reservoir				
Upstream		X		X
Downstream		X	X	
River Form				
Meandering	X	X	Unknown	Unknown
Straight		X	Unknown	Unknown
Braided		X	Unknown	Unknown
Bank Erosion		X	Unknown	Unknown
Vegetated Banks	X		Unknown	Unknown
Head Cuts		X	X	
Diversion				
Clear water diversion		X		X
Overloaded w/sediment		X	X	
Channel Straightened		X	X	
Deforest Watershed		X		X
Drought Period	X			X
Wet Period		X	X	
Bed Material Size				
Increase		X		X
Decrease		X	Unknown	X

[1]The observed condition refers to location of the bridge on the alluvial fan, i.e., on the upstream or downstream portion of the fan.

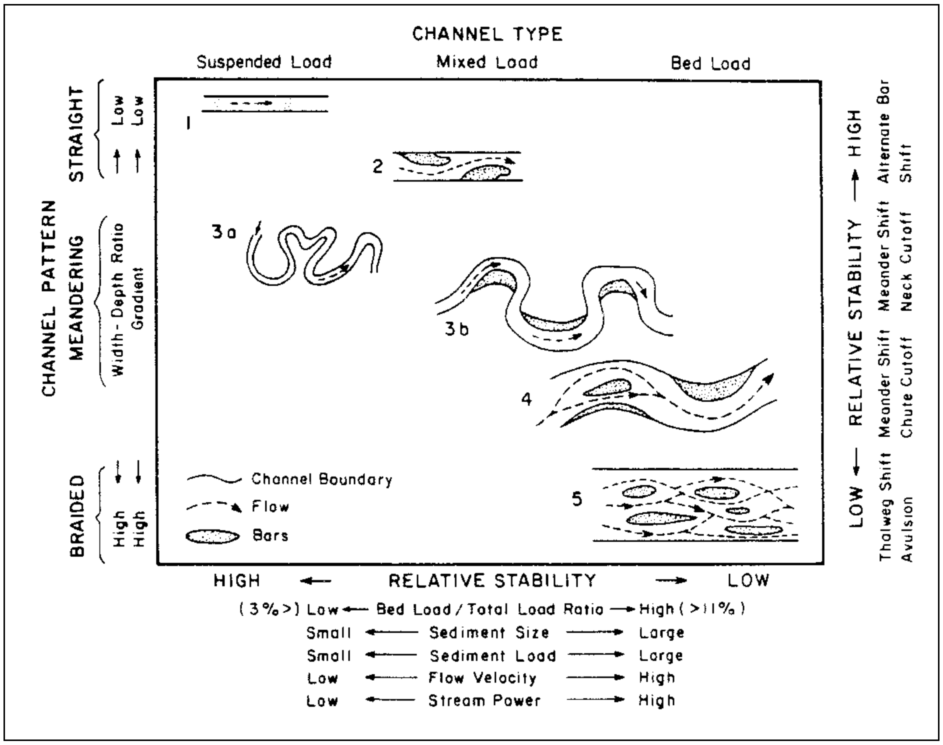


Figure 3.2. Channel classification and relative stability as hydraulic factors are varied (after Shen et al.).[16]

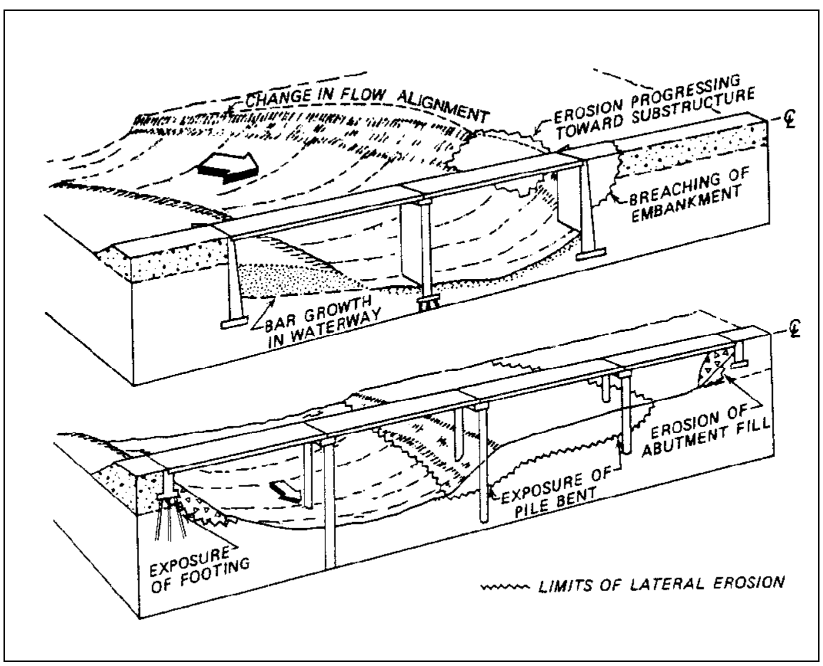


Figure 3.3. Hydraulic problems at bridges attributed to erosion at a bend or to lateral migration of the channel (after Brice and Blodgett).[10, 11]

3.5.4 Step 4. Evaluate Lateral Stability

The effects of lateral instability of a stream at a bridge are dependent on the extent of the bank erosion and the design of the bridge. Bank erosion can undermine piers and abutments located outside the channel and erode abutment spill slopes or breach approach fills. Where bank failure is by a rotational slip, lateral pressures on piers located within the slip zone may cause cracks in piers or piling or displacement of pier foundations. Migration of a bend through a bridge opening changes the direction of flow through the opening so that a pier designed and constructed with a round-nose acts as a blunt-nosed, enlarged obstruction in the flow, thus accentuating local and contraction scour. Also, the development of a point bar on the inside of the migrating bend can increase contraction at the bridge if the outside bank is constrained from eroding. Figure 3.3 illustrates some of the problems of lateral erosion at bridges.

A field inspection is a critical component of a qualitative assessment of lateral stability. A comparison of observed field conditions with the descriptions of stable and unstable channel banks presented in Section 2.3.9 helps qualify bank stability. Similarly, field observations of bank material, composition and existing failure modes can provide insight on bank stability, based on the descriptions of cohesive, non-cohesive and composite banks given in Section 2.3.9 (see also Appendix B). An evaluation of lateral stability in conjunction with the design of a bridge should take the performance of existing nearby bridges into account. The experience of such structures which have been subjected to the impacts of the stream can provide insight into response at a nearby structure.

Lateral stability assessment can also be completed from records of the position of a bend at two or more different times; aerial photographs or maps are usually the only records available. Surveyed cross sections are extremely useful although rarely available. Some progress is being made on the numerical prediction of loop deformation and bend migration (Level 3 type analyses). At present, however, the best available estimates are based on past rates of lateral migration at a particular reach. In using the estimates, it should be recognized that erosion rates may fluctuate substantially from one period of years to the next.

Measurements of bank erosion on two time-sequential aerial photographs (or maps) require the identification of reference points which are common to both. Useful reference points include roads, buildings, irrigation canals, bridges and fence corners. This analysis of lateral stability is greatly facilitated by a drawing of changes in bank line position with time. To prepare such a drawing, aerial photographs are matched in scale and the photographs are superimposed holding the reference points fixed. For additional discussion of comparative techniques, see Chapter 6.

A site of potential avulsion (channel shifting to new flow path) in the vicinity of a highway stream crossing should be identified so that steps can be taken to mitigate the effects of avulsion when it occurs. A careful study of aerial photographs will show where overbank flooding has been taking place consistently and where a channel exists that can capture the flow in the existing channel. In addition, topographic maps and special surveys may show that the channel is indeed perched above the surrounding alluvial surface, with the inevitability of avulsion. Generally, avulsion, as the term is used here, will only be a hazard on alluvial fans, alluvial plains, deltas, and wide alluvial valleys. In a progressively aggrading situation, as on an alluvial fan, the stream will build itself out of its channel and be very susceptible to avulsion. In other words, in a cross profile on an alluvial fan or plain, it may be found that the river is flowing between natural levees at a level somewhat higher than the surrounding area. In this case, avulsion is inevitable.

3.5.5 Step 5. Evaluate Vertical Stability

The typical effects associated with bed elevation changes at highway bridges are erosion at abutments and the exposure and undermining of foundations from degradation, or a reduction in flow area from aggradation under bridges resulting in more frequent flow over the highway. Bank caving associated with degradation poses the same problems at bridges as lateral erosion from bend migration, but the problems may be more severe because of the lower elevation of the streambed. Aggrading stream channels also tend to become wider as aggradation progresses, eroding floodplain areas and highway embankments on the floodplain. The location of the bridge crossing upstream, downstream, or on tributaries may cause bed elevation problems (Figure 5.3).

Brown et al., reported that their study indicated that there are serious problems at about three degradation sites for every aggradation site.(26) This is a reflection of the fact that degradation is more common than aggradation, and also the fact that aggradation does not endanger the bridge foundation. It is not an indication that aggradation is not a serious problem in some areas of the United States.

Problems other than those most commonly associated with degrading channels include the undermining of cutoff walls, other flow-control structures, and bank protection. Bank sloughing because of degradation often greatly increases the amount of debris carried by the stream and increases the potential for blocked waterway openings and increased scour at bridges. The hazard of local scour becomes greater in a degrading stream because of the lower streambed elevation.

Aggradation in a stream channel increases the frequency of backwater that can cause damage. Bridge decks and approach roadways become inundated more frequently, disrupting traffic, subjecting the superstructure of the bridge to hydraulic forces that can cause failure, and subjecting approach roadways to overflow that can erode and cause failure of the embankment. Where lateral erosion or increased flood stages accompanying aggradation increase the debris load in a stream, the hazards of clogged bridge waterways and hydraulic forces on bridge superstructures are increased.

Data records for at least several years are usually needed to detect bed elevation problems. This is due to the fact that the channel bottom often is not visible and changes in flow depth may indicate changes in the rate of flow rather than bed elevation changes. Bed elevation changes develop over long periods of time even though rapid change can occur during an extreme flood event. The data needed to assess bed elevation changes include historic streambed profiles, and long-term trends in stage-discharge relationships. Occasionally, information on bed elevation changes can be gained from a series of maps prepared at different times. Bed elevations at railroad, highway and pipeline crossings monitored over time may also be useful. On many large streams, the long-term trends have been analyzed and documented by agencies such as the USGS and the USACE.

3.5.6 Step 6. Evaluate Channel Response to Change

The knowledge and insight developed from evaluation of present and historical channel and watershed conditions, as developed above through Steps 1 through 5, provide an understanding of potential channel response to previous impacts and/or proposed changes, such as construction of a bridge. Additionally, the application of simple, predictive geomorphic relationships, such as the Lane relationship (see Section 4.4.2) can assist in evaluating channel response mechanisms. Section 4.4.3 illustrates the evaluation of stream response based on geomorphic and other qualitative considerations. Additional applications of Level 1 analysis techniques to bridge related stream stability problems can be found in Chapters 5 and 9 of HDS 6.[13]

3.6 LEVEL 2: BASIC ENGINEERING ANALYSES

A flow chart of the typical steps in basic engineering analyses is provided in Figure 3.4. The flow chart illustrates the typical steps to be followed if a Level 1 qualitative analysis resulted in a decision that Level 2 analysis is required (Figure 3.1). The eight basic engineering steps are generally applicable to most stream stability problems. The basic engineering analysis steps lead to a conclusion regarding the need for more detailed (Level 3) analysis or a decision to proceed to bridge design, selection and design of countermeasures, or channel restoration design without more complex studies. Selection and design of countermeasures are discussed in HEC-23.[2]

3.6.1 Step 1. Evaluate Flood History and Rainfall-Runoff Relations

Detailed discussion of hydrologic analysis techniques, in particular the analysis of flood magnitude and frequency, is presented in HDS 2.[22] However, several hydrologic concepts of particular significance to evaluation of stream stability are summarized in the following paragraphs.

Consideration of flood history is an integral step in attempting to characterize watershed response and morphologic evolution. Analysis of flood history is of particular importance to understanding arid region stream characteristics. Many dryland streams flow only during the spring and immediately after major storms. For example, Leopold, et al. found that arroyos near Santa Fe, New Mexico, flow only about three times a year.[27] As a consequence, dryland stream response can be considered to be more hydrologically dependent than streams located in a humid environment. Whereas the simple passage of time may be sufficient to cause change in a stream located in a humid environment, time alone, at least in the short term, may not necessarily cause change in a dryland system due to the infrequency of hydrologically significant events. Thus, the absence of significant morphological changes in a dryland stream or river, even over a period of years, should not necessarily be construed as an indication of system stability.

Although the occurrence of single large storms can often be directly related to system change in any region of the country, this is not always the case. In particular, the succession of morphologic change may be linked to the concept of geomorphic thresholds. Under this concept, although a single major storm may trigger an erosional event in a system, the occurrence of such an event may be the result of a cumulative process leading to an unstable geomorphic condition.

Where available, the study of flood records and corresponding system responses, as indicated by time-sequenced aerial photography or other physical information, may help determine the relationship between morphological change and flood magnitude and frequency. Evaluation of wet-dry cycles can also be beneficial to an understanding of historical system response. Observable historic change may be found to be better correlated with the occurrence of a sequence of events during a period of above average rainfall and runoff than with a single large event. The study of historical wet-dry trends may explain certain complex aspects of system response. For example, a large storm preceded by a period of above-average precipitation may result in less erosion, due to better vegetative cover, than a comparable storm occurring under dry antecedent conditions; however, runoff volumes might be greater due to saturated soil conditions.

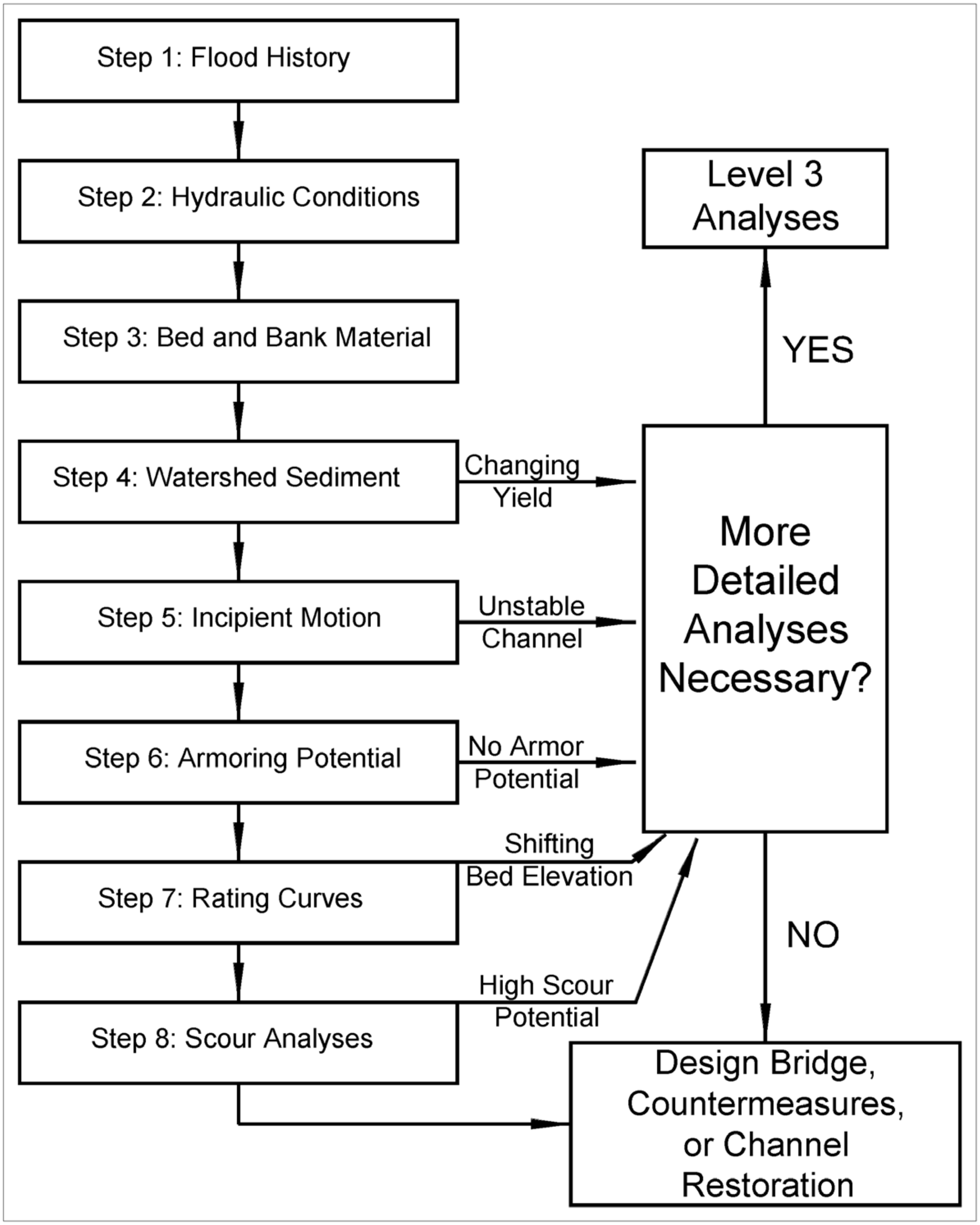


Figure 3.4. Flow chart for Level 2: Basic Engineering Analyses.

A good method to evaluate wet-dry cycles is to plot annual rainfall amounts, runoff volumes and maximum annual mean daily discharge for the period of record. A comparison of these graphs will provide insight into wet-dry cycles and flood occurrences. Additionally, a plot of the ratio of rainfall to runoff is a good indicator of watershed characteristics and historical changes in watershed condition.

3.6.2 Step 2. Evaluate Hydraulic Conditions

Knowledge of basic hydraulic conditions, such as velocity, flow depth and top width, etc., for given flood events is essential for completion of Level 2 stream stability analyses. Incipient motion analysis, scour analysis, assessment of sediment transport capacity, etc. all require basic hydraulic information. Hydraulic information is sometimes required for both the main channel and overbank areas, such as in the analysis of contraction scour.

Evaluation of hydraulic conditions is based on the factors and principles reviewed in Chapter 5. For many river systems, particularly near urban areas, hydraulic information may be readily available from previous studies, such as flood insurance studies, channel improvement projects, etc., and complete re-analysis may not be necessary. However, in other areas, hydraulic analysis based on appropriate analytical techniques will be required prior to completing other quantitative analyses in a Level 2 stream stability assessment. The most common computer models for analysis of water surface profiles and hydraulic conditions are the Corps of Engineers HEC-2 or HEC-RAS (River Analysis System) and the Federal Highway Administration WSPRO.[28,29,30]

3.6.3 Step 3. Bed and Bank Material Analysis

Bed material is the sediment mixture of which the streambed is composed. Bed material ranges in size from huge boulders to fine clay particles. The erodibility or stability of a channel largely depends on the size of the particles in the bed. Additionally, knowledge of bed sediment is necessary for most sediment transport analyses, including evaluation of incipient motion, armoring potential, sediment transport capacity and scour calculations. Many of these analyses require knowledge of particle size gradation, and not just the median (D_{50}) sediment size.

Bank material usually consists of particles the same size as, or smaller than, bed particles. Thus, banks are often more easily eroded than the bed, unless protected by vegetation, cohesion, or some type of protection, such as revetment.

Of the various sediment properties, size has the greatest significance to the hydraulic engineer, not only because size is the most readily measured property, but also because other properties, such as shape and fall velocity, tend to vary with particle size. A comprehensive discussion of sediment characteristics, including sediment size and its measurement, is provided in HDS 6.[13] The following information briefly discusses sediment sampling considerations.

Important factors to consider in determining where and how many bed and bank material samples to collect include:

- Size and complexity of the study area
- Number, lengths and drainage areas of tributaries

- Evidence of or potential for armoring
- Structural features that can impact or be significantly impacted by sediment transport
- Bank failure areas
- High bank areas
- Areas exhibiting significant sediment movement or deposition (i.e., bars in channel).

Tributary sediment characteristics can be very important to channel stability, since a single major tributary or tributary source area could be the predominant supplier of sediment to a system.

The depth of bed material sampling depends on the homogeneity of surface and subsurface materials. Where possible it is desirable to dig down some distance to establish bed-material characteristics. For example, in sand/gravel bed systems the potential existence of a thin surface layer of coarser sediments (armor layer) on top of relatively undisturbed subsurface material must be considered in any sediment sampling. Samples containing material from both layers would contain materials from two populations in unknown proportions, and thus it is typically more appropriate to sample each layer separately. If the purpose of the sampling is to evaluate hydraulic friction or initiation of bed movement, then the surface sample will be of most interest. Conversely, if bed-material transport during a large flood (i.e., large enough to disturb the surface layer) is important, then the underlying layer may be more significant. Methods of analysis are given in HDS 6.[(13)]

3.6.4 Step 4. Evaluate Watershed Sediment Yield

Evaluation of watershed sediment yield, and in particular, the relative increase in yield as a result of some disturbance, can be an important factor in stream stability assessment. Sediment eroded from the land surface can cause silting problems in stream channels resulting in increased flood stage and damage. Conversely, a reduction in sediment supply can also cause adverse impacts to river systems by reducing the supply of incoming sediment, thus promoting channel degradation and headcutting. A radical change in sediment yield as a result of some disturbance, such as a recent fire or long-term land use changes, would suggest that stream instability conditions either already exist, or might readily develop.

Assessment of watershed sediment yield requires understanding the sediment sources in the watershed and the types of erosion that are most prevalent. The physical processes causing erosion can be classified as sheet erosion, rilling, gullying and stream channel erosion. Other types of erosional processes are classified under the category of mass movement, e.g., soil creep, mudflows, landslides, etc. Data from publications and maps produced by the Natural Resources Conservation Service and the USGS can be used along with field observations to evaluate the area of interest.

Quantification of sediment yield is at best an imprecise science. The most useful information is typically obtained not from analysis of absolute magnitude of sediment yield, but rather the relative changes in yield as a result of a given disturbance. One useful approach to evaluating sediment yield from a watershed was developed by the Pacific Southwest Interagency Committee.[(31)] This method, which was designed as an aid for broad planning purposes only, consists of a numerical rating of factors affecting sediment production in a watershed, which then defines ranges of annual sediment yield. The factors are surficial geology, soil climate, runoff, topography, ground cover, land use, upland erosion, and channel erosion and transport.

Other approaches to quantifying sediment yield are based on regression equations, as typified by the Universal Soil Loss Equation (USLE). The USLE is an empirical formula for predicting annual soil loss due to sheet and rill erosion, and is perhaps the most widely recognized method for predicting soil erosion. The USDA Agricultural Handbook 537 provides detailed descriptions of this equation and its terms.[32]

3.6.5 Step 5. Incipient Motion Analysis

An evaluation of relative channel stability can be made by evaluating incipient motion parameters. The definition of incipient motion is based on the critical or threshold conditions where hydrodynamic forces acting on one grain of sediment have reached a value that, if increased even slightly, will move the grain. Under critical conditions, or at the point of incipient motion, the hydrodynamic forces acting on the grain are just balanced by the resisting forces of the particle.

Evaluation of the incipient motion size for various discharge conditions provides insight on channel stability and the magnitude of the flood that might potentially disrupt channel stability. The results of such an analysis are generally more useful for analysis of gravel or cobble-bed systems. When applied to a sand-bed channel, incipient motion results usually indicate that all particles in the bed material are capable of being moved for even very small discharges, a physically realistic result. An equation and techniques for incipient motion analyses are provided in Chapter 6.

3.6.6 Step 6. Evaluate Armoring Potential

The armoring process begins as the non-moving coarser particles segregate from the finer material in transport. The coarser particles are gradually worked down into the bed, where they accumulate in a sublayer. Fine bed material is leached up through this coarse sublayer to augment the material in transport. As sediment movement continues and degradation progresses, an increasing number of non-moving particles accumulate in the sublayer. Eventually, enough coarse particles can accumulate to shield, or "armor" the entire bed surface.

An armor layer sufficient to protect the bed against moderate discharges can be disrupted during high flow, but may be restored as flows diminish. Therefore, as in any hydraulic design, the analysis must be based on a certain design event. If the armor layer is stable for that design event, it is reasonable to conclude that no degradation will occur under design conditions. However, flows exceeding the design event may disrupt the armor layer, resulting in further degradation. While armoring of the bed by the coarser material size fraction can temporarily reduce the rate of degradation and stabilize the stream system, armoring cannot be counted on as a long-term solution.

Potential for development of an armor layer can be assessed using incipient motion analysis and a representative bed-material composition. In this case the representative bed-material composition is that which is typical of the depth of anticipated degradation. For given hydraulic conditions the incipient motion particle size can be computed as referenced above in Step 5. If no sediment of the computed size or larger is present in significant quantities in the bed, armoring will not occur.

The D_{90} or D_{95} size of the representative bed material is frequently found to be the size armoring the channel when degradation is arrested. Armoring is probable when the computed incipient motion size is equal to or smaller than the D_{95} size in the bed material. A simple equation for determining armoring potential is given in Chapter 6.

3.6.7 Step 7. Evaluation of Rating Curve Shifts

When stream gage data are available, such as that collected by the USGS, an analysis of the stage-discharge rating curve over time can provide insight on stream stability. For example, a rating curve that was very stable for many years, but suddenly shifts might indicate a change in watershed conditions causing increased channel erosion or sedimentation, or some other change related to channel stability. Similarly, a rating curve that shifts continually would be a good indicator that channel instability exists. However, it is important to note that not all rating curve shifts are the result of channel instability. Other factors promoting a shift in a rating curve include changes in channel vegetation, ice conditions, or beaver activity.

The most common cause of rating curve shifts in natural channel control sections is generally scour and fill.[(33)] A positive shift in the rating curve results from scour, and the depth, and hence, the discharge are increased for a given stage. Conversely, a negative shift results from fill, and the depth and discharge will be less for a given stage.

Shifts may also be the result of changes in channel width. Channel width may increase due to bank-cutting, or decrease due to undercutting of steep streambanks. In meandering streams, changes in channel width can occur as point bars are created or destroyed.

Analysis of rating curve shifts is typically available from the agency responsible for the stream gage. If such information is not available, field inspection combined with the methods described by Rantz can be utilized to analyze observed rating curve shifts.[(33)] If the shifts can be traced to scour, fill, or channel width changes, such information will be a reliable indicator of potential channel instability.

Gaging stations at which continuous sediment data are collected may also provide clues to the existence of gradation problems. Any changes in the long-term sediment load may indicate lateral movement of the channel, gradation changes, or a change in sediment supply from the watershed.

Where an extended historical record is available, one approach to using gaging station records to determine long-term bed elevation change is to plot the change in stage through time for a selected discharge. This approach is often referred to as establishing a "specific gage" record.

Figure 3.5 shows a plot of specific gage data for a discharge of 14 m^3/sec (500 cfs) from about 1910 to 1980 for Cache Creek in California. Cache Creek has experienced significant gravel mining with records of gravel extraction quantities available since about 1940. When the historical record of cumulative gravel mining is compared to the specific gage plot, the potential impacts are apparent. The specific gage record shows more than 3 m (10 ft) of long-term degradation in a 70-year period.

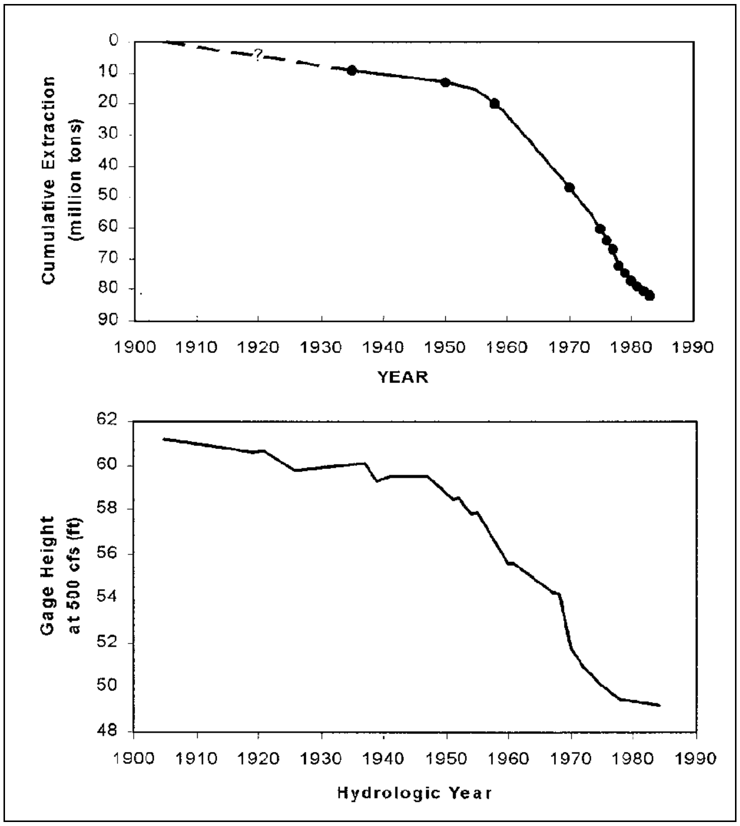


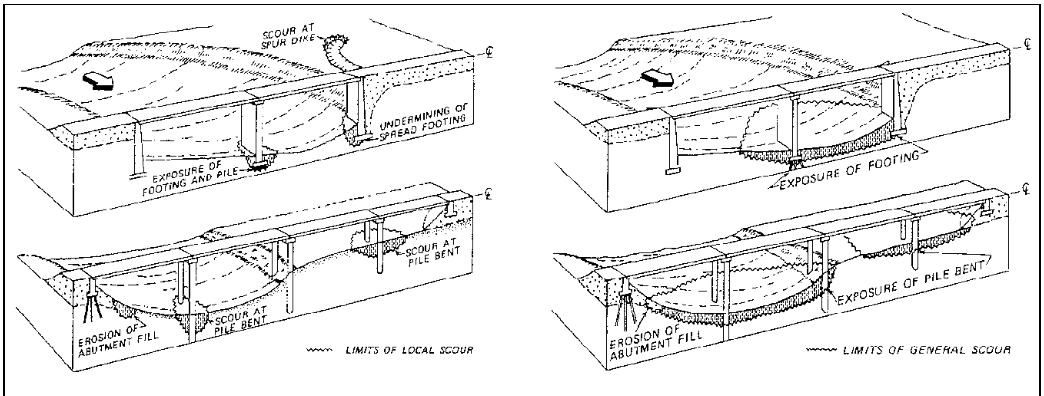
Figure 3.5. Specific gage data for Cache Creek, California.

3.6.8 Step 8. Evaluate Scour Conditions

Section 5.5.1 provides an overview of scour at bridge crossings and HEC-18 provides detailed computational procedures.(1) Figure 3.6 illustrates common scour related problems at bridges. These problems are attributable to the effects of obstructions to the flow (local scour) and contraction of the flow or channel deepening at the outside of a bend. Calculation of the three components of scour, i.e., local scour, contraction scour and aggradation/ degradation, quantifies the potential instability at a bridge crossing. As shown in the comprehensive analysis low chart (Figure 1.1), HEC-18(1) is the primary source for guidance on these issues.

3.7 LEVEL 3: MATHEMATICAL AND PHYSICAL MODEL STUDIES

Detailed evaluation and assessment of stream stability can be accomplished using either mathematical or physical model studies. A mathematical model is simply a quantitative expression of the relevant physical processes involved in stream channel stability. Various types of mathematical models are available for evaluation of sediment transport, depending on the application (watershed or channel analysis) and the level of analysis required. The use of such models can provide detailed information on erosion and sedimentation throughout a study reach, and allows evaluation of a variety of "what-if" questions. HDS 6(13) provides a survey of 1- and 2-dimensional mathematical models available for alluvial river analyses and HEC-18(1) summarizes the capabilities of 1- and 2-dimensional mathematical models for unsteady flow tidal hydraulic analyses.



(a) Obstructions to flow

(b) Contraction of the flow or channel deepening at the outside of a bend.

Figure 3.6. Local scour and contraction scour related hydraulic problems at bridges related to (a) obstructions to the flow or (b) contraction of the flow or channel deepening at the outside of a bend.[10,11]

Similarly, physical model studies completed in a hydraulics laboratory can provide detailed information on flow conditions and to some extent, sediment transport conditions, at a bridge crossing. The hydraulic laws and principles involved in scaling physical models are well defined and understood, allowing accurate extrapolation of model results to prototype conditions. Physical model studies can sometimes provide better information on complex flow conditions than mathematical models, due to the complexity of the process and the limitations of 2- and 3-dimensional mathematical models. Often the use of both physical and mathematical models can provide complementary information (see HDS 6).[13]

The need for detailed information and accuracy available from either mathematical or physical model studies must be balanced by the time and resources available. As the analysis becomes more complicated, accounting for more factors, the level of effort necessary becomes proportionally larger. The decision to proceed with a Level 3 type analysis has historically been made only for high risk locations, extraordinarily complex problems, and for forensic analysis where losses and liability costs are high; however, the importance of stream stability to the safety and integrity of all bridges suggests that Level 3 type analyses should be considered more routinely. The widespread use of personal computers and the continued development of more sophisticated software have greatly facilitated completion of Level 3 type investigations and have reduced the level of effort and cost required.

3.8 ILLUSTRATIVE EXAMPLES

The FHWA manual, "River Engineering for Highway Encroachments," provides a discussion of design considerations for highway encroachment and river crossings in Chapter 9.[13] This discussion includes principal factors for design, procedures for evaluation and design, and conceptual examples. The procedures for evaluation and design of river crossings and encroachments parallel the three-level approach of this chapter. A series of short conceptual discussions in Chapter 9 of HDS 6 illustrate the application of qualitative (Level 1) techniques, and a series of short case studies provide various applications. Finally, Chapter 10 of HDS 6 presents two overview examples which illustrate various steps in the three-level approach.[13]

CHAPTER 4

RECONNAISSANCE, CLASSIFICATION, AND RESPONSE

Level 1 Analysis Procedures

4.1 INTRODUCTION

Identification of the geomorphic factors that can affect stream stability in the bridge reach provides a useful first step in detecting existing or potential channel instability. Consideration of fundamental geomorphic principles can lead to a qualitative prediction, in terms of trends, of the most likely direction of channel response to natural and human-induced change in the watershed and river system. However, more general methods of river classification can also provide insight on potential instability problems common to a given stream type.

A necessary first step in any channel classification or stability analysis is a field site visit. Geomorphologists have developed stream reconnaissance guidelines and specific techniques, including checklists, which will be useful to the highway engineer during a site visit. In addition, a rapid assessment methodology which uses both geomorphic and hydraulic factors can help identify the most likely sources of stability problems in a stream reach. This chapter extends the geomorphic concepts introduced in Chapter 2 to include guidance and checklists for geomorphic reconnaissance, a consideration of stream channel classification concepts, qualitative techniques for evaluating channel response, and reference to rapid assessment methodologies for channel instability and scour. The geomorphic reconnaissance, in particular, provides a systematic approach to gathering the data necessary to apply the quantitative analysis techniques of Chapter 6.

4.2 STREAM RECONNAISSANCE

The design and protection of a structure at a stream crossing requires identification of the cause and extent of channel instability problems. The problems may result from a wide variety of geomorphic processes operating at various scales within the watershed. Some of these processes may be operating locally, others may be active within a given reach, and still others may be associated with the response of the entire fluvial system to changes in rainfall-runoff and sediment yield within the entire basin. Therefore, it is important to understand the relationship of any project site to the stream system and the basin geomorphology, and to see the channel within the project reach as part of an interlinked system with complex feedback mechanisms.

As indicated in Chapter 2, there are numerous geomorphic factors that influence stream stability and, potentially, bridge stability at highway stream crossings. It is important to document these factors and existing conditions not only at the proposed project site, but also within a reasonable distance upstream and downstream of the site as well. Identifying the linkages within a fluvial system, as outlined in the Level 1 and 2 analysis procedures of Chapter 3, involves observation and interpretation of data obtained during a site visit, i.e., through the use of stream reconnaissance. This section presents reconnaissance techniques and checklists to support a field site visit. In addition, a stream reconnaissance offers the best opportunity to evaluate the potential for a watershed and stream system to produce potentially damaging quantities of drift (vegetative debris), which can have a catastrophic impact on bridge stability. Techniques for recognizing the potential for drift accumulations are also presented in this section.

4.2.1 Stream Reconnaissance Techniques

The most comprehensive method of documenting stream and watershed conditions is through the use of a detailed geomorphological stream reconnaissance. Although there have been many methods of stream reconnaissance proposed, they have often been unstructured, primarily qualitative in nature, and have been tailored to the specific needs of the project for which they were being conducted. Thorne (1998) has developed a comprehensive handbook that can be used to document stream channel and watershed conditions.[34]

The purpose of a stream reconnaissance is summarized as follows:[34]

- Supply a methodological basis for field studies of channel form and process.

- Present a format for the collection of qualitative information and quantitative data on the stream system.

- Provide a basis for progressive morphological studies that start with a broadly focused watershed baseline study, continue through a fluvial audit of the channel system, and culminate with a detailed investigation of the geomorphological forms and processes in critical reaches.

- Supply the data and input information to support techniques of geomorphological classification, analysis, and prediction necessary to support sustainable river engineering, conservation, and management.

Thorne's handbook includes stream reconnaissance record sheets and guidelines for a detailed geomorphological stream reconnaissance. Appendix C presents a modified version of the stream reconnaissance sheets that can be used in documenting the stability and conditions of a stream system. The stream reconnaissance record sheets consist of four sections. Section 4 can be used for each bank (left and right) and should be properly identified. The four sections are:

Section 1 – Scope and Purpose.
Section 2 – Region and Valley Description.
Section 3 – Channel Description.
Section 4 – (Left & Right) Bank Survey.

Although the sheets appear complex, they were designed to produce a comprehensive record of the morphology of the stream and its surroundings, and be applicable to a wide range of river types and sizes in diverse settings. With this in mind, one should resist the temptation to omit filling out parts of the sheets for the purposes of expediency or because of perceived irrelevance, since the data may be used for other applications in the future. However, this does not preclude the customization of the sheets to a particular region, basin, or river through the removal of extraneous material rather than the omission of entire topics or sections.

<u>Section 1 – Scope and Purpose</u>. This section (see Appendix C) is used to document the purpose of the study, the nature of any morphology related problems to be addressed, basic logistical information, and the limits of the study area. The reconnaissance trip should have a clearly defined purpose, aims, and objectives. Omission of any sections or topics should be recorded and justified in this section.

Section 2 – Region and Valley Description (Parts 1-5). This section is used: first, to describe the surrounding landscape, establish the nature of the river basin, and define the relationship between the channel and its valley; and, second, to identify any lateral or vertical channel instability problems relative to the valley in terms of trend, severity, and extent. The geological setting, sedimentary characteristics, and land use practices in the basin, valley, and floodplain surrounding the stream channel are documented. Much of this information can be completed in the office through the use of topographic, geologic, and land use maps together with aerial photography or satellite images. In large basins, or where access is limited, an overflight may be necessary. Detailed descriptions of many of the geomorphic features discussed in the following paragraphs can be found in Chapter 2.

In Part 1 (Figure 4.1), the objective is to characterize the landscape surrounding the river valley relative to terrain (topography), drainage pattern, surface geology, rock type, land use, and vegetation. The *terrain*, or topography, defines the amount of energy available to do geomorphic work and the responsiveness of the watershed to stability problems. The planform or *drainage pattern* of the drainage network, which is generally indicative of the underlying geology and topography, is also identified. The eight common types of patterns are shown in Figure 4.2. *Surface geology* and underlying *rock type* directly and indirectly determine erosion resistance and strongly affect sediment yield and delivery. *Land use* strongly influences the runoff hydrograph and has an impact on sediment yields. *Vegetation* also has a significant influence on basin hydrology, affecting both runoff and sediment yield.

PART 1: AREA AROUND RIVER VALLEY

Terrain	Drainage Pattern	Surface Geology	Rock Type	Land Use	Vegetation
Mountains	Dendritic	Bed rock	Sedimentary	Natural	Temperate forest
Uplands	Parallel	Weathered soils	Metamorphic	Managed	Boreal forest
Hills	Trellis	Glacial Moraine	Igneous	Cultivated	Woodland
Plains	Rectangular	Glacio/Fluvial	None	Urban	Savanna
Lowlands	Radial	Fluvial		Suburban	Grassland
	Annular	Lake Deposits	**Specific Rock Types (if known)**		Desert scrub
	Multi-Basin	Wind blown (loess)			Extreme Desert
	Contorted				Tundra or Alpine
					Agricultural land

Figure 4.1. Reconnaissance sheet - area around river valley.

In Part 2 (Figure 4.3), the characteristics of the river valley and valley sides are described. The *location of the river* is defined relative to a valley or some other physiographic setting (the rest of this section may remain uncompleted if the river is not confined between valley walls). *Valley shape* is noted relative to being symmetrical or asymmetrical. The *height* and *side slope angle* of the valley sides define the potential to drive large-scale channel instability through the input of debris or sediment to the fluvial system. *Valley side failures*, their frequency, and *location* may be indicative of large scale, lateral geomorphic activity and possible valley widening, and defines how sediment is delivered to the system. Valley side mass failure mechanisms are shown in Figure 4.4.

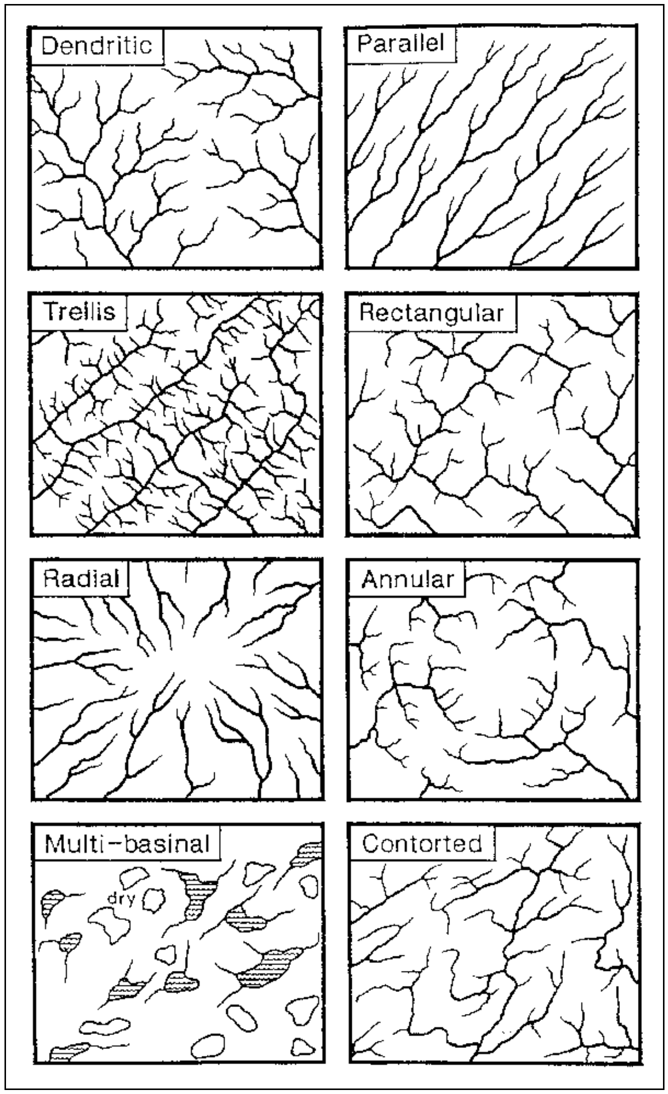


Figure 4.2. Basic drainage patterns (from Howard 1967).[35]

PART 2: RIVER VALLEY AND VALLEY SIDES					
Location of River	Height	Side Slope Angle	Valley Shape	Valley Side Failures	Failure Locations
In Valley	< 5 m	< 5 degrees	Symmetrical	None	None
On Alluvial Fan	5 - 10 m	5-10 degrees	Asymmetrical	Occasional	Away from river
On Alluvial Plain	10 - 30 m	10-20 degrees		Frequent	Along river
IN a Delta	30 - 60 m	20-50 degrees			(Undercut)
In Old Lake Bed	60 - 100 m	> 50 degrees			
	> 100 m		**Failure Type**		(see Figure 4.4)

Figure 4.3. Reconnaissance sheet - river valley and valley sides.

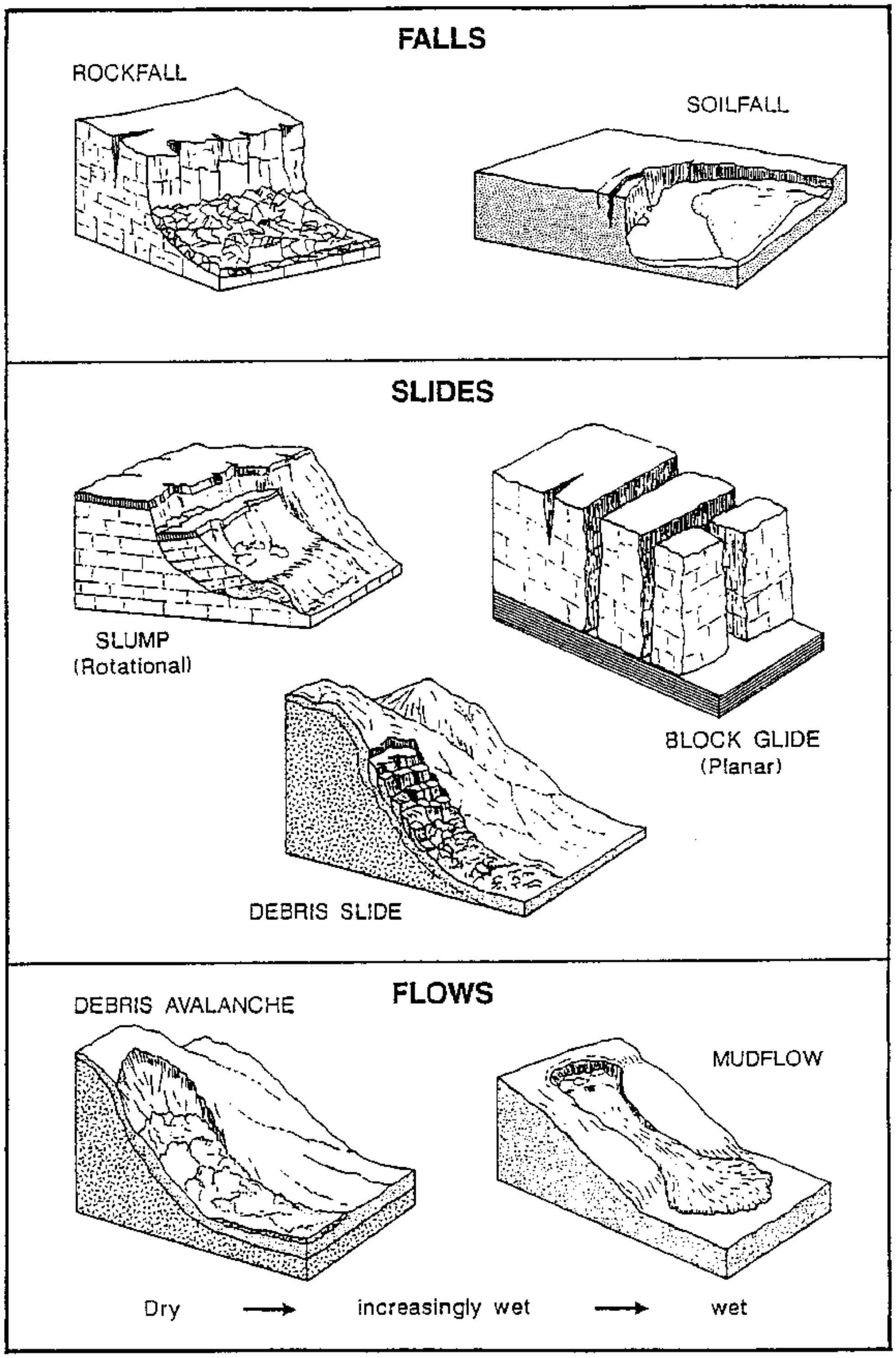


Figure 4.4. Typical valley side mass failure mechanisms (after Varnes 1958).[36]

In Part 3 (Figure 4.5), the valley floor and floodplain (see Figure 2.6) characteristics are documented. *Valley floor type* and *width* define the susceptibility of the stream to destabilization by valley side slope failures relative to runoff and erosion processes operating on the valley side slopes. *Flow resistance* records Manning's "n" values of flow resistance for the left and right overbank areas, which can be used in hydraulic analysis of flow and sediment movement during flooding (see Chapter 5). *Surface geology* defines the composition and, consequently, the resistance to erosion, of the surficial materials making up the valley floor or floodplain. *Land use*, especially urban or industrial development of the floodplain or valley floor, has a considerable effect on the stream system because of the impacts of channelization, bank protection, and flood control works. *Vegetation* is important in terms of floodplain hydrology, overbank hydraulics, and sediment dynamics. Vegetation is also important relative to the potential for drift (vegetative debris), accumulations along the stream and on bridges, as will be discussed later (see Section 4.2.3). In turn, the *riparian buffer strip* and its *width* have a significant influence on natural stream processes, channel stability, and environmental conditions.

PART 3: FLOODPLAIN (VALLEY FLOOR)					
Valley Floor Type	Valley Floor Data	Surface Geology	Land Use	Vegetation	Riparian Buffer Strip
None	None	Bed rock	Natural	None	None
Indefinite	1 river width	Glacial Moraine	Managed	Unimproved Grass	Indefinite
Fragmentary	1-5 river widths	Glacio/Fluvial	Cultivated	Improved Pasture	Fragmentary
Continuous	5-10 river widths	Fluvial: Alluvium	Urban	Orchards	Continuous
	> 10 river widths	Fluvial: Backswamp	Suburban	Arable Crops	**Strip Width**
	Flow Resistance*	Lake Deposits	Industrial	Shrubs	None
Left Overbank Manning n value		Wind Blown (loess)		Deciduous Forest	< 1 river width
Rght Overbank Manning n value __ (*note: n value for channel is recorded in Part 6)				Coniferous Forest	1-5 river widths
				Mixed Forest	> 5 river widths

Figure 4.5. Reconnaissance sheet - floodplain (valley floor).

In Part 4 (Figure 4.6), the present relationship between the stream and its valley is established relative to being aggraded, adjusted, or incised. *Terraces*, which form a stepped appearance in the valley cross-section profile (Figure 4.7), are indicative of past vertical instability. The nature and magnitude of past vertical instability is indicated by the number of terraces which demonstrates the potential for dynamic vertical adjustment of the system through floodplain cut and fill sequences. The presence or absence of *trash lines* in the overbank areas, the vertical locations, and their recurrence relative to frequent versus infrequent events help define whether the channel is aggradational, degradational, or stable.

PART 4: VERTICAL RELATION OF CHANNEL TO VALLEY					
Terraces	**Overbank Deposits**	**Levees**	**Levee Data**	**Levee Description**	**Trash Lines**
None	None	None	Height (m)	None	Absent
Indefinate	Silt	Natural	Side Slope (o)	Indefinite	Present
Fragmentary	Fine sand	Constructed	**Levee Condition**	Fragmentary	Height above
Continuous	Medium sand	**Instability Status**	None	Continuous	floodplain (m)
Number of Terraces ___	Coarse sand	Stable	Intact	Left Bank	
	Gravel	Degrading	Local Failures	Right Bank	
	Boulders	Aggrading	Frequent failures	Both Banks	

Figure 4.6. Reconnaissance sheet - vertical relation of channel to valley.

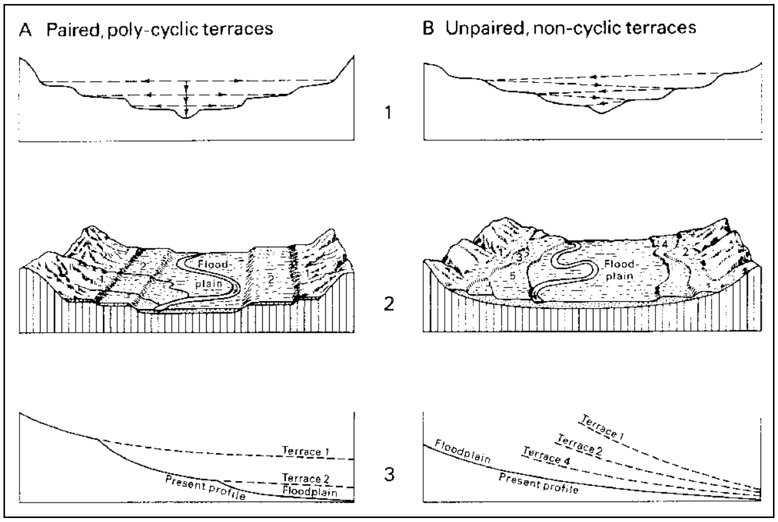


Figure 4.7. Valley cross-sections, plan view, and profiles of (A) paired, polycyclic and (B) unpaired, non-cyclic river terraces (Chorley et al. 1984).[37]

Although vertical floodplain accretion in a dynamically stable system is normal, heavy *overbank deposits* (sedimentation) may be indicative of an aggrading system. *Levees* and *levee descriptions* deal with natural and artificial levees that are present along a channel as a result of overbank flooding. Natural levees, which form by overbank sedimentation during flooding, may become prominent if the stream is carrying a heavy sediment load and has a high frequency of overbank flooding. Artificial levees are constructed in areas where flooding is unacceptable. *Levee data* and *levee condition* record the height, side slope angle, and stability of existing levees. The instability status defines whether vertical instability in the system is ongoing or has ceased.

In Part 5 (Figure 4.8), the present relationship between the stream and its valley is established relative to lateral stability or channel migration, and fluvial landforms indicative of lateral instability. *Planform* represents the geometry of the channel as viewed from above and can be classified based on a simple classification scheme shown in Figure 4.9 (see Chapter 2 and Section 4.3 for additional discussion). It should be noted that in reality there is a continuum of river patterns. *Planform data* as shown in Figure 4.10 is recorded on the characteristic dimensions of a typical meander. *Lateral activity* and resultant *floodplain features* as shown in Figure 4.11 are recorded for the current type of planform evolution.

PART 5: LATERAL RELATION OF CHANNEL TO VALLEY

Planform		Planform Data		Lateral Activity		Floodplain Features	
Straight		Bend Radius		None		None	
Sinuous		Meander belt width		Meander progression		Meander scars	
Irregular		Wavelength		Increasing amplitude		Scroll bars+sloughs	
Regular meanders		Meander Sinuosity		Progression+cutoffs		Oxbow lakes	
Irregular meanders		**Location in Valley**		Irregular erosion		Irregular terrain	
Tortuous meanders		Left		Avulsion		Abandoned channel	
Braided		Middle		Brading		Braided deposits	
Anastomosed		Right					

Figure 4.8. Reconnaissance sheet - lateral relation of channel to valley.

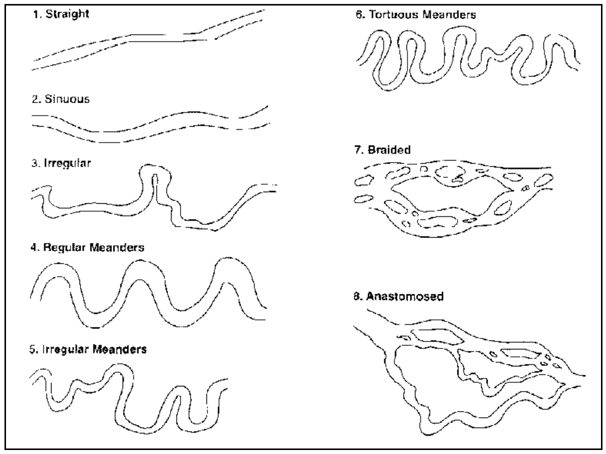


Figure 4.9. Guide to classification of river channel planform pattern.[34]

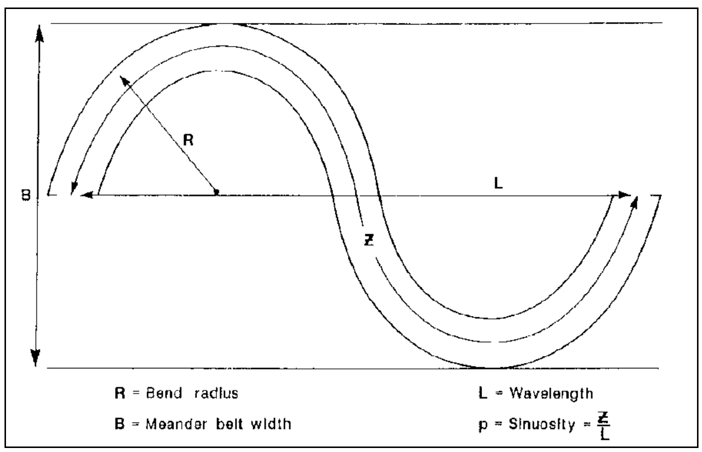


Figure 4.10. Definition of meander planform parameters.[34]

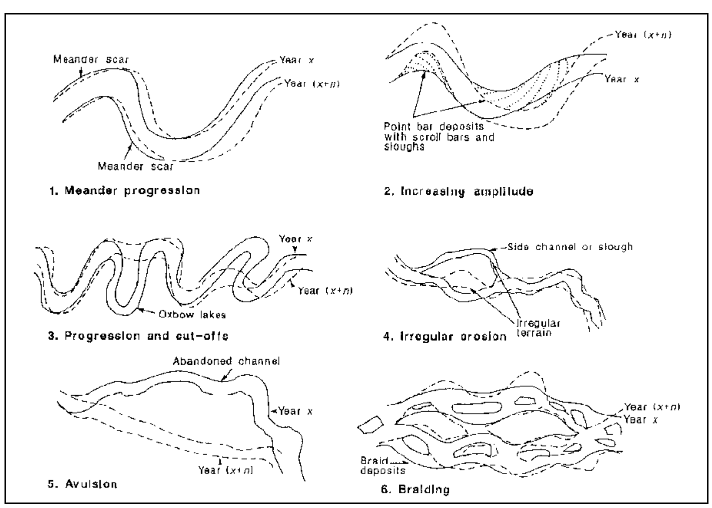


Figure 4.11. Types of lateral activity and typical associated floodplain features.[34]

Section 3 – Channel Description (Parts 6 and 7). General channel dimensions, flow type, geological and artificial controls on vertical and lateral movement, bed sediment characteristics, and the presence of sedimentary forms and features within the channel are documented in this section.

In Part 6 (Figure 4.12), the channel is characterized relative to dimensions, flow regime, and possible controls on bed scour and bank retreat. This information can be used to describe and define the channel hydraulics, boundary conditions, and potential instability. *Dimension* measurements need not be detailed or precise but should be representative of the channel in the study reach and based on a reach-average of several measurements. Estimates of Manning's "n" and mean velocity may be somewhat subjective.

Flow type describes the flow regime based on the principles of free surface flow. Uniform/tranquil flow is fully turbulent, sub-critical with approximately uniform flow velocity. Uniform/shooting flow is super-critical flow with uniform flow velocity. Pools and riffles are alternating deeps and shallows with slower, flatter and faster, steeper flow, respectively. Tumbling flow represents high gradient streams ($\geq$ 1%) with coarse bed material that disrupts the water surface creating locally super-critical flow. Step/pool flow occurs in very steep gradient channels (>10%) with boulder steps and plunge pools. *Bed and width controls* and *types* define the nature and extent of any bed and bank controls that limit vertical incision or lateral migration and/or widening due to local geology, bed, bank, and floodplain materials (including clay plugs and backswamp deposits), large woody debris jams, or engineered structures.

PART 6: CHANNEL DESCRIPTION

Dimensions	Flow Type	Bed Controls	Control Types	Width Controls	Control Types
Av. top bank width (m) ____	None	None	None	None	None
Av. channel depth (m) ____	Uniform/Tranquil	Occasional	Solid bedrock	Occasional	Bedrock
Av. water width (m) ____	Uniform/Rapid	Frequent	Weathered bedrock	Frequent	Boulders
Av. water depth (m) ____	Pool+Riffle	Confined	Boulders	Confined	Gravel armor
Reach slope ____	Steep+Tumbling	Number of controls ____	Gravel armor	Number of controls ____	Revetment
Mean velocity (m/s) ____	Steep+Steppool		Cohesive materials		Cohesive materials
Manning's n value ____	(Note: Flow type on day of observation)		Bridge protection		Bridge abutments
			Grade control structures		Dikes or groins

Figure 4.12. Reconnaissance sheet - channel description.

In Part 7 (Figure 4.13), the morphology of the bed and bar sediments are characterized in order to estimate the bed material mobility, transport rate, and to gauge the potential for bed instability. *Bed material* is characterized qualitatively based on the predominant sediment size. *Bed armor* is coarse surface sediment that is identified as either static or mobile. Static armor (pavement) is immobile under all but catastrophic flood flow conditions. Mobile armor is mobilized during events of moderate magnitude and recurrence. *Sediment depth* in the channel defines the amount of sediment available for transport and can be indicative of vertical instability. *Bedforms* record form roughness elements on the channel bed and islands or bars record macro bed features and divided flow. *Bar types* define the shape of bars within the channel (Figure 4.14). *Bed and bar surface* and *substrate* (below any armor layer) data represent quantitative data based on sieve-by-weight (bulk sample) or size-by-number (pebble count sample) of sediment samples taken at representative bed or bar locations. *Channel sketch map* and *representative cross-section* are visual representations of the plan view and profile of the channel that includes all pertinent features of the channel and floodplain and all survey and sampling sites (see Appendix C). *Photography* of important features can be an important tool. Location and orientation of photos should also be noted.

PART 7: BED SEDIMENT DESCRIPTION					
Bed Material	Bed Armour	Surface Size Data	Bed Forms (Sand)	Bar Types	Bar Surface Data
Clay	None	D50 (mm)	Flat bed (none)	None	D50 (mm)
Silt	Static-armour	D84 (mm)	Ripples	Pools and riffles	D84 (mm)
Sand	Mobile-armour	D16 (mm)	Dunes	Alternate bars	D16 (mm)
Sand and gravel			Bed form height (m)	Point bars	
Gravel and cobbles	**Sediment Depth**	**Substrate Size Data**	**Island or Bars**	Mid-channel bars	**Bar Substrate Data**
Cobbles + boulders	Depth of loose	D50 (mm)	None	Diagonal bars	D50 (mm)
Boulders + bedrock	sediment (cm)	D84 (mm)	Occasional	Junction bars	D84 (mm)
Bedrock		D16 (mm)	Frequent	Sandwaves + dunes	D16 (mm)

Figure 4.13. Reconnaissance sheet - bed sediment description.

Section 4 – (Left and Right) Bank Survey (Parts 8-12). The morphology of the banks is documented in detail and includes the geometry, sedimentary characteristics, vegetation, erosional processes, geotechnical failure mechanisms, and the extent of toe sediment buildup. A comprehensive and detailed evaluation of the banks and their dynamics is at the heart of the reconnaissance. It is the basis for planform evolution and bankline migration, and supplies information in support of the selection of appropriate approaches to modeling bank processes and appropriate bank management strategies.

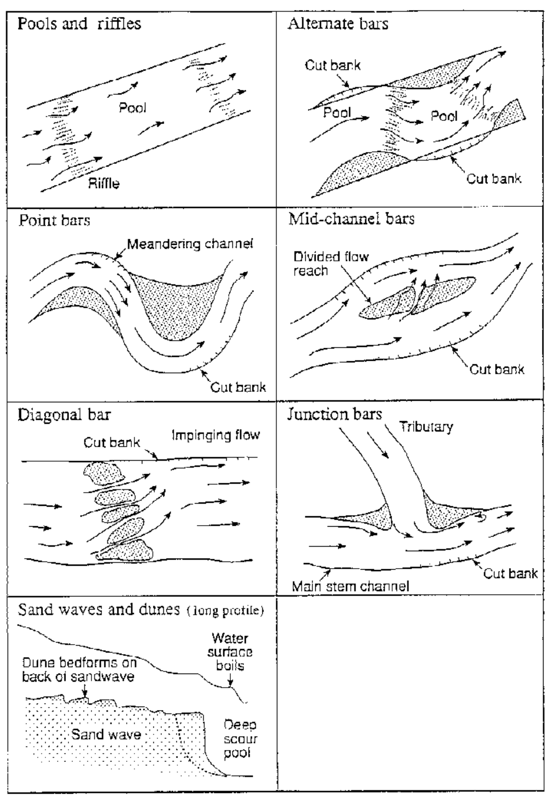


Figure 4.14. Channel bar classification and bedforms.[34]

In Part 8 (Figure 4.15), the bank characteristics are described in detail relative to type, materials, countermeasures, dimensions, shape, and degree of cracking. *Type* classifies the bank based on being composed of non-cohesive, cohesive, composite, or layered bank materials. *Protection status* records the presence or absence and type of bank protection. *Bank materials* define the composition of the bank including any major stratigraphic layering and the thickness of stratigraphic layers within the bank are recorded. The material composition and location of the stratigraphic horizons are defined under the *distribution and description* of bank materials topic. *Average bank height* and *slope* record overall representative height and steepness of the bank. *Bank profile shape* defines the form of the bank profile as shown in Figure 4.16. *Tension cracks*, indicative of inevitable failure, may be present along the top of the bank and their depth is recorded.

PART 8: LEFT (OR RIGHT) BANK CHARACTERISTICS

Type	Bank Materials	Layer Tghickness	Average Bank Height	Bank Profile Shape	Tension Cracks
Noncohesive	Silt/clay	Material 1 (m)	Average height (m)	(Figure 4.16)	None
Cohesive	Sand/silt/clay	Material 2 (m)			Occasional
Composite	Sand/silt	Material 3 (m)	**Average Bank Slope**		Frequent
Layered	Sand	Material 4 (m)	angle (degrees)		**Crack Depth**
Even Layers	Sand/gravel				Proportion of
Thick+thin layers	Gravel	**Distribution and Description of Bank Materials in Bank Profile**			bank height
Number of layers	Gravel/cobbles	**Material Type 1**	**Material Type 2**	**Material Type 3**	**Material Type 4**
Protection Status	Cobbles	Toe	Toe	Toe	Toe
Unprotected	Cobbles/boulders	Mid-bank	Mid-bank	Mid-bank	Mid-bank
Hard points	Boulders/bedrock	Upper bank	Upper bank	Upper bank	Upper bank
Toe protection		Whole bank	Whole bank	Whole bank	Whole bank
Revetments		D50 (mm)	D50 (mm)	D50 (mm)	D50 (mm)
Dykefields		Sorting coefficient	Sorting coefficient	Sorting coefficient	Sorting coefficient

Figure 4.15. Reconnaissance sheet - left (or right) bank characteristics.

In Part 9 (Figure 4.17), vegetation characteristics along the bank face are described because of the effects on bank morphology, erodibility, and stability. The general types of *vegetation* along the bank face and the orientation of their trunks (vertical or degree of leaning) relative to the bank and channel are described. Depth of rooting, which affects bank cohesiveness, and susceptibility to environmental hazards, which can affect bank stability, are indicated by the *types* and *species* of trees present along the bank. *Density + spacing* define the degree of vegetative cover and, consequently, indicates the amount of erosion protection afforded by the vegetation. Exposed or adventitious *roots* define the relationship with the bank surface relative to aggradation, degradation, or erosion. The location of vegetation on the bank also affects the stability of the bank. *Diversity, health, age, height*, and *lateral extent* of vegetation all affect bank stability and can be indicators of past channel instability. The profile of the bank, important details on bank morphology and vegetation characteristics, and any photographic documentation are recorded in the *bank profile sketch* (see Appendix C).

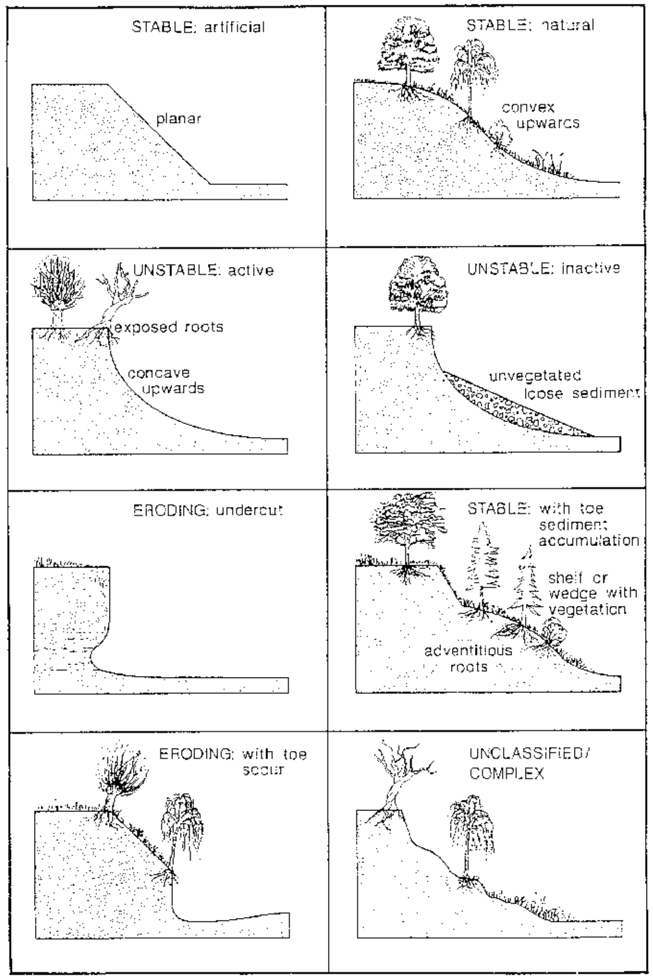


Figure 4.16. Classification and morphology of typical bank profiles.[34]

PART 9: LEFT (OR RIGHT) BANK-FACE VEGETATION					
Vegetation	Tree Types	Density + Spacing	Location	Health	Height
None/fallow	None	None	Whole bank	Healthy	Short
Artificially cleared	Deciduous	Sparse/clumps	Upper bank	Fair	Medium
Grass and flora	Coniferous	Dense/clumps	Mid-bank	Poor	Tall
Reeds and sedges	Mixed	Sparce/continuous	Lower bank	Dead	Height (m)
Shrubs	**Tree Species**	Dense/continuous			
Saplings	(if known)	**Roots**	**Diversity**	**Age**	**Lateral Extent**
Trees		Normal	Mono-stand	Imature	Wide belt
Orientation		Exposed	Mixed stand	Mature	Narrow belt
Angle of leaning (0)		Adventitious	Climax-vegetation	Old	Single row

Figure 4.17. Reconnaissance sheet - left (or right) bank vegetation.

In Part 10 (Figure 4.18), details pertinent to a good understanding of the erosional processes and their distribution along the bank are recorded. The *erosion location* is documented relative to major channel features. The *present status* and *rate* of active or inactive bank erosion (retreat) or advancement (accretion) is also documented where possible. The *processes* responsible for bank erosion and the distribution of the different processes that may be operating on different parts of the bank are identified. Parallel or impinging flow erosion results in detachment and removal of intact grains or aggregates of grains from the bank face by flow that is either parallel or oblique to the long-stream direction. Piping is caused by seepage of groundwater (sapping) from the bank face, especially in high banks, and detaches and entrains grains from the bank. Freeze/thaw processes can remove individual grains to blocks of bank material from the bank or weakens the bank by destroying bank cohesion, increasing its susceptibility to erosion. Sheet erosion removes surface material by non-channelized surface runoff over the bank edge and down the bank face. Rills and gullies form when sufficient uncontrolled surface runoff forms small channels. Wind and vessels cause erosion of the bank through the generation of waves, which increase near-bank velocities and shear stresses, detaches and erodes bank particles, and causes dramatic fluctuations in bank pore water pressures through rapid fluctuations in water level. Ice rafting can mechanically damage the bank making it susceptible to erosion. Other types of erosion processes include trampling by animals and man or by off-road vehicles. Where different erosion processes are operating on different parts of the bank, they should be identified and recorded.

PART 10: LEFT (OR RIGHT) BANK EROSION

Erosion Location				Present Status		Rate of Retrreat	Dominant Process			
General		Opposite a structure		Intact		m/yr (if applicable	Parallel flow		Rilling + gullying	
Outside meander		Adjacent to structure		Eroding: dormant		and known) ___	Impinging flow		Wind waves	
Inside meander		D/S of structure		Eroding: active			Piping		Vessel forces	
Opposite a bar		U/S of structure		Advancing: dormant		**Rate of Advance**	Freeze/thaw		Ice rafting	
Behind a bar		Other (write in)		Advancing: active		m/yr (if applicable	Sheet erosion		Other (write in)	
						and known) ___				

Figure 4.18. Reconnaissance sheet - left (or right) bank erosion.

In Part 11 (Figure 4.19), the geotechnical characteristics of bank failures are identified and recorded. Failures may or may not coincide with bank erosion, so the *location* is identified relative to major channel features and the stability *status* of the bank is classified. Failure scars and blocks are prominent features of bank failure and their presence and appearance should be noted. The *failure mode* identifies the type of failure resulting from bank instability and is dependent on bank material composition as described in Chapter 2 and Appendix B. The distribution on the bank of all modes of failure are identified and recorded. A brief description of each of the major failure modes follows:

<u>Soil/rock fall</u> – failure of grains, grain assemblages, or blocks from often undercut, steep, eroding banks with little cohesion.

<u>Shallow slide</u> – is a shallow-seated failure in bank material with little cohesion that occurs along a plane parallel to the ground surface.

<u>Rotational slip</u> – is a deep-seated mass failure in cohesive material that occurs along a curved surface leaving an arcuate scar in the bank and back-tilting toward the bank of the failed mass.

Slab-type block – is a failure in cohesive material formed from sliding and forward toppling of a deep-seated mass into the channel. Tension cracks are often present in the bank.

Cantilever failure – forms in composite and layered banks where undermining of a less cohesive lower layer causes the collapse of the resultant overhanging block of cohesive material into the channel.

Pop-out failure – is formed by a piece of the lower bank falling out as a result of saturation and seepage flow in the lower part of a steep, cohesive bank.

Piping failure – forms when part of the bank collapses as a result of high groundwater seepage pressures and rates of flow.

Dry granular flow – also known as dry ravel and soil avalanches, is a flow-type failure of non-cohesive, dry, granular bank material in an oversteepened bank.

Wet earth flow – is a viscous failure of the bank due to the increased weight of the bank and the loss of cohesion resulting from saturation.

PART 11: LEFT (OR RIGHT) BANK GEOTECH FAILURES					
Failure Location		Present Status	Failure Scars + Blocks	Apparent Failure Mode	
General	Opposite a structure	Stable	None	Soil/rock fall	Pop-out failure
Outside meander	Adjacent to structure	Unreliable	Old	Shallow slide	Piping failure
Inside meander	D/S of structure	Unstable: dormant	Recent	Rotational slip	Dry granular flow
Opposite a bar	U/S of structure	Unstable: active	Fresh	Slab-type block	Wet earth flow
Behind a bar	Other (write in)		Contemporary	Cantilever failure	Other (write in)

Figure 4.19. Reconnaissance sheet - left (or right) bank geotechnical failures.

In Part 12 (Figure 4.20), the supply of toe sediment and the degree of removal or accumulation are evaluated relative to basal endpoint control and stability of the bank (see Appendix B). *Stored bank debris* records the presence of material derived from erosion or failure of the bank that is stored along the toe of the bank. *Vegetation* is classified since it can accelerate the accumulation of sediment along the bank toe. *Age* relates to the maturity of the accumulated sediment based on the maturity of vegetation established on the deposit. *Tree species* and *health* provide information on physiology, growth patterns, biomass, and physiography relative to the toe deposit maturity and stability. As noted previously, roots define whether a channel and the toe deposits are undergoing aggradation, degradation or are stable. *Existing debris storage* is an estimate of the total volume of the bank-derived debris that has accumulated at the bank toe.

Stream reconnaissance and the record sheets should not be used as a substitute for conventional hydrographic, hydraulic, and geotechnical site surveys, but rather, should precede and complement such surveys.

PART 12: LEFT (OR RIGHT) BANK TOE SEDIMENT ACCUMULATION					
Stored Bank Debris	Vegetation	Age	Health		Existing Debris Storage
None	None/fallow	Immature	Healthy		No bank debris
Individual grains	Artifically cleared	Mature	Unhealthy		Little bank debris
Aggregates+crumbs	Grass and flora	Old	Dead		Some bank debris
Root-bound clumps	Reeds and sedges	Age in Years			Lots of bank debris
Small soil blocks	Shrubs		**Tree Species**	**Roots**	
Medium soil blocks	Saplings		(if known)	Normal	
Large soil blocks	Trees			Adventitious	
Cobbles/boulders				Exposed	
Boulders					

Figure 4.20. Reconnaissance sheet - left (or right) bank toe sediment accumulation.

4.2.2 Specific Applications

The geomorphological stream reconnaissance sheets[34] serve different purposes and have a wide variety of applications. Some of those applications include:

Field Identification of Channel Instability Near Structures – With regard to bridges and other highway related structures in the stream environment, the stream reconnaissance sheets can be used to ensure that rapid and accurate assessments of stream channel stability are conducted by the engineers most concerned with inspection and maintenance of these structures (see Section 4.5 and Appendix D).

Stream Classification – The qualitative and quantitative information gathered on the stream reconnaissance sheets can be applied to almost any existing stream classification system (see Section 4.3) including those of Brice,[38] Schumm,[39] Rosgen,[40,41] and Figure 2.6 in Chapter 2.

Engineering-Geomorphic Analysis of Streams – The broader spatial scale and scope of the stream reconnaissance provides a basis for subsequent quantitative work, thereby increasing the efficiency and utility of future hydraulic and sediment transport studies (see applications in Chapter 6).

Supplying Input to Stable Channel Design Techniques – Compilation of selective qualitative and semi-quantitative data through the use of the sheets is necessary to characterizing existing channels, identifying flow and sediment processes, and estimating the severity of any flow or sediment-related problems. These are important steps in pre-feasibility and feasibility studies prior to the design of bridges, channel stabilization, and other engineering works (see Chapters 6 and 7).

Assessment, Modeling, and Control of Bank Retreat – Because conventional geotechnical engineering analyses of bank stability are site-specific and require a detailed site investigation, the data gathered on the stream reconnaissance sheets can be used in engineering-geomorphic bank erosion and stability analyses developed for reach-scale, and possibly system-wide, assessments (see Appendix B).

As a Training Aid – The sheets can be used to train staff inexperienced in field methods and techniques.

To Establish a Permanent Record of Stream Condition – The record sheets provide a medium that permanently documents the results of a stream reconnaissance trip and can provide the input for an expert system or GIS database.

4.2.3 Assessment of Potential Drift Accumulations

Accumulations of large woody debris, primarily floating debris (drift), can cause increased backwater, increased local scour at bridge piers and abutments, increased lateral forces on bridges, and promote bed and bank scour. The results of detailed studies by Diehl and Bryan[(42)] and Diehl[(43)] throughout the United States revealed several conclusions about drift accumulation. The potential for drift accumulation depends on channel, bridge, and basin characteristics. Drift that accumulates at bridges comes primarily from trees undermined by bank erosion. Rivers with unstable channels have the most bank erosion and the most drift. In addition, abundant drift in the channel can aggravate channel instability. Most drift floats along the thread of the stream where flow is deepest and fastest. Logs longer than the channel width accumulate in jams, or are broken into shorter pieces. Drift piles up against obstacles such as bridge piers that divide the flow at the water surface. Drift is trapped most effectively by groups of obstacles separated by narrow gaps that are narrower than the longest logs within the drift accumulation. Accumulations of drift begin at the water surface, but may grow downward toward the streambed through accretion.

Most published information regarding drift is anecdotal and qualitative. In addition, current design guidelines treat drift as a threat to bridges, but do not include methods for estimating the size and likelihood of drift accumulations. Although an interim procedure for estimating pier scour associated with drift is proposed in HEC-18 Appendix D,[(1)] it also is subjective, relying on engineering judgment and experience.

A detailed study conducted by the U.S. Geological Survey, in cooperation with the Federal Highway Administration, provides guidelines for the assessment of drift potential in the form of a detailed drift-assessment method. The following paragraphs describe the drift assessment method and guidelines for the assessment of drift potential as proposed by Diehl.[(43)] The use of these guidelines requires engineering judgment tempered by regional experience with drift problems.

There are three major phases to assessing the potential for drift accumulation at a bridge, which can be further subdivided into eight tasks (Table 4.1). The first two phases and related tasks are discussed below. The third phase, as proposed by Diehl,[(43)] will not be discussed here since they provide only a qualitative methodology for estimating the potential amount of accumulation of drift at a site. Much of this information and data can be collected as part of the evaluation of vegetation in Parts 1, 3, 9, and 12 of the Stream Reconnaissance Record Sheets (Appendix C).

Potential for drift delivery. In the first phase, the potential for a river to deliver drift is evaluated based on the potential for woody debris to be introduced into the channel and for drift to be transported downstream to the bridge site. Although observations of drift provide the most direct evidence of the potential for drift delivery, a lack of drift at a particular site does not indicate a low potential of drift delivery, since infrequent catastrophic events or changes in basin and channel stability may provide abundant drift in the future.

Table 4.1. Major Phases and Tasks in Evaluating Potential for Drift Accumulation at a Bridge.[43]	
Major Phase	Tasks
1. Estimate potential for drift delivery	a. Estimate potential for drift delivery to the site b. Estimate size of largest drift delivered c. Assign location categories to all parts of the bridge crossing
2. Estimate drift potential on individual bridge elements	a Assign bridge characteristics to all immersed parts of the bridge b. Determine accumulation potential for each part of the bridge
3. Calculate hypothetical accumulations for the entire bridge	a. Calculate hypothetical accumulation of medium potential b. Calculate hypothetical accumulation of high potential c. Calculate hypothetical chronic accumulation

Direct evidence for high delivery potential includes the following observations:

- Multiple cases of drift accumulation at bridges.
- Chronic drift accumulation at one or more sites.
- Drift accumulation at sites where potential for drift accumulation would be low if drift were not abundant.
- Abundant drift in the channel.
- Past need for drift removal in the channel system.

Direct evidence of low potential for drift delivery may be indicated by:

- Negligible drift delivered during major events, especially at sites with high trapping potential or at typical drift-accumulation sites.
- All drift accumulates in the forested channel upstream.
- The drift in the channel is stationary during floods as a result of low flow velocity.

Potential for drift generation. Evidence of existing or potential bank erosion can be considered indirect evidence of potential drift generation. Indirect evidence includes the following observations:

- Widespread bank erosion upstream.
- History of changes in the upstream channel system, including degradation, active lateral migration, widening, channelization, changes in drainage, or dams.
- Prospects of changes in the channel system.
- Hydraulic and geomorphic factors indicative of stream instability as described by Diehl.

- Widespread timber harvesting in the basin.

- History or prospect of marked changes in basin land use.

Observations of indirect evidence for low drift generation potential includes:

- The inability of woody vegetation to grow along the channel system and on steep slopes leading down to stream channels.

- The channel system is stable and is unlikely to undergo any significant change.

The potential delivery of drift will be controlled by the ability of the stream to transport it where indirect evidence indicates that the rate of drift generation is high or could become high. One should assume that a given stream can transport drift unless there is evidence to the contrary. Stable, densely forested streams transport little drift and can be assumed to have a low delivery potential as long as the forest has not been cleared.

Channel dimensions, particularly width, upstream from a site can influence the size of drift that can be transported and, consequently, the potential size of accumulations. Possible changes in channel dimensions associated with potential future stream instability should be accounted for when estimating channel dimensions. The channel depth required to float logs is estimated to be the diameter of the butt plus the distance the root mass extends below the butt, or roughly 3 to 5 percent of the estimated log length. The maximum log length is estimated on the basis of the narrowest channel width immediately upstream from a site, which is measured perpendicular to the banks or lines of permanent vegetation at inflection points between bends. Diehl recommends estimating log length at a given site as the smallest of three values:(43)

Width of the channel upstream from the site.

- Maximum length of sturdy logs, which is roughly defined by the height of mature trees on the banks.

- In much of the United States, 9 m (30 ft) plus one quarter of the width of the channel upstream from the site.

<u>Drift delivery locations at a site.</u> Drift delivery at a highway crossing is localized and the location of accumulations can vary among piers and spans. Therefore, the potential for drift delivery should be evaluated at each pier and span. In general, floating material is transported along a relatively narrow drift path defined by secondary circulation currents converging at the surface within the channel. Piers located in this position are the most common sites of accumulation. The drift path typically coincides with the thread (thalweg) or center of the channel in straight reaches. The middle of the drift path generally lies between the thalweg and the outer bank in curved reaches. The drift path should be evaluated relative to flooding since it may not remain within the confines of the channel of meandering streams during out of bank flooding.

The potential for drift accumulation can also be strongly influenced by bridge characteristics. The width of horizontal opening and elevation of vertical openings between fixed elements of a bridge opening affects potential drift accumulation. Pieces of drift in the longest size fraction delivered to a site may come in contact with a bridge element, rotate downstream, and become lodged against another element, thereby trapping other debris. Skew also reduces the effective width of horizontal openings and increases the potential for debris trapping. Since most drift is transported at the surface, drift can become trapped between the bridge superstructure and the streambed when the water level is at or above the bottom of the superstructure. Drift can accumulate along or below the superstructure or may become lodged between the superstructure and streambed if they rotate vertically.

Narrow openings of structural elements of the bridge at the water surface also determine whether drift is deflected or trapped. Multiple closely spaced pier or pile groups, closely spaced rows of piers, or exposed pier footing piles are examples of narrow flow-carrying openings that can trap and accumulate drift. Where a pile bent or a pier composed of a single row of columns is skewed to the flow, either during normal or flood flows, debris can become trapped and accumulate within the narrow intervening apertures. Existing drift accumulations will also trap additional drift. The bridge superstructure or other bridge elements with flow-carrying openings or protrusions at or below the water surface can also accumulate drift if flood stages are sufficient. Freeboard (the distance between the water surface and elevation of the lowest element of the superstructure) should be large enough to pass the largest expected tree root ball.

There is considerable direct and indirect evidence of drift generation that can be collected and used to evaluate the potential for drift accumulation at a site. Most of this information can be collected as part of a stream reconnaissance. Diehl provides a methodology, including flow charts, to further estimate the potential for drift accumulation.(43) A comparable qualitative estimate can be made during a field reconnaissance or by bridge maintenance personnel with an intimate knowledge of the site.

4.3 STREAM CHANNEL CLASSIFICATION

4.3.1 Overview

Channel classification systems provide engineers with useful information on typical characteristics associated with a given river type and establish a common language as a basis for communication. Classification requires identifying a range of geomorphological channel types that minimizes variability within them and maximizes variability between them.(44) Given the complexity of natural systems, inevitably some information is sacrificed in the attempt to simplify a continuum of channel geomorphic characteristics into discrete intervals for classification. However, enough useful information can result from stream channel classification to make the effort worthwhile.

Although classifications are initially useful for clarity of communication and as an index of the numerous types of channels that exist, it is the characteristics of an individual channel that are important in defining channel processes and response. Classification systems, alone, are of little value for deriving process significance or predicting channel response (see for example, Miller and Ritter 1996).(45) From a practical perspective, measurements of sinuosity, width-depth ratio, gradient, dimensions (width, depth), and sediment type (bed and bank) when combined with measurements or calculation of discharge, flow velocity and stream power will provide the information necessary for the understanding of a river and the knowledge required to evaluate stability and predict future change. When such quantitative information about a river is available, classifications are only the first step in evaluating channel stability and predicting channel change (Figures 1.1 and 3.1).

The most basic form of river classification uses channel pattern or planform to define three river types: straight, meandering, or braided. The discussion of geomorphic factors that affect stream stability in Chapter 2 uses this simple classification (Figure 2.6), and the "typical" planform characteristics of each stream type are discussed in Sections 2.3.10 and 2.3.11. Section 4.4.2 (see for example, Figure 4.27) illustrates how the definitions of a simple classification can be extended with empirical data to provide reasonably definitive conclusions regarding stream type. Other approaches to channel classification use independent variables, such as discharge and sediment load to determine stream type.

4.3.2 Channel Classification Concepts

As noted, rivers are often categorized as either straight, meandering, or braided. These categories identify the three major alluvial river types. An alluvial river is one that is flowing in a channel that has bed and banks composed of sediment transported by the river. That is, the channel is not confined by bedrock or terraces, but it is flanked by a floodplain. In addition to these three basic river "types," there are also anabranching alluvial rivers and rivers that are termed wandering. Brice[(38)] illustrates the range of channel types for meandering, braided, and anabranching channels (see Figure 4.21, which expands the simpler classification of Figure 2.6).

Figure 4.21 shows the difference between low sinuosity, straight channels and meandering channels, as well as the difference between bar-braided and island-braided channels. It also demonstrates that the braided river occupies one channel whereas the anabranching channel has multiple channels separated by a vegetated floodplain.

The majority of the work on rivers has been concentrated on alluvial rivers. In order to develop a broader understanding of these rivers it is necessary to relate them to the independent variables that control channel size and morphology (shape, pattern, gradient). Channel size is clearly related to the volume of water conveyed by the channel. On average, channel width increases downstream as the square root of discharge[(46)], and gradient decreases downstream as discharge increases. Assuming a graded stream, one that is neither progressively aggrading or degrading, the type of sediment transported by the river has a major influence on channel shape, pattern, and gradient. Table 4.2 summarizes a classification of alluvial channels based on the relative proportions of sand and silt-clay transported by a stream. Based on studies of rivers on the great plains of the U.S.A. and the riverine plain of Australia, it was determined that suspended-load streams that transported very little bedload were narrow, deep, gentle, and sinuous whereas bed-load streams were wide, shallow, steep, and relatively straight. This classification related channel characteristics to type of sediment load. During experimental studies it was further determined that valley gradient exerted a major influence on channel patterns.

Figure 3.2 in Chapter 3 suggests that the range of channels from straight through braided forms a continuum, but experimental work and field studies have indicated that within the continuum, river-pattern thresholds can be identified where the pattern changes between straight, meandering, and braided. The pattern changes take place at critical values of stream power, gradient, and sediment load.[(47)]

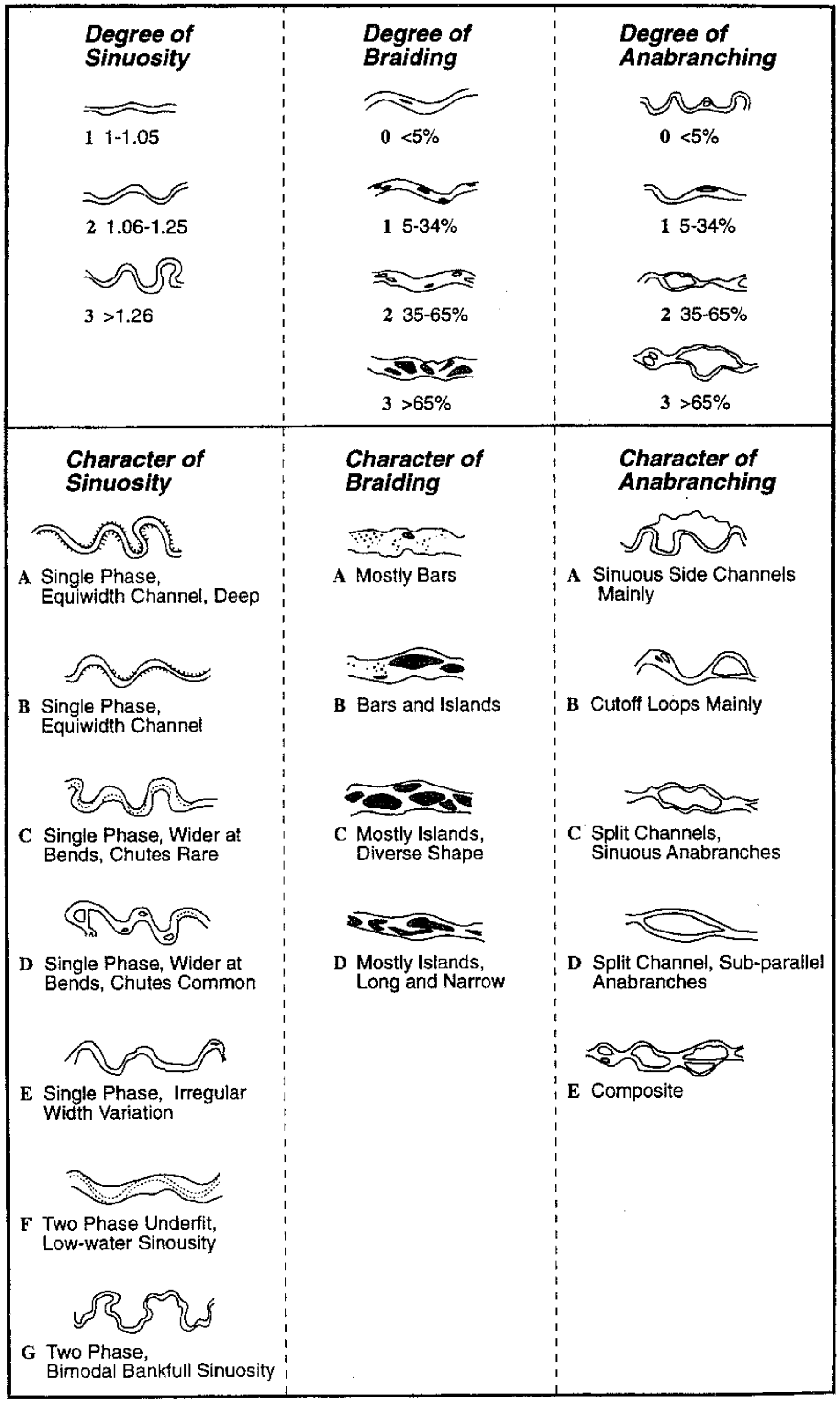


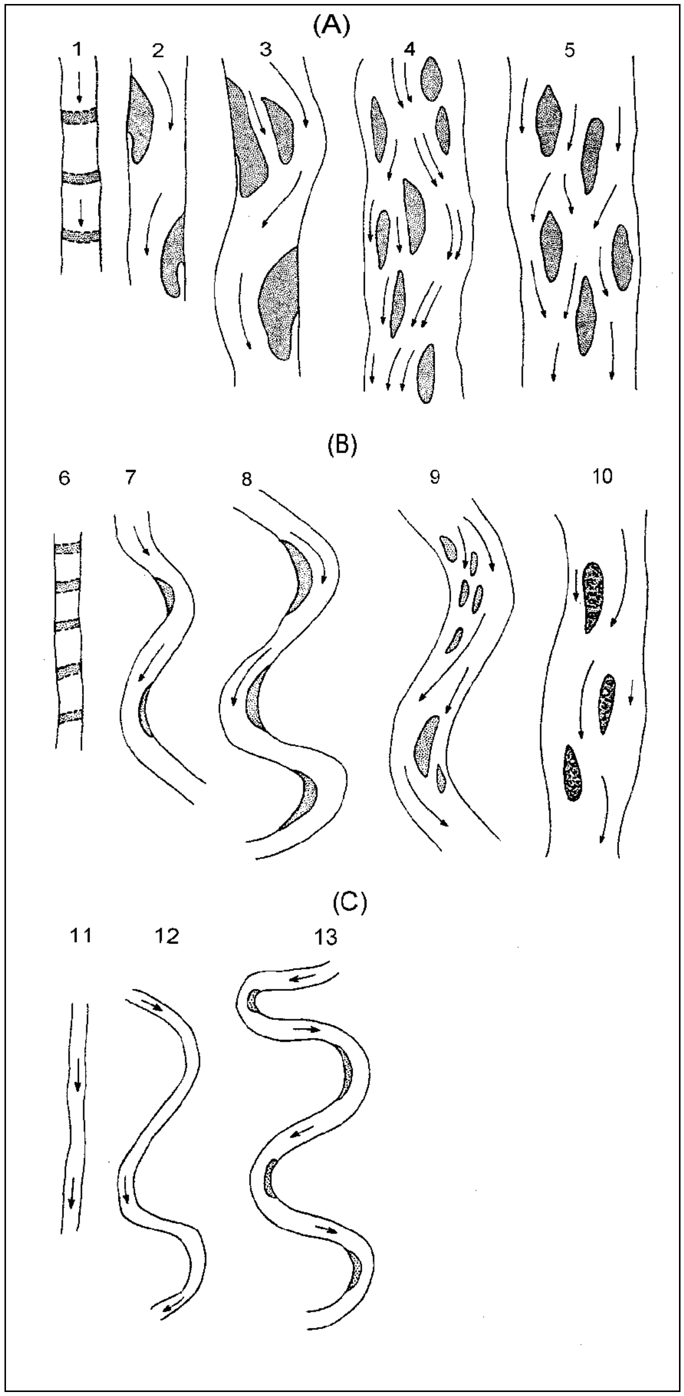
Figure 4.21. Alluvial channel pattern classification devised by Brice (after Brice 1975).[38]

Table 4.2. Classification of Alluvial Channels (from Schumm 1977).[39]				
Mode of Sediment Transport and Type of Channel	Bedload (percentage of total load)	Channel Stability		
		Stable (graded stream)	Depositing (excess load)	Eroding (deficiency of load)
Suspended Load	<3	Stable suspended-load channel. Width/depth ratio <10; sinuosity usually >2.0; gradient, relatively gentle	Depositing suspended load channel. Major deposition on banks cause narrowing of channel; initial streambed deposition minor.	Eroding suspended-load channel. Streambed erosion predominant; initial channel widening minor.
Mixed Load	3-11	Stable mixed-load channel. Width/depth ratio >10 <40; sinuosity usually <2.0 >1.3; gradient, moderate	Depositing mixed-load channel. Initial major deposition on banks followed by streambed deposition.	Eroding mixed-load channel. Initial streambed erosion followed by channel widening.
Bed Load	>11	Stable bed-load channel. Width/depth ratio >40; sinuosity usually <1.3; gradient, relatively steep	Depositing bed-load channel. Streambed deposition and island formation.	Eroding bed-load channel. Little streambed erosion; channel widening predominant.

In addition to the channel patterns shown in Figure 3.2, there are five basic bed-load channel patterns (Figure 4.22A) that have been recognized during experimental studies of channel patterns.[39] These five basic bed-load channel patterns can be extended to mixed-load and suspended-load channels to produce 13 patterns (Figure 4.22). As indicated above, patterns 1-5 are bed-load channel patterns (Figure 4.22A), patterns 6-10 are mixed-load channel patterns (Figure 4.22B), and patterns 11-13 are suspended-load channel patterns (Figure 4.22C). For each channel type, pattern changes can be related to increasing valley slope, stream power, and sediment load.

The different bed-load channel patterns (Figure 4.22A) can be described as follows: Pattern 1: straight, essentially equal-width channel, with migrating sand waves; Pattern 2: alternate-bar channel with migrating side or alternate bars and a slightly sinuous thalweg, Pattern 3: low-sinuosity meandering channel with large alternate bars that develop chutes; and Pattern 4: transitional meandering-thalweg braided channel. The large alternate bars or point bars have been dissected by chutes, but a meandering thalweg can be identified. Pattern 5 is a bar-braided channel.

As compared to the bed-load channel pattern, the five-mixed load patterns (Figure 4.22B) are relatively narrower and deeper, and there is greater bank stability. The higher degree of bank stability permits the formation of narrow, deep straight channels (Pattern 6), and alternate bars stabilize because of the finer sediments, to form slightly sinuous channels (Pattern 7). Pattern 8 is a truly meandering channel, wide on the bends, relatively narrow at the crossings, and subject to chute cutoffs. Pattern 9 maintains the sinuosity of a meandering channel, but due to the greater sediment transport the presence of bars gives it a composite sinuous-braided appearance. Pattern 10 is an island-braided channel that is relatively more stable than that of bedload channel 5.



Increasing Valley Slope
Increasing Stream Power
Increasing Sediment Load

Figure 4.22. The range of alluvial channel patterns: (A) Bed-load channel patterns, (B) Mixed-load channel patterns, (C) Suspended-load channel patterns (from Schumm 1981).[48]

Suspended-load channels (Figure 4.22C) are narrow and deep. Suspended-load Pattern 11 is a straight, narrow, deep channel. With only small quantities of bed load, this type of channel will have the highest sinuosity of all (Patterns 12 and 13).

It must be stressed that the preceding classification applies to adjustable alluvial rivers, with sediment loads primarily of sand, silt and clay, which would be considered regime channels by Montgomery and Buffington[49] who have considered the full range of channels from high mountain bedrock channels to those described previously (Figures 4.21 and 4.22). This classification starts at the drainage divide (Figure 4.23) and moves down through bedrock and colluvial depressions or chutes to the point where one can recognize fluvial channels. Five distinct reach morphologies are identified: cascade, step-pool, plane-bed, pool-riffle, and dune- ripple (regime). Most of these reaches will be confined by valley walls and terraces in contrast to the alluvial regime channels. Table 4.3 summarizes the important characteristics of each channel type.

Rosgen[40,41] developed a comprehensive system for classifying natural rivers. This system divides streams into seven major types on the basis of degree of entrenchment, gradient, width/depth ratio, and sinuosity. Within each major category there are six subcategories depending on the dominant type of bed/bank materials. The classification system shows a distinct bias toward streams that are relatively small and steep. For example, of the stream types categorized based on dominant bed material, seven are braided, 30 are entrenched, in the sense that overbank floods are confined by valley walls or terraces, and four are narrow, sinuous mountain meander-type channels. The basic framework of Rosgen's method is set out in Figures 4.24 and 4.25. This classification is comprehensive in its scope, but requires "a strong geomorphological insight and understanding to apply consistently and usefully."[44] For a discussion of Rosgen’s approach to channel restoration, see Chapter 7.

4.4 QUALITATIVE EVALUATION OF CHANNEL RESPONSE

4.4.1 Overview

The major complicating factors in river mechanics are: (1) the large number of interrelated variables that can simultaneously respond to natural or imposed changes in a stream system, and (2) the continual evolution of stream channel patterns, channel geometry, bars and forms of bed roughness with changing water and sediment discharge. In order to understand the responses of a stream to human activities and nature, a few geomorphic concepts are presented here. Quantitative techniques for analysis of channel stability are introduced in Chapter 6.

The dependence of stream form on slope, which may be imposed independent of other stream characteristics, is illustrated schematically in Figure 4.26.[13,47] Any natural or artificial change which alters channel slope can result in modifications to the existing stream pattern. For example, a cutoff of a meander loop increases channel slope. Referring to Figure 4.26 this shift in the plotting position to the right could result in a shift from a relatively tranquil, meandering pattern toward a braided pattern that varies rapidly with time, has high velocities, is subdivided by sandbars, and carries relatively large quantities of sediment. Conversely, it is possible that a decrease in slope could change an unstable braided stream into a meandering one.

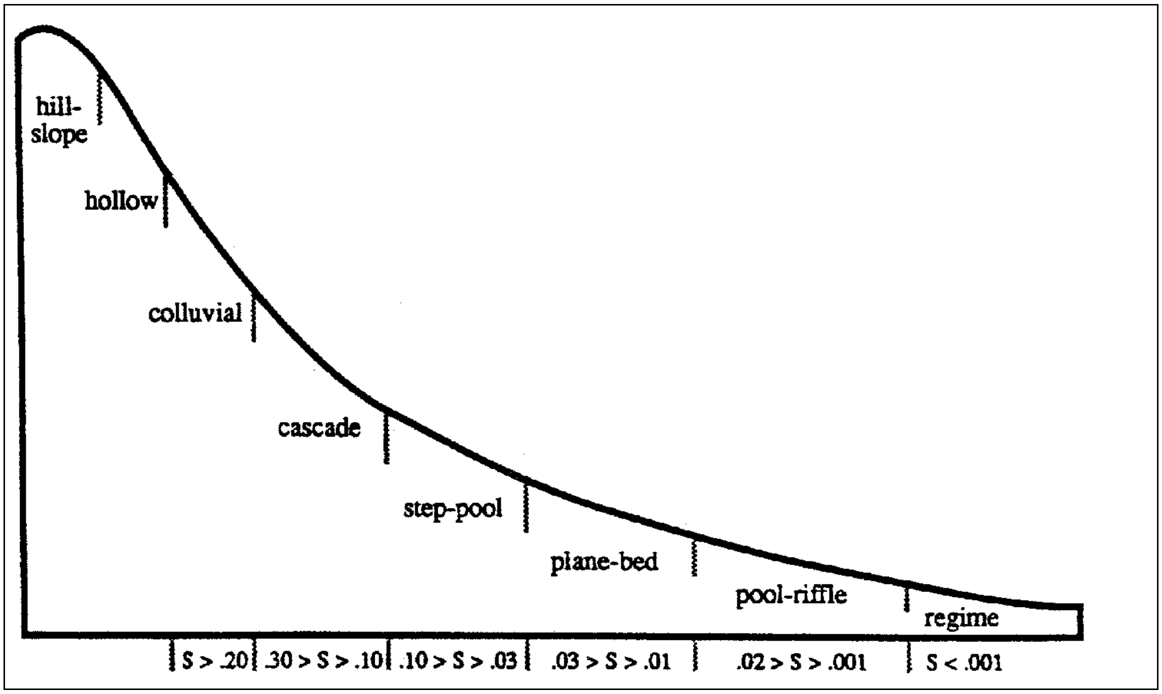


Figure 4.23. Idealized long profile from hillslopes and unchanneled hollows downslope through the channel network showing the general distribution of alluvial channel types (from Montgomery and Buffington 1997).[49]

Table 4.3. Classification of Channel-Reach Morphology in Mountain Drainage Basins of the Pacific Northwest (from Montgomery and Buffington 1997).[53]

	Dune Ripple	Pool Riffle	Plane Bed	Step Pool	Cascade	Bedrock	Colluvial
Typical bed material	Sand	Gravel	Gravel-cobble	Cobble-boulder	Boulder	Rock	Variable
Bedform pattern	Multilayered	Laterally oscillatory	Featureless	Vertically oscillatory	Random	Irregular	Variable
Dominant Roughness Elements	Sinuosity, bedforms (dunes, ripples, bars) grains, banks	Bedforms (bars, pools), grains, sinuosity, banks	Grains, banks	Bedforms (steps, pools), grains, banks	Grains, banks	Boundaries (bed and banks)	Grains
Dominant Sediment Sources	Fluvial, bank failure	Fluvial, bank failure	Fluvial, bank failure, debris flows	Fluvial, hillslope, debris flows	Fluvial, hillslope, debris flows	Fluvial, hillslope, debris flows	Hillslope, debris flows
Sediment Storage Elements	Overbank, bedforms	Overbank, bedforms	Overbank	Bedforms	Lee and stoss sides of flow obstructions	Pockets	Bed
Typical Confinement	Unconfined	Unconfined	Variable	Confined	Confined	Confined	Confined
Typical Pool Spacing (channel widths)	5 to 7	5 to 7	None	1 to 4	<1	Variable	Unknown

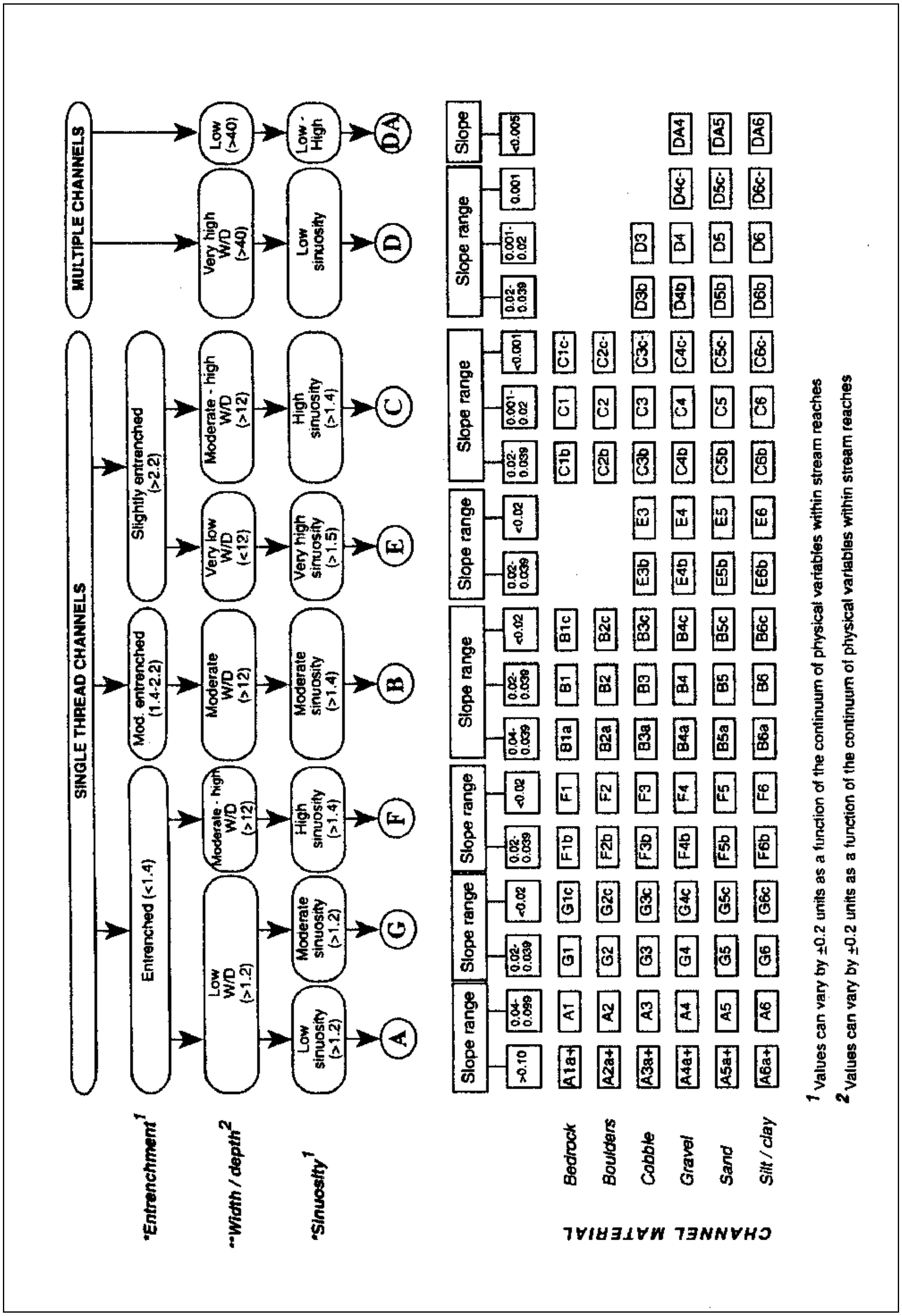


Figure 4.24. Key to classification of rivers in Rosgen's method (modified from Rosgen 1994[40] by Thorne[44]).

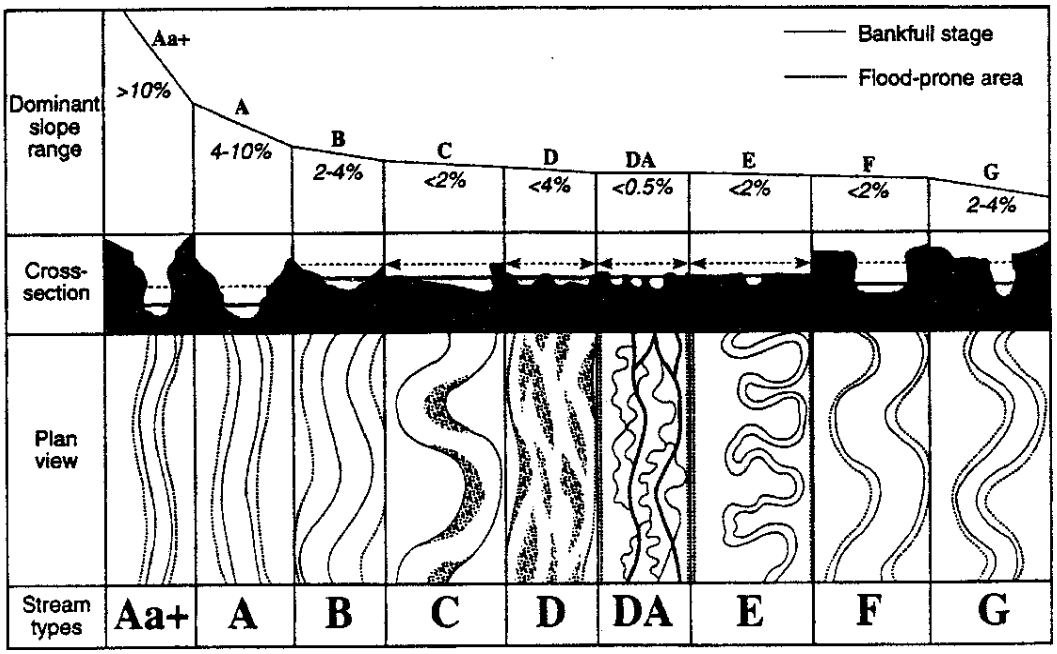


Figure 4.25. Longitudinal, cross-sectional, and planform views of major stream types in Rosgen's method (modified from Rosgen 1994[40] by Thorne[44]).

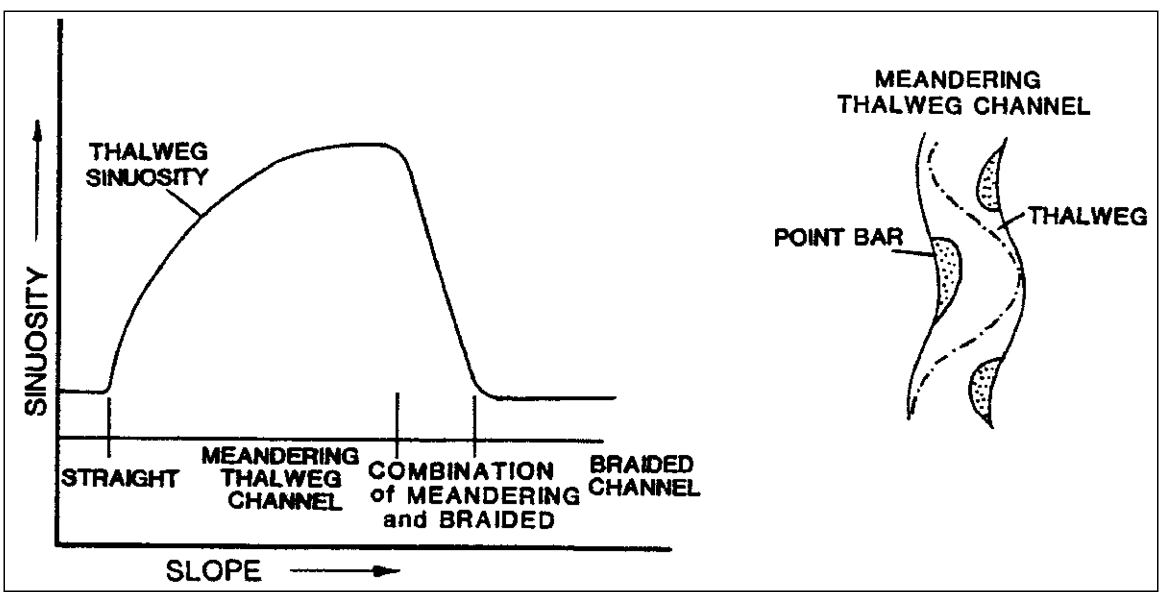


Figure 4.26. Sinuosity vs. slope with constant discharge (after HDS 6).[13]

4.4.2 Lane Relation and Other Geomorphic Concepts

The significantly different channel dimensions, shapes, and patterns associated with different quantities of discharge and amounts of sediment load indicate that as these independent variables change, major adjustments of channel morphology can be anticipated. Further, a change in hydrology may cause changes in stream sinuosity, meander wave length, and channel width and depth. A long period of channel instability with considerable bank erosion and lateral shifting of the channel may be required for the stream to compensate for the hydrologic change. The reaction of a channel to changes in discharge and sediment load may result in channel dimension changes contrary to those indicated by many regime equations. For example, it is conceivable that a decrease in discharge together with an increase in sediment load could cause a decrease in depth and an increase in width.

Figures 4.27a and b illustrate the dependence of sand-bed stream form on channel slope and discharge. According to Lane, a sand-bed channel meanders where:(50)

$$SQ^{0.25} \leq K_u \tag{4.1}$$

where:

K_u = 0.00070 SI
K_u = 0.0017 English

and:

S = channel bed slope, m/m (ft/ft)
Q = mean annual discharge, m^3/s (ft^3/s)

Similarly, a sand-bed channel is braided where:

$$SQ^{0.25} \geq K_u \tag{4.2}$$

where:

K_u = 0.0041 SI
K_u = 0.010 English

The zone between the lines defining braided streams and meandering streams in Figures 4.27a and b is the transitional range, i.e., the range in which a stream can change readily from one stream form to the other.

Many rivers in the United States are classified as intermediate sand-bed streams and plot in this zone between the limiting curves defining meandering and braided stream. If a stream is meandering but its discharge and slope borders on the transitional zone, a relatively small increase in channel slope may cause it to change, with time, to a transitional or braided stream.

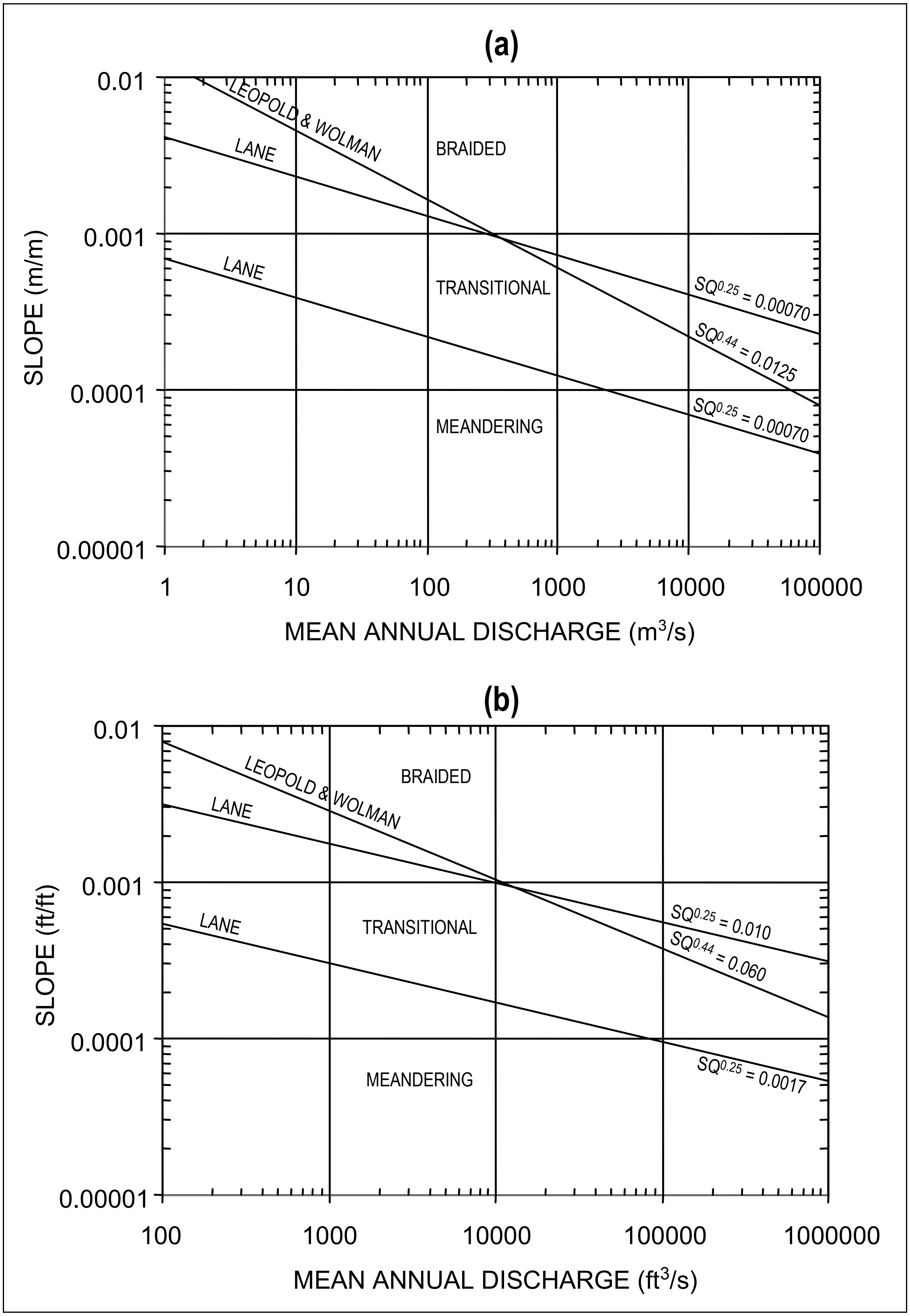


Figure 4.27a, b. Slope-discharge relationship for braiding or meandering in sand-bed streams (after Lane).[50] a = SI Units b = English Units

Leopold and Wolman plotted slope and discharge for a variety of natural streams.[51] They observed that a line could separate meandering from braided streams. The equation of this line is:

$$SQ^{0.44} = K_u \tag{4.3}$$

where:

K_u = 0.00125 SI
K_u = 0.06 English

Streams classified as meandering by Leopold and Wolman are those whose sinuosity is greater than 1.5. Braided streams are those which have relatively stable alluvial islands and, therefore, two or more channels. They note that sediment size is related to slope and channel pattern but do not try to account for the effect of sediment size on the morphology of streams. They further note that braided and meandering streams can be differentiated based on combinations of slope, discharge, and width/depth ratio, but regard width as a variable dependent mainly on discharge.

Long reaches of many streams have achieved a state of equilibrium, for practical engineering purposes. These stable reaches are called "graded" streams by geologists and "poised" streams by engineers. However, this condition does not preclude significant changes over a short period of time or over a period of years. Conversely, many streams contain long reaches that are actively aggrading or degrading (see Section 2.4). These aggrading and degrading channels pose definite hazards to highway crossings and encroachments, as compared with poised streams.

Regardless of the degree of channel stability, human activities may produce major changes in stream characteristics locally and throughout an entire reach. All too frequently, the net result of a stream "improvement" is a greater departure from equilibrium than existed prior to "improvement." Designers of stream channel modifications should invariably seek to enhance the natural tendency of the stream toward equilibrium and a stable condition. This requires an understanding of the direction and magnitude of change in channel characteristics which will result from the actions of man and nature. This understanding can be obtained by:

- Studying the stream in a natural condition
- Having knowledge of the sediment and water discharge
- Being able to predict the effects and magnitude of future human activities
- Applying to these a knowledge of geology, soils, hydrology, and hydraulics of alluvial rivers

Predicting the response to channel modifications is a very complex task. There are large numbers of variables involved in the analysis that are interrelated and can respond to changes in a stream system in the continual evolution of stream form. The channel geometry, bars, and forms of bed roughness all change with changing water and sediment discharges. Because such a prediction is necessary, useful methods have been developed to qualitatively and quantitatively predict the response of channel systems to changes.

Quantitative prediction of response can be made if all of the required data are known with sufficient accuracy (see Chapter 6). Often, however, available data are not sufficient for quantitative estimates, and only qualitative estimates are possible. For example, Lane studied the changes in stream morphology caused by modifications of water and sediment discharges and developed simple qualitative relationships among the most important variables indicating stream behavior.(52) Similar but more comprehensive treatments of channel response to changing conditions in streams have been presented by Leopold and Maddock, Schumm, and Santos-Cayado.(46,53,54) All research results support the relationship originally proposed by Lane:

$$QS \propto Q_s D_{50} \tag{4.4}$$

where:

Q	=	Discharge
S	=	Energy slope
Q_s	=	Sediment discharge
D_{50}	=	Median sediment size

This proportional relationship (Equation 4.4) is very useful to predict qualitatively channel response to climatological changes, stream modifications, or both. The geomorphic relation expressed is only an initial step in analyzing long-term channel response problems. However, this initial step is useful because it warns of possible future difficulties related to channel modifications. Examples of its use are given in the next section and in HDS 6.(13)

4.4.3 Stream System Response

Streambed aggradation or degradation affects not only the stream in which a bed elevation change is initiated, but also tributaries to the stream and the stream to which it is tributary. Thus, the stream system is in an imbalanced condition regarding sediment supply and sediment transport capacity, and it will seek a new state of equilibrium. A few examples are cited to illustrate the system-wide response to natural and human-induced changes. These examples also illustrate the use of several geomorphic concepts introduced in Section 4.4.2 and in the discussion of Section 2.4.

Example 1. A degrading principal stream channel will cause its tributaries to degrade, thus contributing additional sediment load to the degrading stream. This larger sediment load will slow the rate of degradation in the principal stream channel and may halt or reverse it for a period of time if the contribution is large enough or if a tributary transports material which armors the bed of the degrading stream.

Using Equation 4.4, the basic response of the principal stream can be expressed as:

$$QS^+ \propto Q_s^+ D_{50}$$

Here, it is assumed that water discharge (Q) and sediment size (D_{50}) remain unchanged. **(Note: When neither + or - appears as a superscript in the Lane relationship, conditions remain unchanged)**. Thus, the increase in sediment discharge (Q_s^+) derived from the tributary stream must result in an increase in slope (S^+) on the principal stream if the geomorphic balance expressed by the Lane relationship is to hold. The increase in slope then slows or reverses the original degradation of the principal stream which initiated the stream system response.

Example 2. The sediment supply available for transport by a reach of stream may be reduced by changes in the watershed which reduce erosion, mining of sand and gravel from the streambed upstream of the reach, or the construction of a dam to impound water upstream of the reach. In general, for the two latter cases, sediment transported by the stream is trapped in the mined areas or reservoir and mostly clear water is released downstream. Figure 4.28 illustrates the principle by use of the example of a dam. Referring to Equation 4.4, a decrease in sediment discharge will cause a decrease in slope, if the discharge and median sediment size remain constant, or:

$$QS^{-} \alpha Q_s^{-} D_{50}$$

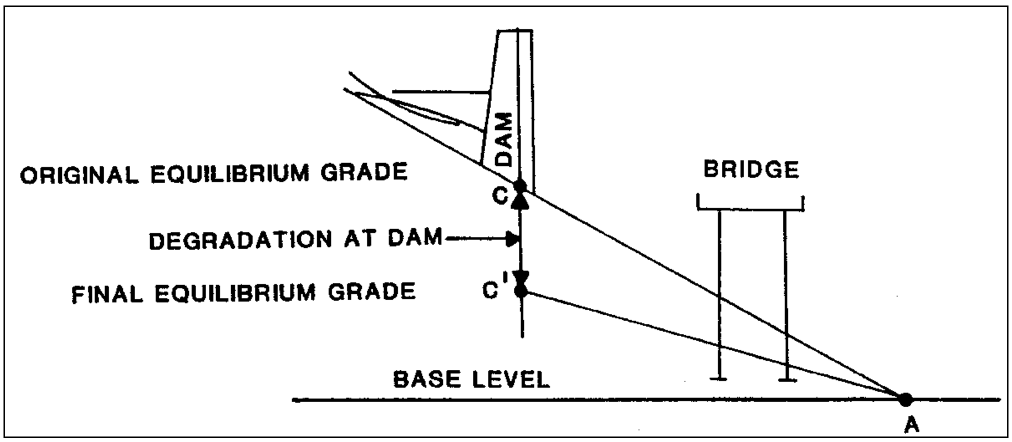
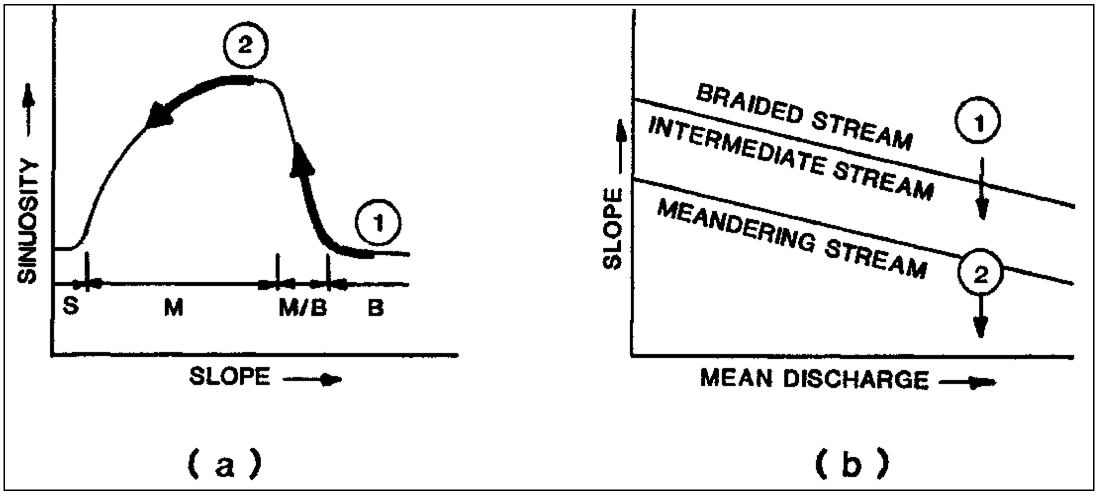


Figure 4.28. Changes in channel slope in response to a decrease in sediment supply at point C.

The original equilibrium channel gradient (Figure 4.28) is represented by the line CA. A new equilibrium grade represented by C'A will result from a decrease in sediment supply. The dam is a control in the channel which prevents the effects from extending upstream. Except for the channel control formed by the dam, similar effects are experienced at any location which undergoes a reduction in sediment supply.

Referring to Figure 4.26, for a low sinuosity braided stream, this decrease in slope below the dam could result in an increase in sinuosity and a change in planform toward a combination meandering/braided stream (see (1) on Figure 4.29a). If the stream below the dam were initially a meandering stream at near maximum sinuosity for the original slope, the decrease in slope below the dam could shift the planform of the stream toward a reduced sinuosity, meandering thalweg channel (see 2 on Figure 4.29a).

A similar result can be derived from Figure 4.27. For an initially braided channel pattern below the dam [(1) on Figure 4.29b], a decrease in slope below the dam could indicate a tendency to shift the stream's plotting position downward, possibly into the intermediate stream range (i.e., a combination of meandering and braided as on Figure 4.29a). For an initially meandering stream [(2) on Figure 4.29b], the decrease in slope below the dam could indicate a tendency toward a less meandering channel (as on Figure 4.29a). It should be noted that both of these cases have assumed a constant discharge (Q).



Figures 4.29a and b. Use of geomorphic relationships of Figures 4.26 and 4.27 in a qualitative analysis.

As discussed in Section 2.4, the effects downstream of a dam are more complex than a simple reduction in sediment supply. If the reservoir is relatively small and water flow rates downstream are not significantly affected, degradation may occur downstream initially and aggradation may then occur after the reservoir fills with sediments. Except for local scour downstream of the dam, the new equilibrium grade may approach line CA (Figure 4.28) over the long term. This could apply to a diversion dam or other small dam in a stream.

Dams constructed to impound water for flood control or water supply usually have provisions for sediment storage. Over the economic life of the project, essentially clear water is released downstream. For practical purposes, the sediment supply to downstream reaches is permanently reduced. Reservoirs developed for these purposes, however, also reduce the water flow rates downstream. Referring to Equation 4.4, a reduction in discharge (Q) may have a moderating effect on the reduction in slope S and, consequently, on degradation at the dam CC' in Figure 4.28. If sediment discharge or sediment size remain constant below the dam (e.g., a tributary downstream continues to bring in a large sediment discharge), this would be expressed as:

$$Q^{-}S^{+} \alpha Q_s D_{50}$$

Considering the more likely scenario of stream response to a dam, both water discharge (Q) and sediment discharge (Q_s) would decrease. It is also possible that sediment size (D_{50}) in the reach below the dam would increase due to armoring or tributary sediment inflow. Using Equation 4.4, this complex result could be expressed as:

$$Q^{-}S^{\pm} \alpha Q_s^{-} D_{50}^{+}$$

Here, the resulting response in slope ($S^{\pm}$) would depend on the relative magnitude of changes in the other variables in the relationship.

4.4.4 Complex Response

Generally, a simple qualitative evaluation of stream system response assumes that the stream is "graded" or "poised," that is, in a condition of steady-state equilibrium.[39] This condition in a process-response system is maintained by self-regulation or negative feedback, which operates to counteract or reduce the effects of external change on the system so that it returns to an equilibrium condition. For a qualitative evaluation of stream stability at highway structures this is a reasonable initial assumption; however, stream system response can be much more complex.

The fluvial system can be viewed either as a physical system, where the workings of and relations among the components of the system are the major concern, or as a historical system, where change is viewed from a longer term perspective (see, for example, Figures 2.1 and 2.2). As Schumm[39] points out, in actuality the fluvial system is a physical system with a history. When viewed over the longer span of an erosion cycle (geologic time scale) the characteristics of the system progressively change; however, a state of "dynamic" equilibrium may exist if there is a long-term balance (on an engineering time scale) between the water and sediment supplied by the watershed and that transported by the stream system. When dynamic equilibrium exists, bed scour and fill and bankline migration may occur, but on an engineering time scale, reach averaged characteristics and the balance between sediment inflow and sediment outflow are maintained.

To add to the complexity of stream system response, some change may be episodic rather than progressive. Fluvial systems may change through time to a condition of incipient instability, without a change of external influences. Exceeding such a geomorphic threshold during, for example, a major flood can lead to rapid, non-progressive (episodic), and potentially catastrophic change in a stream system. Schumm[39] cites as an example, a valley in a semi-arid region where sediment storage through time progressively increases valley slope until failure (erosion) occurs. Another common example of a geomorphic threshold is the progressive increase in channel sinuosity and meander amplitude until a cutoff of a meander loop or avulsion occurs. This is due to channel lengthening, increased resistance, and gradient reduction that accompany increases in sinuosity. A history of meander growth and cutoff is shown for two rivers in Figure 2.5. Meander migration and "optimal" bend shape are discussed in more detail in Sections 6.2.1 and 6.2.2.

Figure 2.2 provides an example of complex response on a time scale of interest to the highway engineer if bridges cross or highway structures encroach on the affected stream system. Another example is the response of a drainage basin to "rejuvenation," that is, the lowering of the base level of the main channel by long-term degradation. When base level (bed elevation) is lowered, erosion and channel adjustments occur near the mouth of the basin and, in fact, the main channel probably will be adjusted to the change long before the tributaries have responded.[39] However, when the tributaries are in turn rejuvenated as they adjust to the new base level, the increased sediment production is delivered to a main channel that has already adjusted to the base level change, but not to the increased sediment loads from upstream. Thus, the original incision would not be the only adjustment made by the main channel. In fact, a complex sequence of responses could be expected before the stream system attains a new condition of dynamic equilibrium; and all bridges or highway structures, not only on the main channel, but also on the tributaries, could be affected.

An example of analyzing river pattern thresholds and complex response using Figure 4.27 is presented in HDS 6, Chapter 5.[13] Design considerations for highway encroachments and river crossings for both simple and complex situations are presented in HDS 6, Chapter 9.

4.5 RAPID ASSESSMENT OF CHANNEL STABILITY

Given the time constraints for bridge inspections and the expense of conducting lengthy geomorphic studies, it would be desirable to have a technique for rapid channel stability assessments. Johnson et al.[55] reviewed existing methods and concluded that there are a number of methods currently available for assessing channel stability. Some require the expertise of an experienced geomorphologist while others require only some period of training. All of these methods are, at least in part, based on subjective observations of a variety of parameters that describe the characteristics of the channel and surrounding floodplain.

For example, Simon and Downs[56] developed a method for assessing stability of channels that have been straightened. This work is based on an earlier study by Simon et al.[57] for the evaluation, modeling, and mapping of potential bridge scour in west Tennessee. In this method, a field form is provided for the collection of data in a 1.5 to 2-hour period. The data is then summarized on a ranking sheet. For each category on the ranking sheet, a weight is assigned where the value of the weights was selected based on the experience of the authors. A total rating is derived by summing the weighted data in each category. The higher the rating, the more unstable the channel. It was found that for streams in western Tennessee, a rating of 20 or more indicated an unstable channel that could threaten bridges and land adjacent to the channel. The rating system provides a systematic method for evaluating stability; however, the final ratings cannot be compared to streams evaluated in other geomorphic, geologic, or physiographic regions. In addition, some of the parameters are very difficult to assess, particularly in the absence of a stream gage. For example, considerable weight is placed on the identification of the stage of channel evolution. To properly assess this stage, it is necessary to determine whether the channel is in the process of widening, degrading, or aggrading. The determination of aggradation or degradation typically requires at least several years of stream bed elevation data and cannot usually be determined during a brief site visit.[55]

The U.S. Geological Survey developed a method to determine a “potential scour index” for assessment and estimates of maximum scour at selected bridge sites in Iowa.[58] This work was completed in cooperation with the Iowa Highway Research Board and the Iowa Department of Transportation and was also based on the Western Tennessee study by Simon et al.[57]

The potential scour index used in the USGS study is comprised of 11 principal stream stability and scour components. A value is assigned to each component according to the results of an onsite evaluation, and the potential scour index is the sum of the component values. Larger values of the index suggest a greater likelihood for scour-related problems to occur. Evaluation of several of the index components is somewhat subjective and assigned values may vary depending on the inspector’s judgment and experience. However, no single component dominates the potential-scour index, and variations in the assigned values probably tend to cancel each other out when the components are summed to produce the index.[58]

The 11 principal index components are:

- Bed material
- Bed protection (i.e., riprap)
- Stage of channel evolution
- Percentage of channel constriction
- Number of bridge piers in the channel
- Percentage of blockage by debris
- Bank erosion
- Proximity of river meander impact point to bridge
- Pier skew
- Mass wasting (bank failure) at bridge
- Angle of approach of high flows

A potential scour assessment is used to help determine whether a bridge may be vulnerable to scour. Although a potential scour assessment cannot predict actual scour during a flood, it provides a measure of the likelihood of scour-related problems occurring, both during a flood and over time as the channel-evolution processes work on the stream. The assessment is accomplished by an onsite evaluation using a scour-inspection form.

Using the USGS method, potential scour assessments were performed at 130 highway bridges throughout Iowa. The drainage areas upstream from the bridges range from 60 to 20,163 km^2 (23 to 7,785 mi^2). All of the bridges were structures supported by abutments and possibly one or more piers. The ages of the bridges ranged from less than 5 to more than 70 years. The results of the assessments are summarized in USGS Water-Resources Investigation Report 95-4015.[(58)]

As noted, Johnson et al.,[(55)] after a review of existing methods and parameters for evaluating channel stability developed a systematic rapid channel stability assessment method for gravel bed channels. Their method is based on 13 qualitative and quantitative indicators of geomorphic and hydraulic processes that are rated, weighted, and summed to produce a stability rating. Some of these indicators have been introduced in Chapter 2 and most would be identified during a stream reconnaissance as recommended in Chapter 4 (see also Appendix C). The Johnson et al.,[(55)] rapid channel stability assessment is presented in Appendix D.

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CHAPTER 5

HYDRAULIC FACTORS AND PRINCIPLES

Level 2 Analysis Procedures

5.1 INTRODUCTION

The design of highway stream crossings and countermeasures to prevent damage from streamflow requires assessment of factors that characterize streamflow and channel conditions at each bridge site. The importance of hydraulic or flow factors in the crossing design process is influenced by the importance of the bridge and by land use on the floodplain, among other things. The geometry and location of the highway stream crossing are important considerations in evaluating the interaction of the structure and the flow at the crossing in terms of potential stream instability issues. In addition, hydraulic factors have a significant influence on the design of bridge substructure components when scour and stream stability are considered.

5.2 BASIC HYDRAULIC PRINCIPLES

The basic equations of flow are continuity, energy, and momentum. They are derived from the laws of (1) conservation of mass; (2) conservation of energy; and (3) conservation of linear momentum, respectively. Analyses of flow problems are much simplified if there is no acceleration of the flow or if the acceleration is primarily in one direction (one-dimensional flow), that is, the accelerations in other directions are negligible. However, a very inaccurate analysis may occur if one assumes accelerations are small or zero when in fact they are not. In the simplest cases, or as a first approximation of flow conditions, steady, uniform flow can be assumed; that is hydraulic variables do not change with time at a cross section or with distance along the channel.

Applications of the basic principles of flow are reviewed in detail in FHWA's "Introduction to Highway Hydraulics" (HDS 4).[59] The user is referred to standard fluid mechanics texts or "River Engineering for Highway Encroachments" (HDS 6) for their derivations.[13] The continuity and energy equations are particularly useful in evaluating potential stream stability problems. In addition, the basic Manning equation for open channel flow introduces the important concept of hydraulic resistance to flow. These are reviewed briefly in the following sections.

5.2.1 Continuity Equation

The continuity equation is based on conservation of mass, that is, matter can neither be created or destroyed (except for mass-energy interchange). For steady flow of incompressible fluids it is:

$$V_1 A_1 = V_2 A_2 = Q = VA \qquad (5.1)$$

where:

V = Average velocity in the cross section perpendicular to the area, m/s (ft/s)
A = Area perpendicular to the velocity, m^2 (ft^2)
Q = Volume flow rate or discharge, m^3/s (ft^3/s)

Equation 5.1 is applicable when the fluid density is constant, the flow is steady, there is no significant lateral inflow or seepage (or they are accounted for) and the velocity is perpendicular to the flow area (Figure 5.1). Note that the product of area (A) and velocity (V) which is the discharge, is constant from section to section.

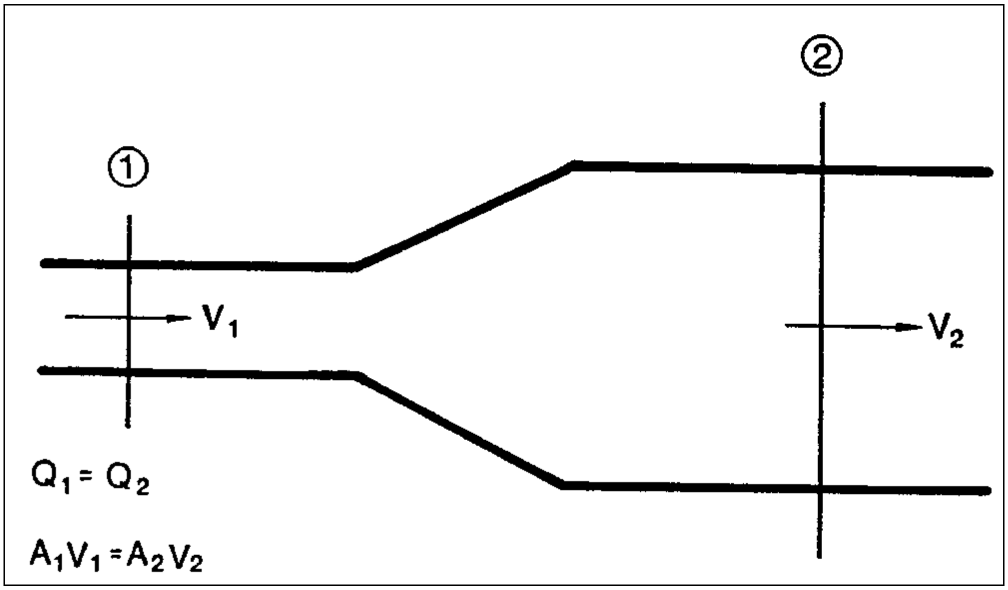

Figure 5.1. Sketch of the continuity concept.

5.2.2 Energy Equation

The energy equation is derived from the first law of thermodynamics which states that energy must be conserved at all times. In practical terms, this means that the energy at one section of the flow is equal to the energy at another section plus the losses in between. The energy equation for steady incompressible flow is:

$$Z_1 + y_1 + \frac{V_1^2}{2g} = Z_2 + y_2 + \frac{V_2^2}{2g} + h_L \tag{5.2}$$

where:

Z	=	Elevation above some datum, m (ft)
y	=	Depth of flow at a point, m (ft)
V	=	Mean velocity, m/s (ft/s)
h_L	=	Energy head loss, m (ft)

The terms of the energy equation are illustrated in Figure 5.2.

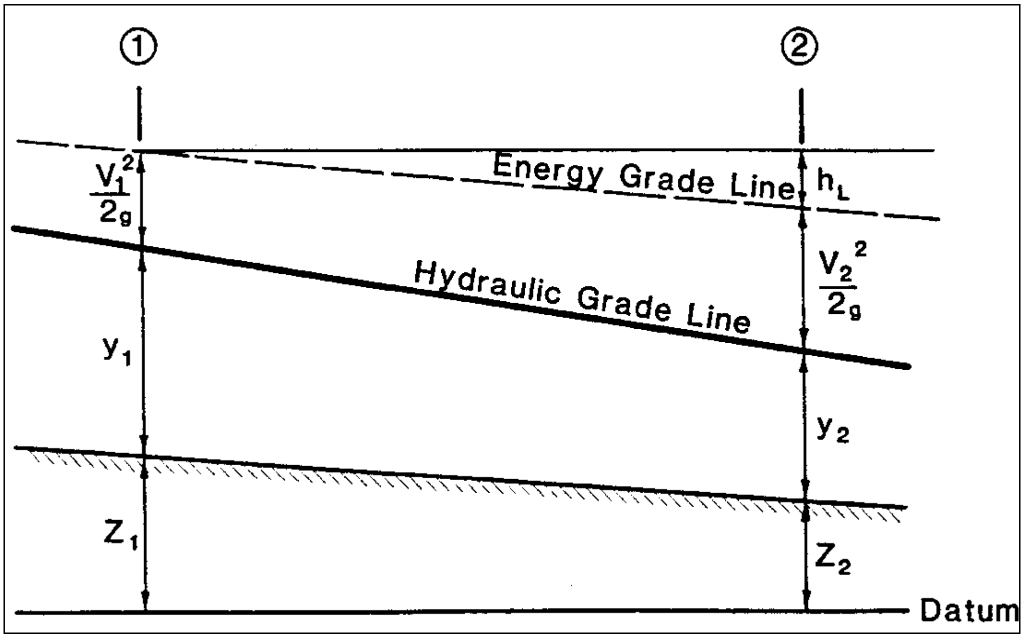

Figure 5.2. Sketch of the energy concept for open channel flow.

5.2.3 Manning's Equation

Water flows in a sloping channel because of the force of gravity. The flow is resisted by the friction between the water and wetted surface of the channel. For uniform flow, the volume of water flowing (Q), the depth of flow (y), and the velocity of flow (V) depend upon the channel shape, roughness (n), and slope of the channel bed (S_0). Various equations have been devised to determine the velocity and discharge under steady, uniform flow conditions in open channels. A useful equation is the one that is named for Robert Manning, an Irish engineer. Manning's equation for the velocity of flow in open channels is:

$$V = \frac{K_u}{n} R^{2/3}\ S^{1/2} \qquad (5.3)$$

where:

V = Mean velocity, m/s (ft/s)
n = Manning's coefficient of channel roughness
R = Hydraulic radius, m (ft)
S = Energy slope, m/m (ft/ft)

For steady, uniform flow $S = S_0$

K_u = 1.0 SI
K_u = 1.486 English

Over many decades, a catalog of values of Manning's n has been assembled so that an engineer can estimate the appropriate value by knowing the general nature of the channel boundaries.(60) A pictorial guide for assisting with selection of an appropriate roughness coefficient is given in USGS Water Supply Paper 1849.(61) Methods for estimating resistance to flow are discussed in detail in Section 5.3.4

The hydraulic radius, R, is a shape factor that depends only upon the channel dimensions and the depth of flow. It is computed by the equation:

$$R = \frac{A}{P} \tag{5.4}$$

where:

A = Cross-sectional area of flowing water in m^2 (ft^2) perpendicular to the direction of flow

P = Wetted perimeter or the length, m (ft), of wetted contact between a stream of water and its containing channel, perpendicular to the direction of flow

By combining the continuity equation for discharge (Equation 5.1) with Equation 5.3, the Manning's equation can be used to compute discharge directly

$$Q = \frac{K_u}{n} A R^{2/3} S^{1/2} \tag{5.5}$$

In many computations, it is convenient to group the cross-sectional properties into a term called conveyance, K,

$$K = \frac{K_u}{n} A R^{2/3} \tag{5.6}$$

or

$$Q = K \sqrt{s} \tag{5.7}$$

and

$$K = \frac{Q}{\sqrt{s}} \tag{5.8}$$

Conveyance can be considered a measure of the carrying capacity of the channel, since it is directly proportional to discharge (Q).

5.3 HYDRAULIC FACTORS AFFECTING STREAM STABILITY

5.3.1 Overview

Hydraulic, location, and design factors important to the highway engineer are introduced in Figure 5.3. Each of the hydraulic factors has an effect on stream stability at a bridge crossing. Since the geometry and location of the bridge crossing can also affect stream stability, the most significant factors related to bends, confluences, alignment, and highway profile are also summarized. In addition, some general concepts related to the hydraulic design of bridges are discussed in Section 5.5.

5.3.2 Magnitude and Frequency of Floods

The hydrologic analysis for a stream crossing consists of establishing peak flow-frequency relationships and such flow-duration hydrographs as may be necessary. Flood-frequency relationships are generally defined on the basis of a regional analysis of flood records, a gaging station analysis, or both. Regional analyses have been completed for all states by the USGS, and the results are generally applicable to watersheds which are unchanged by man. Flood-frequency relationships at gaged sites can be established from station records which are of sufficient length to be representative of the total population of flood events on that particular stream. The Pearson Type III distribution with log transformation of flood data is recommended by the Water Resources Council for station flood data analysis.[62] Where flood estimates by regional analysis vary from estimates by station analysis, factors such as gaging station record length and the applicability of the regional analysis to that specific site should be considered, as well as high water information, flood data, and information of floods at existing bridges on the stream.

The term "design flood" is purposely avoided in the above discussion because of the implication that a stream crossing can be designed for a unique flood event. In reality, a range of events should be examined to determine which design condition is most advantageous, insofar as costs and risks are concerned. If a design flood is designated for purposes of stream stability analysis, it probably should be that event which causes the greatest stress to the highway stream crossing system, that is, the flood magnitude and stage which is at incipient overtopping of the highway.

Hydrologic analysis establishes the probability of occurrence of a flood of given magnitude in any one year period. It also is the first step in establishing the probability of occurrence of the flood event which will pass through bridge waterways in the highway-stream crossing system without overtopping the highway. FHWA's HDS 2 should be referred to for more detailed information and guidelines on hydrologic analysis.[22] The second step is the determination of the stage-discharge relationship, flow and velocity distributions, backwater, scour, etc., (i.e., the hydraulics of the crossing system, as discussed in the remainder of this section).

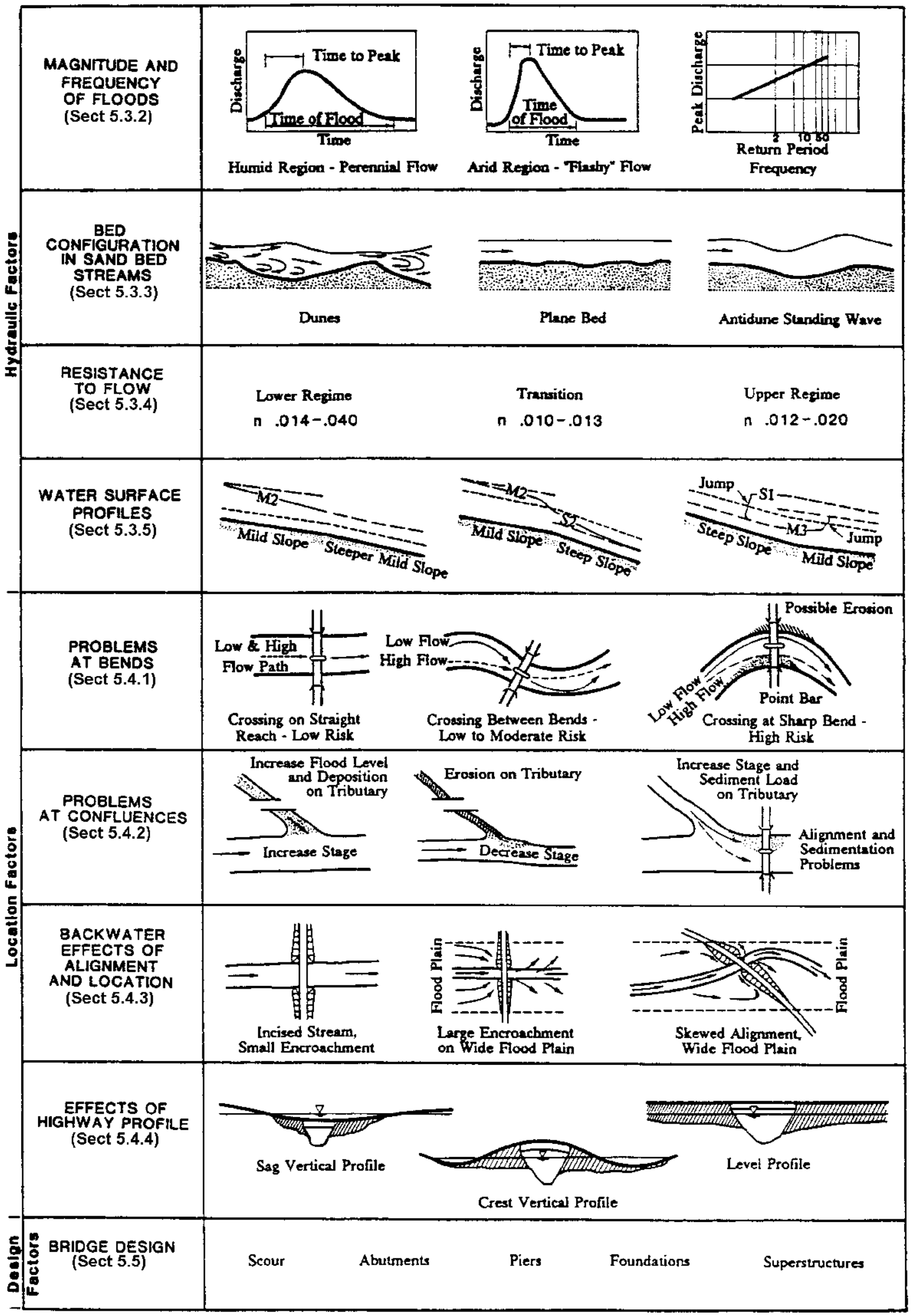

Figure 5.3. Hydraulic, location, and design factors that affect stream stability.

5.3.3 Bed Configurations in Sand-Bed Streams

In sand-bed streams, sand material is easily eroded and is continually being moved and shaped by the flow. The interaction between the flow of the water-sediment mixture and the sand-bed creates different bed configurations which change the resistance to flow, velocity, water surface elevation and sediment transport. Consequently, an understanding of the different types of bed forms that may occur and a knowledge of the resistance to flow and sediment transport associated with each bed form can help in analyzing flow in an alluvial channel. More specific to this discussion, it is necessary to understand what bed forms will be present so that the resistance to flow can be estimated and flood stages and water surface profiles can be computed.

Flow Regime. Flow in alluvial sand-bed channels is divided into two regimes separated by a transition zone.(13) Forms of bed roughness in sand channels are shown in Figure 5.4a, while Figure 5.4b shows the relationships between water surface and bed configuration. The flow regimes are:

- The lower flow regime, where resistance to flow is large and sediment transport is small. The bed form is either ripples or dunes or some combination of the two. Water-surface undulations are out of phase with the bed surface, and there is a relatively large separation zone downstream from the crest of each ripple or dune. The velocity of the downstream movement of the ripples or dunes depends on their height and the velocity of the grains moving up their backs.

- The transition zone, where the bed configuration may range from that typical of the lower flow regime to that typical of the upper flow regime, depending mainly on antecedent conditions. If the antecedent bed configuration is dunes, the depth or slope can be increased to values more consistent with those of the upper flow regime without changing the bed form; or, conversely, if the antecedent bed is plane, depth and slope can be decreased to values more consistent with those of the lower flow regime without changing the bed form.

- Resistance to flow and sediment transport also have the same variability as the bed configuration in the transition. This phenomenon can be explained by the changes in resistance to flow and, consequently, the changes in depth and slope as the bed form changes.

- The upper flow regime, in which resistance to flow is small and sediment transport is large. The usual bed forms are plane bed or antidunes. The water surface is in phase with the bed surface except when an antidune breaks, and normally the fluid does not separate from the boundary.

- There is no direct relationship between the classification of upper and lower flow regime and Froude Number (supercritical/subcritical flow).

Effects of Bed Forms at Stream Crossings. At high flows, most sand-bed stream channels shift from a dune bed to a transition or a plane bed configuration. The resistance to flow is then decreased to one-half to one-third of that preceding the shift in bed form. The increase in velocity and corresponding decrease in depth may increase scour around bridge piers, abutments, spur dikes or banks and may increase the required size of riprap. However, maximum scour depth with a plane bed can be less than with dunes because of the absence of dune troughs. On the other hand, the decrease in stage resulting from planning out of the bed will decrease the required elevation of the bridge, the height of embankments across the floodplain, the height of any dikes, and the height of any channel control works that may be needed. The converse is also true.

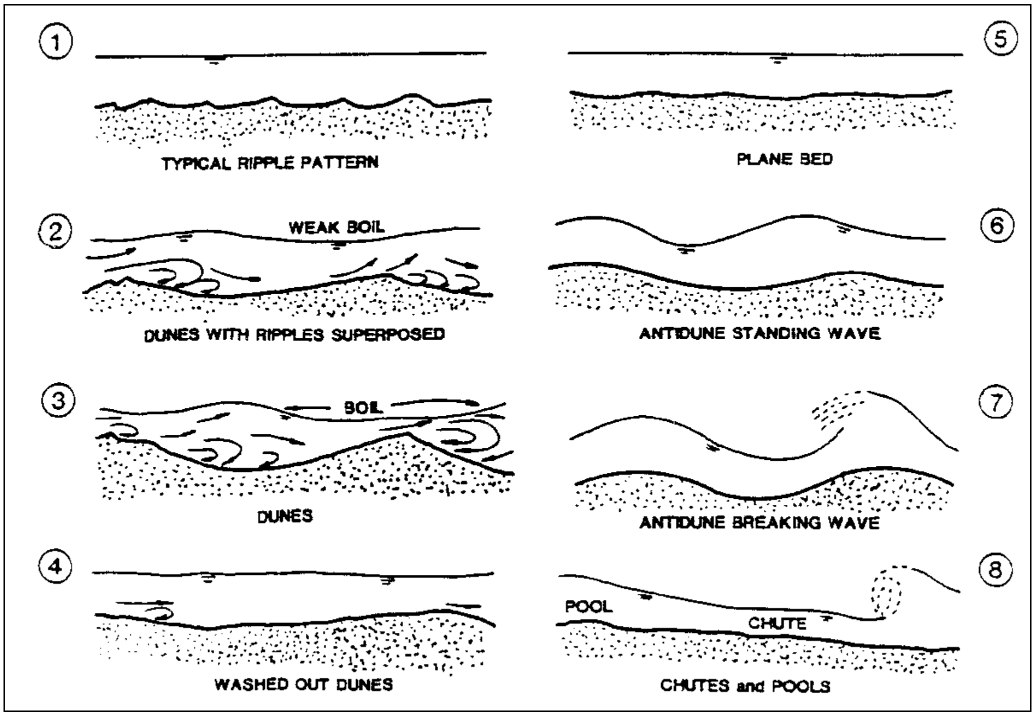

Figure 5.4(a). Forms of bed roughness in sand channels (after HDS 6).[13]

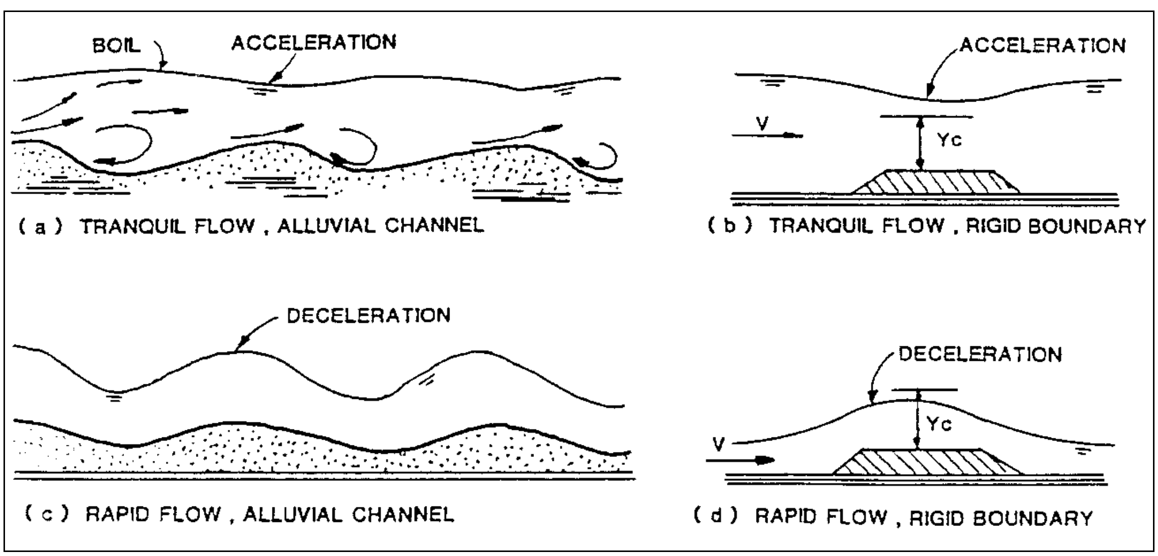

Figure 5.4(b). Relation between water surface and bed configuration (after HDS 6).[13]

Another effect of bed forms on highway crossings is that with dunes on the bed, there is a fluctuating pattern of scour on the bed and around piers. The average height of dunes is approximately one-third to one-half of the average depth of flow, and the maximum height of a dune may approach the average depth of flow. If the average depth of flow is 3 m (10 ft), maximum dune height may be on the order of 3 m (10 ft), half of which would be below the mean elevation of the bed. With the passage of a dune through a bridge opening, an increase in local scour would be anticipated when the trough of the dune arrives at the bridge. It has been determined experimentally that local scour increases by 30 percent or more over equilibrium scour depth with the passage of a large dune trough (see HEC-18).[1]

A very important effect of bed forms and bars is the change of flow direction in channels. At low flow, the bars can be residual and cause high velocity flow along or at a pier or other structures in the streambed, causing deeper than anticipated scour.

Care must be used in analyzing crossings of sand-bed streams in order to anticipate changes that may occur in bed forms and the impact of these changes on the resistance to flow, sediment transport, and the stability of the reach and highway structures. As described in Section 5.3.4, with a dune bed, the Manning's n (see Section 5.2.3) could be as large as 0.040. Whereas, with a plane bed, the n value could be as low as 0.010. A change from a dune bed to a plane bed, or the reverse, can have an appreciable effect on depth and velocity. In the design of a bridge or a stream stability or scour countermeasure, it is good engineering practice to assume a dune bed (large n value) when establishing the water surface elevations, and a plane bed (low n value) for calculations involving velocity.

5.3.4 Resistance to Flow

Use of the Manning's equation (Section 5.2.3) to compute flow in open channels and floodplains assumes one-dimensional flow. Procedures for summing the results of computations for subsections to obtain results for the total cross section involve use of the following assumptions: (1) mean velocity in each subsection is the same, (2) the total force resisting flow is equal to the sum of forces in the subsections, and (3) total flow in the cross section is equal to the sum of the flows in the subsections. This implies that the slope of the energy grade line is the same for each subsection (Figure 5.2). Assumption (3) is the basis for computing total conveyance for a cross section by adding conveyances of subsections (see Section 5.2.3).

Resistance to Flow in Channels. The general approach for estimating the resistance to flow in a stream channel is to select a base n value for materials in the channel boundaries assuming a straight, uniform channel, and then to make corrections to the base n value to account for channel irregularities, sinuosity, and other factors which affect the resistance to flow.[13,63] Equation 5.9 is used to compute the equivalent material roughness coefficient "n" for a channel:

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m \tag{5.9}$$

where:

n_b	=	Base value for straight, uniform channel
n_1	=	Value for surface irregularities in the cross section
n_2	=	Value for variations in shape and size of the channel
n_3	=	Value for obstructions
n_4	=	Value for vegetation and flow conditions
m	=	Correction factor for sinuosity of the channel

Table 5.1 provides base n values for stable channels and sand channels, while Table 5.2 provides adjustment factors for use in Equation 5.9. Richardson et al. and Arcement and Schneider provide more detailed descriptions of conditions that affect the selection of appropriate values.(13,60)

Resistance to Flow in Sand-Bed Channels. The value of n varies greatly in sand-bed channels because of the varying bed forms that occur with lower and upper flow regimes. Figure 5.5 shows the relative resistance to flow in channels in lower regime, transition, and upper regime flow and the bed forms which exist for each regime.

Sand-bed channels with bed materials having a median diameter from 0.14 to 0.4 mm usually plane out during high flows. Manning's n values change from as large as 0.040 at low flows to as small as 0.010 at high flow. Table 5.3 provides typical ranges of n values for sand-bed channels.

Table 5.1. Base Values of Manning's n (n_b).

Channel or Floodplain Type	Median Size, Bed Material		Base n Value	
	Millimeters (mm)	Inches (in)	Benson and Dalrymple	Chow
Sand Channels	0.2	--	0.012	--
	.3	--	0.017	--
(Only for upper regime	.4	--	0.020	--
flow where grain	.5	--	0.022	--
roughness is	.6	--	0.023	--
predominant)	.8	--	0.025	--
	1.0	--	0.026	--
Stable Channels and Floodplains				
Concrete	--	--	0.012 - 0.018	0.011
Rock cut	--	--	--	0.025
Firm soil	--	--	0.025 - 0.032	0.020
Coarse sand	1 - 2	--	0.026 - 0.035	--
Fine gravel	--	--	--	0.024
Gravel	2 - 64	0.08 – 2.5	0.028 - 0.035	--
Coarse gravel	--	--	--	0.026
Cobble	64 - 256	2.5 – 10.1	0.030 - 0.050	--
Boulder	> 256	> 10.1	0.040 - 0.070	--

Table 5.2. Adjustment Factors for the Determination of n Values for Channels.			
	Conditions	n Value	Remarks
n_1	Smooth	0	Smoothest channel
	Minor	0.001-0.005	Slightly eroded side slopes
	Moderate	0.006-0.010	Moderately rough bed and banks
	Severe	0.011-0.020	Badly sloughed and scalloped banks
n_2	Gradual	0	Gradual Changes
	Alternating Occasionally	0.001-0.005	Occasional Shifts From Large to small sections
	Alternating Frequently	0.010-0.015	Frequent changes in cross-sectional shape
n_3	Negligible	0-0.004	Obstructions < 5% of cross-section area
	Minor	0.005-0.015	Obstruction < 15% of cross-section area
	Appreciable	0.020-0.030	Obstruction 15-50% of cross-section area
	Severe	0.040-0.060	Obstruction > 50% of cross-section area
n_4	Small	0.002-0.010	Flow depth > 2 x vegetation height
	Medium	0.010-0.025	Flow depth > vegetation height
	Large	0.025-0.050	Flow depth < vegetation height
	Very Large	0.050-0.100	Flow depth < 0.5 vegetation height
m	Minor	1.00	Sinuosity < 1.2
	Appreciable	1.15	1.2 < Sinuosity < 1.5
	Severe	1.30	Sinuosity > 1.5

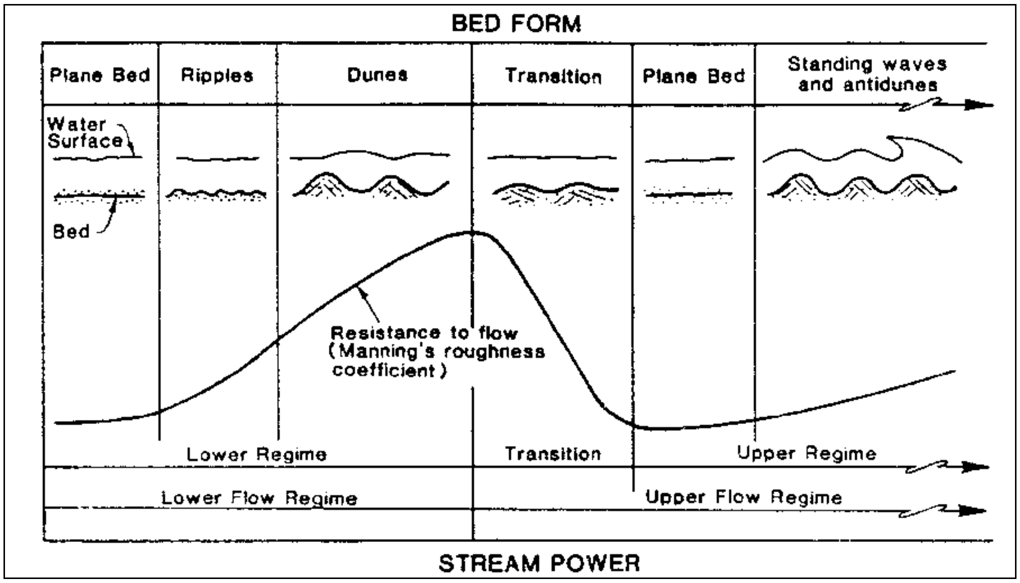

Figure 5.5. Relative resistance to flow in sand-bed channels (after Arcement and Schneider).[60]

Table 5.3. Manning's n (n_b) Roughness Coefficients for Alluvial Sand-bed Channels (no vegetation[1]).	
Lower Flow Regime	
Plane bed	0.014 - 0.020
Ripples	0.018 - 0.030
Dunes	0.020 - 0.040
Transition	
Washed out dunes	0.014 - 0.025
Upper Flow Regime	
Plane bed	0.010 - 0.013
Standing Waves	0.012 - 0.015
Antidunes	0.012 - 0.020
[1]Data are limited to sand channels with D_{50} < 1.0 mm.	

Resistance to Flow in Coarse Material Channels. A coarse material channel may range from a gravel bed channel up to the cobble-boulder channels typical of mountainous regions. The latter type channels may have bed material that is only partly submerged making it difficult to determine the channel roughness. However, for gravel and small cobble and boulder-bed channels analysis of data from many rivers, canals and flumes shows that channel roughness can be predicted by the following equation:[64]

$$n = K_u \, D_{50}^{1/6} \tag{5.10}$$

where:

D_{50} is measured in mm (inches)

K_u = 0.0152 SI
K_u = 0.04 English

Alternately, Limerinos developed Equation 5.11 from samples on streams having bed materials ranging in size from small gravel to medium size boulders.[65]

$$n = \frac{K_u\ R^{1/6}}{1.16 + 2.08\ \log\left(\frac{R}{D_{84}}\right)} \tag{5.11}$$

where:

R = Hydraulic radius, m (ft)
D_{84} = 84th percentile (percent finer) size of bed material, m (ft)

K_u = 0.113 SI
K_u = 0.0926 English

Flow depth, Y, may be substituted for the hydraulic radius, R in wide channels (W/Y > 10). Note that Equation 5.11 also applies to sand-bed channels in upper regime flow.[60]

The alternative to use of Equations 5.10 or 5.11 for gravel-bed streams is to select a value of n from Table 5.1. Because of the range of values in the table, it would be advisable to verify the selected value by use of one of the above equations if flow depth or velocities will significantly affect a design. HDS 6 also gives equations for this case.[13]

Resistance to Flow on Floodplains. Arcement and Schneider modified Equation 5.9 for channels to make it applicable for the estimation of n values for floodplains.[60] The correction factor for sinuosity, m, becomes 1.0 for floodplains, and the value for variations in size and shape, n_2, is assumed equal to zero. Equation 5.9, adapted for use on floodplains, becomes:

$$n = n_b n_1 + n_3 + n_4 \tag{5.12}$$

where:

n_b = Base value of n for a bare soil surface
n_1 = Value to correct for surface irregularities
n_3 = Value for obstructions
n_4 = Value for vegetation

Selection of the base n value for floodplains is the same as for channels. The USGS Water Supply Paper 2339 is recommended for a detailed discussion of factors which affect flow resistance in floodplains.[60]

5.3.5 Water Surface Profiles

The water surface profile in a stream or river is a combination of gradually varied flow over long distances, and rapidly varied flow over short distances. Due to various obstructions in the flow, such as bridges, the actual flow depth over longer reaches is either larger or smaller than the normal depth defined by Manning's uniform flow equation. In the immediate vicinity of the obstruction, the flow can be rapidly varied.

Gradually Varied Flow. In gradually varied flow, changes in depth and velocity take place slowly over a large distance, resistance to flow dominates and acceleration forces are neglected. The calculation of a gradually varied flow profile is well defined by analytical procedures (e.g., see HDS 6), which can be implemented manually or more commonly by computer programs such the FHWA WSPRO program, or the U.S. Army Corps of Engineers (USACE) HEC River Analysis System (RAS).[13,28,29,30] A qualitative analysis of the general characteristics of the backwater curve is often useful prior to quantitative evaluation. Such an analysis requires locating control points, determining the type of profile upstream and downstream of the control points, and then sketching the backwater curves. For example, Figure 5.3 illustrates several typical profiles that would result from a control represented by a change in bed slope. HDS 6 provides a detailed discussion of water surface profiles for gradually varied flow.[13]

Rapidly Varied Flow. In rapidly varied flow, changes in depth and velocity take place over short distances, acceleration forces dominate and resistance to flow may be neglected. The calculation of certain types of rapidly varied flow are well defined by analytical procedures, such as the analysis of hydraulic jumps, but analysis of other types of rapidly varied flow, such as flow through bridge openings (Figure 5.6) are a combination of analytical and empirical relationships. The FHWA document Hydraulics of Bridge Waterways, provides a procedure for manual calculation of the backwater created by certain types of flow conditions at bridge openings.[66] Gradually varied flow computer programs, such as WSPRO and HEC-RAS include analysis of bridge backwater, but do not calculate undular jump conditions or the flow through the bridge when flow accelerations are large, that is, large change in velocity either in magnitude or direction.[28,29]

Superelevation of Water Surface at Bends. Because of the change in flow direction which results in centrifugal forces, there is a superelevation of the water surface in bends. The water surface is higher at the concave bank than at the convex bank (Figure 5.7). The total superelevation is measured from waters edge to waters edge. Half this amount is added to the average water surface elevation to obtain the water surface elevation at the concave (outside) bank. The resulting transverse slope can be evaluated quantitatively. By assuming velocity equal to average velocity, the following equation was derived for superelevation for subcritical flow:[67] Other equations for superelevation are given in HDS 6.[13]

$$\Delta Z = \frac{V^2}{g r_c}(r_o - r_i) \qquad (5.13)$$

where:

g	=	Acceleration of gravity, 9.81 m/s^2 (32.2 ft/s^2)
r_o	=	Radius of the outside bank at the bend, m (ft)
r_I	=	Radius of the inside bank, m (ft)
r_c	=	Radius of the center of the stream, m (ft)
ΔZ	=	Difference in water surface elevation between the concave and convex banks, m (ft)
V	=	Average velocity, m/s (ft/s)

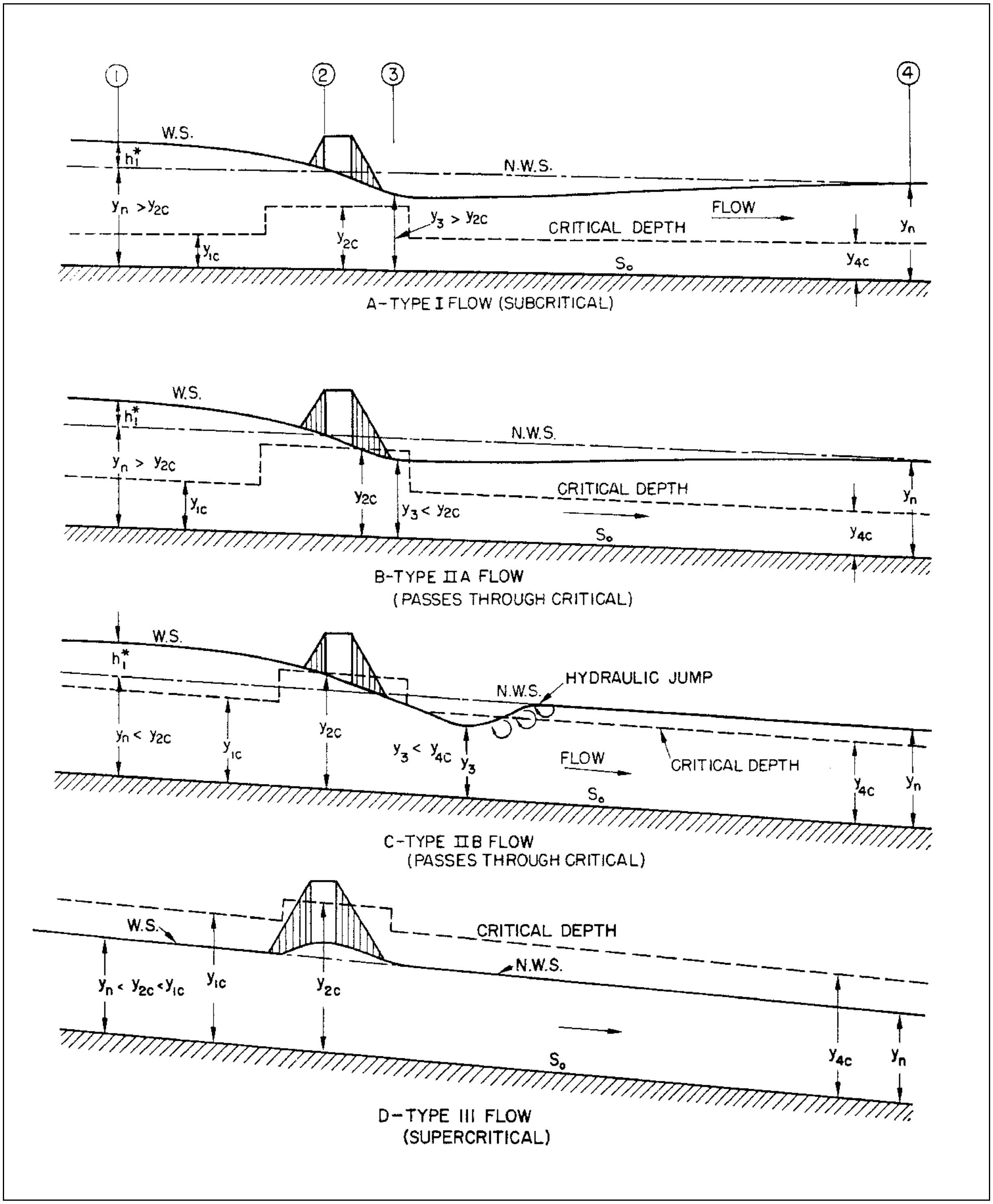

Figure 5.6. Types of water surface profiles through bridge openings (after Bradley).[66]

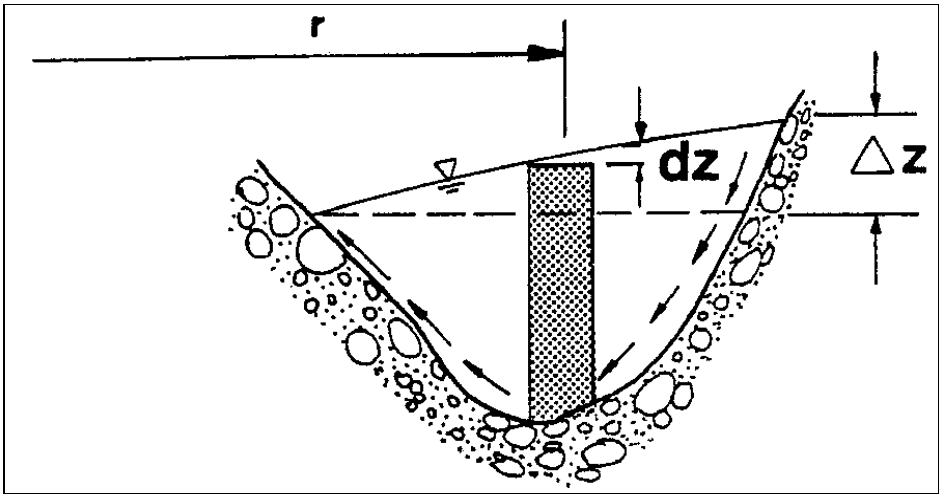

Figure 5.7. Superelevation of water surface in a bend.

5.4 GEOMETRY AND LOCATION OF HIGHWAY STREAM CROSSINGS

5.4.1 Problems at Bends

The location of a highway stream crossing is important because of the inherent instability of streams at some locations (see Chapter 2) and because the crossing system can contribute to instability. In general, a crossing on a straight reach is preferred because stability problems are usually minor. Low-flow and high-flow paths (thalwegs) are generally similar for a straight reach, reducing the risk of problems related to alignment and orientation of bridge piers and superstructures (Figure 5.3).

For a relatively stable meandering stream, a bridge crossing at the inflection point between bends generally reduces the risk of instability problems. At the inflection point, the low-flow and high-flow paths are comparable (Figure 5.3) and the crossing is in a zone where deposition and erosion are usually moderate. However, countermeasures against meander migration may still be required.

More hydraulic problems occur at alluvial stream crossings at or near bends than at all other locations because bends are naturally unstable. In addition, ice and floating debris tend to create greater problems in bends than in straight reaches. Other problems at bends include the shifting of the thalweg which can result in unanticipated scour at piers because of changes in flow direction and velocities, and nonuniform velocity distribution which could cause scour of the bed and bank at the outside of the bend and deposition in the inside of the bend (Figure 5.3). The high velocities at the outside of the bend or downstream of the bend can contribute substantially to local scour on abutments and piers.

5.4.2 Problems at Confluences

Hydraulic problems may also be experienced at crossings near stream confluences. Crossings of tributary streams are affected by the stage of the main stream (See Chapter 2). Aggradation of the channel of the tributary may occur if the stage of the main stream is high during a flood on the tributary, and scour in the tributary may occur if the stage in the main stream is low. Similarly, problems at a crossing of the larger stream can result from varying flow distribution and flow direction at various stages in the stream and its tributary, and from sediment deposited in the stream by the tributary (Figure 5.3). Tributaries entering the main channel upstream of a main channel bridge can also cause varying flow distribution and direction at various stages (flows) in the main channel and the tributary.

5.4.3 Backwater Effects of Alignment and Location

As flow passes through a channel constriction, most of the energy losses occur as expansion losses downstream of the contraction. This loss of energy is reflected by a rise in the water surface and the energy line upstream from the constriction. Upstream of bridges, the rise in water level above the normal water surface (that which would exist without the bridge) is referred to as the bridge backwater (Figure 5.6). However, many bridges do not cause backwater even at high flows even though they constrict the flows.[13] Hydraulic engineers are concerned with backwater with respect to flooding upstream of the bridge; backwater elevation with respect to the highway profile; and the effects on sediment deposition upstream, scour around embankments, contraction scour due to the constriction, and local scour at piers.

The effects of highway-stream crossing alignments on backwater conditions shown in Figure 5.8 are based on:

- Backwater resulting from a long skewed or curved roadway embankment (Figure 5.8a) may be quite large for wide floodplains. In effect, the bridge opening is located up-valley from one end of the embankment and the water level at the downstream extreme of the approach roadway, as at point A in Figure 5.8a, can be significantly higher than at the bridge.

- Backwater in an incised stream channel without substantial overbank flow (Figure 5.8b) is seldom large, but contraction and local scour may be severe. Backwater results from encroachment in the channel by approach embankments and from piers located in the channel.

- Backwater resulting from a normal crossing of the valley where road approach embankments block overbank flow (Figure 5.8c) may be significant. General and local scour may be severe if a significant quantity of flow is diverted from the floodplain to the bridge waterway.

5.4.4 Effects of Highway Profile

A highway stream crossing is a system consisting of the stream and its floodplain, the bridge(s) and the approach roadways on the floodplain. All floods which occur during the life of the crossing system will pass either through the bridge waterways provided or through the waterways and over the highway. The highway profile and alignment control the quantity of flow which must pass through waterway openings. Flood frequency should be considered in the design of bridge components and may influence highway profile and alignment.

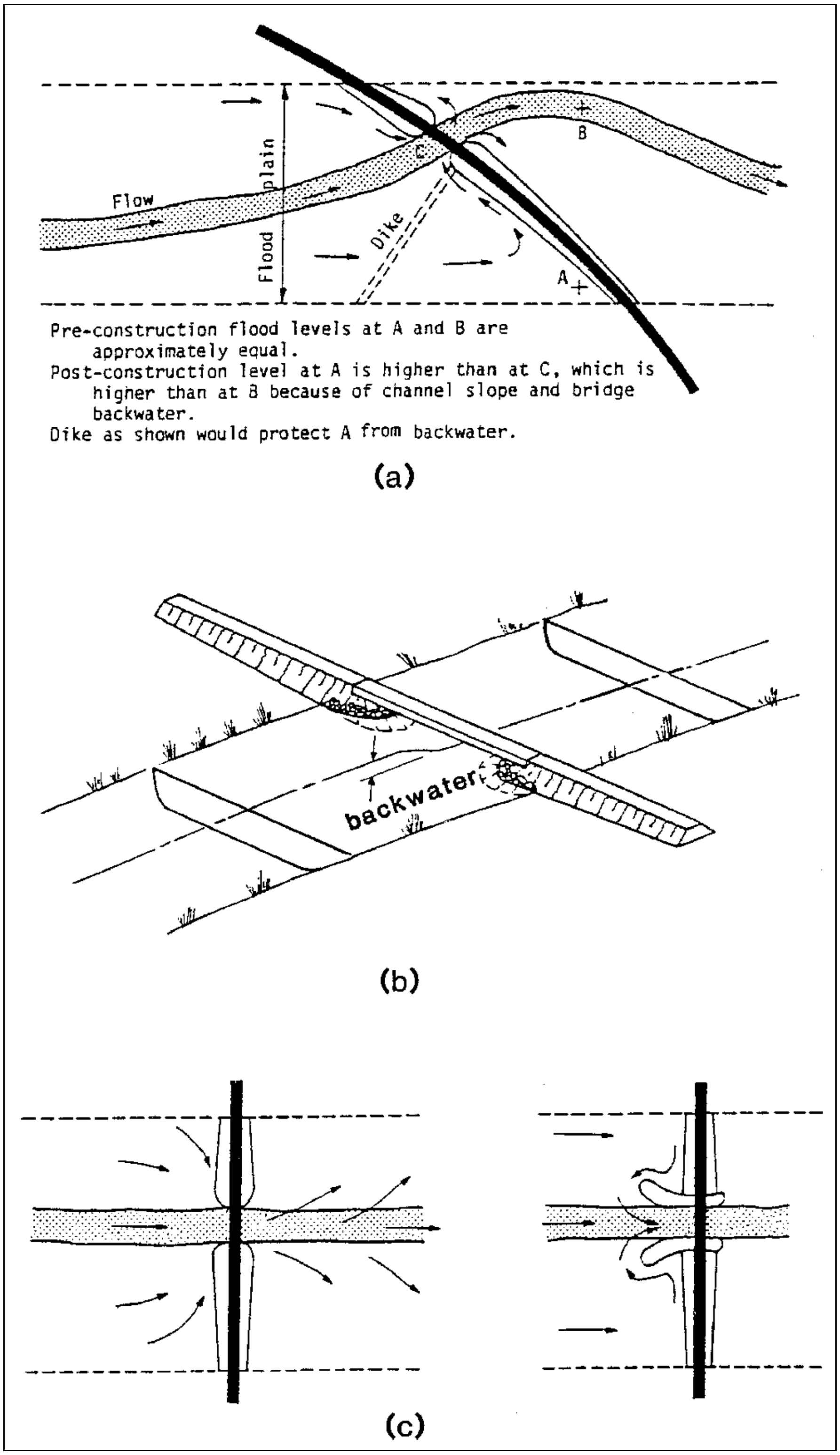

Figure 5.8. Backwater effect associated with three types of stream crossings: (a) a skewed alignment across a floodplain, (b) constriction of channel flow, and (c) constriction of overbank flow (after Neill).[68]

The stage-discharge relationship for the stream and backwater associated with a crossing design are the hydraulic considerations for establishing the highway profile. Profile alternatives are dependent on site topography and other site constraints, such as land use, traffic requirements, and flood damage potential. Figures 5.9a, b, and c illustrate profile alternatives, namely, a sag vertical curve, a crest vertical curve on the bridge or a rolling profile, and a level profile. A distinctive aspect of the sag vertical curve, as depicted in Figure 5.9a, is the certainty that the bridge structure will be submerged before overflow of the roadway will occur. Therefore, the magnitude and probability of occurrence of such a flood event should be considered in the design of the waterway opening and bridge components. A variation of the sag vertical curve where the low point of the curve is located on a floodplain rather than on the bridge affords relief to the bridge waterway. Bridges on level profiles and sag vertical curves are susceptible to debris accumulation on the superstructure, impact forces, buoyant forces, and accentuated contraction and local scour.

The crest vertical profile illustrated in Figure 5.9b provides protection to the bridge in that flood events exceeding the stage of the low point in the sag vertical curve will, in part, flow over the roadway. This relieves the bridge and the bridge waterway of stresses to which bridges on sag vertical curves and level profiles are subjected.

Regardless of the profile, when the superstructure is submerged (pressure flow through the bridge), pier scour is increased. In some cases the local scour with pressure flow will be two to three times deeper than for free flow.(1)

5.5 BRIDGE DESIGN

The design of bridge components must consider the effects on the local stability of a stream because of scour caused by the bridge encroachment on the stream (Figure 5.3). It is prudent to utilize designs which minimize undesirable stream response, to the extent practicable. This applies to component design as well as to the design of the total crossing system, including countermeasures against stream instability. The term countermeasure, as used here, is not necessarily an appurtenance to the highway stream crossing, but may be an integral part of the highway or bridge (for further discussion see HEC-23).(2)

The location and size of bridge openings influence stream stability. Encroachment in the stream channel by abutments and piers reduces the channel section and may cause significant contraction scour. Severe constriction of floodplain flow may cause approach embankment failures and serious contraction scour in the bridge waterway. Auxiliary (relief) openings should be carefully designed to avoid excessive diversion of floodplain flow to main channel bridge openings on wide floodplains and at skewed crossings of floodplains.

5.5.1 Scour at Bridges

Scour at bridges consists of three components: (1) long-term aggradation or degradation of the stream channel (natural or human-induced), (2) contraction scour due to constriction or the location of the bridge, and (3) local scour. In general, the three components are additive (for further discussion see HEC-18.(1)

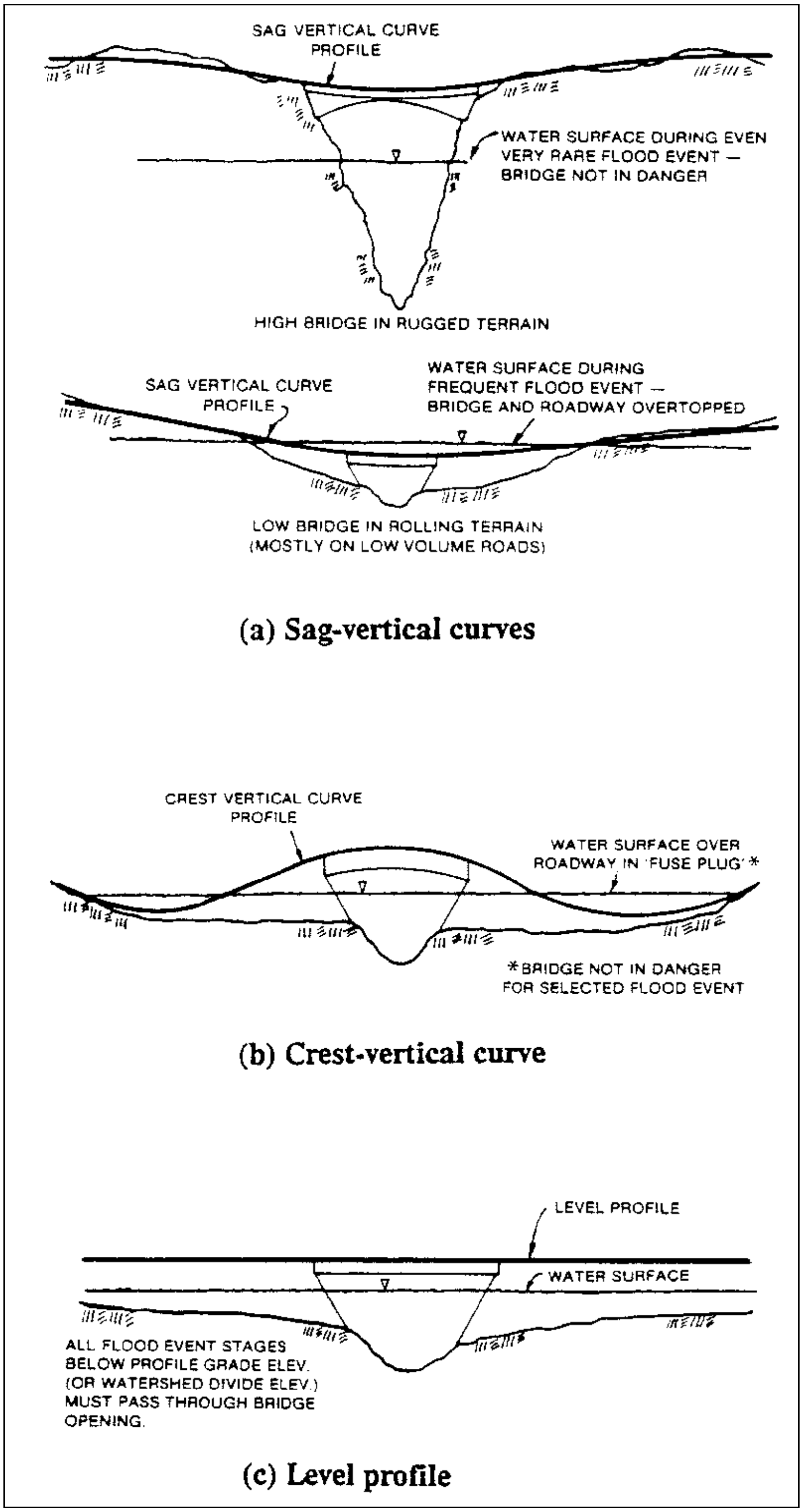

Figure 5.9. Various highway profiles: (a) sag-vertical curves, (b) crest-vertical curve, and (c) level profile.[69]

Scour can be related to the following factors: (1) channel slope and alignment, (2) channel shifting, (3) bed sediment size distribution, (4) antecedent floods and surging phenomena, (5) accumulation of debris, logs, or ice, (6) flow contraction, flow alignment, and flow depth, (7) pier and abutment geometry and location, (8) type of foundation, (9) natural or man-induced modification of the stream, and (10) failure of a nearby structure.

The rate of scour depends on the erosive forces exerted on the channel boundary and the resistance of the material to erosion. Resistance to erosion in fine cohesive material results from molecular forces. Resistance in noncohesive material depends primarily on bed sediment size distribution and density.

Under steady flow conditions, scour processes gradually approach an equilibrium condition; however, equilibrium scour conditions are not necessarily attained during a single flow event. Bridge crossings are generally subjected to unsteady flow conditions, and a series of events are often required to reach equilibrium or maximum scour depth. Deposition often occurs during the recession of the hydrograph, and the maximum scour depth measured after the flood is generally less than the maximum depth of scour reached during the flood event.

Gravel mining in the streambed can cause severe stream instability. Therefore, it is essential to monitor sand and gravel mining so that countermeasures can be installed to stabilize the stream in the vicinity of a highway facility. Where possible, mining should be managed so that instabilities in the stream system will be minimized (see additional discussion in Section 2.4.3).

Methods and equations for determining scour at piers and abutments are given in HEC-18.(1) Countermeasures for stream instability, pier scour, and abutment scour are discussed in HEC-23.(2)

5.5.2 Abutments

Bridge abutments are classified as spill-through, vertical wall, or vertical wall with wingwalls. Abutments are susceptible to damage by scour depending on flow distribution, foundation materials, velocities and other factors. However, scour at spill-through abutments is about 50 percent smaller than at vertical wall abutments subjected to the same scouring actions.

In addition to the effects of abutment shape, scour at abutments is affected by the skew of approach flow at the abutment, soils materials, encroachment on the floodplain and in the channel, and the amount of overbank flow diverted to the bridge waterway by approach fills to the bridge. Equations and methods for computing abutment scour are presented in HEC-18.(1)

5.5.3 Piers

The number of piers in any stream channel should be limited to a practical minimum and, if possible, piers should not be located in the channel of small streams. Piers properly oriented with the flow do not contribute significantly to bridge backwater, but they can contribute to contraction scour. Piers should be aligned with flow direction at flood stage in order to minimize the opportunity for debris collection, to reduce the contraction effect of piers in the waterway, to minimize ice forces and the possibility of ice dams forming at the bridge, and to minimize backwater and local scour.

Pier orientation is difficult where flow direction changes with stage or time. Cylindrical piers or some variation thereof, are probably the best alternative if orientation is critical. A solid pier will not collect as much debris as a pile bent or a multiple-column bent. Rounding or streamlining the leading edges of piers helps to decrease the accumulation of debris and reduces local scour. Recent studies have provided additional data on the effects of footings and the behavior of pile groups.[1,70] Guidance pertaining to pier foundations is presented in HEC-18.[1]

Piers located on a bank or in the stream channel near the bank are likely to cause lateral erosion of the bank. Piers located near the streambank on the floodplain are vulnerable to undermining by bank scour and meander migration. Piers which must be placed in such locations should be founded at elevations safe from undermining.[1]

5.5.4 Bridge Foundations

The types of foundations used for bridges include piles, piles with pile caps, spread footings, footings on piles or drilled shafts, drilled shafts, and caissons. Spread footings are used where sound rock is relatively shallow, but failures have occurred where spread footings were set in erodible rock.

Piling usually are dependent on the surrounding material for skin friction and lateral stability. In some locations, they can be carried to bedrock or other dense materials for bearing capacity. Tip elevation for piling should be based on estimates of potential scour depths as well as bearing in order to avoid losing lateral support and load carrying capacity after scour. Pile bearing capacity derived from driving records has little validity if the material through which the piles were driven is scoured away during a flood.

Caissons are used in large rivers and are usually sunk to dense material by excavation inside the caisson. Founding depths are such that scour is not usually a problem after construction is completed; however, severe contraction scour has developed at some bridges, because of contraction of flow from the large piers.

Attention should be given to potential scour resulting from channel shifts in designing foundations on floodplains. Also, the thalweg in channels should not be considered to be in a fixed location. Consideration should be given, therefore, to duplicating the foundation elevations of the main channel piers on adjacent floodplain piers. The history of stream channel activity can be very useful in establishing foundation elevations (see Chapter 2).

5.5.5 Superstructures

Hydraulic forces that should be considered in the design of a bridge superstructure include buoyancy, drag, and impact from ice and floating debris (for discussion, see HEC-18, Chapter 2[1]). The configuration of the superstructure should be influenced by the highway profile, the probability of submergence, expected problems with ice and debris, and flow velocities, as well as the usual economic, structural and geometric considerations. Superstructures over waterways should provide structural redundancy, such as continuous spans (rather than simple spans). The catastrophic bridge failures on Schoharie Creek and the Hatchie River due to scour and stream instability involved non-redundant bridges.[15,20]

CHAPTER 6

QUANTITATIVE TECHNIQUES FOR STREAM STABILITY ANALYSIS

Application of Level 2 Analysis Procedures

6.1 INTRODUCTION

Highway and bridge design, scour and stream stability analyses, bridge rehabilitation and countermeasure design, and channel restoration projects are all affected by changes in the morphologic characteristics of a stream. While qualitative techniques (Chapters 2 and 4) and classification and reconnaissance (Chapter 4) provide insight on channel processes, the application of quantitative geomorphic and engineering techniques may be necessary to evaluate the potential impact of changes in channel morphology for highway planning, design, and rehabilitation.

In general, the highway engineer needs to address three questions in regard to stream stability:

- What is the bank stability at the highway structure?
- What is the lateral (planform) stability of the stream channel?
- What is the vertical (profile) stability of the streambed?

The effects of lateral (planform) instability of a stream on a highway encroachment or bridge crossing are dependent on the extent of the bank erosion or channel migration and the design of the encroachment or bridge. Bank erosion can undermine piers and abutments located outside the channel and erode abutment spill slopes or breach approach fills. Migration of a bend through a bridge opening changes the direction of flow (angle of attack) through the opening, accentuating local and contraction scour. This chapter provides quantitative techniques to evaluate the lateral stability of a channel including: meander characteristics and prediction of the effects of lateral channel migration.

The typical effects associated with bed elevation (vertical) changes at highway bridges are erosion at abutments and the exposure and undermining of piers from degradation or scour, or a reduction in flow area from aggradation under bridges. Aggrading and degrading channels can also change planform, potentially eroding floodplain areas and highway embankments on the floodplain. In this chapter, specific quantitative procedures for estimating incipient motion and armoring characteristics of the streambed are presented. An indication of relative channel stability can be obtained from an application of an equation for incipient motion particle size developed from the Shields diagram. Determining the critical or threshold conditions at which hydrodynamic forces are sufficient to move a sediment particle provides insight on what flow conditions might mobilize the bed and affect channel vertical stability. A simple procedure developed by the U.S. Bureau of Reclamation for determining the depth of degradation necessary to produce an armor layer sufficient to arrest vertical instability is also presented.

Going beyond a comparison of historic streambed profiles or simple quantitative techniques to assess streambed vertical stability requires considerable expertise in sediment transport analyses. However, sediment continuity analysis and equilibrium slope concepts provided in this chapter offer a relatively straight forward approach to more detailed vertical stability analyses. If a more rigorous analysis of channel vertical dynamics is desired, application of the U.S. Army Corps of Engineers HEC-6 computer model[24] or the FHWA BRI-STARS model[23] can be considered.

Finally, the highway engineer must be cognizant of the potential need to restore or rehabilitate environmentally degraded stream channels when designing, constructing, and maintaining highway stream crossings. Chapter 7 provides an introduction to channel restoration concepts and reference to recently published guidelines for channel restoration design.

6.2 LATERAL CHANNEL STABILITY

Under ideal circumstances, a stable channel is one that does not change in size, form, or position over time. However, all alluvial channels change to some degree and, therefore, have some degree of inherent instability. An unstable channel is one with a rate or magnitude of change that is sufficiently large to be a significant factor in the design and maintenance of engineered structures within the river environment.

Although a stream or river may appear unstable, this does not necessarily indicate that it is not an equilibrium or regime channel. Based on the relationship of channel width, depth, and slope to discharge, most natural alluvial channels have probably attained or approached a state of equilibrium at one time or another. Yet, these channels migrate laterally at rates ranging from imperceptible to very rapidly. Thus, equilibrium or regime channels may not necessarily be stable in the practical engineering sense. An actively migrating channel may maintain its equilibrium slope and cross section while posing a threat or hazard to engineered structures. Some types of lateral instability are shown in Figure 4.11.

Bank retreat and active meander migration produce lateral instability and channel widening. As discussed in Appendix B, there are two mechanisms by which banks retreat: fluvial entrainment and mass failure. The specific failure mechanisms at a given location are related to the characteristics of the bank material. Commonly, mass failure and fluvial entrainment act in concert; fluvial erosion scours the bank toe followed by oversteepening and failure of the bank. Removal of the failed bank material from the base of the bank occurs through fluvial erosion and the process is repeated.

The bank erosion process can result from channel incision (degradation), flow around bends, flow deflection due to local deposition or obstructions, aggradation, or any combination of these. Flow around a bend can cause erosion at the toe of the outside or convex bank and subsequent bank failure due to increased shear stress on the outside of the bend. Fluvial entrainment through grain detachment can be a significant process in areas of concentrated flow and high shear stress (e.g., on the outside of bends). However, studies of bank erosion processes indicate that mass failure and subsequent fluvial transport of the failed material is the primary mechanism by which the lateral adjustment occurs.

It is important to note that fluvial erosion of previously failed bank material plays a significant role in determining the rates of bank retreat. Fluvial activity controls the state of basal endpoint control and removal of the failed material results in the formation of steeper banks and may induce toe erosion by removing the material along the toe that buttresses the bank slope (see Appendix B).[71] These factors rejuvenate the process of bank erosion by mass failure. Without basal erosion, mass failure of the bank material would lead to bank slope reduction and stabilization within a relatively short period of time.[71,72]

6.2.1 Meander Migration

Meandering streams are classified as either actively or passively meandering. An actively meandering stream has sufficient stream power to deform its channel boundaries through active bed scour, bank erosion, and point bar growth. Conversely, while a passively meandering stream is sinuous, it does not migrate or erode its banks.

Initiation of Meanders. Although there is no completely satisfactory explanation of how or why meanders develop,(73) it is known that meanders are initiated by localized bank retreat which alternates from one side of the channel to the other in a more or less regular pattern. In addition, deformation of the channel bed may be an important prerequisite that modifies the pattern of flow prior to meandering. It is believed that secondary helicoidal flow develops spontaneously in straight channels as a result of vortices generated at the boundary walls (Figure 6.1).(74,75) A pair of surface-convergent helical cells will form if vortices develop along both banks. Inequalities in bank roughness may induce asymmetry in these cells and periodic reversal of the dominant cell. This periodically reversing helicoidal flow has an important influence on the pattern of erosion and deposition through meanders, and more specifically by forming a meandering thalweg and alternating bars.(74) In addition, macroturbulent flow and the bursting process (i.e., streamwise fluctuations in the velocity field) are also important components in bank deformation.(76,77)

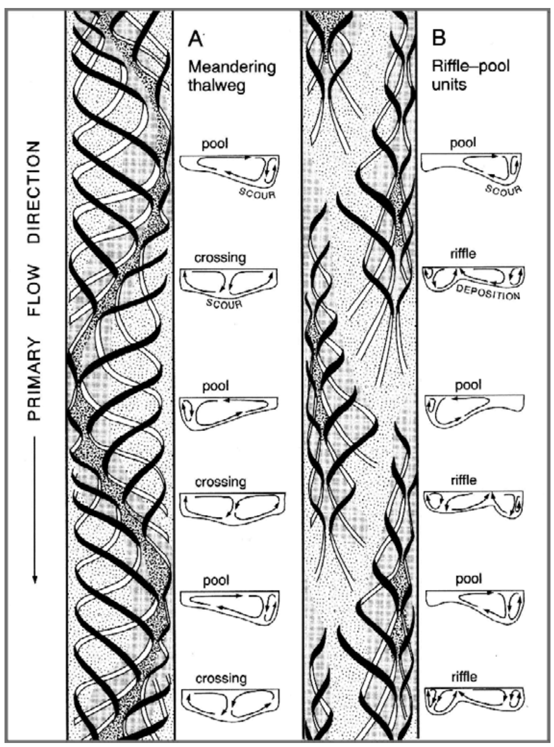

Figure 6.1. Models of flow structure and associated bed forms in straight alluvial channels:(73) (A) Einstein and Shen's(74) model of twin periodically reversing, surface-convergent helical cells, (B) Thompson's(78) model of surface-convergent flow produced by interactions between the flow and a mobile bed, creating riffle-pool units of alternate asymmetry. Black lines indicate surface currents, and white lines represent near-bed currents.

Flow Pattern Through Meander Bends. The primary features of the flow pattern through meander bends are:

- Superelevation of the water surface against the outside (convex) bank (Figure 5.7)
- Transverse current directed towards the outer bank at the surface and towards the inner bank at the bed producing a secondary circulation additional to the main downstream flow
- Maximum-velocity current which moves from near the inner bank at the bend entrance to near the outer bank at the bend exit, crossing the channel at the zone of maximum bend curvature

The interaction between centrifugal force acting outwardly on the water as it flows around the bend and an inward-acting pressure gradient force driven by the cross stream tilting of the water surface is reflected in the above characteristics. The transverse current and the primary downstream flow component combine to produce the helicoidal motion to the flow. The superelevation of the water surface against the outer bank of a bend produces a locally steep downstream energy gradient and, in turn, a zone of maximum boundary shear stress in close proximity to the outer bank just downstream of the bend apex (Figure 6.2A). The maximum shear stress zone shifts outward further upstream as a result of the bar-pool topography and cross-sectional asymmetry characteristic of meander bends.

Secondary currents, which are usually weaker than primary ones, influence the distribution of velocity and boundary shear stress. Markham and Thorne(79) divided the bend cross-section into three regions relative to the pattern of secondary flow (Figure 6.2B):

- Mid-channel region, helicoidal flow is well established passing nearly 90 percent of the flow
- Cell of opposite circulation develops in the *outer bank region*: the strength of this cell increases with discharge, the steepness of the bar, and the acuteness of the bend
- Inner bank region where shoaling over the point bar induces a net outward flow, forcing the core of maximum velocity more rapidly toward the outer bank;(80,81) increasing stage tends to reduce the shoaling, allowing an inward component of near-bed flow over the bar top

The location and timing of the flow pattern varies with discharge, bend tightness, and cross-sectional form. Primary currents are dominant at high discharges because the main flow follows a straighter path, but secondary currents are relatively strong at intermediate discharges.(82) The degree of superelevation and the strength of the secondary circulation increase in tighter bends (i.e., low R_c/W). In bends where $R_c/W < 2$, flow impinges on the outer bank at a sharper angle causing flow separation and generating a strong back-eddy along the outer bank near the bend apex, possibly inducing sedimentation along the outer bank upstream of the bend apex.(83,84) The width/depth ratio exerts a major influence on flow pattern.(79) Point bar development is more extensive and the shoaling effect over the bar directs the inner-bank flow radially outward when the width/depth ratio is relatively large. However, in narrow, deep channels, especially where $W/y < 10$, bars are less likely to form, thus reducing the shoaling effect and allowing an inward movement of near-bed flow.

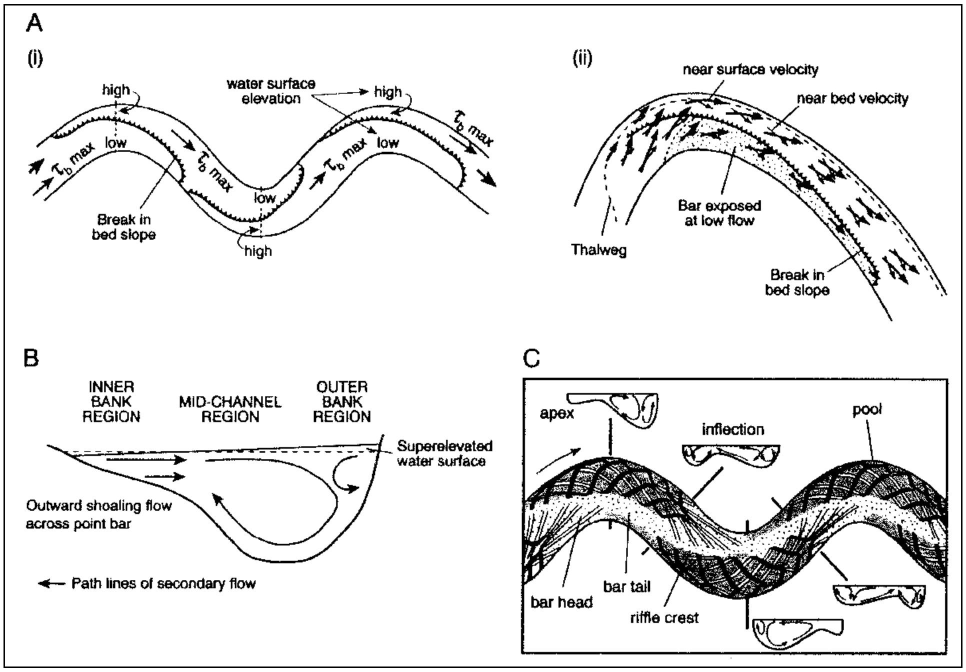

Figure 6.2. Flow patterns in meanders:[73] (A) (i) Location of maximum boundary shear stress (τ_b), and (ii) flow field in a bend with a well-developed point bar (after Dietrich),[81] (B) Secondary flow at a bend apex showing the outer bank cell and the shoaling-induced outward flow over the point bar (after Markham and Thorne),[79] (C) Model of the flow structure in meandering channels (after Thompson).[78] Black lines indicate surface currents and white lines represent near-bed currents.

The pattern of primary and secondary currents influences the distribution of erosion and deposition in meanders. In general, erosion in the bend is concentrated along the outer bank downstream of the bend apex where the currents are strongest, while point bar building predominates in a parallel position along the opposite bank, with material supplied by longitudinal and transverse currents. This produces a largely downvalley component to meander migration.

Meander Geometry. Meanders are defined by their geometry; specifically by their shape, bend radius, and wavelength (Figure 4.10). Consistent relationships exist between these meander parameters and channel width. Relative to the planform of a sinuous channel, pools are located at meander bends and riffles are situated at the crossings between bends. The riffle spacing, which is generally 5 to 7 times the width (W), is approximately half the meander wavelength (λ), which is 10 to 14 times the width (Figure 2.4). The radius of curvature (R_c) of bend is generally 2 to 3 times the width.

Langbein and Leopold characterized meander geometry in terms of a sine-generated curve defined by the following equation:[85]

$$\theta = \omega \sin\left(\frac{2\pi x}{\lambda}\right) \qquad (6.1)$$

where:

- θ = Channel direction
- ω = Maximum angle between a channel segment and the mean downvalley axis
- x = Sinusoidal function of distance, m (ft)
- λ = Meander wave length, m (ft)

This curve closely approximates the curve of minimum variance, or least work in turning around the bend, and describes the form of symmetrical meander paths relatively well. However, real meanders are asymmetrical and deviate significantly from idealized, perfectly symmetrical, sine-generated curves. Bend asymmetry occurs because the point of deepest scour and maximum attack on the outer (convex) bank in a bend is usually located downstream of the geometric apex of the bend. This causes the bend to migrate downstream through time, becoming skewed in the downvalley direction as they shift.

Leopold and Wolman established a link between meander wavelength and channel width over several orders of scale of flow in a variety of natural environments.[51,86] Their equations (referred to as hydraulic geometry relationships) were developed from meander characteristics of free-flowing regime channels as follows (SI units):

$$\lambda = 11.0\ W^{1.01} \tag{6.2}$$

$$A_m = 3.0\ W^{1.1} \tag{6.3}$$

$$\lambda = 4.6\ R_c^{0.98} \tag{6.4}$$

$$R_c = 2.3\,W \tag{6.5}$$

where:

- λ = Meander wavelength (m or ft) measured along the axis of the channel
- W = Channel topwidth (m or ft) at the dominant discharge
- A_m = Meander amplitude (m or ft)
- R_c = Bend centerline radius of curvature (m or ft)

and the constants in Equations 6.2 through 6.4 are 10.9, 2.7, and 4.7 in English units, respectively.

Subsequent reanalysis of the Leopold and Wolman data by Richards has resulted in an acceptable linear relationship of meander wavelength of the form:[87]

$$\lambda = 12.34\ W \tag{6.6}$$

The coefficient in this equation is very close to being twice the systematic riffle-pool spacing in a straight channel as defined by $2\pi W$ or 5-7W (Figure 2.4b). Hydraulic geometry relationships show that channel topwidth should be closely related to discharge in an alluvial channel. Thus, there should be a relationship between discharge and wavelength. Although it is well established that width is approximately proportional to the square root of discharge, the determination of the discharge that is physically most significant in shaping meanders is still under debate. It is likely that meander geometry is related to a range of discharges, the competence of which varies with boundary materials. Therefore, the degree and magnitude of lateral instability on a meandering stream is most likely dependent on a combination of its bank material composition and discharge.

Schumm analyzed large empirical data sets for sand bed channels in an attempt to account for the effect of boundary materials on meander wavelength explicitly by using a weighted silt-clay index of the bed and bank sediments.[88] As seen in the following equations, as the proportion of fine material in the bed and banks increases, the meander wavelength decreases (SI units):

$$\lambda = 1935\, Q_m^{0.34}\; M^{-0.74} \tag{6.7}$$

$$\lambda = 618\; Q_b^{0.43}\; M^{-0.74} \tag{6.8}$$

$$\lambda = 395\; Q_{ma}^{0.48}\; M^{-0.74} \tag{6.9}$$

where:

Q_m = Mean annual discharge (m^3/s or ft^3/s)
Q_b = Bankfull discharge (m^3/s or ft^3/s)
Q_{ma} = Mean annual flood (m^3/s or ft^3/s)
M = Percent silt-clay in the channel boundary

and the constants in Equations 6.7 through 6.9 are 1890, 438, and 234 for English units, respectively.

This indicates that the greater erosion resistance of silt-clay banks results in a narrow cross-section with steeper banks and tighter, shorter wavelength bends than those channels with non-cohesive or less cohesive, easily eroded banks. In addition, Fisk's work on the Lower Mississippi River indicates that the form of most meanders is influenced by variations in the erodibility of the materials in the outer bank.[89,90]

Schumm also demonstrated the relationship of channel sinuosity to the weighted silt-clay index and the form ratio (width/depth) using the following:

$$P = 0.94\; M^{0.25} \tag{6.10}$$

$$P = 3.50\; F^{-0.27} \tag{6.11}$$

where:

P = Planform sinuosity
F = Width/depth ratio

These equations link the characteristic wavelength of meandering channels to the formative flow in the channel, its width, and the nature of the boundary materials.

The combination of the wavelength relations, width, and bend radius described above yields the following relationship:

$$R_c \approx 2 \text{ to } 3\ W \qquad (6.12)$$

For radius-to-width ratios (R_c/W) of 2 to 3, Bagnold showed that energy losses due to the curving of flow in the bend were minimized.[91] Plots of both meander migration rate and bend scour depth as a function of bend tightness also peak sharply at a R_c/W of between 2 and 3, indicating that these bends are the most effective at eroding their bed and banks (see Figure 6.3 and related discussion). The fact that many bends in nature develop and retain an R_c/W value of 2 to 3 while migrating across the floodplain may be consistent with their conformance to the most efficient hydraulic shape, which also maximizes their geomorphic effectiveness.[44]

Thorne examined the distribution of bend scour with bend geometry in a study of the Red River and determined that in very long radius bends ($R_c/W > 10$) mean scour pool depth is about 1.5 times the mean riffle (crossing) depth, and the maximum scour depth is between 1.7 and 2 times the mean crossing depth.[92] Scour depths ranged from 2 to 4 times the mean crossing depth for bends with R_c/W values between 2 and 4, with the greatest scour associated with R_c/W of about 2. Evidence suggests that maximum scour depths decrease with decreasing bend radius for extremely tight bends with $R_c/W < 2$.

Care should be taken when using these relationships for the rehabilitation or restoration of meanders to an optimal form at specific sites. As Knighton states: "These various relationships indicate a self-similarity of meander geometry over a wide range of scales and environmental conditions. However, the regularity which they imply is not everywhere apparent, and the use of single parameters provides only a partial and often subjective characterization of meander form."[73] Chapter 7 provides an introduction to channel restoration concepts.

6.2.2 Evaluation and Prediction of Lateral Migration

In general, most streams are sinuous to some degree and the majority of bank retreat and lateral migration occurs along meander bends. As such, the following discussion on evaluating and predicting lateral migration will focus on meander bends. Three methods of determining lateral stability and migration rates will be discussed: (1) the analysis of sequential historic aerial photographs, maps, and surveys; (2) the use of the curvature ratio (R_c/W) to determine the optimal bend shape; and (3) the use of the radial stress concept to determine the maximum force per unit area on the outside margin of a bend.

Aerial Photograph Analysis. The most accurate means of measuring changes in channel geometry and lateral adjustments is through repetitive surveys of the channel cross section. However, this data is rarely available. The next easiest and relatively accurate method of determining migration rates and direction is through the comparison of sequential historical aerial photography (photos), maps, and surveys. Brice provides a comprehensive methodology for conducting a stream stability and meander migration assessment using a comparative analysis of aerial photos, maps, and channel surveys.[38,93]

Accuracy in such an analysis is greatly dependent on the period over which migration is evaluated, the amount and magnitude of internal and external perturbations forced on the system over time, and the number and quality of sequential aerial photos and maps. The analysis will be much more accurate for a channel that has coverage consisting of multiple data sets (aerial photos, maps, and surveys) covering a long period of time (several tens of years to more than 100 years) versus an analysis consisting of only two or three data sets covering a short time period (several years to a few tens of years). Predictions of migration for channels that have been extensively modified or have undergone major adjustments attributable to extensive land use changes will be much less reliable than those made for channels in relatively stable watersheds.

Historical aerial photos and maps can be obtained from a number of federal, state, and local agencies (Table 3.1). Extensive topographic map coverage of the United States at a variety of scales can be obtained from the local or regional offices of the U.S. Geological Survey. In general, both air photos and maps are required to perform a comprehensive and relatively accurate meander migration assessment. Since the scale of aerial photography is often approximate, contemporary maps are usually needed to accurately determine the true scale of air photos. Distortion of the image on aerial photos is also a common problem and becomes greater as one moves further away from the center of the photo. Expensive equipment, which is generally needed to rectify and eliminate aerial photo distortion, is often unavailable, so distortion and scale differences must be accounted for by some other means. The scale problem is easily rectified through the use of multiple distance measurements taken between common reference points on the photos and maps. The measurements of distance between several reference-point pairs common to both the photos and maps are then averaged to define an average scale for the photos. Common reference points can include cultural features such as building corners, roads or fences and their intersections, irrigation channels and canals, or natural features such as isolated rock outcrops, large boulders, and trees, drainages and stream confluences, and the irregular boundaries of water bodies.

The accurate delineation of a bankline on aerial photos is primarily dependent on the density of vegetation at the top of the bank. Top bank is easily defined if stereo-pairs of photos are available. However, single photos can be used relatively easily if one knows what to look for. For banks with little or no vegetation, the top of the bank is easily identified. The abrupt change between the water and the top of the bank along the convex bank in a bend or an eroding cutbank is defined by an abrupt change in the contrast and color (color photo) or gray tone (black and white photo). Usually the water is significantly darker than the top of bank. Along the concave or inner bank of a bend, exposed bar sediment is lighter colored than the river or the top of bank. The top bank along a point bar is usually defined by persistent vegetation such as mature trees and shrubs.

Where vegetation becomes increasingly dense along a bank, small sections of the top of the bank may be visible such that a line can be drawn connecting the sections. Often, the top of the bank may be completely obscured by vegetation and one may be required to locate the top of the bank by approximation. In this case, one can assume that the trunks of the largest trees growing along the river are nearly vertical and are located just landward of the top of the bank. Therefore, a line that approximates the top of the bank may be drawn just riverward of the center of the tree. The amount of error involved with this method increases with decreasing stream size.

If the density of vegetation along a stream is such that an accurate delineation of the top of the bank cannot be made, then the use of the channel centerline may be required. The centerline is drawn with reference to bankfull conditions. Therefore, the channel centerline can and often does cross the exposed portions of point bars. Usually the channel centerline can be delineated more easily than a bankline masked by vegetation since the centerline can be drawn equidistant from the edge of mature vegetation on either side of the channel.

There are three general methods of assessing lateral bank erosion and meander migration using maps and aerial photographs. The following discussion will deal with assessments using air photos, but the same methods can be used when making assessments or measurements from maps. In order of increasing complexity and accuracy, distances of lateral retreat can be:

- Estimated by visual comparison of two air photos flown at different times

- Measured by scaling distances directly from the bank to fixed reference points common to both photographs

- Measured on a drawing on which historic channel banklines taken from sequential air photos are superimposed at the same scale

The first method provides a preliminary assessment of stability, especially where significant changes in bank position have occurred. The second method requires measurements made along a line described by two reference points on either side of the bank that are common to both photos. The second method will usually only provide a few accurate measurements along the bank, depending on the number of reference points and the number of lines that can be drawn across the bend. Additional problems may be associated with the location of the lines since they may not be perpendicular to bank retreat nor allow a measurement at the point of maximum retreat.

The third method is relatively easy and accurate. This method requires that the banklines and the common reference points from each historic air photo be traced onto a transparent or semi-transparent sheet after they have been enlarged or reduced to a common scale. The channel centerline can also be delineated on the same sheet at the same time. Then, each bankline or centerline is transferred to and superimposed on a common sheet such that a sequential comparison of the banklines or centerlines can be made. The total bankline area eroded can be measured for each period and divided by the bankline length to define the average bank retreat. Dividing either the maximum distance or the average distance of bank retreat by the number of years between air photos results in a maximum or average migration rate, respectively. Drawing a line perpendicular to centerline at the location of maximum retreat defines the direction of maximum retreat. This process is repeated for each series of sequential photos. Based on the measurements between years, one may be able to define migration rates relative to significant hydrologic or geomorphic events. Overall rates can also be determined by summing the distances and dividing by the total number of years between the earliest and latest photos.

Measuring bankline versus centerline retreat is more meaningful, especially if the channel is widening concurrent with channel migration. Although measurements of centerline migration do not account for channel widening, they do provide a more accurate measurement of the overall direction of channel migration, which may be used to make predictions on the direction of channel migration in the future.

In addition, the meander wavelength, amplitude, sinuosity, and radius of curvature for each time period can be measured from the overlays (Figure 4.10). The radius of curvature can be measured through the use of a circle template. The radius is determined by matching a circle with known radius as closely as possible to the centerline of the channel. For irregular meanders containing small bends within the larger meander bend, it may be necessary to measure both the overall bend radius and the secondary radii of the internal bends. The center point of the circle and the outside bank at the bend apex define the points from which the meander amplitude is measured. In order to determine sinuosity, a line is drawn between two points over the channel planform and parallel to the valley axis. Sinuosity is determined by measuring the straight-line downvalley distance and the channel centerline distance between the two common points on the valley line. Meander wavelength is measured along the valley axis as well.

Optimal Bend Shape. The preferred method for estimating the rate and magnitude of migration involves the use of empirical data or historical migration rates. When such data are not available or future conditions are significantly different than historical conditions, the maximum lateral migration distance that can be expected over the long term can be estimated based upon the optimal bend shape (the shape most commonly found on freely meandering, unconfined, alluvial rivers). While the "optimal" shape may be the most natural bend shape, since it minimizes the resistance to flow, it may maximize the natural channel migration potential (see Section 7.3).

The rate of migration is largely controlled by bend geometry, especially by channel curvature (R_c/W). Hickin and Nanson[83,84,94] demonstrated through detailed studies of more than 125 bends on 19 river reaches in Canada that the rate of migration reaches a maximum when $2 < R_c/W < 3$. The rate decreases rapidly on either side of this range (Figure 6.3). At the lower end of the range, the decrease may be attributable to the large increase in resistance or a decrease in outer-bank radial force as R_c/W falls below 2.

Due to the loss of energy associated with flow through a bend, a maximum bend sharpness exists beyond which further significant lateral erosion is unlikely to occur. It has been shown that the maximum lateral erosion rate for a meander bend occurs when the ratio of radius of curvature to channel width is in the range of about 2 to 4 (Figure 6.3). For R_c/W values less than about 2, the erosion rate reduces sharply due to energy loss in the bend, and in very tight bends ($R_c/W << 2$), deposition may actually occur along the outer bank of the bend. Under this condition, the rate of lateral migration significantly decreases or migration stops and the bend either cuts off or avulses (i.e., undergoes an abrupt shift in channel course).

Observations indicate that river meanders tend to a value of R_c/W of between 2 and 3 (Equation 6.5). This range of bend sharpness seems to result in a minimum value of resistance to flow, with flow resistance increasing rapidly as R_c/W decreases below 2. In addition, meanders develop to minimize the variance of shear and friction through the bend. Langbein and Leopold[85] showed that the planform for such a meander follows the approximate shape of a sine-generated curve (Equation 6.1).

As previously discussed (Section 6.2.1), a typical meander wavelength is approximately 10 to 14 channel widths. Considering the sinusoidal characteristics of a meander as defined by Equation 6.1, the maximum deviation of a channel from a straight line (Δ_{max}) will occur when the ratio R_c/W is at its minimum. Using Equation 6.1, it can be shown that the minimum value of R_c/W (i.e., maximum bend sharpness) for a sine-generated curve occurs at a sinuosity of 1.5. The average value of R_c/W varies from 2.0 for $\lambda/W = 10$ to 2.8 for $\lambda/W = 14$. For these conditions, the maximum offset of the channel from a straight line for a sine-generated curve with minimum radius of curvature is approximately one-fourth the meander wavelength, or one-half the distance between the endpoints (crossings) for a given channel bend (Figure 6.4). Thus, a rough approximation of the maximum lateral erosion distance (Δ_{max}) is:

$$\Delta_{max} = 2.5 \text{ to } 3.5\, W_D \qquad (6.13)$$

where:

W_D = Channel width associated with the dominant discharge, Q_D

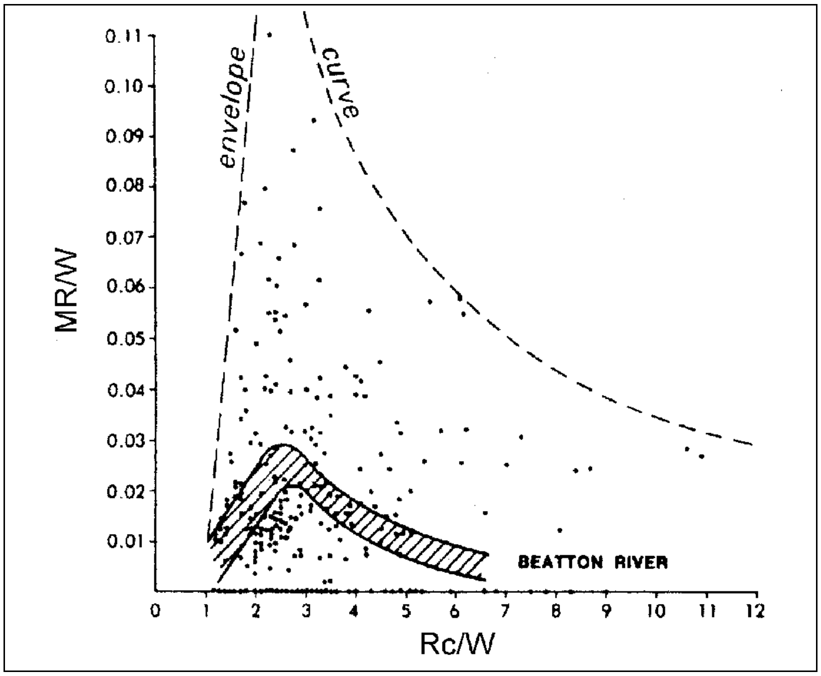

Figure 6.3. The relationship between the ratio of migration rate (MR) to channel width (W) and the ratio of radius of curvature (Rc) to width for several rivers in Canada.[94]

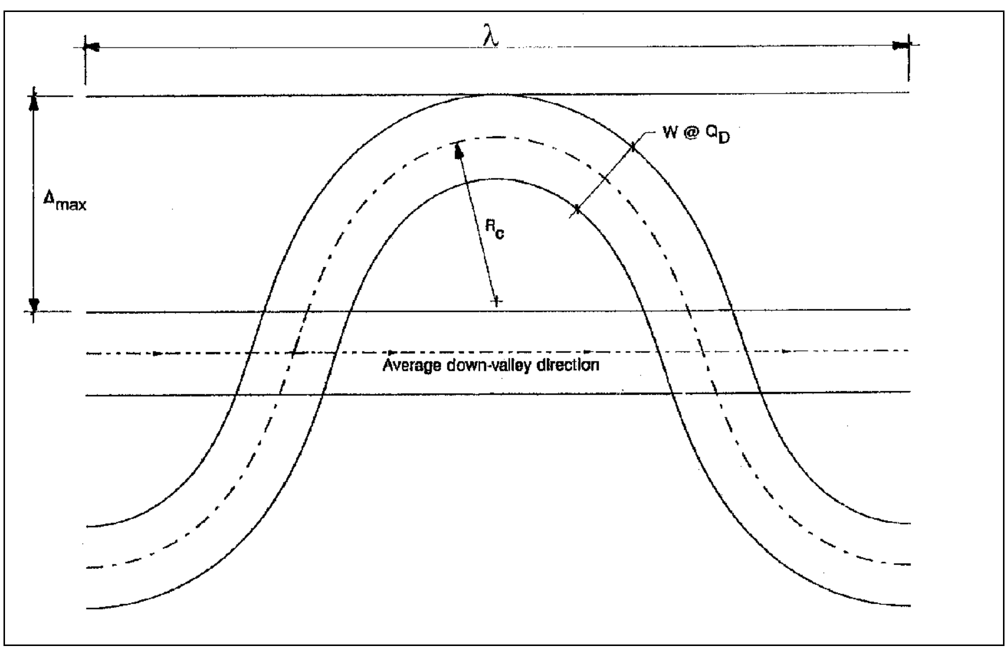

Figure 6.4. Schematic of an idealized meander bend illustrating the variables described in Equation 6.13.

The dominant discharge is the flow 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. It is the discharge which determines the principal dimensions and characteristics of a natural channel. The dominant formative discharge depends on the maximum and mean discharge, duration of flow, and flood frequency. For fully adjustable, perennial streams, it is normally assumed that the dominant (or channel forming) discharge is approximately equivalent to the mean annual flood peak, varying from about the 1.5-year return period peak discharge (humid regions) to the 10-year peak discharge (arid regions). When considering hydraulic geometry relationships, the dominant discharge can be taken to be the bankfull discharge, which has a return period of approximately 1.5 years in many natural channels.

The technique described above is part of Albuquerque Metropolitan Arroyo Flood Control Authority's (AMAFCA) Sediment and Erosion Design Guide[(95)] which establishes simplified procedures for use by public agencies and private engineers when establishing an erosion limit line, also referred to as the Prudent Line. The Prudent Line concept is based on the maximum lateral erosion distance (Δ_{max}) with the primary goal of maintaining natural or naturalistic channels while protecting adjacent property through incorporation of erosion barriers, setbacks, and selective stabilization.

6.3 VERTICAL CHANNEL STABILITY

6.3.1 Overview

Vertical channel stability was introduced in Chapter 2 (Section 2.4) and in Chapter 4 (Section 4.4) through discussion of the sediment continuity concept and the Lane relationship ($QS \propto Q_s D_{50}$). In the Lane relationship, the channel is assumed to be responding to a change in discharge or sediment supply and is moving from one equilibrium geometry to another, either by a change in slope or a change in sediment size. The sediment continuity concept compares the upstream sediment supply (inflow) with the channel's ability to convey sediment (transport capacity). A difference in the inflow of sediment and the transport capacity results in either aggradation or degradation of the channel bed. While these two concepts result in a prediction of channel response in the vertical (aggradation or degradation), they do not provide a prediction of the amount of aggradation or degradation required to reach a new equilibrium state or how quickly the channel will adjust.

Chapter 3 includes a discussion of three levels of analysis: Qualitative Geomorphic Analyses (Level 1), Basic Engineering Analyses (Level 2) and Mathematical or Physical Modeling Studies (Level 3). These three levels of analysis provide the engineer with an understanding of the likely direction of vertical instability and predictions of the amounts and rates of vertical adjustment.

In Level 1 (Qualitative Geomorphic Analyses), land use change, evaluation of vertical stability and prediction of channel response are discussed. Land use change is a common cause of vertical instability as it provides the change in flow or sediment supply causing the channel response. As discussed Section 3.5.5, historic bed elevation changes can be determined by comparing channel longitudinal profiles or comparing channel cross sections. Direct evidence of channel degradation includes (1) exposed utility crossings, (2) exposed bridge foundations, (3) channel banks failing due to excessive height and (4) comparison of channel profiles and cross sections. Bridge inspection reports, which should include soundings at each bent, are a valuable tool for assessing historic channel vertical stability and can be used to predict future trends. If a historic trend is identified, extrapolation can be used to estimate future aggradation or degradation over the life of the bridge. However, if the channel is reaching a new equilibrium condition, the extrapolation will over predict future change. Conversely, if the channel is responding to more recent conditions, extrapolation of historic rates may under predict future change.

In Level 2 (Basic Engineering Analyses), watershed sediment yield, incipient motion, armoring, and rating curve shifts are introduced as factors that influence vertical stability. Changing watershed sediment yield is one factor controlling sediment supply. In coarser bed materials, the channel bed may only be mobilized for relatively high flows and an incipient motion analysis provides insight on the frequency of bed mobilization and vertical stability. When a significant portion of the bed material cannot be moved even during extreme flows, an armor layer can arrest degradation. If a USGS stream gage is located near the bridge, review of historic rating curves (stage-discharge relationships) for the gage can be used to infer vertical stability (see Section 3.6.7). If the discharge increases for a particular stage (positive shift), then the channel has probably degraded.

Level 3 (Mathematical or Physical Modeling Studies) includes sediment transport modeling. Sediment routing using computer models is the most rigorous application of the sediment continuity concept and can be used to determine single event or long-term bed elevation changes in a river.

This section includes expanded discussion on the topics of predicting aggradation and degradation. For degradation, additional discussion on incipient motion analysis and armoring is presented. Expanding on the topic of channel response, stable slope analysis is included for estimation of a new equilibrium slope after the channel has adjusted to a new sediment supply. The topic of sediment continuity is also covered in more detail than in Chapter 2. Combining sediment continuity and transport relationships results in predictive tools for degradation and aggradation rates and amounts. These concepts, which can be used directly to estimate long-term aggradation or degradation, are the basis of sediment routing models.

6.3.2 Degradation Analysis

Incipient Motion. Incipient motion is the condition where the hydraulic forces acting on a sediment particle are equal to the forces resisting motion. The particle is at a critical condition where a slight increase in the hydraulic forces will cause the particle to move. The hydraulic forces consist of lift and drag and are usually represented in a simplified form by the shear stress of the flow acting on the particle. Incipient motion conditions can be analyzed using the Shields diagram or by the following equation developed from the diagram:

$$D_c = \frac{\tau_o}{K_s(\gamma_s - \gamma)} \tag{6.14}$$

where:

- D_c = Diameter of the sediment particle at the critical condition, m (ft)
- τ_o = Boundary shear stress, Pa (lb/ft^2)
- γ = Specific weight of water, N/m^3 (lb/ft^3)
- γ_s = Specific weight of sediment, N/m^3 (lb/ft^3)
- K_s = Dimensionless coefficient often referred to as the Shields parameter

The Shields parameter can range from 0.03 to 0.10 for natural sediments based on particle shape, angularity, gradation and imbrication. The use of 0.047 for sand sizes provides reasonable results,[96,97] but lower values (0.03) are commonly used for gravel and cobble sizes.

Equation 6.14 can be used to calculate a sediment particle size that will move for a particular hydraulic condition or to calculate the shear stress required to move a particular particle size. The average shear stress acting on the channel (γRS) includes all the factors contributing to resistance to flow (Sections 5.2.3 and 5.3.4). Only the shear stress acting on the individual particles should be used for this calculation. For sand sizes, the base value of Manning's n is representative of the grain resistance and the shear stress can be computed from:

$$\tau_o = \frac{\gamma n^2 V^2}{K_u^2 R^{(1/3)}} \tag{6.15}$$

where:

- n = Manning roughness coefficient
- V = Average channel velocity, m/s (ft/s)
- R = Hydraulic radius, m (ft)
- K_u = 1.0 SI
- K_u = 1.486 English

For coarser grained materials (gravel and larger) the Manning roughness coefficient is a function of grain size and flow depth. The shear stress can be computed from:

$$\tau_o = \frac{\rho V^2}{\left[5.75 \log\left(\frac{12.27 R}{k_s}\right)\right]^2} \tag{6.16}$$

where:

- ρ = Density of water, kg/m^3 (slugs/ft^3)
- k_s = Grain roughness usually taken as 3.5 D_{84} for gravel and coarser bed material, m (ft)

Equation 6.16 is essentially Equation 6.15 with the Limerinos equation (Equation 5.11) substituted for Manning's n. In the Limerinos equation, the grain roughness is equivalent to 3.5 times D_{84}, although for poorly graded material grain roughness can be as low as 1.0 to 2.0 times D_{84}. The hydraulic depth (channel area divided by topwidth) can be substituted for hydraulic radius, R, in Equations 6.15 and 6.16 when the width-depth ratio exceeds 10.

An incipient motion example problem is solved in Appendix E.

<u>Armoring</u>. Armoring occurs when the hydraulic forces are sufficient to move a portion of the bed material but insufficient to move the larger sizes. Under these conditions, the smaller material is transported and removed from the bed leaving the coarse material or an armor layer. Armor layers often form in gravel bed rivers during the recession of floods. These armor layers may be disturbed during the next major flood and re-form during the flood

recession. In a degrading stream with sufficient amounts of large particles, especially downstream of a dam, the large particles can form a permanent armor (pavement) which is stable under all flow conditions and arrests further degradation. The stability of an armor or pavement is relative to the armor forming discharge. If that discharge is exceeded, further degradation will occur.

The incipient motion equation can be used to determine the critical size of material that can resist a particular hydraulic condition. If at least five percent of the material is larger than the critical size (D_{95} or smaller), armoring can occur. The following equation is used to predict the amount of degradation that would need to occur to form an armor layer:[98]

$$Y_s = y_a\left(\frac{1}{P_c} - 1\right) \tag{6.17}$$

where:

Y_s = Depth of degradation or scour required to form the armor layer, m (ft)
y_a = Thickness of the armor layer, m (ft)
P_c = Percent of material coarser than the critical particle size expressed as a decimal fraction

Figure 6.5 illustrates armor layer development. The thickness of the armor layer ranges from one to three times the critical size (D_c) determined from the Shields incipient motion relation. A minimum of two times the critical size is required for a relatively stable armor layer.

An armoring example problem is solved in Appendix E.

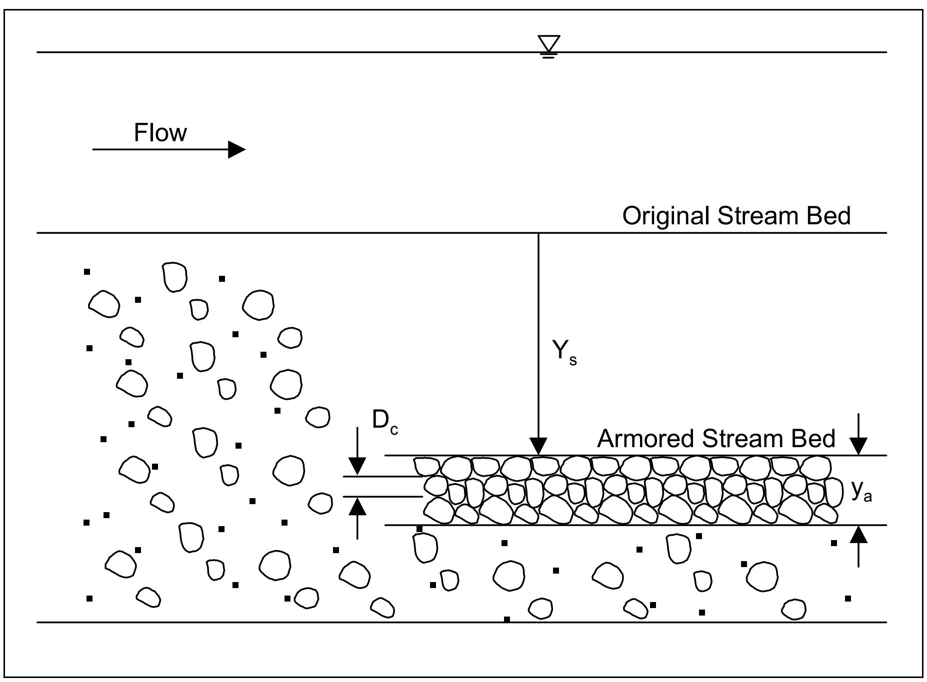

Figure 6.5. Channel armoring.

Equilibrium Slope Analysis. For clear-water releases of flow from dams or detention ponds, the channel immediately downstream would be expected to degrade until the reduction in slope results in a boundary shear stress too low to entrain the bed material. In a sand bed channel, the channel slope would have to be extremely low to reach incipient motion conditions and the amount of degradation could be significant. For a gravel bed channel, channel degradation would also occur, although, in addition to the reduction in slope, the formation of a pavement could arrest degradation. Depending on the bed and bank materials, the degrading channel can narrow as it deepens or the banks can become unstable and the channel can widen. Channel widening temporarily replenishes sediment supply.

For the case of no sediment supply from upstream, combining the incipient motion relation (Equation 6.14) and the Manning equation (Equation 5.3) results in an estimate of the equilibrium slope where bed material movement ceases:

$$S_{eq} = \left[K_s D_c \left(\frac{\gamma_s - \gamma}{\gamma} \right) \right]^{(10/7)} \left(\frac{K_u}{qn} \right)^{(6/7)} \qquad (6.18)$$

where:

S_{eq} = Channel Slope at which particles D_c will no longer move
q = Channel discharge per unit width, m^2/s (ft^2/s)
K_s = Shields parameter
K_u = 1.0 SI
K_u = 1.486 English
n = Manning roughness coefficient
D_c = Critical bed material size, m (ft)

This relationship assumes that the channel width remains constant for future conditions. The critical size (D_c) used in this equation should be D_{90} because the bed will coarsen as degradation occurs.

Another approach to determining an equilibrium slope under conditions of no upstream sediment supply is presented by the USBR using the Meyer-Peter Muller equation for beginning of transport.(98) If adjustment of the hydraulic depth due to the reduction in channel slope is included in the equation, the USBR equation is:

$$S_{eq} = K_u \frac{(D_{50})^{10/7} n^{9/7}}{(D_{90})^{5/14} q^{6/7}} \qquad (6.19)$$

where:

K_u = 28.0 SI
K_u = 60.1 English

The degradation computed from the reduction in slope could result in channel narrowing or bank failure and channel widening. Also, the appropriate discharge for use in the equation is difficult to select. A range of discharges are responsible for forming the channel. Given long periods of time, extreme discharges would ultimately be responsible for forming the channel under these conditions. An initial estimate for the clear-water condition is to use the bankfull discharge recognizing that as the channel degrades the dimensions will adjust.

A more typical situation involves a reduction in sediment supply. In this case, the equilibrium slope can be predicted using sediment transport relationships. As shown in the Lane relationship (Chapter 4), a reduction in sediment supply or an increase in discharge can cause a reduction in channel slope and degradation. The new equilibrium slope will produce hydraulic conditions where the channel sediment transport capacity matches the upstream sediment supply. This procedure can be performed using sediment transport equations directly or through simplified relationships. Sediment transport equations are presented in detail in HDS 6[13] and are discussed later in this chapter.

It is often useful to develop a sediment transport capacity relationship for a river reach in the form of:

$$q_s = aV^bY^c \tag{6.20}$$

where:

q_s	=	Sediment transport capacity per unit width, m^2/s (ft^2/s)
V	=	Channel average velocity, m/s (ft/s)
Y	=	Channel average depth, m (ft)
a,b,c	=	Coefficient and exponents

The coefficient and exponents can be determined from fitting Equation 6.20 to observed data or a sediment transport equation appropriate to the stream conditions. If the coefficient and exponents are fit to Yang's sediment transport equation for sand,[99] reasonable results (generally within 25 percent) are produced by the following equations. In English units the coefficients are:

$$a = 0.025\, n^{(2.39-0.8\log(D_{50}))}(D_{50} - 0.07)^{-1.4} \tag{6.21}$$

$$b = 4.93 - 0.74\log(D_{50}) \tag{6.22}$$

$$c = -0.46 + 0.65\log(D_{50}) \tag{6.23}$$

where:

D_{50}	=	Mean sediment size, mm (for both SI and English applications)
n	=	Manning's n

For metric units, b and c are unchanged, but the coefficient, a, must be multiplied by a factor of $0.3048^{(2-b-c)}$ when using Equation 6.21. **The range of data used to develop Equations 6.21 through 6.23 is shown in Table 6.1**.

Table 6.1. Range of Parameters.	
Parameter	Value Range
D_{50}, mm	0.1 - 2.0
Velocity, m/s (ft/s)	0.61 - 2.44 (2.0 - 8.0)
Depth, m (ft)	0.61 - 7.62 (2.0 - 25)
Slope	0.00005 - 0.002
Manning's n	0.015 - 0.045
Froude Number	0.07 - 0.70
Unit Discharge, m^2/s (ft^2/s)	0.9 - 18.6 (1.0 - 200)

For specific values of a, b, and c, the equilibrium slope can then be computed from:

$$S_{eq} = \left(\frac{a}{q_s}\right)^{\frac{10}{3(c-b)}} q^{\frac{2(2b+3c)}{3(c-b)}} \left(\frac{n}{K_u}\right)^2 \qquad (6.24)$$

where:

- S_{eq} = Equilibrium slope for the channel to match the upstream sediment supply
- q_s = Upstream sediment supply per unit width, m^2/s (ft^2/s)
- q = Unit discharge, m^2/s (ft^2/s)
- K_u = 1.0 SI
- K_u = 1.486 English

In the case of a reduction in sediment supply to a reach that was previously in equilibrium and with all other characteristics remaining constant (discharge, roughness and channel width), the equilibrium slope can be related to the existing channel slope by simplifying Equation 6.24 to produce:

$$S_{eq} = S_{ex}\left(\frac{Q_{s(future)}}{Q_{s(existing)}}\right)^{\frac{10}{3(b-c)}} \qquad (6.25)$$

where:

- S_{ex} = Existing channel slope
- Q_s = Sediment supply, m^3/s (ft^3/s)

The sediment supply, Q_s, for existing conditions can be measured or computed. The sediment supply for future conditions must be computed using an applicable sediment transport relationship.(13) Equations 6.24 and 6.25 also assume that channel width and bed material size remain constant as the channel degrades. The appropriate discharge for use in these equations is the effective discharge, which is defined as the discharge responsible for the greatest amount of sediment transport and, therefore, is considered to be responsible for channel formation. If the sediment rating curve is combined with a flow duration curve, the flow that is responsible for transporting the greatest quantity of sediment is the effective discharge.

Because Equations 6.24 and 6.25 use sediment transport capacity and sediment supply where each is determined from the same sediment transport relationship, the selection of the discharge does not greatly affect the equilibrium slope prediction. The bankfull discharge can be used as a reasonable estimate when additional information is unavailable.

Base Level Control. The equilibrium slope calculations provide an estimate for the slope adjustment inferred by the Lane relationship but do not yield a prediction of the extent or amount of degradation or the amount of time required to reach equilibrium. In a sediment deficient reach, degradation occurs first at the upstream end of the reach and progresses downstream. The downstream extent of degradation is limited by some vertical control to the channel base level (Figure 6.6). The base level control could be a geologic outcrop of erosion resistant material or extremely coarse material. In a tributary channel, the confluence with a much larger river could act as a downstream control. Lakes, reservoirs or the ocean can also act as controls. Grade control structures and culverts can also limit the extent of degradation downstream. If none of these controls exist, then degradation will continue until the channel reaches the equilibrium slope along the entire profile or until armoring takes place. As tributaries contribute sediment to the downstream channel, the effects of the reduced upstream sediment supply are diminished. The amount of ultimate degradation at a location upstream of the base level control can be estimated from the equilibrium slope computation as:

$$Y_s = L(S_{ex} - S_{eq}) \tag{6.26}$$

where:

Y_s	=	Ultimate degradation amount, m (ft)
L	=	Distance upstream of base level control, m (ft)

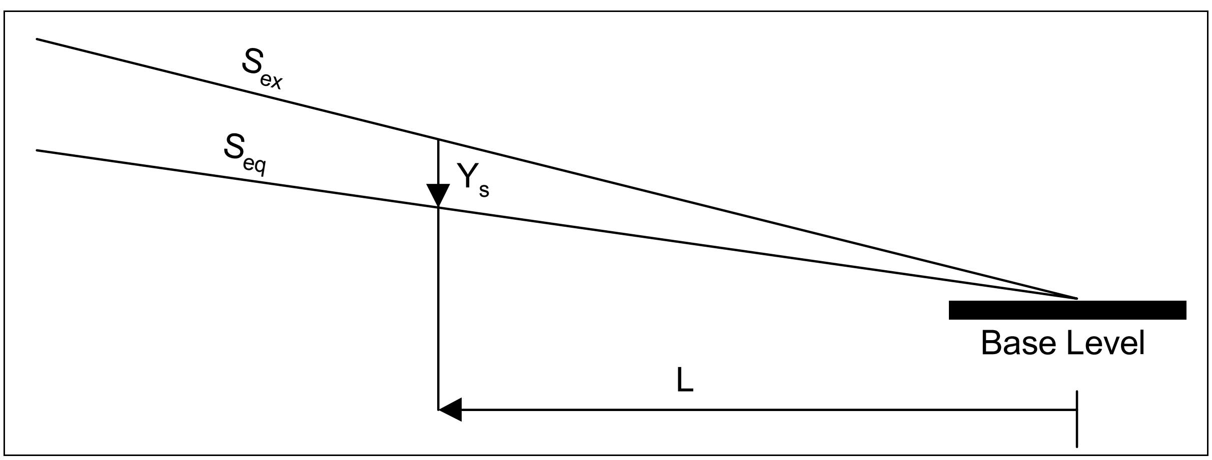

Figure 6.6. Base level control and degradation due to changes in slope.

Another consideration for base level control occurs when a control is removed or lowered on a primary channel and channel degradation progresses upstream. When a primary channel degrades, the base level control is lowered for each of its tributaries and degradation can progress up these channels. Figure 6.7 illustrates two types of upstream migrating degradation. Headcuts form in cohesive sediment and often form vertical drops with plunge pools at the base of the drop. Nickpoints form in non-cohesive sediments in which the over-steepened reach translates upstream. In each case, the cause of the degradation is a lowering of the downstream base level control. Headcuts and nickpoints are best identified though channel reconnaissance (Section 4.2) and it is reasonable to assume that the amount of degradation will be consistent over the entire stream reach.

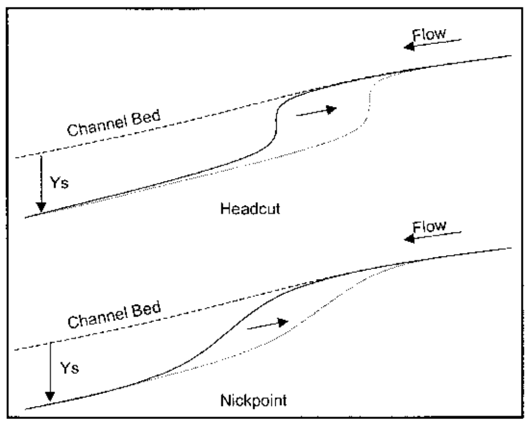

Figure 6.7. Headcuts and Nickpoints.

An equilibrium slope example problem is solved in Appendix E.

6.3.3 Sediment Continuity Analysis

Sediment Transport Concepts. Figure 6.8 shows the various modes of sediment transport. Sediment transport formula are developed to predict bed load, suspended bed material load or bed material load based on the sediment size and hydraulic conditions. Wash load is not hydraulically controlled, but is dependent on the supply of fine material from watershed and bank erosion. At high wash load concentrations the transport capacity of the bed material load can increase significantly. River Engineering for Highway Encroachments[13] includes an in-depth discussion of sediment transport processes, equations for predicting sediment transport and recommendations on the selection of an appropriate equation. This section will focus on two relatively easy to use bed material load equations that can be used in a sediment continuity analysis: Yang's equations for sand and gravel.[99] The sand equation is:

$$\log C_t = 5.435 - 0.286\log\frac{\omega D_{50}}{\nu} - 0.457\log\frac{U_*}{\omega} + \left(1.799 - 0.409\log\frac{\omega D_{50}}{\nu} - 0.314\log\frac{U_*}{\omega}\right)\log\left(\frac{VS}{\omega} - \frac{V_{cr}S}{\omega}\right) \qquad (6.27)$$

and for gravel:

$$\log C_t = 6.681 - 0.633 \log \frac{\omega D_{50}}{\nu} - 4.816 \log \frac{U_*}{\omega} + \left(2.784 - 0.305 \log \frac{\omega D_{50}}{\nu} - 0.282 \log \frac{U_*}{\omega}\right) \log\left(\frac{VS}{\omega} - \frac{V_{cr} S}{\omega}\right) \quad (6.28)$$

where:

C_t	=	Sediment concentration in parts per million by weight
ω	=	Fall velocity of the sediment, m/s (ft/s)
ν	=	Kinematic viscosity, m^2/s (ft^2/s)
U_*	=	Shear velocity ($\sqrt{gRS}$), m/s (ft/s)
V	=	Velocity, m/s (ft/s)
V_{cr}	=	Critical Velocity, m/s (ft/s)
S	=	Energy slope

In the above equations, the dimensionless critical velocity is given by:

$$\frac{V_{cr}}{\omega} = \frac{2.5}{\log \frac{U_* D_{50}}{\nu} - 0.06} + 0.66 \text{ for } 1.2 < \frac{U_* D_{50}}{\nu} < 70 \quad (6.29)$$

and

$$\frac{V_{cr}}{\omega} = 2.05 \text{ for } \frac{U_* D_{50}}{\nu} \geq 70 \quad (6.30)$$

The sediment discharge per unit channel width is:

$$q_s = \frac{qC_t}{\frac{\gamma_s}{\gamma} x 10^6} \quad (6.31)$$

where: q_s is in m^2/s (ft^2/s).

Based on these or other sediment transport relationships, the sediment transport capacity of individual river cross sections in a channel reach can be predicted. The sediment transport can then be used to compute volumes of material being transported and, by comparing with sediment supply to a reach, aggradation and degradation rates can be predicted. For specific site conditions, simplified relationships in the form of Equation 6.20 can be fit to the results of the more rigorous sediment transport equations (such as 6.27 and 6.28) and estimates of equilibrium slope can be made.

Sediment Continuity Analysis for Aggradation or Degradation. The transport rates can be determined for a range of discharges and combined with a flow duration curve to determine the effective channel discharge. The sediment transport rates can also be summed for a specific flood hydrograph to predict single event aggradation or degradation. In order to do this the sediment supply and the reach transport capacity must be computed. As shown in Figure 2.12, the difference between sediment inflow and outflow results in either bed aggradation or degradation. The volume of material either eroded or deposited is:

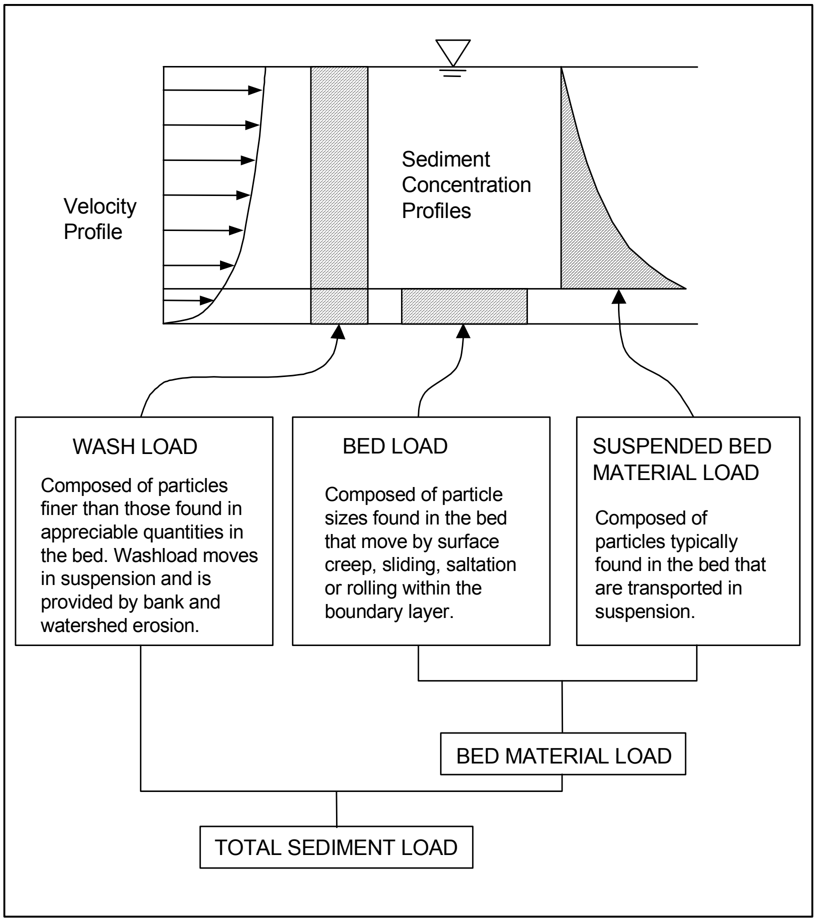

Figure 6.8. Definition of sediment load components.

$$\Delta V = V_{s(inflow)} - V_{s(outflow)} \tag{6.32}$$

where:

ΔV	=	Volume of sediment stored or eroded, m^3 (ft^3)
$V_{s(inflow)}$	=	Volume of sediment supplied to a reach, m^3 (ft^3)
$V_{s(outflow)}$	=	Volume of sediment transport out of a reach, m^3 (ft^3)

The inflowing and outflowing sediment volumes are equal to:

$$V_s = q_s W \Delta t \tag{6.33}$$

where:

W	=	Channel width, m (ft)
Δt	=	Time increment, s
q_s	=	Unit sediment discharge, m^2/s (ft^2/s)

Equation 6.33 can be summed over a hydrograph to determine sediment volumes during a flood event or can be combined with a flow duration curve to predict long-term rates. The amount of aggradation or degradation is then computed with:

$$\Delta Z = \frac{\Delta V}{WL(1-\eta)} \tag{6.34}$$

where:

ΔZ = Change in bed elevation, m (ft)
η = Porosity of the bed material (volume of the voids/total volume of a sample)
L = Reach length, m (ft)

Because channel aggradation or degradation are adjustments towards a new equilibrium condition, the hydraulic model should be adjusted by the amounts computed in Equation 6.34 before a new flood hydrograph is analyzed. Also, the stability of the new bank heights should be assessed to determine whether channel widening will occur.

A sediment continuity analysis example is solved in Appendix E.

Sediment Transport Modeling. The sediment continuity analysis described above can be complex and labor intensive. Sediment transport models use the above procedures to route sediment down a channel and adjust the channel geometry to reflect imbalances in sediment supply and transport capacity. The BRI-STARS(23) and HEC-6(24) models are examples of sediment transport models that can be used for single event or long-term degradation estimates. The information needed to run these models includes:

1. Channel and floodplain geometry
2. Structure geometry
3. Roughness
4. Geologic or structural vertical controls
5. Downstream water surface relationship
6. Event or long term inflow hydrographs
7. Tributary inflow hydrographs
8. Bed material gradations
9. Upstream sediment supply
10. Tributary sediment supply
11. Selection of appropriate sediment transport relationship
12. Depth of alluvium

These models perform hydraulic and sediment transport computations on a cross section basis and adjust the channel geometry prior to proceeding with the next time step. Because the actual flow hydrograph is input, the simplifying assumption of using an effective discharge is avoided. BRI-STARS(23) also has an option where width adjustment can be predicted.

CHAPTER 7

CHANNEL RESTORATION CONCEPTS

7.1 INTRODUCTION

The quantitative techniques for stream stability analysis presented in Chapter 6 can be used to evaluate the lateral (planform) and vertical (profile) stability of a stream channel and, in some cases, predict the potential for future channel instability. These same techniques can also be applied to the restoration and rehabilitation of environmentally degraded stream channels. This chapter provides an introduction to currently available guidelines for channel restoration design.

7.2 CHANNEL RESTORATION AND REHABILITATION

Over the last several years, numerous agencies and practitioners have published guidelines for stream corridor restoration and channel rehabilitation design. For example, in 1998, 15 Federal agencies and partners published a manual, Stream Corridor Restoration - Principles, Processes and Practices.[(100)] This document represents a cooperative effort by the participating agencies to produce a common technical reference on stream corridor restoration. Recognizing that no two stream corridors and no two restoration initiatives are identical, this technical document broadly addresses the elements of restoration that apply in the majority of situations encountered.

As a general goal, the stream corridor restoration manual promotes the use of ecological processes (physical, chemical, and biological) and minimally intrusive solutions to restore self-sustaining stream corridor functions. It provides information necessary to develop and select appropriate alternatives and solutions, and to make informed management decisions regarding valuable stream corridors and their watersheds. In addition, the document recognizes the complexity of most stream restoration work and promotes an integrated approach to restoration. It supports close cooperation among all participants in order to achieve a common set of objectives.

From the perspective of the stream corridor, restoration and rehabilitation are defined as follows:

- Restoration is the process of repairing damage to the diversity and dynamics of ecosystems. Ecological restoration is the process of returning an ecosystem as closely as possible to predisturbance conditions and functions. Implicit in this definition is that ecosystems are naturally dynamic. It is therefore not possible to recreate a system exactly. The restoration process reestablishes the general structure, function, and dynamic, but self-sustaining, behavior of the ecosystem.

- Rehabilitation is making the land useful again after a disturbance. It involves the recovery of ecosystem functions and processes in a degraded habitat. Rehabilitation does not necessarily reestablish the predisturbance condition, but does involve establishing geological and hydrologically stable landscapes that support the natural ecosystem mosaic.

Whether a highway project involves restoration or rehabilitation activities, the complexities of the stream corridor system need to be considered. Previous chapters have emphasized the necessity of a stream system approach to stream stability analyses (see for example, Figure 3.1).

Rosgen's 1996 text,[41] Applied River Morphology, extends his classification system (Figures 4.24 and 4.25) to include concepts and applications for river restoration. He notes that we are now in an unprecedented era of stream restoration, working to "put the kinks back into channelized, over-widened streams." While these restoration efforts are much needed, as with many new programs, restoration efforts run the risk of working counter to natural stability concepts. He concludes that stream classification can assist in river restoration by:

- Enabling more precise estimates of quantitative hydraulic relationships associated with specific stream and valley morphologies.
- Establishing guidelines for selecting stable stream types for a range of dimensions, patterns, and profiles that are in balance with the river's valley slope, valley confinement, depositional materials, streamflow, and sediment regime of the watershed.
- Providing a method for extrapolating hydraulic parameters and developing empirical relationships for use in the resistance equations and hydraulic geometry equations needed for restoration design.
- Developing a series of meander geometry relationships that are uniquely related to stream types and their bankfull dimensions.
- Identifying the stable characteristics for a given stream type by comparing the stable form to its unstable or disequilibrium condition.

According to Rosgen,[41] implementing a stream restoration project requires answering four basic questions:

- What are the observed problems?
- What caused the problem?
- What stream type should this be?
- What is the probable stable form of the stream type under the present hydrology and sediment regime?

Thus, the first step in a channel restoration project is to identify the problems observed in the reach of concern. The stream reconnaissance techniques discussed in Section 4.2 and field check lists of Appendix C support a determination of the nature and extent of the observed problems. A rapid assessment methodology such as that presented in Appendix D can help in evaluating how serious the problem is.

To determine what caused the problem, a qualitative assessment of important geomorphic factors influencing stream stability (Chapter 2) can provide an initial indication, but generally a more detailed analysis following the Level 1 and Level 2 procedures of Chapter 3 will be required. Understanding land use change in the contributing watershed, and its effects on the delivery (both timing and quantity) of water and sediment to the stream system is critical to identifying the complex interrelationships that are responsible for a stream instability problem (Figures 3.1 and 3.4).

To develop a restoration solution for a degraded stream, it is often useful to review a variety of stream channel classifications based on planform, sediment load, and hydraulic and geomorphic parameters to determine potential stream types consistent with watershed and valley features, and the existing stream system. The classification concepts of Section 4.3 are useful for this purpose. However, a successful restoration project will require developing a stable form for the stream considering the existing hydrologic and sediment regime. Here one must develop a stream that is stable laterally (in planform, see Section 6.2) and stable vertically (in profile, see Section 6.3).

The ultimate test of restoration design is the ability of the reconfigured channel to achieve a state of dynamic equilibrium considering the size and volume of sediment delivered from upstream (see Section 4.4.4). The sediment continuity concepts of Section 6.3 can be used for a preliminary evaluation of stream system stability, but a more detailed analysis using water and sediment routing computer models such as the USACE HEC-6 model(24) or the FHWA BRI-STARS model(23) may be required for large rivers or complex projects. The FHWA HDS 6 manual(13) provides background, concepts and applications of sediment transport technology.

A recent manual, Channel Rehabilitation: Processes, Design, and Implementation, by the U.S. Army Corps of Engineers Engineering Research and Development Center(101) recognizes that regardless of the goals of the rehabilitation project, the fundamentals of planning activities should be followed. A typical planning process for channel restoration involves the following general steps:

- Preliminary planning to establish the scope, goals, preliminary objectives, and general approach for restoration

- Baseline assessments and inventories of project location to assess the feasibility of preliminary objectives, to refine the approach to restoration, and to provide for the project design

- Design of restoration projects to reflect objectives and limitations inherent to the project location

- Evaluation of construction to identify, correct, or accommodate for inconsistencies with project design

- Monitoring of parameters important for assessing goals and objectives of restoration

Based on these guidelines, a systematic approach to initiating, planning, analyzing, implementing, and monitoring of channel restoration and rehabilitation projects can be developed.

In addition, the AASHTO Highway Drainage Guidelines,(102) Volume X, contains detailed guidelines for stream modification and mitigation practices, particularly regarding aquatic habitat and wetland functions. AASHTO's Model Drainage Manual,(103) Appendix D suggest a number of strategies to develop channel mitigation geometries when disturbance of a channel is determined to be unavoidable. Three alternatives are suggested to maintain a stream's functional values, including: grade control structures, fish habitat structures, and bendway bank protection. Conceptual sketches for a variety of structures are provided in the Model Drainage Manual.

7.3 DESIGN CONSIDERATIONS FOR CHANNEL RESTORATION

The U.S. Army Corps of Engineers Waterways Experiment Station (WES) is currently developing a systematic methodology for hydraulic design of channel restoration projects.[101] The methodology incorporates both fluvial geomorphologic principles and engineering analysis. It includes use of hydraulic geometry relationships, analytical determination of stable channel dimensions, and a sediment impact assessment. This methodology, which will meet the needs of the highway engineer in many situations, is outlined in this section (from a paper prepared by Copeland and Hall).[104] Reference to the USACE manual, Channel Rehabilitation: Processes, Design, and Implementation,[101] is suggested for more detail.

When the existing channel is stable, the wave length and sinuosity should be maintained in any channel restoration scheme.[104] The USACE methodology is intended for cases where an historically stable channel has been realigned creating instability, or where hydrologic and/or sediment inflow conditions have changed so much that the channel is currently unstable. Stability is defined as the ability to pass the incoming sediment load without significant degradation or aggradation. Bank erosion and bankline migration are natural processes and may continue in a stable channel. When bankline migration is deemed unacceptable, then engineering solutions may be employed to prevent bank erosion. Hydraulic Engineering Circular (HEC-23) presents design guidelines for a range of stream instability countermeasures and discusses bioengineering and biotechnical solutions.[2]

It should be noted that the following design methodology is currently (2000) being evaluated as part of the U.S. Army Corps of Engineers Flood Damage Reduction and Stream Restoration Research Program. However, the steps outlined provide a reasonable approach for the highway engineer faced with a channel restoration design requirement.

Step 1. Determine the design width of the channel. The design width is related to the idealized "bankfull width" which is the channel topwidth that occurs when the channel-forming (dominant) discharge occurs. Current research by the USACE suggests that the effective discharge is the best representation of the channel forming discharge. The effective discharge is the increment of discharge that transports the most sediment on an annual basis. This discharge may be determined by integrating a sediment transport rating curve with the annual flow-duration curve. Where possible, it is important to attempt to verify this channel-forming discharge with field indicators of bankfull discharge.

Several techniques are available for determining the design width as a function of the channel-forming discharge in stable alluvial streams. In order of preference they are:[104]

1. Develop a width vs. effective discharge relationship for the project stream. This can be accomplished by measuring the average width in stable reaches where the effective discharge can be calculated. These channel reaches may be in the project reach itself or in reference reaches upstream and/or downstream from the project. This is referred to as the analogy method. This technique is inappropriate for streams where the reference reaches are in disequilibrium.

2. Find stable reaches of streams with similar hydrologic, hydraulic, and sediment characteristics in the region and develop a hydraulic geometry relationship for width vs. effective discharge. This technique is also inappropriate for streams where the reference reaches are in disequilibrium.

3. If a reliable width vs. effective discharge relationship cannot be determined from field data, analytical methods discussed in Step 2 may be employed to obtain a range of feasible solutions. If the channel width is constrained due to right-of-way limits, select the required width and be prepared to provide bank protection.

The composition of the bank is very important in the determination of a stable channel width. It has been shown that the percentage of cohesive materials in the bank and the amount of vegetation on the bank significantly affect the stable channel width. General guidance is available in the U.S. Army Engineer Manual EM-1110-2-1418,[105] and Hey and Thorne 1986[106] (see also Appendix B).

Step 2. Calculate a stable channel slope and depth. In sand-bed streams, sediment transport is typically significant and an analytical procedure that considers both sediment transport and bed form roughness is required to determine a stable channel slope and depth. Analytical approaches calculate the design variables of width, slope, and depth from the independent variables of discharge, sediment inflow, and bed-material composition. Three equations are required for a unique solution of the three dependent variables. Flow resistance and sediment transport equations are readily available (see Sections 5.3.4 and 6.3.3). A hydraulic geometry width predictor can be used as the third equation. Alternatively, the stable-channel analytical method in the U.S. Army Engineer hydraulic design package SAM [107] may be used to determine a depth and slope for the width selected in Step 1 (see also Section 6.3).

Step 3. Determine a stable channel meander wave length for the planform. The most reliable hydraulic geometry relationship for meander wave length is wave length vs. width. As with the determination of channel width, preference is given to wave length predictors from stable reaches of the existing stream either in the project reach or in reference reaches. Lacking data from the existing stream, general guidance is available from several literature sources (see Section 6.2.1).

Step 4. Calculate the channel length for one meander wave length.

$$\text{meander length} = \frac{\text{wave length x valley slope}}{\text{channel slope}} \tag{7.1}$$

Step 5. Layout a planform using the meander wave length as a guide. One way to accomplish this task is to cut a string to the appropriate length and lay it out on a map. Another, more analytical approach, is to assume a sine-generated curve for the planform shape as suggested by Langbein and Leopold[85] (see Equation 7.1) and calculate x-y coordinates for the planform. This rather tedious numeric integration can be accomplished using a computer program such as the one in the USACE SAM hydraulic design package.[107] The sine-generated curve produces a very uniform meander pattern. A combination of the string layout method and the analytical approach would produce a more natural planform.

Check the design radius of curvature to width ratio, making sure it is within the normal range of 2 to 4 (see Section 6.2.2). If the meander length is too great, or if the required meander belt width is unavailable, grade control may be required to reduce the channel slope. While this bend geometry minimizes resistance to flow, it may maximize the natural channel migration potential. If this migration rate is unacceptable, bankline revetment may be required.

In streams that are essentially straight (sinuosity less than 1.2) riffle and pool spacing may be set as a function of channel width. As an empirical guide, a spacing of 6-10 channel widths can be used, with the lower end for steeper channels and the higher end for flatter channels. Two times this riffle spacing gives the total channel length through one meander pattern (Section 6.2.2).

Step 6. Conduct a sediment impact assessment. The purpose of the sediment impact assessment is to determine the long-term stability of the restored reach in terms of aggradation and/or degradation.(108) This can be accomplished using a sediment budget approach for relatively simple projects or by using a numerical model which incorporates solution of the sediment continuity equation for more complex projects (see Section 6.3.3).

With a sediment budget analysis, average annual sediment yield with the design channel is compared to the average annual sediment yield of the existing channel, if the existing channel is stable, or of the upstream supply reach, if the existing channel is unstable. Large differences in calculated sediment yield indicate channel instability. The USACE suggests(101) that the most reliable way to determine the long-term effects of changes in a complex mobile-bed channel system is to use a numerical model such as HEC-6.(24) Alternatively, the FHWA BRI-STARS(23) model could be used for this purpose.

The fact that application of a numerical sediment model requires knowledge of sediment transport and river mechanics should not be a deterrent to its use; that knowledge is required for any responsible design work in a river system. It should be expected that an analysis of system response in a complicated system, such as a mobile-bed river system, will require some engineering effort.(104) Channel restoration design should not be undertaken without reference to the principles of fluvial geomorphology and river engineering hydraulics as presented in this manual (HEC-20) and FHWA's HDS 6.(13)

CHAPTER 8

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APPENDIX A

METRIC SYSTEM, CONVERSION FACTORS, AND WATER PROPERTIES

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APPENDIX A

Metric System, Conversion Factors, and Water Properties

The following information is summarized from the Federal Highway Administration, National Highway Institute (NHI) Course No. 12301, "Metric (SI) Training for Highway Agencies." For additional information, refer to the Participant Notebook for NHI Course No. 12301.

In SI there are seven base units, many derived units and two supplemental units (Table A.1). Base units uniquely describe a property requiring measurement. One of the most common units in civil engineering is length, with a base unit of meters in SI. Decimal multiples of meter include the kilometer (1000m), the centimeter (1m/100) and the millimeter (1 m/1000). The second base unit relevant to highway applications is the kilogram, a measure of mass which is the inertial of an object. There is a subtle difference between mass and weight. In SI, mass is a base unit, while weight is a derived quantity related to mass and the acceleration of gravity, sometimes referred to as the force of gravity. In SI the unit of mass is the kilogram and the unit of weight/force is the newton. Table A.2 illustrates the relationship of mass and weight. The unit of time is the same in SI as in the English system (seconds). The measurement of temperature is Centigrade. The following equation converts Fahrenheit temperatures to Centigrade, $^\circ C = 5/9\ (^\circ F - 32)$.

Derived units are formed by combining base units to express other characteristics. Common derived units in highway drainage engineering include area, volume, velocity, and density. Some derived units have special names (Table A.3).

Table A.4 provides useful conversion factors from English to SI units. The symbols used in this table for metric units, including the use of upper and lower case (e.g., kilometer is "km" and a newton is "N") are the standards that should be followed. Table A.5 provides the standard SI prefixes and their definitions.

Table A.6 provides physical properties of water at atmospheric pressure in SI system of units. Table A.7 gives the sediment grade scale and Table A.8 gives some common equivalent hydraulic units.

Table A.1. Overview of SI Units.		
	Units	Symbol
Base units		
length	meter	m
mass	kilogram	kg
time	second	s
temperature*	kelvin	K
electrical current	ampere	A
luminous intensity	candela	cd
amount of material	mole	mol
Derived units		
Supplementary units		
angles in the plane	radian	rad
solid angles	steradian	sr
*Use degrees Celsius (°C), which has a more common usage than kelvin.		

Table A.2. Relationship of Mass and Weight.			
	Mass	Weight or Force of Gravity	Force
English	slug pound-mass	pound pound-force	pound pound-force
metric	kilogram	newton	newton

Table A.3. Derived Units With Special Names.			
Quantity	Name	Symbol	Expression
Frequency	hertz	Hz	s^{-1}
Force	newton	N	$kg \cdot m/s^2$
Pressure, stress	pascal	Pa	N/m^2
Energy, work, quantity of heat	joule	J	$N \cdot m$
Power, radiant flux	watt	W	J/s
Electric charge, quantity	coulomb	C	$A \cdot s$
Electric potential	volt	V	W/A
Capacitance	farad	F	C/V
Electric resistance	ohm	Ω	V/A
Electric conductance	siemens	S	A/V
Magnetic flux	weber	Wb	$V \cdot s$
Magnetic flux density	tesla	T	Wb/m^2
Inductance	henry	H	Wb/A
Luminous flux	lumen	lm	$cd \cdot sr$
Illuminance	lux	lx	lm/m^2

Table A.4. Useful Conversion Factors.			
Quantity	From English Units	To Metric Units	Multiplied By*
Length	mile yard foot inch	km m m mm	1.609 0.9144 0.3048 25.40
Area	square mile acre acre square yard square foot square inch	km^2 m^2 hectare m^2 m^2 mm^2	2.590 4047 0.4047 0.8361 0.09290 645.2
Volume	acre foot cubic yard cubic foot cubic foot 100 board feet gallon cubic inch	m^3 m^3 m^3 L (1000 cm^3) m^3 L (1000 cm^3) cm^3	1233 0.7646 0.02832 28.32 0.2360 3.785 16.39
Mass	lb kip (1000 lb)	kg metric ton (1000 kg)	0.4536 0.4536
Mass/unit length	plf	kg/m	1.488
Mass/unit area	psf	kg/m^2	4.882
Mass density	pcf	kg/m^3	16.02
Force	lb kip	N kN	4.448 4.448
Force/unit length	plf klf	N/m kN/m	14.59 14.59
Pressure, stress, modulus of elasticity	psf ksf psi ksi	Pa kPa kPa MPa	47.88 47.88 6.895 6.895
Bending moment, torque, moment of force	ft-lb ft-kip	N · m kN · m	1.356 1.356
Moment of mass	lb · ft	m	0.1383
Moment of inertia	lb · ft^2	kg · m^2	0.04214
Second moment of area	in^4	mm^4	416200
Section modulus	in^3	mm^3	16390
Power	ton (refrig) Btu/s hp (electric) Btu/h	kW kW W W	3.517 1.054 745.7 0.2931
*4 significant figures; underline denotes exact conversion			

Table A.4. Useful Conversion Factors (continued).			
Quantity	From English Units	To Metric Units	Multiplied by*
Volume rate of flow	ft^3/s cfm cfm mgd	m^3/s m^3/s L/s m^3/s	0.02832 0.0004719 0.4719 0.0438
Velocity, speed	ft/s	m/s	<u>0.3048</u>
Acceleration	f/s^2	m/s^2	<u>0.3048</u>
Momentum	lb · ft/sec	kg · m/s	0.1383
Angular momentum	lb · ft^2/s	kg · m^2/s	0.04214
Plane angle	degree	rad mrad	0.01745 17.45
*4 significant figures; underline denotes exact conversion			

Table A.5. Prefixes.					
Submultiples			Multiples		
deci	10^{-1}	d	deka	10^{1}	da
centi	10^{-2}	c	hecto	10^{2}	h
milli	10^{-3}	m	kilo	10^{3}	k
micro	10^{-6}	μ	mega	10^{6}	M
nano	10^{-9}	n	giga	10^{9}	G
pica	10^{-12}	p	tera	10^{12}	T
femto	10^{-15}	f	peta	10^{15}	P
atto	10^{-18}	a	exa	10^{18}	E
zepto	10^{-21}	z	zetta	10^{21}	Z
yocto	10^{-24}	y	yotto	10^{24}	Y

Table A.6. Physical Properties of Water at Atmospheric Pressure in SI Units.

Temperature		Density	Specific Weight	Dynamic Viscosity	Kinematic Viscosity	Vapor Pressure	Surface Tension[1]	Bulk Modulus
Centigrade	Fahrenheit	kg/m^3	N/m^3	$N \cdot s/m^2$	m^2/s	N/m^2 abs.	N/m	GN/m^2
0°	32°	1,000	9,810	1.79×10^{-3}	1.79×10^{-6}	611	0.0756	1.99
5°	41°	1,000	9,810	1.51×10^{-3}	1.51×10^{-6}	872	0.0749	2.05
10°	50°	1,000	9,810	1.31×10^{-3}	1.31×10^{-6}	1,230	0.0742	2.11
15°	59°	999	9,800	1.14×10^{-3}	1.14×10^{-6}	1,700	0.0735	2.16
20°	68°	998	9,790	1.00×10^{-3}	1.00×10^{-6}	2,340	0.0728	2.20
25°	77°	997	9,781	8.91×10^{-4}	8.94×10^{-7}	3,170	0.0720	2.23
30°	86°	996	9,771	7.97×10^{-4}	8.00×10^{-7}	4,250	0.0712	2.25
35°	95°	994	9,751	7.20×10^{-4}	7.24×10^{-7}	5,630	0.0704	2.27
40°	104°	992	9,732	6.53×10^{-4}	6.58×10^{-7}	7,380	0.0696	2.28
50°	122°	988	9,693	5.47×10^{-4}	5.53×10^{-7}	12,300	0.0679	
60°	140°	983	9,643	4.66×10^{-4}	4.74×10^{-7}	20,000	0.0662	
70°	158°	978	9,594	4.04×10^{-4}	4.13×10^{-7}	31,200	0.0644	
80°	176°	972	9,535	3.54×10^{-4}	3.64×10^{-7}	47,400	0.0626	
90°	194°	965	9,467	3.15×10^{-4}	3.26×10^{-7}	70,100	0.0607	
100°	212°	958	9,398	2.82×10^{-4}	2.94×10^{-7}	101,300	0.0589	

[1]Surface tension of water in contact with air

Table A.7. Physical Properties of Water at Atmospheric Pressure in English Units.

Temperature		Density	Specific Weight	Dynamic Viscosity	Kinematic Viscosity	Vapor Pressure	Surface Tension[1]	Bulk Modulus
Fahrenheit	Centigrade	$Slugs/ft^3$	Weight lb/ft^3	$lb\text{-}sec/ft^2$	ft^2/sec	lb/in^2	lb/ft	lb/in^2
32	0	1.940	62.416	0.374×10^{-4}	1.93×10^{-5}	0.09	0.00518	287,000
39.2	4.0	1.940	62.424					
40	4.4	1.940	62.423	0.323	1.67	0.12	.00514	296,000
50	10.0	1.940	62.408	0.273	1.41	0.18	.00508	305,000
60	15.6	1.939	62.366	0.235	1.21	0.26	.00504	313,000
70	21.1	1.936	62.300	0.205	1.06	0.36	.00497	319,000
80	26.7	1.934	62.217	0.180	0.929	0.51	.00492	325,000
90	32.2	1.931	62.118	0.160	0.828	0.70	.00486	329,000
100	37.8	1.927	61.998	0.143	0.741	0.95	.00479	331,000
120	48.9	1.918	61.719	0.117	0.610	1.69	.00466	332,000
140	60.0	1.908	61.386	0.0979	0.513	2.89		
160	71.1	1.896	61.006	0.0835	0.440	4.74		
180	82,2	1.883	60.586	0.0726	0.385	7.51		
200	93.3	1.869	60.135	0.0637	0.341	11.52		
212	100	1.847	59.843	0.0593	0.319	14.70		

[1] Surface tension of water in contact with air

Table A.8. Sediment Particles Grade Scale.

Size				Approximate Sieve Mesh Openings Per Inch		Class
Millimeters		Microns	Inches	Tyler	U.S. Standard	
4000-2000	-----	-----	160-80	-----	-----	Very large boulders
2000-1000	-----	-----	80-40	-----	-----	Large boulders
1000-500	-----	-----	40-20	-----	-----	Medium boulders
500-250	-----	-----	20-10	-----	-----	Small boulders
250-130	-----	-----	10-5	-----	-----	Large cobbles
130-64	-----	-----	5-2.5	-----	-----	Small cobbles
64-32	-----	-----	2.5-1.3	-----	-----	Very coarse gravel
32-16	-----	-----	1.3-0.6	-----	-----	Coarse gravel
16-8	-----	-----	0.6-0.3	2 1/2	-----	Medium gravel
8-4	-----	-----	0.3-0.16	5	5	Fine gravel
4-2	-----	-----	0.16-0.08	9	10	Very fine gravel
2-1	2.00-1.00	2000-1000	-----	16	18	Very coarse sand
1-1/2	1.00-0.50	1000-500	-----	32	35	Coarse sand
1/2-1/4	0.50-0.25	500-250	-----	60	60	Medium sand
1/4-1/8	0.25-0.125	250-125	-----	115	120	Fine sand
1/8-1/16	0.125-0.062	125-62	-----	250	230	Very fine sand
1/16-1/32	0.062-0.031	62-31	-----	-----	-----	Coarse silt
1/32-1/64	0.031-0.016	31-16	-----	-----	-----	Medium silt
1/64-1/128	0.016-0.008	16-8	-----	-----	-----	Fine silt
1/128-1/256	0.008-0.004	8-4	-----	-----	-----	Very fine silt
1/256-1/512	0.004-0.0020	4-2	-----	-----	-----	Coarse clay
1/512-1/1024	0.0020-0.0010	2-1	-----	-----	-----	Medium clay
1/1024-1/2048	0.0010-0.0005	1-0.5	-----	-----	-----	Fine clay
1/2048-1/4096	0.0005-0.0002	0.5-0.24	-----	-----	-----	Very fine clay

Table A.9. Common Equivalent Hydraulic Units.

Volume

Unit	Equivalent							
	cubic inch	liter	u.s. gallon	cubic foot	cubic yard	cubic meter	acre-foot	sec-foot-day
liter	61.02	1	0.264 2	0.035 31	0.001 308	0.001	810.6 E - 9	408.7 E - 9
U.S. gallon	231.0	3.785	1	0.133 7	0.004 951	0.003 785	3.068 E - 6	1.547 E - 6
cubic foot	1728	28.32	7.481	1	0.037 04	0.028 32	22.96 E - 6	11.57 E - 6
cubic yard	46 660	764.6	202.0	27	1	0.746 6	619.8 E - 6	312.5 E - 6
$meter^3$	61 020	1000	264.2	35.31	1.308	1	810.6 E - 6	408.7 E - 6
acre-foot	75.27 E + 6	1 233 000	325 900	43 560	1 613	1 233	1	0.504 2
sec-foot-day	149.3 E + 6	2 447 000	646 400	86 400	3 200	2 447	1.983	1

Discharge (Flow Rate, Volume/Time)

Unit	Equivalent					
	gallon/min	liter/sec	acre-foot/day	$foot^3$/sec	million gal/day	$meter^3$/sec
gallon/minute	1	0.063 09	0.004 419	0.002 228	0.001 440	63.09 E - 6
liter/second	15.85	1	0.070 05	0.035 31	0.022 82	0.001
acre-foot/day	226.3	14.28	1	0.504 2	0.325 9	0.014 28
$feet^3$/second	448.8	28.32	1.983	1	0.646 3	0.028 32
million gal/day	694.4	43.81	3.068	1.547	1	0.043 82
$meter^3$/second	15 850	1000	70.04	35.31	22.82	1

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APPENDIX B

BANK EROSION AND FAILURE MECHANISMS

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APPENDIX B

Bank Erosion and Failure Mechanisms

B.1 FACTORS INFLUENCING BANK RETREAT

The erosion, instability, and/or retreat of a stream bank is dependent on the processes responsible for the erosion of material from the bank and the mechanisms of failure resulting from the instability created by those processes. Bank retreat is often a combination of these processes and mechanisms varying at seasonal and sub-seasonal timescales. Bank retreat processes may be grouped into three categories: weakening and weathering processes, direct fluvial entrainment, and mass failure. The general factors which influence the various bank retreat processes and mechanisms are shown in Table B.1. The impact of these processes on bank retreat is dependent on site characteristics, especially near-bank hydraulic fields, bank height, and the geotechnical properties of the bank material. A basic understanding of the principles and processes described in the following sections will aid in the completion of Part 11 of the Field Reconnaissance Record Sheets (Appendix C) which deal with bank geotechnical evaluations. As indicated in Chapter 2, the resistance of a stream bank to erosion and failure is closely related to several characteristics of the bank material, which can be broadly classified as noncohesive, cohesive, or composite.

Table B.1. Factors Influencing Bank Retreat Processes and Mechanisms (after Lawler et al. 1997).[1]

Subaerial Processes	Microclimate, especially temperature Bank composition, especially silt/clay percentage
Fluvial Processes	Stream power Shear stress Secondary currents Local slope Bend morphology Bank composition Vegetation Bank moisture content
Mass Failure	Bank Height Bank angle Bank composition Bank moisture content or pore water pressure/tension

B.2 PROCESSES OF WEAKENING AND WEATHERING

The processes of weakening and weathering reduce the strength of intact bank material and decrease bank stability. Mass wasting of bank materials is related to these processes, which in turn are associated directly with soil moisture conditions.[2,3] The processes, which depend on both climatic conditions and on the properties of the bank, fall into two groups: those operating within the bank to reduce its strength, and those acting on the bank surface to loosen and detach particles or aggregates.

B.2.1 Strength Reduction

The effective strength of poorly drained banks can be reduced by positive pore-water pressure. The most critical condition occurs during heavy or prolonged precipitation, snowmelt runoff, or rapid drawdown after a high flow stage. Positive pore water pressures in a bank act to reduce friction and effective cohesion, which can lead to liquefaction (a complete loss of strength and flow-type failure) in extreme cases. Even if no significant pore water pressures develop, the stability of a saturated bank will be reduced due to the increase in unit weight that results from saturation.

Cycles of wetting and drying cause shrinkage and swelling of the soil material, which leads to the development of micro-failure planes, desiccation cracks, and downslope soil creep. Freezing and thawing of water in pores, cracks, or fissures can break soil units apart and weaken bank material by reducing granular interlocking and, hence, the friction angle, and by destroying any cohesion. A similar effect can be created by the relaxation of normal load and lateral earth pressure due to lateral stream cutting or overburden removal. Movement of water through the bank can lead to leaching of clay particles by solution or suspension and softening of the bank material, thereby causing a reduction in bank material cohesion.

B.2.2 Surface Erosion

Overland flow occurs when bank materials become fully saturated or when the rate of precipitation locally exceeds the infiltration capacity of the soil mass. In turn, this can lead to surface erosion of the bank through the processes of sheet erosion, rilling, and gullying. Similar types of erosion can occur as a result of return flow from flooded overbank and floodplain areas. In addition, the importance of these surface erosion processes is largely dependent on the vegetative cover of the bank. The presence of dense riparian vegetation can reduce surface erosion rates by several orders of magnitude when compared to non-vegetated banks.[(2)] However, the introduction of trees into the channel from bank failures can cause local scour and significant additional local bank erosion.

B.3. FLUVIAL ENTRAINMENT

Bank retreat is produced by fluvial entrainment in two ways. First, sediment may be directly entrained from the bank (by detaching and/or moving grains or aggregates) and transported downstream. Second, flow may scour the channel bed at the base of the bank (increasing bank angle and height) and induce the gravitational failure of the bank. This type of failure mechanism is probably of greatest importance when the banks are located on the concave (outside) margin of a bend where scour depths during a flood may range from 1.75 to 2 times the depth of flow in sand-bed streams.[(4)]

Shear stress along the bed and banks as generated by flow in the channel is directly proportional to the velocity gradient close to the channel boundary. In order for the boundary material to remain in equilibrium it must supply an internally derived, equal and opposite shear strength. If the velocity gradient becomes steeper, a point is eventually reached where the internal shear strength (the resistance to motion of the boundary material) equals the fluid shear stress. Any subsequent increase in the fluid shear stress must result in entrainment of the boundary material.

B.3.1 Non-cohesive Material

Individual grains from non-cohesive materials are entrained by pivoting, rolling, or sliding. The stability of the surface grain can be assessed by resolving the forces which act on the grain into those that tend to cause motion and those that tend to resist it.[5] However, Parker has shown that this approach is inappropriate in gravel-bed streams that are transporting significant amounts of bedload.[6] The Task Committee on Sedimentation[7] developed a relationship that was dependent on defining the critical boundary shear stress, but, as Thorne indicates, this method has limited usefulness because of the stochastic nature of the distribution and fluctuation of shear stress and particle size distributions.[2]

B.3.2 Cohesive Material

The mechanics of fluvial entrainment of cohesive bank material are even less well understood. Tractive stress approaches have been attempted, but these suffer from the fact that little consideration has been given to the nature of the soil unit which is entrained or to the mechanism of failure at the time of entrainment.[2] Further, delineation of materials as cohesive on the basis of grain-size distributions may be misleading because most fine-grained cohesive materials form very strongly bonded aggregates, which are composed of clay, silt and sand. In fact, many fine-grained aggregate particles can behave as low density sand and gravel particles.[8,9] Thus, fluvial erosion of cohesive soil often occurs through entrainment of aggregates rather than discrete particles.

B.4. BASAL ENDPOINT CONTROL

Material is delivered to the basal area of a bank by mechanical bank failures and erosion. The removal of this material from the basal area depends almost entirely on fluvial entrainment and downstream transport (Figure B.1). The amount of basal accumulation of bank material depends on the relative rates of supply by bank failures and erosion and removal by fluvial entrainment. Where the flow is able to remove all the sediment supplied to the basal area and scour of the basal area continues, bank erosion will also continue. In contrast, where the rate of supply exceeds the rate of removal, bank stability will be increased with respect to gravity failures because loading and buttressing the base of the slope effectively reduces the bank angle and height. Neill[10] has argued that the bedload transport rate must set an upper limit to local erosion rates over a period of time, and Nanson and Hickin[11] support this view. Carson and Kirkby[12] characterize the balance between basal supply and removal in terms of three states of basal endpoint control, as follows:

(a) Impeded Removal. If bank failures supply material to the base at a higher rate than it is removed, then basal accumulation results, thus decreasing the bank angle and vertical height and increasing bank stability.

(b) Unimpeded Removal. Bank failures and erosion supply material to the base at the same rate that it is removed resulting in bank recession by parallel retreat, the rate being controlled by the degree of fluvial activity at the base of the bank. Slope angle and basal elevation remain relatively unchanged.

(c) Excess Basal Capacity. Basal scour is greater than the rate of supply of material. This causes bed scour and basal lowering which increases the bank height and angle and promotes bank failure.

An understanding of this information can be helpful when completing Part 12 of the Field Reconnaissance Record Sheets (Appendix C) which deals with bank toe sediment accumulations.

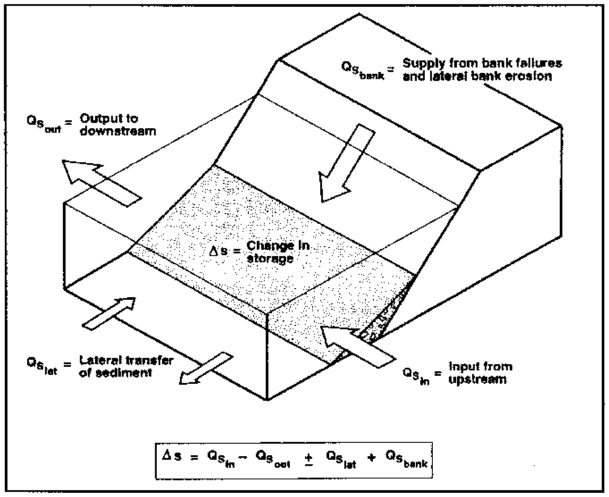

Figure B.1. Schematic representation of sediment fluxes to and from river bank basal zones.[13]

B.5 MECHANICS OF BANK FAILURE

The mechanics of bank failure, which result from the operation of the processes of erosion as outlined above are closely related to the size, geometry, and stratigraphy of the banks and to the geotechnical properties of the bank material. Based on the stratigraphy and physical properties, banks can be classified as non-cohesive, cohesive, and composite as described in Chapter 2. Hey et al. compiled a useful summary of bank failure modes and characteristics which is shown in Figure B.2.[14] Data for much of the information discussed below can be collected using the Stream Reconnaissance Record Sheets (Appendix C) as described in Chapter 4.

B.5.1 Non-cohesive Banks

The shear strength (s) of non-cohesive banks can be described by the modified Coulomb equation with no cohesion which accounts for the normal stress on the bank (σ), pore water pressure of the bank (μ), and the apparent angle of internal friction of the bank material (ϕ').[15] The effect of pore water pressure on the shear strength of non-cohesive banks is dependent on whether the banks are drained, undrained, or submerged.

Under drained conditions, pore water pressure is not a factor and, therefore, the stability of the bank becomes dependent only on the bank angle and the angle of internal friction.[16] Failure occurs by dislodgment of individual grains from the surface of the bank or by shallow slip along a plane or slightly curved surface (Figure B.2a). Deep-seated failures are rare in non-cohesive banks because the shear strength increases with depth more rapidly than shear stress.[17] Weakening and weathering processes can act to decrease packing densities and granular interlocking, thus reducing the friction angle to less than the slope angle, thereby resulting in failure. The friction angles for loosely-packed, non-cohesive materials range from 20 to 35 degrees. Erosion of the lower part of a non-cohesive bank or the bed adjacent to the bank can cause bank oversteepening, which results in slip failures higher up the bank (Figure B.2b).

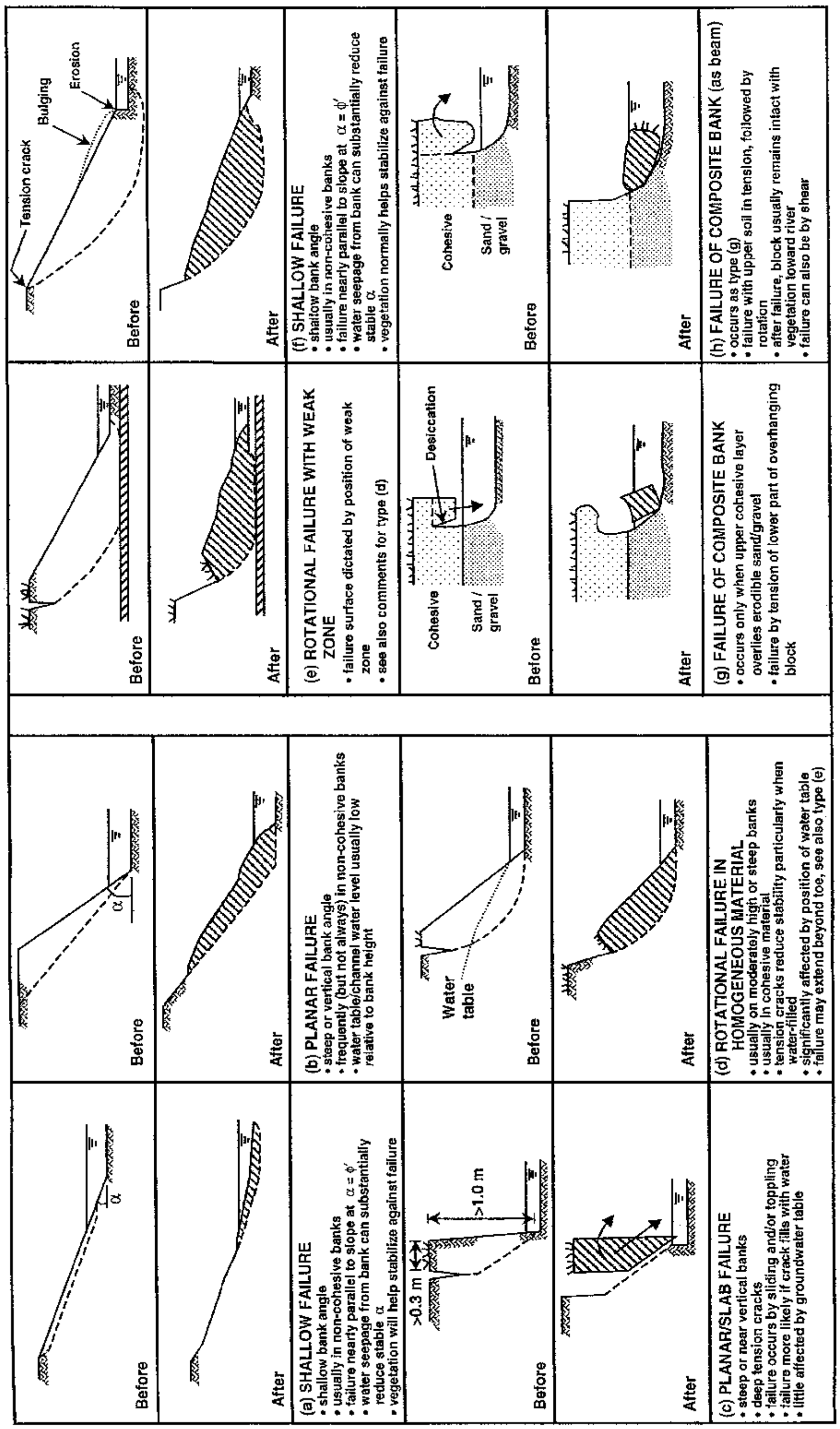

Figure B.2. Models and characteristics of bank failure.[14]

Under undrained conditions the shear strength of non-cohesive banks is significantly affected by pore water pressure. A positive pore water pressure, which may occur during rapid drawdown, results in a limiting slope angle that is smaller than the friction angle. If the bank is partially saturated the pore water pressure is negative allowing the bank angle to exceed the friction angle. The non-cohesive materials can behave like weakly cohesive soils under this condition due to the capillary effects in partly filled pores.(2) This condition disappears if the material is completely dry or fully saturated.

Undrained non-cohesive banks fail in a manner similar to drained ones with the added effects of positive pore water pressure. Shallow slips and individual grain detachment are the common modes of failure. Piping in the lower bank, caused by high seepage pressures, can cause failure higher up the bank due to oversteepening. In addition, fully saturated, loosely packed, cohesionless materials may fail by liquifaction.

B.5.2 Cohesive Banks

The shear strength for cohesive banks in the modified Coulomb equation increases by adding the cohesion (c') of the bank material. Unlike non-cohesive banks where stability is independent of bank height, both the bank angle and height determine the stability of cohesive banks. Failure mechanisms in cohesive materials fall into three categories: rotational slip, shallow slip, and plane slip. Although shallow slips do occur in cohesive material,(2) failure generally occurs by deep-seated slip because the strength of cohesive materials increases at a lesser rate with depth than does shear stress.(15)

The stability of a cohesive bank can be evaluated by considering the ratio of disturbing and restoring forces acting on the most critical failure surface to produce a factor of safety. This approach requires that the shape of the failure surface be known. For low, steep banks, the most simple and reasonable approach is to use the Culmann method, which assumes a planar surface passing through the toe of the bank producing a planar or slab type failure (Figure B.2c). The Culmann formula for this type of failure assumes a planar shear surface along which slab or wedge failure occurs and is based on total, rather than effective, stress principles.

In addition, the effects of cracks or fissures in the soil must be accounted for when analyzing the stability of banks. Cracks may be inherent in the soil fabric, or they may develop to relieve tension stress at the top of a steep slope.

Rotational Slip Failure. This type of failure can be further characterized as a base, toe, or slope failure depending on where the failure arc intersects the ground surface (Figure B.3, see also Figure B.2d). The ratio of restoring to disturbing moments about the center of the failure arc defines the factor of safety. The simplified solution for the factor of safety per unit length along the bank assumes that interslice forces act horizontally and accounts for pore water pressure.(18) Since there is no simple way to locate the critical slip circle, a number of possible locations must be evaluated, which requires iterative calculations. Therefore, stability charts that predict the worst case have been developed.(16,19,20,21) However, failure surfaces are seldom circular and undrained conditions may be critical, both of which limit the applicability of these charts for natural river banks.(22)

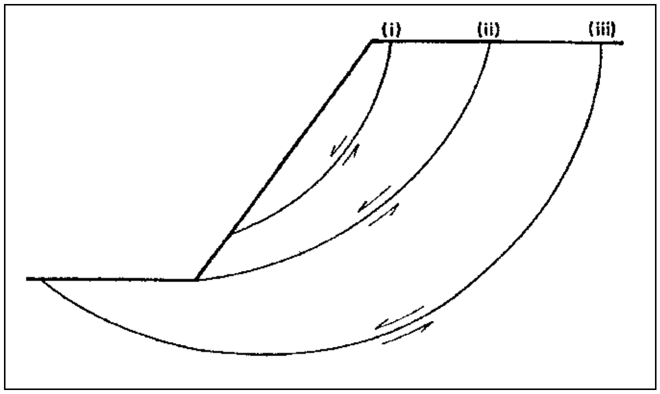

Figure B.3. Rotational slip failures in a cohesive bank: (i) slope failure, (ii) toe failure, and (iii) base failure.[2]

Well established procedures developed in geotechnical engineering may be used to analyze rotational slips.[23,24] Research indicates that rotational slips mainly occur in cohesive banks with angles less than about 60 degrees. Osman and Thorne attained reasonable results using a slope stability program developed to assess bank stability with respect to rotational slip for a variety of undercut and oversteepened banks.[25,26]

Shallow Slip Failure. Shallow slips occur frequently, but have less impact on a river bank than deep seated rotational failures.[2] Shallow slip failure takes place along an almost planar surface parallel to the bank surface. Theoretical analysis of shallow slips by the method of slices suggests that these should be confined to non-cohesive materials, but shallow slips in cohesive material do occur naturally. The discrepancy can be explained by the presence of tensile stress in the soil due to lateral stream cutting which causes fissures in the soil. This leads to the movement of water through the soil causing softening, leaching, and possible piping, all of which reduce the effective cohesion, and makes the cohesive soil behave like a non-cohesive one.

Plane Slip Failure. In low, steep banks the most critical failure surface is almost planar, passes through the toe of the bank, and produces a slab or block of soil that slides downward and outwards followed by toppling forward into the channel (Figure B.2c). Plane slip failure is the most common type failure for eroding river banks. As slope angle decreases and height increases, plane slip becomes much less likely. The Culmann analysis, which is based on the total stress principles and assumes a planar shear surface along which slab or wedge failure occurs, is used to analyze this type of failure (Figure B.4a). The critical bank height for the plane slip type of failure is proportional to 4 times the bank material cohesion (c), inversely proportional to the unit weight of the bank material (γ), and is related to the bank slope angle (θ), and the bank material friction angle (ϕ).

As the bank angle decreases, the assumption of a planar shear surface rapidly becomes invalid since deep-seated failures of high banks with low slope angles are usually curved as a result of changes with depth in the orientation of the principal stresses in the soil. Plane slips become less likely and the Culmann analysis seriously overestimates bank stability as slope angle decreases and bank height increases.

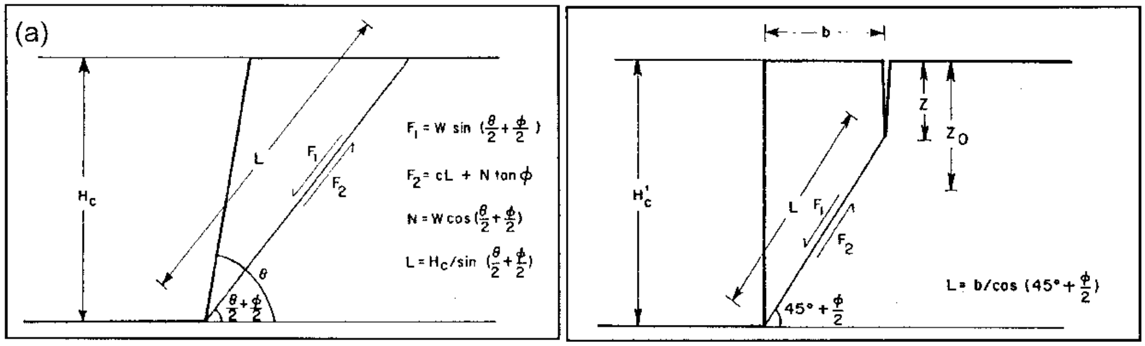

Figure B.4. Culmann analysis for (a) plane slip failure and (b) plane slip failure modified to account for tension cracking.[2]

In many cases river banks are very steep and almost vertical. In the case of a vertical bank, the bank slope angle is removed from the Culmann analysis. In addition, the Culmann analysis described above does not account for possible tension cracking. Therefore, for a vertical bank with a tension crack that may extend about one-half the bank height in soils of negligible tensile strength, Thorne has modified the Culmann analysis such that the depth of the tensile stress of the bank (z_o) is subtracted from the original critical bank height (Figure B.4b).[2] The depth of the tensile stress may be calculated from the Mohr diagram (see any standard civil engineering reference.[27]

Lawler[28] constructed a series of Culmann-type bank stability curves that can be used to predict the critical bank height required to produce wedge or slab failures for a given range of saturated bulk unit weights (γ), cohesions (c), and friction angles (ϕ). In high banks, the presence of a tension crack does not significantly change the failure surface geometry since z_o is only a few percent of the bank height. Therefore, the potential for cracking in high banks can be accounted for by simply reducing the length of the failure surface by that portion within the tensile zone.

B.5.3 Composite Banks

Composite banks are composed of cohesive and non-cohesive materials stratified into discrete and discontinuous layers. In alluvial materials, the interfingering of cohesive and non-cohesive materials can be related to lateral migration of channels and the resulting juxtaposition of channel and non-channel depositional environments. However, fluvial entrainment of the failed or eroded basal material is vital to the process. Thus, the rate of retreat of composite banks in the medium to long term is dependent on the stability of the lower bank and toe zone. The individual erosion processes and failure mechanics operating on a bank composed of a single type of material are combined to reflect the multiplicity of the bank material types in composite banks.[2] Failure mechanisms include rotational slip, plane slip, and cantilever slip.

Rotational Slip Failure. Where a cohesive layer underlies a non-cohesive layer (e.g., gravel) at depth in a high composite bank (Figure B.5a, see also Figure B.2e), fluvial erosion of the lower bank can result in oversteepening and failure of the cohesive upper bank. The likelihood of rotational failure increases with increasing thickness of the cohesive layer. The critical slip surface is classified as a toe or slope failure depending on the height of the contact surface in the bank (Figure B.5a).

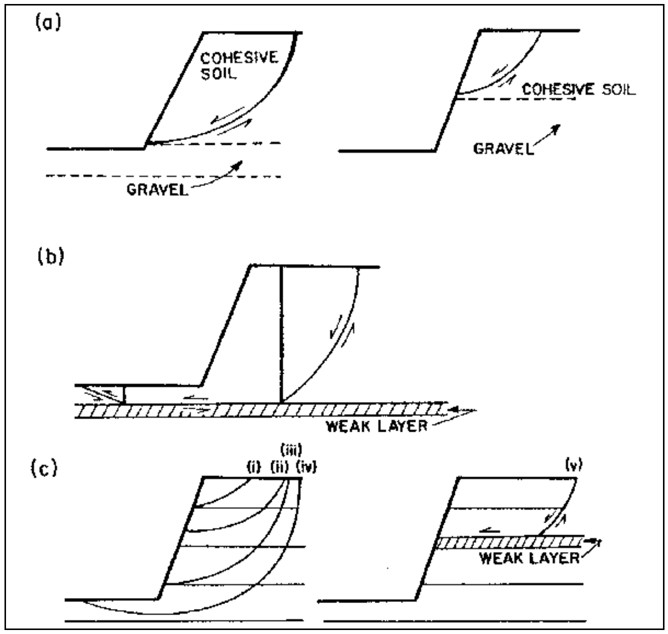

Figure B.5. (a) Rotational slip failure of the upper cohesive unit of a high composite bank. Toe or slope failure is determined by location of the contact between the soil and gravel. (b) Composite failure surface relative to a weak substratum. (c) Slip failures in a multilayered bank: (i)-(iv) possible failure surface locations within or between layers depending on soil properties and bank geometries; (v) critical influence of a weak layer.(2)

If there is excess pore water pressure or softening of the base of the cohesive layer, the contact surface between the cohesive and non-cohesive units can become a plane of weakness. The critical failure surface takes on a composite form if this weak layer is present (Figure B.5b). Bank stability is estimated based on a comparison of the forces causing and resisting movement of the central failure block away from the bank. The most critical surface must be located through a number of trial calculations because the points of intersection of the composite failure surface with the plane of weakness are unknown.(29) Calculation of the location of the critical failure surface in a multilayered bank (Figure B.5c) also requires a number of iterations since failure may occur within one layer or between layers. Where one or more weak layers are present, the longest part of the failure surface will probably be located in the weakest layer.(29) Although Morgenstern and Price(30) and Sarma(31) have developed improved stability analyses dealing with composite banks, their analyses have not been evaluated with regard to field data.(2)

<u>Plane Slip Failure</u>. Plane slips and slab failures occur on low banks in general and can be expected on high banks with thin cohesive layers. A thin cohesive layer underlain by a non-cohesive layer (e.g., sand or gravel) is often well drained, so pore water pressure can be ignored and desiccation cracking may occur. When a cohesive layer underlies a non-cohesive layer, the decrease in permeability may produce a plane of strong seepage pressure, which can lead to piping or liquefaction of the non-cohesive material resulting in oversteepening and failure higher up the bank.

Cantilever Failure. Cantilever failures occur when cohesive material overlies a non-cohesive layer, which is removed by fluvial erosion, resulting in an overhanging block of cohesive material (Figure B.6). They generally occur on low banks and are most common in settings where the river is transporting a significant gravel load because floodplain stratigraphy is usually composed of a fining-upward sequence. An increase in the width of the overhang or cantilever by further undercutting, weakening by wetting, or cracking eventually exceeds the equilibrium state of the block and it fails. Failure occurs by shear, beam, or tensile failure and is dependent on block geometry.[32] Tension and desiccation cracks are of considerable importance and must be accounted for. Once cantilever failure of the block occurs, its removal is dependent on fluvial entrainment.

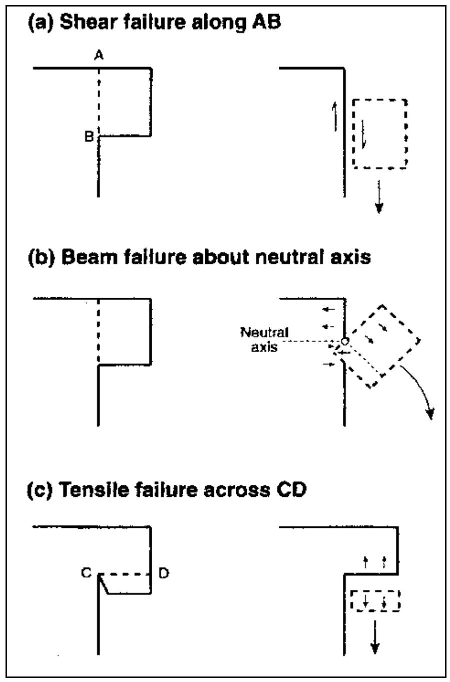

Figure B.6. Mechanisms of cantilever failure on composite banks.[22]

B.6 ESTIMATING CRITICAL BANK HEIGHT

As previously indicated, the stability of the bank with respect to mass failure is dependent on soil properties and bank geometry. Bed lowering and lateral erosion are the two most common processes that act to steepen the bank and cause bank instability. For estimating critical bank height for steep, cohesive banks, a simple slope stability analysis can be developed. Reference is suggested to the analysis approach derived by Osman and Thorne[33] to predict bank stability response to lateral erosion and bed degradation.

Thorne and Osman[34] also developed a modeling technique to study the effects of channel widening and bank-sediment contribution on flow energy, stream power, and the rate and extent of bed lowering during degradation, and the influence of outer bank stability on bed and failure using a critical shear stress concept to account for lateral erosion and a slope stability criterion for mass failure. Again, a review by the reader is recommended prior to evaluating lateral erosion and bank instability problems in detail for a given site.

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APPENDIX C

STREAM RECONNAISSANCE RECORD SHEETS

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STREAM RECONNAISSANCE RECORD SHEETS

(Modified from Thorne, 1998) [1]

SECTION 1 - SCOPE AND PURPOSE

Brief Problem Statement:

Purpose of Stream Reconnaissance:

Logistics of Reconnaissance Trip:

RIVER:	LOCATION:	DATE: From: To:
PROJECT:	STUDY REACH:	
SHEET COMPLETED BY:		
RIVER STAGE:	TIME START:	TIME FINISH:

General Notes and Comments on Reconnaissance Trip:

SECTION 2 - REGION AND VALLEY DESCRIPTION

PART 1: AREA AROUND RIVER VALLEY

Terrain	Drainage Pattern	Surface Geology	Rock Type	Land Use	Vegetation
Mountains ☐	Dendritic ☐	Weathered Soils ☐	Metamorphic ☐	Managed ☐	Temperate forest ☐
Uplands ☐	Parallel ☐	Glacial Moraine ☐	Igneous ☐	Cultivated ☐	Boreal forest ☐
Hills ☐	Trellis ☐	Glacio/Fluvial ☐	None ☐	Urban ☐	Woodland ☐
Plains ☐	Rectangular ☐	Fluvial ☐		Suburban ☐	Savanna ☐
Lowlands ☐	Radial ☐	Lake Deposits ☐			Temperate grassland ☐
	Annular ☐	Wind blown (loess) ☐			Desert scrub ☐
	Multi-Basin ☐		**Specific Rock Types (if known)**		Extreme Desert ☐
	Contorted ☐				Tundra or Alpine ☐
					Agricultural land ☐

Notes and Comments:

PART 2: RIVER VALLEY AND VALLEY SIDES

Location of River	Height	Side Slope Angle	Valley Shape	Valley Side Failures	Failure Locations
In Valley ☐	< 5 m ☐	< 5degrees ☐	Symmetrical ☐	None ☐	None ☐
On Alluvial Fan ☐	5 - 10 m ☐	5-10 degrees ☐	Asymmetrical ☐	Occasional ☐	Away from river ☐
On Alluvial Plain ☐	10 - 30 m ☐	10-20 degrees ☐		Frequent ☐	Along river ☐ (Undercut)
In a Delta ☐	30 - 60 m ☐	20-50 degrees ☐			
In Old Lake Bed ☐	60 - 100 m ☐	>50 degrees ☐			
	> 100 m ☐		**Failure Type** ____ (see sketch in manual)		

Notes and Comments:

PART 3: FLOOD PLAIN (VALLEY FLOOR)

Valley Floor Type	Valley Floor Data	Surface Geology	Land Use	Vegetation	Riparian Buffer Strip
None ☐	None ☐	Bed rock ☐	Natural ☐	None ☐	None ☐
Indefinite ☐	< 1 river width ☐	Glacial Moraine ☐	Managed ☐	Unimproved Grass ☐	Indefinite ☐
Fragmentary ☐	1 - 5 river widths ☐	Glacio/Fluvial ☐	Cultivated ☐	Improved Pasture ☐	Fragmentary ☐
Continuous ☐	5-10 river widths ☐	Fluvial: Alluvium ☐	Urban ☐	Orchards ☐	Continuous ☐
	>10 river widths ☐	Fluvial: Backswamp ☐	Suburban ☐	Arable Crops ☐	**Strip Width**
		Lake Deposits ☐	Industrial ☐	Shrubs ☐	None ☐
	Flow Resistance*	Wind Blown (Loess) ☐		Deciduous Forest ☐	< 1 river width ☐
	Left Overbank Manning n value ___			Coniferous Forest ☐	1 - 5 river widths ☐
	Right Overbank Manning n value ___	(* note: n value for channel is recorded in Part 6)		Mixed Forest ☐	> 5 river widths ☐

Notes and Comments:

PART 4: VERTICAL RELATION OF CHANNEL TO VALLEY

Terraces	Overbank Deposits	Levees	Levee Data	Levee Description	Trash Lines
None ☐	None ☐	None ☐	Height (m) ☐	None ☐	Absent ☐
Indefinate ☐	Silt ☐	Natural ☐	Side Slope (o) ☐	Indefinite ☐	Present ☐
Fragmentary ☐	Fine sand ☐	Constructed ☐		Fragmentary ☐	Height above
Continuous ☐	Medium sand ☐		**Levee Condition**	Continuous ☐	flood plain (m) ___
Number of Terraces ___	Coarse sand ☐	**Instability Status**	None ☐	Left Bank ☐	
	Gravel ☐	Stable ☐	Intact ☐	Right Bank ☐	
	Boulders ☐	Degrading ☐	Local Failures ☐	Both Banks ☐	
		Aggrading ☐	Frequent failures ☐		

Notes and Comments:

PART 5: LATERAL RELATION OF CHANNEL TO VALLEY

Planform	Planform Data	Lateral Activity	Floodplain Features	Location in Valley
Straight ☐	Bend Radius ____	None ☐	None ☐	Left ☐
Sinuous ☐	Meander belt width ____	Meander progression ☐	Meander scars ☐	Middle ☐
Irregular ☐	Wavelength ____	Increasing amplitude ☐	Scroll bars+sloughs ☐	Right ☐
Regular meanders ☐	Meander Sinuosity ____	Progression+cut-offs ☐	Oxbow lakes ☐	
Irregular meanders ☐		Irregular erosion ☐	Irregular terrain ☐	
Tortuous meanders ☐		Avulsion ☐	Abandoned channel ☐	
Braided ☐		Braiding ☐	Braided Deposits ☐	
Anastomosed ☐				

Notes and Comments:

SECTION 3 - CHANNEL DESCRIPTION

PART 6: CHANNEL DESCRIPTION

Dimensions	Flow Type	Bed Controls	Control Types	Width Controls	Control Types
Av. top bank width (m)	None	None	None	None	None
Av. channel depth (m)	Uniform/Tranquil	Occasional	Solid Bedrock	Occasional	Bedrock
Av. water width (m)	Uniform/Rapid	Frequent	Weathered Bedrock	Frequent	Boulders
Av. water depth (m)	Pool+Riffle	Confined	Boulders	Confined	Gravel armor
Reach slope	Steep + Tumbling	Number of controls	Gravel armor	Number of controls	Revetments
Mean velocity (m/s)	Steep + Step/pool		Cohesive Materials		Cohesive Materials
			Bridge protection		Bridge abutments
Manning's n value	(Note: Flow type on day of observation)		Grade control structures		Dykes or groines

Notes and Comments:

PART 7: BED SEDIMENT DESCRIPTION

Bed Material	Bed Armour	Surface Size Data	Bed Forms (Sand)	Bar Types	Bar Surface data
Clay ☐	None ☐	D50 (mm) ___	Flat bed (None) ☐	None ☐	D50 (mm) ___
Silt ☐	Static-armour ☐	D84 (mm) ___	Ripples ☐	Pools and riffles ☐	D84 (mm) ___
Sand ☐	Mobile-armour ☐	D16 (mm) ___	Dunes ☐	Alternate bars ☐	D16 (mm) ___
Sand and gravel ☐			Bed form height (m) ___	Point bars ☐	
gravel and cobbles ☐	**Sediment Depth**	**Substrate Size Data**	**Island or Bars**	Mid-channel bars ☐	**Bar Substrate data**
cobbles + boulders ☐	Depth of loose	D50 (mm) ___	None ☐	Diagonal bars ☐	D50 (mm) ___
boulders + bedrock ☐	Sediment (cm) ___	D84 (mm) ___	Occasional ☐	Junction bars ☐	D84 (mm) ___
Bed rock ☐		D16 (mm) ___	Frequent ☐	Sand waves + dunes ☐	D16 (mm) ___

Notes and Comments:

Channel Sketch Map

Map Symbols
(to be determined by field crew)

Study reach limits	North point	Cut bank	Photo point
Cross-section	Flow direction	Exposed island/bar	Sediment sampling point
Bank profile	Impinging flow	Structure	Significant vegetation

Representative Cross-section

SECTION 4 - LEFT (OR RIGHT) BANK SURVEY

PART 8: LEFT (OR RIGHT) BANK CHARACTERISTICS

Type	Bank Materials	Layer Thickness	Ave. Bank Height	Bank Profile Shape	Tension Cracks
Noncohesive ☐	Silt/clay ☐	Material 1 (m) ___	Average height (m) ___	(see sketches in manual)	None ☐
Cohesive ☐	Sand/silt/clay ☐	Material 2 (m) ___		☐	Occasional ☐
Composite ☐	Sand/silt ☐	Material 3 (m) ___	**Ave. Bank Slope**		Frequent ☐
Layered ☐	Sand ☐	Material 4 (m) ___	angle (degrees) ___		**Crack Depth**
Even Layers ☐	Sand/gravel ☐				Proportion of
Thick+thin layers ☐	Gravel ☐				bank height ___
Number of layers ___	Gravel/cobbles ☐				
	Cobbles ☐				
Protection Status	Cobbles/boulders ☐				
Unprotected ☐	Boulders/bedrock ☐				
Hard points ☐					
Toe protection ☐					
Revetments ☐					
Dyke Fields ☐					

Distribution and Description of Bank Materials in Bank Profile

Material Type 1	Material Type 2	Material Type 3	Material Type 4
Toe ☐	Toe ☐	Toe ☐	Toe ☐
Mid-Bank ☐	Mid-Bank ☐	Mid-Bank ☐	Mid-Bank ☐
Upper Bank ☐	Upper Bank ☐	Upper Bank ☐	Upper Bank ☐
Whole Bank ☐	Whole Bank ☐	Whole Bank ☐	Whole Bank ☐
D50 (mm) ___	D50 (mm) ___	D50 (mm) ___	D50 (mm) ___
sorting coefficient ___	sorting coefficient ___	sorting coefficient ___	sorting coef. ___

Notes and Comments:

PART 9: LEFT (OR RIGHT) BANK-FACE VEGETATION

Vegetation	Tree Types	Density + Spacing	Location	Health	Height
None/fallow ☐	None ☐	None ☐	Whole bank ☐	Healthy ☐	Short ☐
Artificially cleared ☐	Deciduous ☐	Sparse/clumps ☐	Upper bank ☐	Fair ☐	Medium ☐
Grass and flora ☐	Coniferous ☐	dense/clumps ☐	Mid-bank ☐	Poor ☐	Tall ☐
Reeds and sedges ☐	Mixed ☐	Sparce/continuous ☐	Lower bank ☐	Dead ☐	Height (m) ___
Shrubs ☐		Dense/continuous ☐			
Saplings ☐	**Tree species**				
Trees ☐	(if known)	**Roots**	**Diversity**	**Age**	**Lateral Extent**
	☐	Normal ☐	Mono-stand ☐	Imature ☐	Wide belt ☐
Orientation	☐	Exposed ☐	Mixed stand ☐	Mature ☐	Narrow belt ☐
Angle of leaning (o) ___	☐	Adventitious ☐	Climax-vegetation ☐	Old ☐	Single row ☐

Notes and Comments:

Bank Profile Sketches

Profile Symbols

(to be determined by field crews)

Bank Top Edge	Failed debris	Engineered Structure
Bank Toe	Attached bar	Significant vegetation
Water's Edge	Undercutting	Vegetation Limit

PART 10: LEFT (OR RIGHT) BANK EROSION

Erosion Location		Present Status	Rate of Retreat	Dominant Processes	
General ☐	Opposite a structure ☐	Intact ☐	m/yr (if applicable and known) ___	Parallel flow ☐	Rilling + gullying ☐
Outside Meander ☐	Adjacent to structure ☐	Eroding:dormant ☐		Impinging flow ☐	Wind waves ☐
Inside Meander ☐	Dstream of structure ☐	Eroding:active ☐	**Rate of Advance**	Piping ☐	Vessel Forces ☐
Opposite a bar ☐	Ustream of structure ☐	Advancing:dormant ☐	m/yr (if applicable and known) ___	Freeze/thaw ☐	Ice rafting ☐
Behind a bar ☐	Other (write in) ☐	Advancing:active ☐		Sheet erosion ☐	Other (write in) ☐

Notes and Comments:

PART 11: LEFT (OR RIGHT) BANK GEOTECH FAILURES

Failure Location		Present Status	Failure Scars+Blocks	Apparent Failure Mode	
General ☐	Opposite a structure ☐	Stable ☐	None ☐	Soil/rock fall ☐	Pop-out failure ☐
Outside Meander ☐	Adjacent to structure ☐	Unreliable ☐	Old ☐	Shallow slide ☐	Piping failure ☐
Inside Meander ☐	Dstream of structure ☐	Unstable:dormant ☐	Recent ☐	Rotational slip ☐	Dry granular flow ☐
Opposite a bar ☐	Ustream of structure ☐	Unstable:active ☐	Fresh ☐	Slab-type block ☐	Wet earth flow ☐
Behind a bar ☐	Other (write in) ☐		Contemporary ☐	Cantilever failure ☐	Other (write in) ☐

Notes and Copmments:

PART 12: LEFT (OR RIGHT) BANK TOE SEDIMENT ACCUMULATION

Stored Bank Debris	Vegetation	Age	Health		Existing Debris Storage
None ☐	None/fallow ☐	Immature ☐	Healthy ☐		No bank debris ☐
Individual grains ☐	Artificially cleared ☐	Mature ☐	Unhealthy ☐		Little bank debris ☐
Aggregates+crumbs ☐	Grass and flora ☐	Old ☐	Dead ☐		Some bank debris ☐
Root-bound clumps ☐	Reeds and sedges ☐	Age in Years ☐			Lots of bank debris ☐
Small soil blocks ☐	Shrubs ☐			**Roots**	
Medium soil blocks ☐	Saplings ☐		**Tree species**	Normal ☐	
Large soil blocks ☐	Trees ☐		(if known)	Adventitious ☐	
Cobbles/boulders ☐			______	Exposed ☐	
Boulders ☐			______		

Notes and Comments:

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APPENDIX D

RAPID ASSESSMENT OF CHANNEL STABILITY

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APPENDIX D

Rapid Assessment of Channel Stability

D.1 INTRODUCTION

Given the time constraints for bridge inspections and the expense of conducting lengthy geomorphic studies, it would be desirable to have a technique for rapid channel stability assessments. Johnson et al.(1) have reviewed existing methods and parameters for evaluating channel stability and developed a systematic rapid channel stability assessment method for gravel bed channels. Their method is based on 13 qualitative and quantitative indicators of geomorphic and hydraulic processes that are rated, weighted, and summed to produce a stability rating. Some of these indicators have been introduced in Chapters 2 and 5, and most would be identified during a stream reconnaissance as recommended in Chapter 4.

D.2 PROCEDURE FOR ASSESSING STREAM STABILITY

The procedure for rapid assessment of stream stability developed by Johnson et al.(1) is based on a combination and modification of factors taken from methods proposed by Pfankuch,(2) Simon and Downs,(3) Lagasse et al.,(4) Gordon et al.,(5) and Thorne et al.(6) Quantitative information can be incorporated into the assessment by considering stream power and excess shear stress. However, stream power does not consider the influence of coarser bed material size, so the shear stress ratio is used as an alternative to indicate stability.

The average boundary shear stress is calculated as follows:

$$\tau_o = \gamma R S \qquad \text{(D.1)}$$

where:

- γ = Specific weight of water, N/m^3 (lb/ft^3)
- R = Hydraulic radius, m (ft)
- S = Channel slope (for uniform flow) or friction slope (for non-uniform flow), m/m (ft/ft)

The flow depth (y) can generally be substituted for hydraulic radius (R) for wide, shallow channels. This depth is readily available from gaging stations or can be measured or estimated, and provides a conservative estimate of τ_o. The critical shear stress (τ_c) can be determined from the Shields diagram, which gives τ_c as a function of the particle Reynolds number for uniform, non-cohesive sediments, or it can be calculated from the following:

$$\tau_c = \theta(\gamma_s - \gamma)D \qquad \text{(D.2)}$$

where:

θ = Shields parameter
γ_s = Specific weight of the sediment, kN/m^3 (lb/ft^3)
D = Particle size, m (ft)

The dimensionless Shields parameter is a function of the particle size and packing and generally ranges from 0.01 for loosely packed gravels to more than 0.1 for highly imbricated materials, i.e., particles which overlap or have a shingle arrangement. The median particle size (D_{50}) is used and can be obtained from the sieve data of a bulk sample collected from the channel bed or from a Wolman pebble count that adequately describes the bed material.(7, 8)

The shear stress ratio (τ_e) is the ratio of the average boundary shear stress (τ_o) divided by the critical shear stress at which bed material particles begin to move (τ_c) under bankfull flow conditions for streams with slopes less than 0.02 m/m (ft/ft) (i.e., $\tau_e = \tau_o/\tau_c$). In gravel bed rivers when $\tau_e > 1$, sediment begins to move along the bed.(9, 10) At $\tau_e > 2$, most of the bed is in motion and where $\tau_e > 3$, the entire bed is in motion.

Three steps are proposed in this assessment method:(1)

- The first step is to assess the parameters given in Table D.1 and assign a rating to each parameter. All the indicators except number 10 are observational and are subjective. Channel slope can be estimated from topographic maps or existing surveys.

- After assessing each parameter in Table D.1, each stability indicator is weighted according to the weights in Table D.2.

- The total score is summed and, based on the initial observations, the guidance in Table D.3 is used to determine the ranking of the channel.

Both regional stability indicators (numbers 4, 5, 9, and 10) and local stability indicators (numbers 7, 8, and 11-13) are included in Table D.1 since a regionally stable channel can be destabilized locally along a given reach. Individual indicators are not necessarily indicative of instability; instability is indicated by the combination of indicators. The weights in Table D.2 are based on the previously proposed methods described above and on the impact of each variable. Parameters with very localized impacts in most cases are assigned lower weights.

Although this method is based largely on prior assessment methods and was tested on gravel bed streams, the advantages of a method such as this include:

- The method weights each criterion based on its impact on stream channel instability, giving lower weight to indicators, such as debris jam potential, and greater weight to indicators, such as mass wasting.

- The rapid assessment method does not have a single variable that can dominate the rating of channel stability.

- Evaluation of each indicator is categorized as excellent, good, fair, and poor with three values in each range.

- The method provides several quantitative indicators, such as bed shear stress ratio, while incorporating fewer ambiguous criteria proposed by others.

- The method includes the use of bridge and culvert variables.

Table D.1. Stability Indicators, Descriptions, and Ratings.[1] Range of Values in Ratings Columns Provide Possible Rating Values for Each Factor.				
Stability Indicator	Ratings			
	Excellent (1-3)	Good (4-6)	Fair (7-9)	Poor (10-12)
1. Bank soil texture and coherence	Clay and silty clay; cohesive material	Clay loam to sandy clay loam	Sandy clay to sandy loam	Loamy sand to sand; non-cohesive material
2. Average bank slope angle	Bank slopes <3H:1V (18° or 33%) on both sides	Bank slopes up to 2H:1V (27° or 50%) on one or occasionally both banks	Bank slopes to 1.7H:1V (31° or 60%) common on one or both banks	Bank slopes over 60% common on one or both banks
3. Vegetative bank protection	Wide bank of woody vegetation with at least 90% density and cover. Primarily hard wood, leafy, deciduous trees with mature, healthy, and diverse vegetation located on the bank. Woody vegetation oriented vertically	Medium bank of woody vegetation with 70-90% plant density and cover. A majority of hard wood, leafy, deciduous trees with maturing, diverse vegetation located on the bank. Woody vegetation oriented 80-90°from horizontal with minimal root exposure.	Small bank of woody vegetation with 50-70% plant density and cover. A majority of soft wood, piney, coniferous trees with young or old vegetation lacking in diversity located on or near the top of bank. Woody vegetation oriented at 70-80° from horizontal often with evident root exposure.	Woody vegetation bank may vary depending on age and health with less than 50% plant den-sity and cover. Primary soft wood, piney, coniferous trees with very young, old and dying, and/or monostand vegetation located off of the bank. Woody vegetation oriented at less than 70° from horizontal with extensive root exposure.
4. Bank cutting	Little or none evident. Infrequent raw banks less than 15 cm (5.9 in) high generally.	Some intermittently along channel beds and at prominent constrictions. Raw banks may be up to 30 cm (11.8 in) high.	Significant and frequent. Cuts 30-60 cm (11.8-23.6 in) high. Root mat overhangs.	Almost continuous cuts, some over 60 cm (23.6 in) high. Undercutting, sod-root overhangs, and side failures frequent.
5. Mass wasting or bank failure	No or little evidence of potential or very small amounts of mass wasting. Uniform channel width over the entire reach.	Evidence of infrequent and/or minor mass wasting. Mostly headed over with vegetation. Relatively constant channel width and minimal scalloping of banks.	Evidence of frequent and/or significant occurrences of mass wasting that can be aggravated by higher flows, which may cause undercutting and mass wasting of unstable banks. Channel width quite irregular and scalloping of banks is evident.	Frequent and extensive mass wasting. The potential for bank failure, as evidenced by tension cracks, massive under-cuttings, and bank slumping, is considerable. Channel width is highly irregular and banks are scalloped.
6. Bar development	Bars are mature, narrow relative to stream width at low flow, well vegetated, and composed of coarse gravel to cobbles.	Bars may have vegetation and/or be composed of coarse gravel to cobbles, but minimal recent growth of bar evident by lack of vegetation on portions of the bar.	Bar widths tend to be wide and composed of newly deposited coarse sand to small cobbles and/or may be sparsely vegetated	Bar widths are generally greater than 1/2 the stream width at low flow. Bars are composed of extensive deposits of fine particles up to coarse gravel with little to no vegetation.
7. Debris jam potential	Debris or potential for debris in channel is negligible	Small amounts of debris present. Small jams could be formed.	Noticeable accumulations of all sizes. Moderate downstream debris jam potential possible.	Moderate to heavy accumulations of various size debris present. Debris jam potential significant.
8. Obstructions, flow deflectors, and sediment traps	Rare or not present	Present, causing cross currents and minor bank and bottom erosion	Moderately frequent and occasionally unstable obstructions cause noticeable erosion of the channel. Considerable sediment accumulations behind obstructions	Frequent and often unstable causing a continual shift of sediment and flow. Traps are easily filled causing channel to migrate and/or widen.

Table D.1. Stability Indicators, Descriptions, and Ratings.[1] Range of Values in Ratings Columns Provide Possible Rating Values for Each Factor.				
Stability Indicator	Ratings			
	Excellent (1-3)	Good (4-6)	Fair (7-9)	Poor (10-12)
9. Channel bed material consolidation and armoring	Assorted sizes tightly packed, overlapping, and possibly imbricated. Most material >4 mm (0.16 in).	Moderately packed with some overlapping. Very small amounts of material < 4 mm (0.16 in).	Loose assortment with no apparent overlap. Small to medium amounts of material < 4 mm (0.16 in).	Very loose assortment with no packing. Large amounts of material < 4 mm (0.16 in).
10. Shear stress ratio (Eqs. D.1 and D.2)	$\tau_0 / \tau_c < 1.0$	$1.0 \leq \tau_0 / \tau_c < 1.5$	$1.5 \leq \tau_0 / \tau_c < 2.5$	$\tau_0 / \tau_c \geq 2.5$
11. ‡High flow angle of approach to bridge or culvert	$0° \leq \alpha \leq 5°$	$5° < \alpha \leq 10°$	$10° < \alpha \leq 30°$	$\alpha > 30°$
12. §Bridge or culvert distance from meander impact point	$D_m > 35$ m (Dm > 115 ft)	$20 < D_m \leq 35$ m ($66 < DM \leq 115$ ft)	$10 < D_m \leq 20$ m ($33 < Dm \leq 66$ ft)	$0 < D_m \leq 10$ m ($0 < DM \leq 33$ ft)
13. Percentage of channel constriction	0-5%	6-25%	26-50%	> 50%

‡ α = approach flow angle to bridge or culvert

§ D_m = distance from bridge or culvert upstream to meander impact point

Table D.2. Stability Indicators and Weights for Stability Assessment Scheme.[1]	
Stability Indicator	Weight
1. Bank soil texture and coherence	0.6
2. Average bank slope angle	0.6
3. Vegetative bank protection	0.8
4. Bank cutting	0.4
5. Mass wasting or bank failure	0.8
6. Bar development	0.6
7. Debris jam potential	0.2
8. Obstructions, deflectors, and sediment traps	0.2
9. Bed material consolidation and armoring	0.8
10. Shear stress ratios	1.0
11. High flow angle of approach to bridge	0.8
12. Distance from meander impact point	0.8
13. Percentage of channel constriction	0.8

Table D.3. Overall Rating Ranges.	
Description	Rating (R)
Excellent	$R < 32$
Good	$32 \leq R < 55$
Fair	$55 \leq R < 78$
Poor	$R \geq 78$

This information provides the engineer with a sense of potential problems and can be used to develop a preliminary evaluation of lateral stability based on indicators 1-7 in Table D.1, of vertical stability based on indicators 8-10 in Table D.1, and of overall stability. In addition, this method can be used to determine the need for more detailed assessments, such as the field reconnaissance assessment presented in Chapter 4. Conversely, data obtained during a field reconnaissance can be used to complete a rapid assessment and provide a preliminary evaluation of potential instability problems.

D.3. APPLICATION OF RAPID STABILITY ASSESSMENT

This procedure for the rapid assessment of stream stability was tested on several streams in Pennsylvania and Maryland where bridges had failed as a result of flood-induced local scour.(1) An evaluation of one of the streams is provided here. The pertinent data on the slope, channel bed particle size, width to depth ratio, τ_o, τ_c, and τ_e for the stream are shown in Table D.4.

Table D.4. Observed Data for Example Stream.

	SI	English
Average bankfull width W	8.38 m	27.5 ft
Average Bankfull depth y	0.76 m	2.5 ft
Bankfull width/depth (W/y)	11.0	11.0
Slope	0.0054 m/m	0.0054 ft/ft
D_{50}	9 mm	0.029 ft
Bankfull τ_o	40.3N/m^2	0.84 lb/ft^2
τ_c	5.10 N/m^2	0.11 lb/ft^2
$\tau_e = \tau_o/\tau_c$	7.90	7.90

The stream lies in the Appalachian Plateau physiographic province and has a fairly steep slope with predominantly gravel bed material. The channel banks are typically silty clay to sandy, silty clay. Mass wasting, bank cutting and steep bank slopes are present along the stream. The stability ratings and overall rating for this stream are shown in Table D.5. The combination of these factors indicates that lateral instability is far more likely than vertical instability (see stability indicators 2, 4, and 5, Table D.5).

The Fair rating is not an indicator of failure in itself even though the existing bridge at this site failed due to local abutment scour and/or pier scour. The rating only indicates that the bank and bed are somewhat unstable. Given this rating, protection of the banks upstream and downstream of the bridge could be considered in order to decrease the potential for lateral movement and the continued threat to the safety of any replacement bridge at this site.

Although rapid assessments provide only a relative ranking rather than a quantitative evaluation of magnitudes of change, they do provide the engineer with a sense of potential problems that exist or may develop at a given site. The advantages of this type of assessment are that the criterion weighting is based on its impact on stream channel stability, the more heavily weighted items of this methodology are not region or stream-type specific, and no individual variable can dominate the rating of channel stability. One of the limitations of this methodology is that it has only been tested on several steep streams in

Pennsylvania and Maryland, which are composed of large bed materials and fine-grained banks. **Thus, for a given region or locale, this methodology should be tested and evaluated for reasonableness and modified, as necessary, prior to extensive use elsewhere**.

Table D.5. Stream Ratings for Example Stream.		
Stability Indicator	Rating	Weighted Rating
1	2	1.2
2	12	7.2
3	5	4.0
4	12	4.8
5	12	9.6
6	1	0.6
7	8	1.6
8	5	1.0
9	9	7.2
10	12	12.0
11	5	4.0
12	1	0.8
13	6	4.8
Total	--	58.8
Rating	--	Fair

D.4 REFERENCES

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APPENDIX E

EXAMPLE PROBLEMS FOR QUANTITATIVE TECHNIQUES

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APPENDIX E

Example Problems for Quantitative Techniques

This appendix provides example problems that illustrate techniques for vertical channel stability analysis, which were discussed in detail in Chapter 6. The techniques utilized in these example problems include incipient motion, armoring, equilibrium slope and base level control, and sediment continuity. The example problems are presented in SI units first, followed by the same set of examples in English units.

Example Problem E.1 - Incipient Motion and Armoring Analysis (SI)

A scour vulnerability assessment is being completed for a bridge on a river with well-graded bed material ranging from fine sand to course gravel and cobbles. Determine if the development of an armor layer on the streambed will limit contraction scour. Use principles of incipient motion and armoring to make this assessment and assume a wide channel.

Given:

Design discharge = 1787 m^3/s
Velocity = 3.26 m/s (determined from hydraulic modeling)
Depth = 5.79 m (determined from hydraulic modeling)
Gradation curves from two bed material samples and their average (provided in Figure E.1)
D_{50} = 110 mm (small cobbles)

Solution:

1. Use Equation 6.16 to calculate the boundary shear stress acting on the bed. Since the bed material is well-graded and coarse use $K_s = 3.5D_{84}$, where D_{84} is determined to be 210 mm from Figure E.1.

$$\tau_o = \frac{\rho V^2}{\left[5.75\ \log\left(\frac{12.27\,R}{k_s}\right)\right]^2}$$

$$\tau_o = \frac{1000\,(3.26)^2}{\left[5.75\log\left(\frac{12.27\,(5.79)}{3.5(0.210)}\right)\right]^2} = 81.56\,N/m^2 = 81.56\,Pa$$

2. Knowing the boundary shear stress calculate the bed material size for incipient motion. Use Equation 6.14 assuming Shields parameter = 0.03 for coarse bed material.

$$D_c = \frac{\tau_o}{K_s(\gamma_s - \gamma)}$$

$$D_c = \frac{81.56}{0.03[(2.65)(9810) - 9810)]} = 0.168m$$

The results indicate that during the design flood, hydraulic forces are adequate to transport bed material up to 168 mm in diameter. Figure E.1 indicates that 70 percent of the bed material is less than or equal to this particle diameter. Therefore, 30 percent of the bed material is coarser than D_c.

3. More than 5 percent of the bed material is coarser than D_c. Therefore, armoring is possible. Use Equation 6.17 to estimate the depth of degradation at which an armor layer could form. Assume the armor layer thickness is 3 D_c

$$Y_s = y_a \left(\frac{1}{P_c} - 1 \right)$$

$$y_s = 3(0.168)\left(\frac{1}{0.30} - 1 \right) = 1.2\,m$$

It is expected that the bed would armor after 1.2 m of degradation.

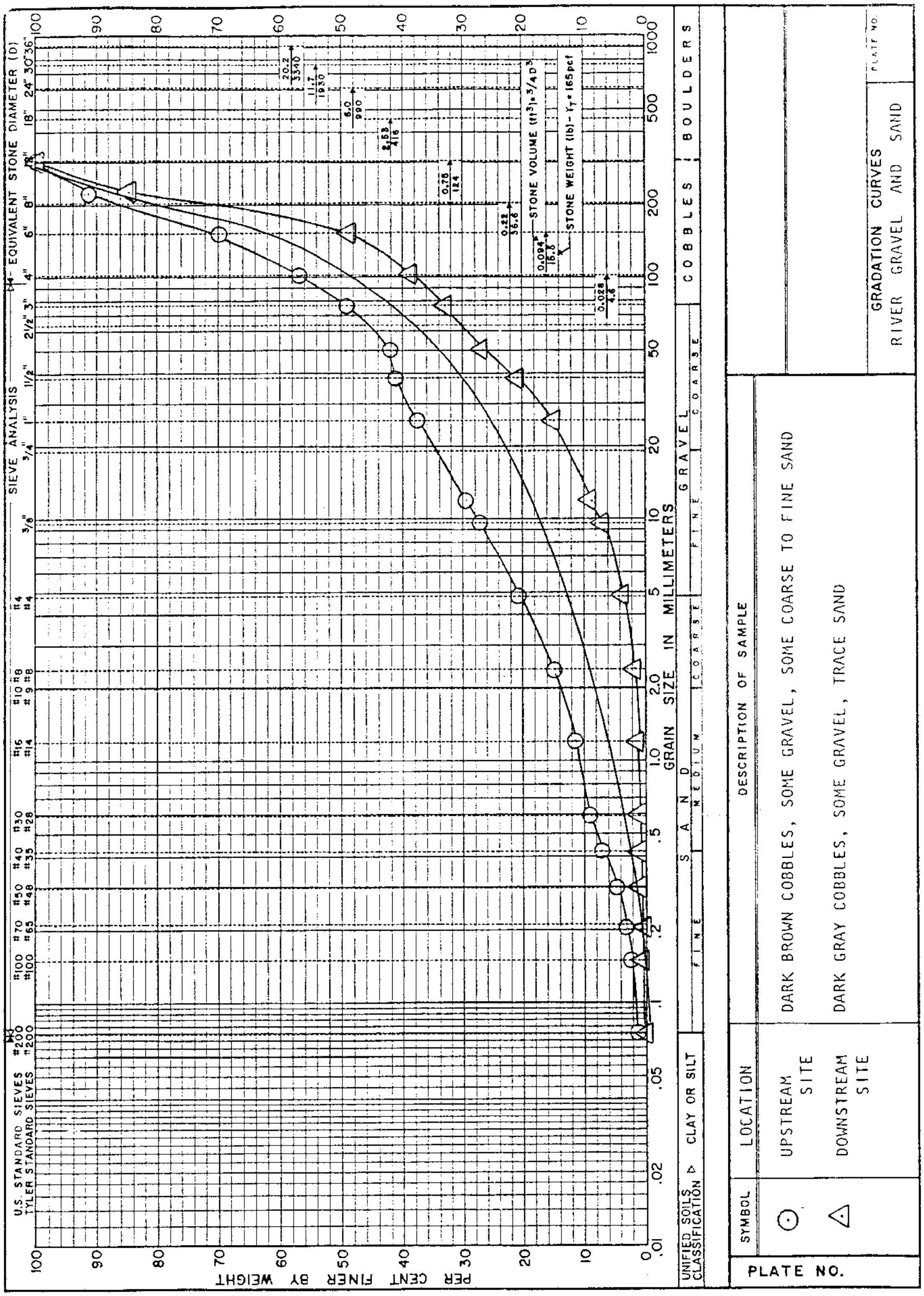

Figure E.1. Bed material size gradation curves.

Example Problem E.2 - Equilibrium Slope Analysis (SI)

The following example was adapted from the USBR.[98] A channel reach receives a majority of its sediment load from an upstream tributary. A small dam on the tributary is proposed to provide local farmers with water for irrigation. The agency responsible for a bridge on the main channel just downstream from the tributary confluence is concerned about the effects of the dam on channel stability. Given the existing hydraulic conditions in the channel reach, calculate the equilibrium slope that is expected to develop over time as a result of (1) removing 100 percent of the sediment supply and (2) reducing the existing supply to 35 percent of the existing value.

Given:

Dominant discharge = 22.1 m^3/s
Sediment supply = 0.00399 m^3/s
Width = 107 m
Depth = 0.32 m
Slope = 0.0014
D_{50} = 0.30 mm
D_{90} = 0.96 mm
Manning's n = 0.027 for the bed of the stream

Solution for part 1:

Use Equation 6.18 to estimate the equilibrium slope assuming the sediment supply has been removed. Assume the Shields parameter is 0.047 and the specific gravity is 2.65 for this bed material.

$$S_{eq} = \left[K_s D_c \left(\frac{\gamma_s - \gamma}{\gamma}\right)\right]^{(10/7)} \left(\frac{K_u}{qn}\right)^{(6/7)}$$

$$S_{eq} = \left[0.047(0.00096)\left(\frac{2.65(9810) - 9810}{9810}\right)\right]^{10/7} \left(\frac{1}{\left(\frac{22.1}{107}\right)0.027}\right)^{6/7}$$

$$S_{eq} = 0.000108\,m/m$$

Use Equation 6.19 to estimate the equilibrium slope assuming the sediment supply has been removed.

$$S_{eq} = K_u \frac{(D_{50})^{10/7}\, n^{9/7}}{(D_{90})^{5/14}\, q^{6/7}}$$

$$S_{eq} = 28.0\ \frac{0.00030^{(10/7)}\ 0.027^{(9/7)}}{0.00096^{(5/14)}\left(22.1/107\right)^{(6/7)}}$$

$$S_{eq} = 0.000115\,m/m$$

Solution for part 2:

Use Equation 6.24 to estimate the equilibrium slope given that the sediment supply has been reduced to 0.35 (0.00399) = 0.00140 m^3/s.

$$b = 4.93 - 0.74\log(D_{50})$$

$$b = 4.93 - 0.74\ \log(0.3) = 5.32$$

$$c = -0.46 + 0.65\log(D_{50})$$

$$c = -0.46 + 0.65\ \log(0.3) = -0.80$$

$$a = 0.025\,n^{(2.39-0.8\log(D_{50}))}\,(D_{50} - 0.07)^{-1.4}$$

$$a = 0.3048^{(2-5.32+0.80)}\left[0.025\,(0.027^{(2.39-0.8\log(0.3))})(0.3 - 0.07)^{-1.4}\right] = 0.000154$$

$$S_{eq} = \left(\frac{a}{q_s}\right)^{\frac{10}{3(c-b)}}\ q^{\frac{2(2b+3c)}{3(c-b)}}\ \left(\frac{n}{K_u}\right)^2$$

$$S_{eq} = \left(\frac{0.000154}{\left(\frac{0.00140}{107}\right)}\right)^{\frac{10}{3(-0.80-5.32)}}\left(\frac{22.1}{107}\right)^{\frac{2(2(5.32)+3(-0.80))}{3(-0.80-5.32)}}\left(\frac{0.027}{1}\right)^2$$

$$S_{eq} = 0.000784\,m/m$$

Use Equation 6.25 to estimate the equilibrium slope given that the sediment supply has been reduced to 0.35 (0.00399) = 0.00140 m^3/s. This equation assumes the reach was previously in equilibrium.

$$S_{eq} = S_{ex}\left(\frac{Q_{s(future)}}{Q_{s(existing)}}\right)^{\frac{10}{3(b-c)}}$$

$$S_{eq} = 0.0014\left(\frac{0.00140}{0.00399}\right)^{\frac{10}{3(5.32+0.80)}}$$

$$S_{eq} = 0.000791\,m/m$$

Example Problem E.3 - Base Level Control (SI)

From Example Problem E.2 there is a concern that changes in bed elevation could threaten the foundation of the bridge that crosses the main channel immediately downstream from the tributary. Given that a base level control exists approximately 2,500 m downstream of the bridge, calculate the degradation at the bridge assuming each of the equilibrium slopes from Example Problem E.2.

Solution:

Equation 6.26 is used to calculate degradation at the bridge assuming the equilibrium slope from Shields.

$$Y_s = L(S_{ex} - S_{eq})$$

$$y_s = 2{,}500\,(0.0014 - 0.000108) = 3.2\,\text{m}$$

Results from Equation 6.26 are presented for all the equilibrium slopes in Table E.1.

Table E.1. Estimates of Degradation at the Bridge for Each Slope From Example E.2.

Method of Calculating Slope	Equilibrium Slope	Degradation (m)
Shields (Equation 6.18)	0.000108	3.2
MPM (Equation 6.19)	0.000115	3.2
Regression (Equation 6.24)	0.000784	1.5
Regression (Equation 6.25)	0.000791	1.5

The computed channel profiles from the bridge downstream to the base level control are presented in Figure E.2. Notice that the computed profiles are almost identical for a given inflowing sediment supply, regardless of the equation used; but the amount of inflowing sediment supply has a significant impact on the computed profile.

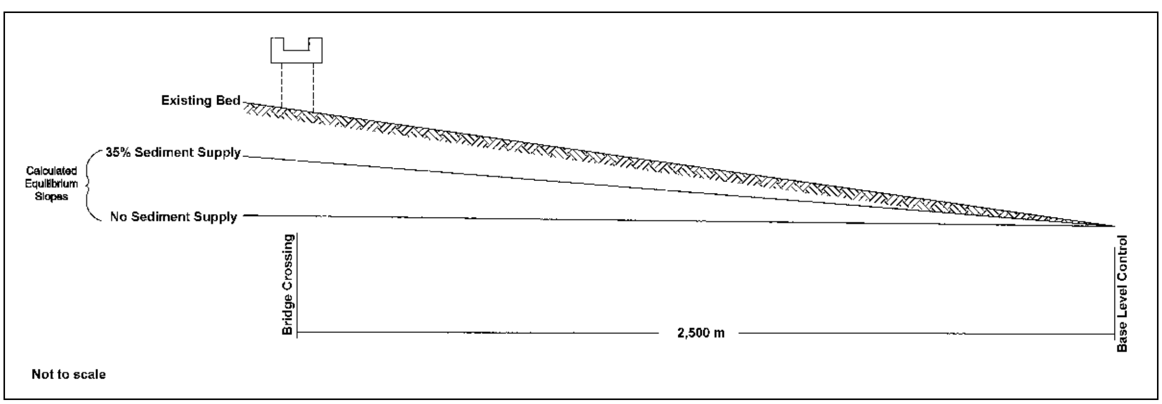

Figure E.2. Computed channel profiles from the bridge downstream to the base level control.

Example Problem E.4 - Sediment Continuity (SI)

For the channel of Example Problem E.2, calculate the average change in bed elevation that is expected by the end of the first water year following construction of the dam. The data are also plotted in Figure E.3. The discharge hydrograph will not change, however, the sediment supplies are expected to be reduced to 35 percent of the existing value as a result of the dam. Table E.2 shows monthly discharges and sediment supplies for a typical water year. Assume the reach is 2,500 m long (the distance to downstream base level control) and that the channel properties: width, slope, particle size and Manning's n are the same as presented in Example Problem E.2. Use Equation 6.20 to calculate sediment transport capacity for the reach.

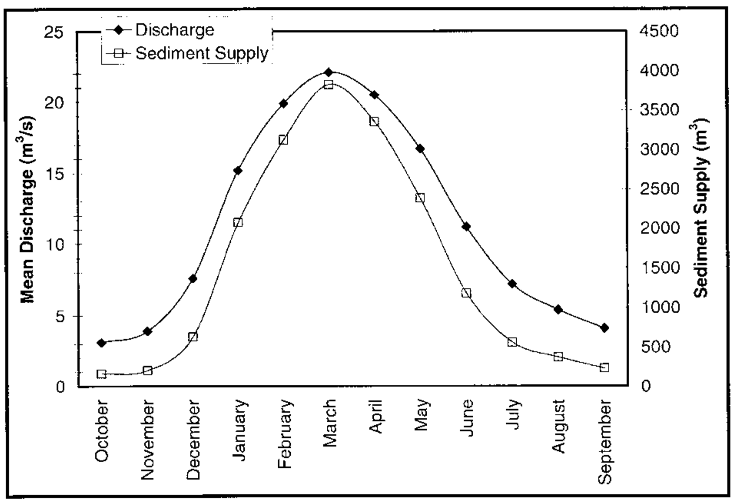

Figure E.3. Plot of average discharge and total sediment supply distribution for year.

Table E.2. Average Discharge and Total Sediment Supply Distribution for the Year.		
Month	Average Discharge (m^3/s)	Sediment Supply (m^3)
October	3.1	130
November	3.9	240
December	7.6	620
January	15.2	2,310
February	19.9	3,120
March	22.1	3,810
April	20.5	3,040
May	16.7	2,380
June	11.2	1,320
July	7.2	650
August	5.4	320
September	4.1	190
	TOTAL	18,130

Solution:

The first step is to calculate the hydraulic properties for each month. The values of depth and velocity are required to calculate sediment transport capacity using Equation 6.20. Assuming a wide rectangular channel, the Manning equation (Equation 5.5) can be rearranged to solve for flow depth. The following is a sample calculation for the month of March:

$$Y = \left[\frac{Qn}{W\,S^{1/2}}\right]^{3/5}$$

$$Y = \left[\frac{(22.1)(0.027)}{(107)(0.0014)^{1/2}}\right]^{3/5} = 0.32\,m$$

Knowing discharge, width, and depth, velocity can be calculated using the continuity equation (Equation 5.1):

$$V = \frac{Q}{A}$$

$$V = \frac{22.1}{(107)(0.32)} = 0.65\,m/s$$

Table E.3 presents the hydraulic properties corresponding to the mean discharge for each month. The channel properties given in Example Problem E.2 were used.

Table E.3. Hydraulic Properties for Each Month of the Year.

Month	Discharge (m^3/s)	Depth (m)	Velocity (m/s)
October	3.1	0.10	0.29
November	3.9	0.11	0.33
December	7.6	0.17	0.42
January	15.2	0.25	0.57
February	19.9	0.30	0.62
March	22.1	0.32	0.65
April	20.5	0.31	0.62
May	16.7	0.27	0.58
June	11.2	0.21	0.50
July	7.2	0.16	0.42
August	5.4	0.14	0.36
September	4.1	0.12	0.32

The next step is to calculate the hydraulic capacity to transport sediment out of the reach for each month. Given that the coefficient and exponents from Equation 6.20 are functions only of D_{50} and Manning's n, their values will be unchanged from Example Problem E.2 and will be the same for each month. From Example Problem E.2, the values of a, b, and c are:

a = 0.000154
b = 5.32
c = -0.80

Sediment transport capacity for each month can be calculated by using Equation 6.20. The following is a sample calculation for the month of March:

$$q_s = aV^bY^c$$

$$Q_s = Wq_s = W(a V^b y^c)$$

$$Q_s = Wq_s = 107[0.000154(0.65)^{5.32}(0.32)^{-0.80}] = 0.0004145\,m^3/s$$

The calculated sediment transport capacity for each month is presented in Table E.4. The total volume of sediment for each month was also calculated by multiplying the capacity and the number of seconds in a month (assuming an average of 2,628,000 seconds per month).

Table E.4. Sediment Transport Capacity for the Year.

Month	Sediment Transport Capacity (m^3/s)	Total Volume of Sediment (m^3)
October	0.000144	380
November	0.000264	690
December	0.000673	1,770
January	0.002511	6,600
February	0.003394	8,920
March	0.004145	10,890
April	0.003306	8,690
May	0.002590	6,810
June	0.001438	3,780
July	0.000707	1,860
August	0.000346	910
September	0.000209	550
	TOTAL	51,850

The volume of degradation can be calculated for each month using Equation 6.32. The sediment inflows are the volume supplies reported in Table E.2 and the sediment outflows are the volume capacities reported in Table E.4. The results of these calculations are shown in Table E.5. For the month of March:

$$\Delta V = V_{s(inflow)} - V_{s(outflow)} = 3{,}810 - 10{,}890 = -7{,}080\,m^3$$

Figure E.4 presents a plot of the inflow and outflow sediment volumes. By looking at the discrepancy between the two curves it is apparent that the reach will degrade by the end of the inflow hydrograph.

Table E.5. Change in Volume and Depth of Bed Material for Each Month.			
Month	Inflow (m^3)	Outflow (m^3)	Change in Volume (m^3)
October	130	380	-250
November	240	690	-450
December	620	1,770	-1,150
January	2,310	6,600	-4,290
February	3,120	8,920	-5,800
March	3,810	10,890	-7,080
April	3,040	8,690	-5,650
May	2,380	6,810	-4,430
June	1,320	3,780	-2,460
July	650	1,860	-1,210
August	320	910	-590
September	190	550	-360
TOTALS	18,130	51,850	-33,720

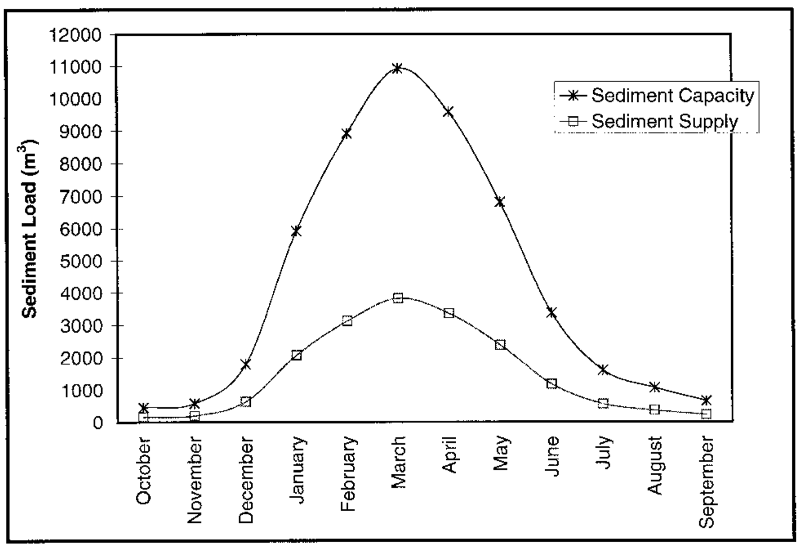

Figure E.4. Inflow (supply) and outflow (capacity) plots corresponding to the inflow hydrograph.

The cumulative change in bed elevation expected to occur by the end of the water year can be computed using Equation 6.34, where ΔV is the total change in volume for the entire year. It is assumed for this bed material that the porosity is 40 percent.

$$\Delta Z = \frac{\Delta V}{WL(1-\eta)}$$

$$\Delta Z = \frac{-33720}{107(2500)(1-0.40)} = -0.21\text{m}$$

The average change in bed elevation for the 2,500-m reach is expected to be -0.21 m by the end of the water year following installation of the dam. Bed lowering at the upstream end of the reach will be greater than the average because degradation begins upstream in a sediment deficient system. In the first water year, degradation could be zero or negligible at the lower portion of the reach.

Example Problem E.5 - Sediment Continuity (SI)

For the channel in Example Problems E.2 through E.4, estimate the number of years it will take for the slope of the main channel to reach equilibrium given that the sediment supply will be reduced to 35 percent of the existing value. Use the total volume deficit from Table E.5 as the annual volume of erosion for the reach. The total volume of sediment that will ultimately be eroded can be calculated from the results of Example Problem E.3.

Solution:

1. Calculate the total volume of sediment that will have been eroded once equilibrium has been reached (see Figure E.2 and assume the degradational "wedge" is a right triangle and account for the porosity of the sediment).

Total Volume = W [1/2 y_s L] = 107 [1/2 (1.5) (2500)] = 200,630 m^3

Sediment Volume = Total Volume (1 - η) = 200,630 (1 - 0.40) = 120,380 m^3

2. Calculate the time to reach slope equilibrium.

$$\text{Time (years)} = \frac{120{,}380\,\text{m}^3}{33{,}720\,\text{m}^3\ /\ \text{yr}} = 3.6\ \text{years (say 4 years)}$$

It is expected that the slope of the main channel will reach equilibrium in about 4 years after construction of the dam on the tributary.

Example Problem E.6 - Incipient Motion and Armoring Analysis (English)

A scour vulnerability assessment is being completed for a bridge on a river with well-graded bed material ranging from fine sand to course gravel and cobbles. Determine if the development of an armor layer on the streambed will limit contraction scour. Use principles of incipient motion and armoring to make this assessment and assume a wide channel.

Given:

Design discharge = 63,100 cfs
Velocity = 10.7 ft/s (determined from hydraulic modeling)
Depth = 19.0 ft (determined from hydraulic modeling)
Gradation curves from two bed material samples and their average (provided in Figure E.5)
D_{50} = 110 mm = 0.361 ft (small cobbles)

Solution:

1. Use Equation 6.16 to calculate the boundary shear stress acting on the bed. Since the bed material is well graded and coarse use $K_s = 3.5D_{84}$, where D_{84} is determined to be 210 mm (0.689 ft) from Figure E.5.

$$\tau_o = \frac{\rho V^2}{\left[5.75 \log\left(\frac{12.27 R}{k_s}\right)\right]^2}$$

$$\tau = \frac{1.94\,(10.7)^2}{\left[5.75 \log\left(\frac{12.27\,(19.0)}{3.5\,(0.689)}\right)\right]^2} = 1.70\,\text{lb}/\text{ft}^2$$

2. Knowing the boundary shear stress calculate the bed material size for incipient motion. Use Equation 6.14 assuming Shields parameter = 0.03 for coarse bed material.

$$D_c = \frac{\tau_o}{K_s(\gamma_s - \gamma)}$$

$$D_c = \frac{1.70}{0.03\,[(2.65)(62.4) - (62.4)]} = 0.550\,\text{ft}$$

The results indicate that during the design flood, hydraulic forces are adequate to transport bed material up to 0.550 ft (168 mm) in diameter. Figure E.5 indicates that 70 percent of the bed material is less than or equal to this particle diameter. Therefore, 30 percent of the bed material is coarser than D_c.

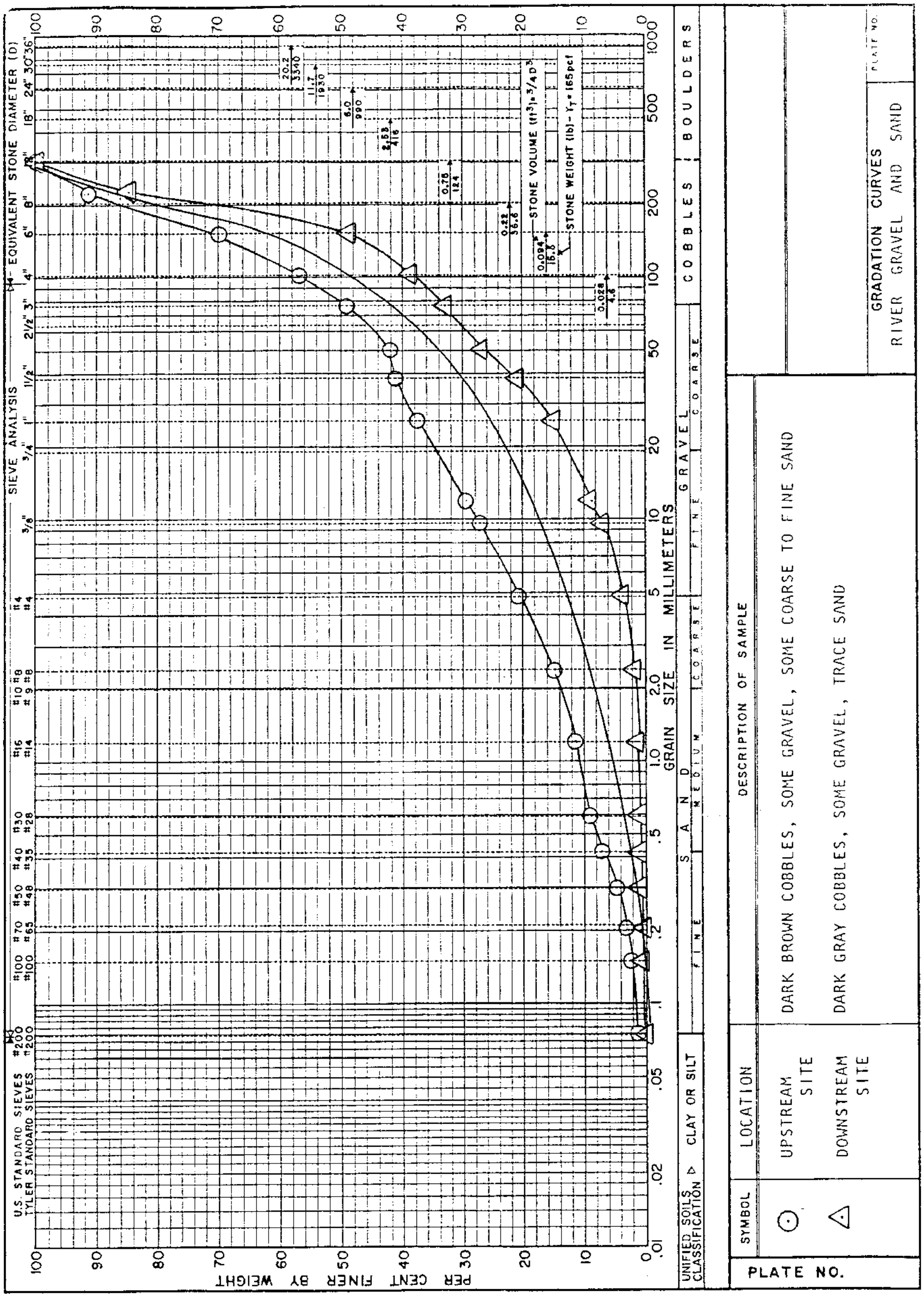

Figure E.5. Bed material size gradation curves.

3. More than 5 percent of the bed material is coarser than D_c. Therefore, armoring is possible. Use Equation 6.17 to estimate the depth of degradation at which an armor layer could form. Assume the armor layer thickness is 3 D_c

$$Y_s = y_a\left(\frac{1}{P_c} - 1\right)$$

$$y_s = 3(0.550)\left(\frac{1}{0.30} - 1\right) = 3.8\,\text{ft}$$

It is expected that the bed would armor after 3.8 ft of degradation.

Example Problem E.7 - Equilibrium Slope Analysis (English)

The following example was adapted from the USBR.[98] A channel reach receives a majority of its sediment load from an upstream tributary. A small dam on the tributary is proposed to provide local farmers with water for irrigation. The agency responsible for a bridge on the main channel just downstream from the tributary confluence is concerned about the effects of the dam on channel stability. Given the existing hydraulic conditions in the channel reach, calculate the equilibrium slope that is expected to develop over time as a result of (1) removing 100 percent of the sediment supply and (2) reducing the existing supply to 35 percent of the existing value.

Given:

Dominant discharge = 780 cfs
Sediment Supply = 0.142 ft^3/s
Width = 350 ft
Depth = 1.05 ft
Slope = 0.0014
D50 = 0.000984 ft (0.30 mm)
D90 = 0.003150 ft (0.96 mm)
Manning's n = 0.027 for the bed of the stream

Solution for part 1:

Use Equation 6.18 to estimate the equilibrium slope assuming the sediment supply has been removed. Assume the Shields parameter is 0.047 and the specific gravity is 2.65 for this bed material.

$$S_{eq} = \left[K_s D_c\left(\frac{\gamma_s - \gamma}{\gamma}\right)\right]^{(10/7)}\left(\frac{K_u}{qn}\right)^{(6/7)}$$

$$S_{eq} = \left[0.047\,(0.003150)\left(\frac{2.65\,(62.4) - 62.4}{62.4}\right)\right]^{(10/7)}\left(\frac{1.486}{\left(\frac{780}{350}\right)0.027}\right)^{(6/7)}$$

$$S_{eq} = 0.000108\,\text{ft / ft}$$

Use Equation 6.19 to estimate the equilibrium slope assuming the sediment supply has been removed.

$$S_{eq} = K_u \frac{(D_{50})^{10/7}\, n^{9/7}}{(D_{90})^{5/14}\, q^{6/7}}$$

$$S_{eq} = 60.1\frac{0.000984^{(10/7)}0.027^{(9/7)}}{0.003150^{(5/14)}\left(\frac{780}{350}\right)^{(6/7)}}$$

$$S_{eq} = 0.000115\,\text{ft / ft}$$

Solution for part 2:

Use Equation 6.24 to estimate the equilibrium slope given that the sediment supply has been reduced to 0.35 (0.142) = 0.050 ft^3/s.

$$a = 0.025\,n^{(2.39-0.8\log(D_{50}))}\,(D_{50} - 0.07)^{-1.4}$$

$$a = 0.025\ (0.027^{(2.39-0.8\log(0.3))})\ (0.3 - 0.07)^{-1.4} = 0.00000770$$

$$b = 4.93 - 0.74\log(D_{50})$$

$$b = 4.93 - 0.74\ \log\ (0.3) = 5.32$$

$$c = -0.46 + 0.65\log(D_{50})$$

$$c = -0.46 + 0.65\ \log\ (0.3) = -0.80$$

$$S_{eq} = \left(\frac{a}{q_s}\right)^{\frac{10}{3(c-b)}}\ q^{\frac{2(2b+3c)}{3(c-b)}}\ \left(\frac{n}{K_u}\right)^2$$

$$S_{eq} = \left(\frac{0.00000770}{\left(\frac{0.050}{350}\right)}\right)^{\frac{10}{3(-0.80-5.32)}}\left(\frac{780}{350}\right)^{\frac{2(2(5.32)+3(-0.80))}{3(-0.80-5.32)}}\left(\frac{0.027}{1.486}\right)^2$$

$$S_{eq} = 0.000789\,\text{ft / ft}$$

Use Equation 6.25 to estimate the equilibrium slope given that the sediment supply has been reduced to 0.35 (0.142) = 0.05 ft^3/s. This equation assumes the reach was previously in equilibrium.

$$S_{eq} = S_{ex}\left(\frac{Q_{s(future)}}{Q_{s(existing)}}\right)^{\frac{10}{3(b-c)}}$$

$$S_{eq} = 0.0014\left(\frac{0.050}{0.142}\right)^{\frac{10}{3(5.32+0.80)}}$$

$$S_{eq} = 0.000793\,\text{ft / ft}$$

Example Problem E.8 - Base Level Control (English)

From Example Problem E.7 there is a concern that changes in bed elevation could threaten the bridge foundation of the bridge that crosses the main channel immediately downstream from the tributary. Given that a base level control exists approximately 8,000 ft downstream of the bridge, calculate the degradation at the bridge assuming each of the equilibrium slopes from the Example Problem E.7.

Solution:

Equation 6.26 is used to calculate degradation at the bridge assuming the equilibrium slope from Shields.

$$Y_s = L(S_{ex} - S_{eq})$$

$$y_s = 8{,}000\,(0.0014 - 0.000108) = 10.3\,\text{ft}$$

Results from Equation 6.26 are presented for all the equilibrium slopes in Table E.6.

Table E.6. Estimates of Degradation at the Bridge for Each Slope from Example E.2.

Method of Calculating Slope	Equilibrium Slope	Degradation (ft)
Shields (Equation 6.18)	0.000108	10.3
MPM (Equation 6.19)	0.000115	10.3
Regression (Equation 6.24)	0.000789	4.9
Regression (Equation 6.25)	0.000793	4.9

The computed channel profiles from the bridge downstream to the base level control are presented in Figure E.2. Notice that the computed profiles are almost identical for a given inflowing sediment supply, regardless of the equation used; but the amount of inflowing sediment supply has a significant impact on the computed profile.

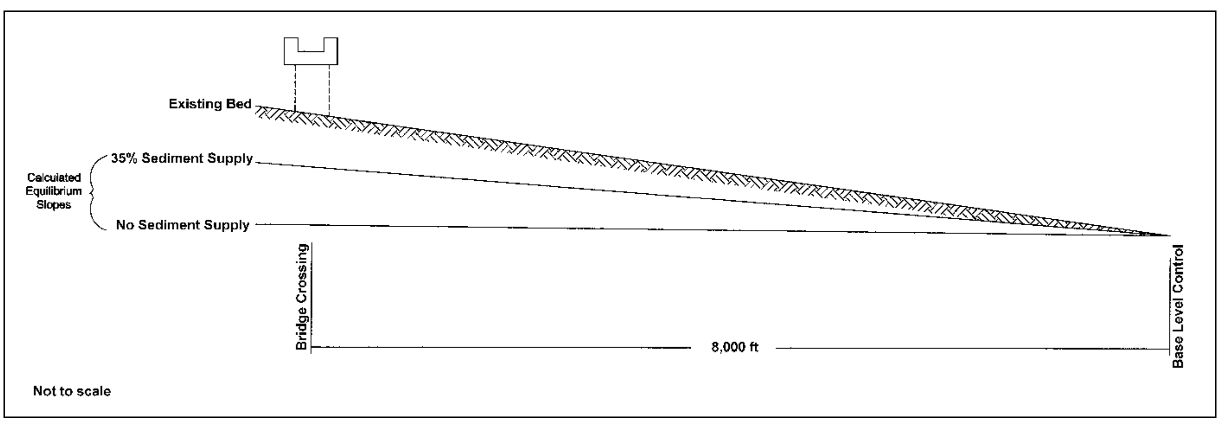

Figure E.6. Computed channel profiles from the bridge downstream to the base level control.

Example Problem E.9 - Sediment Continuity (English)

For the channel of Example Problem E.7, calculate the average change in bed elevation that is expected by the end of the first water year following construction of the dam. The data are also plotted in Figure E.7. The discharge hydrograph will not change, however, the sediment supplies are expected to be reduced to 35 percent of the existing value as a result of the dam. Table E.7 shows monthly discharges and sediment supplies for a typical water year.

Assume the reach is 8,000 ft long (the distance to downstream base level control) and that the channel properties: width, slope, particle size and Manning's n are the same as presented in Example Problem E.7. Use Equation 6.20 to calculate sediment transport capacity for the reach.

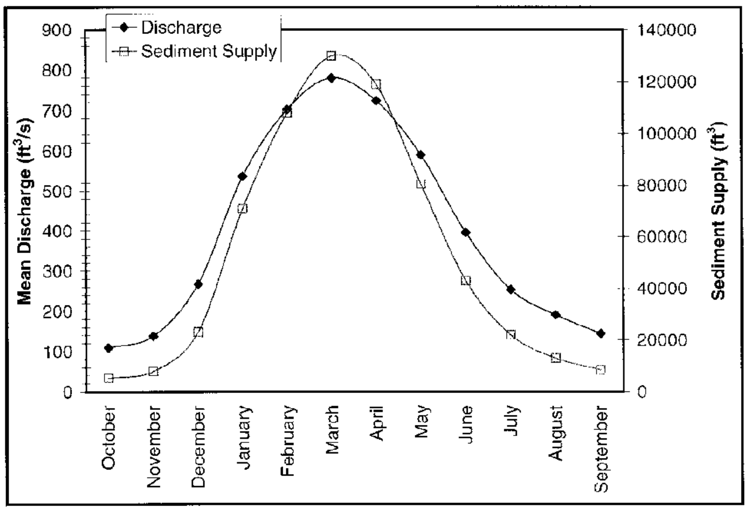

Figure E.7. Plot of average discharge and total sediment supply distribution for year.

Table E.7. Average Discharge and Total Sediment Supply Distribution for the Year.		
Month	Average Discharge (ft^3/s)	Sediment Supply (ft^3)
October	109	5,240
November	138	7,880
December	268	23,060
January	537	70,970
February	703	108,050
March	780	129,840
April	724	118,910
May	590	80,440
June	396	42,940
July	254	21,990
August	191	12,940
September	145	8,500
	TOTAL	630,760

Solution:

The first step is to calculate the hydraulic properties for each month. The values of depth and velocity are required to calculate sediment transport capacity using Equation 6.20. Assuming a wide rectangular channel, the Manning equation (Equation 5.5) can be rearranged to solve for flow depth. The following is a sample calculation for the month of March:

$$Y = \left[\frac{Qn}{1.486\, WS^{1/2}} \right]^{3/5}$$

$$Y = \left[\frac{(780)(0.027)}{1.486\,(350)(0.0014)^{1/2}} \right]^{3/5} = 1.05\,\text{ft}$$

Knowing discharge, width, and depth, velocity can be calculated using the continuity equation:

$$V = \frac{Q}{A}$$

$$V = \frac{780}{(350)(1.05)} = 2.12\,\text{ft}/\text{s}$$

Table E.8 presents the hydraulic properties corresponding to the mean discharge for each month. The channel properties given in Example Problem E.7 were used.

Table E.8. Hydraulic Properties for Each Month of the Year.

Month	Discharge (ft^3/s)	Depth (ft)	Velocity (ft/s)
October	109	0.32	0.97
November	138	0.37	1.07
December	268	0.55	1.39
January	537	0.84	1.83
February	703	0.99	2.03
March	780	1.05	2.12
April	724	1.00	2.07
May	590	0.89	1.89
June	396	0.70	1.62
July	254	0.53	1.37
August	191	0.45	1.21
September	145	0.38	1.09

The next step is to calculate the hydraulic capacity to transport sediment out of the reach for each month. Given that the coefficient and exponents from Equation 6.20 are functions only of D_{50} and Manning's n, their values will be unchanged from Example Problem E.7 and will be the same for each month. From Example Problem E.7, the values of a, b, and c are:

a = 0.00000770
b = 5.32
c = -0.80

Sediment transport capacity for each month can be calculated using Equation 6.20. The following is a sample calculation for the month of March:

$$q_s = aV^bY^c$$

$$Q_s = Wq_s = W\left(a\,V^b\,Y^c\right)$$

$$Q_s = Wq_s = 350\,[0.00000770\,(2.12)^{5.32}\,(1.05)^{-0.80}] = 0.14116\,ft^3\ /\ s$$

The calculated sediment transport capacity for each month is presented in Table E.9. The total volume of sediment for each month was also calculated by multiplying the capacity and the number of seconds in a month (assuming an average of 2,628,000 seconds per month).

Table E.9. Sediment Transport Capacity for the Year.

Month	Sediment Transport Capacity (ft^3/s)	Total Volume of Sediment (ft^3)
October	0.00570	14,980
November	0.00856	22,500
December	0.02507	65,880
January	0.07716	202,780
February	0.11747	308,710
March	0.14116	370,970
April	0.12928	339,750
May	0.08746	229,840
June	0.04668	122,680
July	0.02391	62,840
August	0.01407	36,980
September	0.00924	24,280
	TOTAL	1,802,190

The volume of degradation can be calculated for each month using Equation 6.32. The sediment inflows are the volume supplies reported in Table E.2 and the sediment outflows are the volume capacities reported in Table E.4. The results of these calculations are shown in Table E.5. For the month of March:

$$\Delta V = V_{s(inflow)} - V_{s(outflow)} = 129{,}840 - 370{,}970 = -241{,}130\ ft^3$$

Table E.10. Change in Volume and Depth of Bed Material for Each Month.			
Month	Inflow (ft^3)	Outflow (ft^3)	Change in Volume (ft^3)
October	5,240	14,980	-9,740
November	7,880	22,500	-14,620
December	23,060	65,880	-42,820
January	70,970	202,780	-131,810
February	108,050	308,710	-220,660
March	129,840	370,970	-241,130
April	118,910	339,750	-220,840
May	80,440	229,840	-149,400
June	42,940	122,680	-79,740
July	21,990	62,840	-40,850
August	12,940	36,980	-24,040
September	8,500	24,280	-15,780
TOTALS	630,760	1,802,190	-1,171,430

Figure E.8 presents a plot of the inflow and outflow sediment volumes. By looking at the discrepancy between the two curves it is apparent that the reach will degrade by the end of the inflow hydrograph.

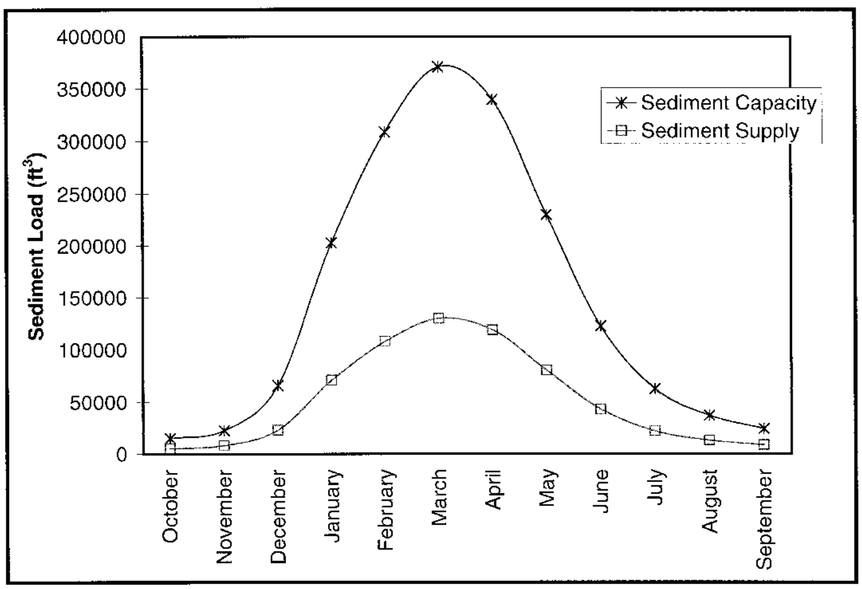

Figure E.8. Inflow (Supply) and Outflow (Capacity) Plots Corresponding to the Inflow hydrograph.

The cumulative change in bed elevation expected to occur by the end of the water year can be computed using Equation 6.34, where ΔV is the total change in volume for the entire year. It is assumed for this bed material that the porosity is 40 percent.

$$\Delta Z = \frac{\Delta V}{WL\,(1-\eta)}$$

$$\Delta Z = \frac{-1171430}{350\,(8000)\,(1-0.40)} = -0.70\,\text{ft}$$

The average change in bed elevation for the 8,000-ft reach is expected to be -0.70 ft by the end of the water year following installation of the dam. Bed lowering at the upstream end of the reach will be greater than the average because degradation begins upstream in a sediment deficient system. In the first water year, degradation could be zero or negligible at the lower portion of the reach.

Example Problem E.10 - Sediment Continuity (English)

For the channel in Example Problems E.7 through E.9, estimate the number of years it will take for the slope of the main channel to reach equilibrium given that the sediment supply will be reduced to 35 percent of the existing value. Use the total volume deficit from Table E.10 as the annual volume of erosion for the reach. The total volume of sediment that will ultimately be eroded can be calculated from the results of Example Problem E.8.

Solution:

1. Calculate the total volume of sediment that will have been eroded once equilibrium has been reached (see Figure E.6 and assume the degradational "wedge" is a right triangle and account for the porosity of the sediment).

Total Volume = W [1/2 y_s L] = 350 [1/2 (4.9) (8,000)] = 6,860,000 ft^3

Sediment Volume = Total Volume (1 - η) = 6,860,000 (1 - 0.4) = 4,116,000 ft^3

2. Calculate the time to reach slope equilibrium.

$$\text{Time (years)} = \frac{4{,}116{,}000 \text{ ft}^3}{1{,}171{,}430 \text{ ft}^3 / \text{yr}} = 3.5 \text{ years (say 4 years)}$$

It is expected that the slope of the main channel will reach equilibrium in about 4 years after construction of the dam on the tributary.