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Overview of Stormflow-Generation Mechanisms That May Be Used to Refine Estimates of Runoff-Coefficient Statistics

By Gregory E. Granato

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Foreword

The mission of the Federal Highway Administration (FHWA) is to continually improve the quality of our Nation's highway system and intermodal connections in a manner that protects and enhances the natural environment and communities affected by transportation. The FHWA must develop and disseminate research products that help FHWA and its partners implement surface transportation programs in a manner that protects and enhances the natural and human environment. More specifically, the Office of Office of Project Development and Environmental Review of the FHWA strives to develop and disseminate skills, tools, and information to redesign Federal environmental and transportation decisionmaking, and to ensure an integrated process at the Federal, State, tribal, and local levels. These tools, techniques and methods are designed to reduce direct and indirect adverse impacts of highways on water quality, habitat, and ecosystems to preserve and enhance human health, biological productivity, and ecological diversity.

This report, the associated computer applications, and data provide tools and techniques for developing planning-level estimates of stormflows at sites receiving highway runoff. This information is vital for assessing the potential for adverse effects of runoff on receiving waters throughout the Nation and it should provide transportation agencies with the tools and information to improve project delivery without compromising environmental protection.

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Overview of Stormflow-Generation Mechanisms That May Be Used to Refine Estimates of Runoff-Coefficient Statistics

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Introduction

Good estimates of volumetric runoff coefficients are needed to estimate stormflows because the stochastic empirical loading and dilution model (SELDM) is designed to use these statistics to generate a random population of stormflow volumes from a random population of precipitation volumes. SELDM generates random populations of runoff coefficients, which are defined as the ratio of stormflow to precipitation, for the highway site and the upstream basin. Conceptually, this approach is based on the assumption that the highway and the upstream basin will be affected by the same storm, but that each will generate stormflows based on characteristics of the drainage area.

The average, standard deviation and skew of the runoff coefficients for the highway and the upstream basin can be estimated using regression equations that relate these runoff-coefficient statistics to the fraction of the total anthropogenic impervious area (primarily pavement and roofs). Regression equations using the fraction of TIA as the explanatory variable are implicitly based on the assumption that the runoff is generated from the TIA. Runoff coefficient statistics, however, may be controlled by other stormflow-generating mechanisms, especially if the fraction of anthropogenic TIA is small and the impervious areas are not connected to stream channels. Runoff coefficient statistics calculated from data compiled as part of SELDM study vary widely among different sites with similar TIA fractions especially for sites with low TIA fractions. Regression equations used to estimate runoff-coefficient statistics from the TIA fraction indicate the best estimate for a given impervious fraction, but the considerable scatter of statistics for individual sites indicates that other factors and other stormflow-generation mechanisms may be predominant in different basins. This appendix provides a brief overview of the literature describing different stormflow-generation mechanisms. The regression estimates are a good first order approximation, but knowledge of basin characteristics and associated stormflow-generation mechanisms described in this appendix may be used to refine these initial estimates of runoff-coefficient statistics. This appendix is a brief overview of runoff-mechanisms described in the literature (**Table 4-1**). The table is not a complete catalog of studies on stormflow-generation mechanisms, but includes several comprehensive literature reviews and examples describing the primary mechanisms. More information may be needed to estimate runoff-coefficient statistics for a given basin; this appendix is an introduction and a source of leads for further investigations.

Table 4-1 Summary of selected studies characterizing rainfall-runoff transformation mechanisms.

[Abbreviations: Report type: RS review/summary; DI data interpretive; MD modeling data. Runoff Mechanisms: IE: infiltration excess (Hortonian) overland flow; TF: Throughflow; SO: Saturation overland flow; GR ground water ridging. An x in the column indicates that the report included a discussion of the mechanism]

Reference	Report type	Location	Runoff Mechanism IE	TF	SOF	GR	Reported findings
Abdul and Gillham, 1989	DI	Ontario, Canada	x		x	x	Ground-water level data showed near-stream ground-water ridging with seepage above the stream level along the banks. Ridging occurred near the stream because soils were close to the water table and were near saturation. Precipitation falling on the seepage face generated saturation overland flow. Tracer tests indicated that preevent (or old) water was about 37 percent of the stormflow discharge in this intermittent stream.
Bay, 1969	DI	USA, MN		x	x		Hydrographs from small forested-bog basins react quickly to precipitation inputs but have very slow stormflow recession times. Under dry conditions the bogs produce throughflow but do provide stormflow retention. During wet conditions, however, bogs are a source of throughflow and saturated overland flows. The bogs have slow recession times under saturated conditions because of the large proportion of very low-slope area in the basins.
Berris, 1995	MD	USA, WA	x	x	x	x	Developed a watershed model using basin characteristics and streamflow data. Used different basin characteristics and rainfall runoff data to interpret importance of different runoff mechanisims in different areas. Determined that infiltration excess overland flow was a major contributor to stormflow from impervious areas and from disturbed pervious areas (many of which recieve runoff from impervious areas). Saturation overland flow was a major contributor to stormflow from depressions, riparian areas. Throughflow was predominant from hilslopes with a relatively high-permeability top layer. Ground-water ridging was predominant in riparian valley-bottom glacial-outwash deposits, which did not have surface saturation.
Boyd and others, 1994	DI	Worldwide	x				In theory, for infiltration excess runoff mechanisims, rainfall runoff relations in urban catchments should follow a three segment line with different slopes for increasing storm sizes. The slope of the segments should characterize the amount of directly contributing impervious area for small storms, total impervious area for larger storms, and total contributing area for the largest storms. Examined data from 26 small urban basins. Found that most basins were characterized by flow from directly connected impervious area, but the basins used were very small and had extensive sewer networks. On basins with impervious and pervious contributions 17-64 percent of storms had pervious contributions, but impervious runoff was three to six times the pervious runoff.
Bullock and Acreman, 2003	RS	Worldwide					Extensive review on the function of wetlands in river basins. Indicates that wetlands may lengthen the storm response, but they are sources of stormflow. Response of wetlands depends on antecedent conditions and position in the watershed.
Burns and others, 2001	DI	USA,GA	x	x	x	x	Indicates that infiltration excess flow from a bedrock outcrop is about 40 percent of the stormflow, Saturation overland flow and ground-water discharge from a riparian wetland is about 42 percent of stormflow and throughflow from the hillslopes is about 18 percent of stormflow. They indicate that that runoff coefficients of a rock outcrop (about 30 percent of the drainage area) were about 0.7, runoff coefficients of a riparian wetland (about 17 percent of the drainage area) ranged from about 0.8 to 2 (because of variations in ground water discharge with antecedent conditions), and runoff coefficients of the remaining upland areas ranged from about 0.1 to 0.2

Table 4-1 Summary of selected studies characterizing rainfall-runoff transformation mechanisms (***continued***).

[Abbreviations: Report type: RS review/summary; DI data interpretive; MD modeling data. Runoff Mechanisms: IE: infiltration excess (Hortonian) overland flow; TF: Throughflow; SO: Saturation overland flow; GR ground water ridging. An x in the column indicates that the report included a discussion of the mechanism]

Reference	Report type	Location	Runoff Mechanism IE	TF	SOF	GR	Reported findings
Cordery and Pilgrim, 1983	DI	Worldwide	x				Analyses data under the assumption of infiltration excess flows for large storms. Indicates that other mechanisims may play a role in rainfall-runoff transformations, but that lumped parameter data analysis methods for entire watersheds can be applied with the assumption of infiltration excess flows (even if other mechanisims predominate). States that the assumption of infiltration excess flows from the entire watersheds reduces the physical realisim of the concept and therefore the definition is somewhat arbitrary. Determine that infiltration excess loss rates cannot be predicted from basin size, soil characteristics, or vegitation type.
Descroix and others, 2007	MD	North-West Mexico	x		x		Infiltration excess overland flows is predominant in arid, semi-arid basins and bsins in which was degraded by overgrazing. This is because soils become crusted, which limits infiltration. Saturation overland flows are predominant in temperate and sub-humid basins. Both may occur, however, in small areas within all the basins because of the topography and antecedent conditions.
Dinicola, 1990	MD	USA, WA	x	x	x		Throughflow from hillslopes mantled with glacial till, ground-water flow from glacial outwash deposits, and saturation overland flow from depressions, stream bottoms, and till-capped hilltops are the main runoff mechanisms in most of the study area. In undisturbed areas, infiltration excess flows are not substantial, but in disturbed areas, infiltration excess flows from impervious areas, nominally pervious areas of compacted and graded soils and pervious areas recieving flows from impervious areas may occur.
Dunne, 1983	RS	--	x	x	x		Infiltration excess is commonly used in lumped parameter models but results are back calculated to fit hypothetical model. Physically-based models, however, help with data interpretations because hydrologic processes are complex and vary with precipitation and antecedent conditions. Infiltration excess is predominant in areas where infiltration rates are low including arid areas, semi-arid areas, paved areas, cultivated fields, mine spoils, construction sites, rural roads, and on clay soils. Infiltration excess also may occur for snowment and rain on snow events if the ground is frozen. In humid areas these areas comprise partial-area runoff., Throughflow occurs where soil conductivity is high including coarse soils and large structural openings. Zones with steep, concave topographic contours. Saturation overland flow may include ground-water discharge and throughflow that emerge in depressions or a break in slope and includes direct precipitation in these areas. Saturation overland flow occurs in thickly vegitated areas with thin soils, high water tables and long concave hillslopes with low slopes. The predominant stormflow mechanisim may change with different antecedent conditions and precipitation amounts.
Dunne and Black 1970	DI	USA, VT		x	x		Saturaturation overland flow (including groundwater discharge from the riparian water table) was the primary source of stormflow in the basin. Throughflow from unsaturated areas was a minor component
Easton and others, 2007	MD	USA, NY	x	x	x		Runoff from impervious areas, which are located in the downstream portion of the basin, dominates stormflow. Model is based on the assumption that runoff from each grid cell is equal to the impervious fraction and runoff from impervious cells may infiltrate in downslope pervious cells. Model indicates that saturation overland flows occur at the base of slopes. Infiltration excess flows occur from impervious areas an adjacent pervious areas that recieve impervious runoff. Measured runoff exceeds modeled runoff for larger storms indicating that some non-impervious runoff may not be fully characterized for large storms.

Table 4-1 Summary of selected studies characterizing rainfall-runoff transformation mechanisms (***continued***).

[Abbreviations: Report type: RS review/summary; DI data interpretive; MD modeling data. Runoff Mechanisms: IE: infiltration excess (Hortonian) overland flow; TF: Throughflow; SO: Saturation overland flow; GR ground water ridging. An x in the column indicates that the report included a discussion of the mechanism]

Reference	Report type	Location	Runoff Mechanism IE	TF	SOF	GR	Reported findings
Fennessey and Miller, 2001	RS	--	x	x	x		A review of rainfall-runoff mechanisims within the context of understanding and managing runoff during and after basin development.
Freer and others, 1997	DI	USA, GA; New Zealand	x				The occurrence and magnitude of throughflow depends on antecedent moisture conditions. If bedrock topography follows the land surface topography then land-surface slope indicates hydraulic gradients, and therefore throughflow delivery to the stream. If studies do not examine bedrock topography, this may affect interpretations about the magnitude of throughflow at the basin scale. Macropores contribute a substantial portion of the total throughflow.
Freeze, 1974	RS	--	x	x	x		A detailed review of stormflow-generation data and modeling methods. Indicates that infiltration excess may be important in areas of low permeability, but that it is not observed in natural forested areas. Indicates that throughflow is commonly observed, but that flowrates cannot account for the majority of the stormflow hydrograph. Indicates that saturation overland flow is a substantial mechanisim in natural basins and that throughflow may contribute to saturation in topographical lows. Indicates that saturation overland flows include direct precipitation and ground-water discharge. Concludes that field scale data is important to understand and quantify stormflow generating mechanisims, but that it is difficult to quantitatively generalize results within and among basins. Use of physical models based on data may help quantify relative magnitudes of different stormflow generating mechanisims.
Gillham, 1984	DI				x	x	Ground water ridging occurs because the capillary fringe extends to the land surface in areas with a shallow ground-water table. In these areas, precipitation inputs can rapidly saturate soils providing a hydraulic gradient to discharge groundwater and saturated surface conditions to initiate saturation overland flow.
Gremillion and others, 2000	MD	USA, FL				x	About 76 percent of stormflow from an undeveloped basin (5 percent urban) and 47 percent of stormflow from a developed basin (27 percent urban) was groundwater discharge
Jones, 1997	DI	Wales		x			Indicates that macropore (pipe) flow may account for as much as 50 percent of stormflow in a stream. Soil pipes occur most frequently in high-rainfall mountainous areas with peaty or podzolic soils. Pipeflow has larger runoff rates and smaller lag times than saturated ground-water through flows, but is less than and slower than saturation overland flows and infiltration excess overland flows.
Kim and others, 2005	DI	British Columbia		x		x	Used a 4.75 meter-long soil pit on a steep forested slope documented a number of sepage zones and macropores. Found that ground-water levels upgradient of the pit changed rapidly with the onset of precipitation but receded slowly. Throughflow increased by 400 percent from dry to wet antecedent conditions. Ground-water discharge (from saturated soils) to the pit was from 44-94 percent of throughflow. During dry periods only a small portion of the uphill slope was contributing to throughflow.
Latron and Gallart, 2007	DI	Spain	x	x	x	x	Infiltration excessrunoff occurs on a poorly vegitated bedrock outcrop in connection with the streambed. Saturation overland flow occurs in topographic flow-convergence areas that formed natural flow channels, and on terraced areas with thin soil layers that had drainage structures.

Table 4-1 Summary of selected studies characterizing rainfall-runoff transformation mechanisms (***continued***).

[Abbreviations: Report type: RS review/summary; DI data interpretive; MD modeling data. Runoff Mechanisms: IE: infiltration excess (Hortonian) overland flow; TF: Throughflow; SO: Saturation overland flow; GR ground water ridging. An x in the column indicates that the report included a discussion of the mechanism]

Reference	Report type	Location	Runoff Mechanism IE	TF	SOF	GR	Reported findings
Leaney and others, 1993	DI	Australia		x			Plot scale study with chemical tracers
McGlynn and McDonnell, 2003		New Zealand	x	x	x	x	Estimate that about 44 percent is GR, about 1 percent is IE about 21 percent is SOF, about 34 percent is TF. About 96 percent evidenced as discharge from headwater riparian areas
McGlynn and others 2004	DI	New Zealand	x	x	x		SOF from small headwater subbasins dominates runoff quick flow
McKillop and others, 1999	ME	Ontario, Canada		x	x		Created a finite difference ground-water/surface-water flow model to simulate conditions in a headwater wetland basin and calibrated to a streamflow record. Under wet conditions the stormflow hydrograph was dominated by saturation overland flow, during dry conditions (water levels below the surface) the stormflow hydrograph was dominated by ground-water discharge from areas that were close to the channel network.
Meyles and others, 2003	DI	Southwest England		x	x		Used time-domain reflectometry in a rural grassy peat-soil basin to monitor soil wetness. In smaller storms with dry antecedent conditions runoff coefficients were less than 0.1 and were approximately equal to the fractional area of the saturated soils in the valley bottom (indicating saturated overland flow). Under wet conditions or large storms saturated soil conditions developed within hill-slope soils and a substantial amount of throughflow occured that followed a kinematic waveprocess. Under these conditions runoff coefficients increased exponentially with increasing storm size up to about 0.65 (indicating the importance of throughflow).
Mosley, 1979	DI	New Zealand		x	x		Minitored precipitation, flows in the unsaturated zone and streamflow for a steep narrow headwater basin in a humid area of new Zeland. He concluded that macropore flow dominated stormflows under these conditions.
O' Brien, 1980	DI	USA, MA		x	x	x	Looked at runoff from two headwater wetland basins. Wetland basins absorb precipitation during dry times but act like impervious area with wet antecedent conditions because of saturation-overland flows. Under dry conditions surface runoff may be comprised of channel precipitation. Estimates that near-stream ground-water discharge commonly accounts for more than 50 percent of stormflows. Soil pipes or seeps occur in wetlands at the interface between silty peat and muck . Measured discharge from a 2.5-inch diameter hole that was 0.5 gal/min.
Ogunkoya and Jenkins, 1993	DI	Scotland		x	x		Three-component hydrograph separation using chemical methods indicates that precipitation, prestorm soil water, and ground water, are about 15, 19 and 66 percent of stormflow, respectively. Physical sources of water are not measured but results indicate that direct precipitation on channels, saturation overland flows on other areas, and throughflow discharge at the base of hill slopes all may be contributors.
O' Loughlin, 1986	MD	Australia			x		Used topographical analysis to predict the extent of saturation overland flow in basins along topographic depressions under different antecedent-wetness conditions. In undeveloped basins the amount of quickflow is proportional to the saturated area, which varies from storm to storm.

Table 4-1 Summary of selected studies characterizing rainfall-runoff transformation mechanisms (***continued***).

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Reference	Report type	Location	Runoff Mechanism IE	TF	SOF	GR	Reported findings
Pearce and others, 1986	DI	New Zealand		x	x		Used chemical-tracer methods to evaluate the components of stormflow in a steep, forested basin with highly conductive soils in a humid environment. Runoff coefficients in this natural basin ranged from 0.03 to .72 during 72 monitored storms. Although the physical mechanisims of throughflow and saturation overland flow were observed in the basin chemical tracers indicate that only about three percent of storm runoff could be attributed to precipitation from the current storm. Observed throughflow and saturation overland flow were attributed to displacement of ground water and soil water from previous storms.
Peters and others, 1995	DI	Ontario, Canada		x			Used chemical-tracer methods and soil trenches to conclude that event (new) water drains to the bedrock surface, mixes with small amounts of pre-event (old) water and flows on the bedrock down slope to discharge to the stream to generate the stormflow hydrograph. Noted that this type of throughflow was important on hillslopes with high-bedrock gradients and a thin soil layer.
Peters and others, 2003	DI	USA, GA		x	x		Has detailed data from 759 storms over 16 water years in a steep forested basin with an ephemeral stream. Data indicates that there are seasonal variations but that stormflow yields (volumetric runoff coefficients) increase substantially once the ground-water table reaches the land surface along the stream channel indicating the importance of ground-water discharge and saturation overland flow to the runoff hydrograph.
Pilgrim 1983	RS	--	x	x	x		There is a tendency to ascribe runoff mechanisims to climates, regions, or basin characteristics, but all may occu within a given basin. Different runoff mechanisims can be calibrated to provide relations between rainfall and runoff.
Roulet, 1991	DI	Ontario, Canada			x		Indicated that outflows are dominated by saturation overland flows from many small streamlets in the wetlands at the bottom of the basin runoff coefficients were small (about 0.01) and were proportional to the area covered by streamlets.
Sklash and Farvolden, 1979	DI	Southern Canada				x	Used chemical methods to indicate that ground-water discharge accounts for most storm discharge (quickflow). Measured ground-water levels below the streambed and at various distances from the stream, which indicates that near-stream ground-water ridging is the mechanisim for quickflow generation. Use a ground-water model based on the geometry of the basin and found that ground-water near the stream forms a ridge before the water table in the upland area responds. Indicates that in areas where the water-table is close to the ground surface infiltrating water quickly saturates the unsaturated zone to discharge ground water near (and under) the stream. Without ground-water head measurements and tracer experiments this may look like saturation overland flow. If ground-water levels decline during prolonged dry periods the ridge may not form, the response to input precipitation will be less, and and other runoff mechanisims may be predominant.
Sklash and others, 1986	DI	New Zealand	x	x	x		Used hydrological and chemical methods to study the response of a small forested catchment. Indicate that Infiltration excess overland flows are limited to small bedrock outcrops on and near the valley bottom, saturation overland flow is limited to the valley bottoms. Chemical methods indicate that stormflow is dominated by old water and that the new-water component can be ascribed to overland flow from small areas of the basin.
Tarboton, 2003	RS		x	x	x	x	A good, educational overview of runoff processes

Table 4-1 Summary of selected studies characterizing rainfall-runoff transformation mechanisms (***continued***).

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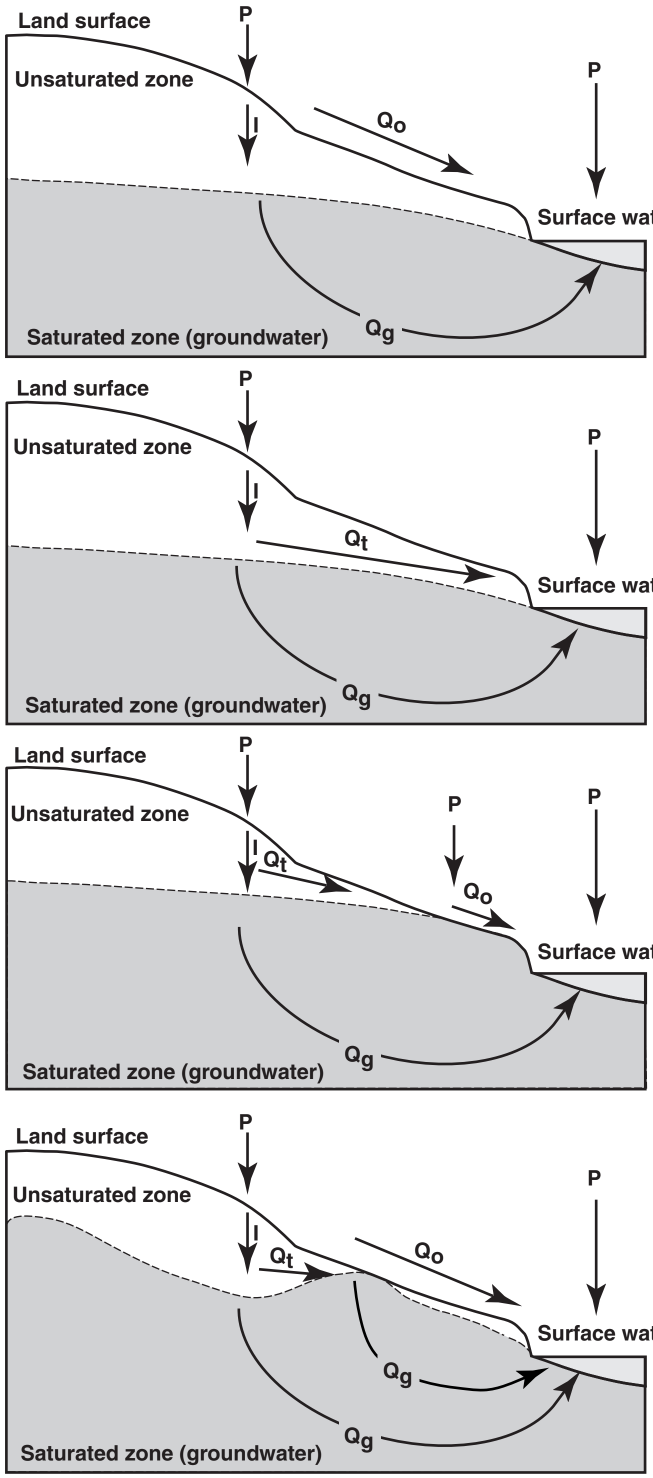
Reference	Report type	Location	Runoff Mechanism IE	TF	SOF	GR	Reported findings
Taylor, 1982	DI	Ontario, Canada			x		Studied stormflow from a rural and suburban basin over several years. In each case, the amount and timing of quickflow was dependent of the extent of saturated soils along the flow network. The suburban basin was studied over sveral years as it converted from rural to suburban. About 9 percent of the basin was converted to impervious surfaces. Infiltrometer tests on developed properties indicates that the construction process reduced the permeability of soils by about 80 percent. However, in this basin the nature of the runoff hydrograph was not changed markedly during many storms because runoff from developed areas infiltrated to ground water in ephemeral stream channels. During these storms the predominance of saturation oveland flow in wetland areas was not different from natural conditions. However, under wet conditions saturation of the ephemeral stream channels generated substantial amounts of stormflow from the developed areas.
Tromp-vanMeerveld and McDonnell 2006	DI	USGS, GA		x			Examined subsurface flows from a hill slope using an instrumented trench for 147 storms. Subsurface flows from storms that were less than 2.16 inches produced little if any throughflow, once this threshold was reached there was an increase in throughflow of almost two orders-of-magnitude. Macropore (pipe) flow was a substantial component of throughflow. Throughflow, however, was a minor component of the total runoff from the basin supporting geochemical analyses that indicate the minor contribution of hillslope flows to the runoff hydrograph at this site.
Uchida and others, 1999	DI	Japan		x			Monitored streamflow and flow from macropores "soil pipes" in a small, steep basin in a humid zone. Indicate that pipeflow can be substantial and has a hydrograph that coincides with the runoff hydrograph from the basin. Provides a table of statistics from this article and nine other studies. Suggests that ephemeral pipeflow occurs in the unsaturated zone as infiltrating water is intercepted by interconnected macropores, and perennial pipe flow occurs from macropores draining saturated upgradient areas (springs).
Uchida and others, 2001	RS	--		x			Provides an overview of 38 macropore (pipe) flow studies around the world. Indicates that pipeflow generates new and old water and that flow volumes increased with larger rain storms. Indicates that the network of macropores collects water and rapidly drains the water to down-slope locations. Indicates that pipeflow may be a large contributor to throughflow, but may not be a large contributor to total stormflow.
Waddington and others 1993	DI	Ontario, Canada		x	x	x	Results indicate that saturation-overland flow is the primary stormflow generation mechanisim in this basin and that the primary source of storm water is from ground-water discharge. Hydrological and chemical tracer methods indicate that pre-event water comprised 77-93 percent of measured stormflows. Ground-water ridging was only observed in one large storm (out of 36 monitored storms). Calculations based on this ridging event indicates that the cground-water ridging phenomenon during this event would only account for about two percent of the basin stormflow. Chemical measurements indicate that 95 percent of macropore discharge was comprised of pre-event water, flow measurements indicate that the contribution was minor.
Ward, 1984	RS	--	x	x	x	x	A good, educational overview of runoff processes with an explanation of each process, examples of where each may occur, and associated references.
Wigmosta and Burges, 1997	MD	USA, WA	x	x	x		Observed apparent infiltration excess flows from residential lawns pervious areas. They also observe slower post-storm runoff from lawn slopes that is attributed to rapid subsurface flow and to Darcy-type flow through a surface layer of dense turf.
Wolock, 1993	MD	--		x	x		Documents TOPMODEL that models streamflow generation using the variable-source-area concept.

Characteristics of Stormflow-Generation Mechanisms

Rainfall-runoff transformation processes are complex and there is substantial uncertainty about the occurrence, timing, and relative importance of different processes in different basins. The term runoff is commonly used to describe the streamflow response to a precipitation event. Use of the term runoff may imply that storm event flows are equivalent to the overland flow that occurs during the event. The term quickflow also is commonly used because storm-event flows from natural areas may result from displacement of pre-event water by precipitation inputs. The term quickflow may include overland flow, soil-water discharges, and ground-water discharges caused by the precipitation event. As such, the soil-water and ground-water discharges included with quickflow are different from baseflow. Quickflow includes water displaced by precipitation inputs, whereas baseflow is considered to be gravity drainage of the underlying aquifer between storm events. The distinction between quickflow and subsequent baseflow commonly is defined using different methods of baseflow separation (Chow, 1964; Linsley and others, 1974; Chow and others, 1988; Nathan and McMahon, 1990; Sloto and Crouse, 1996). The term interflow is sometimes used to describe the soil-water and ground-water discharges included with quickflow that become predominant on the falling limb of the stormflow hydrograph. However, the terms runoff and quickflow may be used synonymously because of substantial uncertainties in the origin of storm-event flows in different basins and uncertainties in the partitioning of storm flow from base flow with different hydrograph separation techniques (**Appendix 1**).

Conceptual models are important for estimating rainfall-runoff transformation from basins with different characteristics. Various runoff-producing mechanisms have been postulated in the literature as a result of hydrologic, water-quality, and isotope measurements of precipitation, ground water, and surface water during storms (**Table 4-1**). There is considerable study and debate about the occurrence, prevalence, and relative importance of different runoff-producing mechanisms in different hydrologic settings. Runoff mechanisms discussed in the literature include infiltration excess (Hortonian) overland flow, saturation overland flow, throughflow, and near-stream discharge caused by ground-water ridging (**fig. 4-1**). The magnitude and predominance of different stormflow-generating mechanisms have been postulated on the basis of surface-water flow measurements, water-level measurements, soil moisture measurements, and the chemistry and isotope signature of stormflow (including precipitation, soil water, ground water and storm water runoff). Similar results from such measurements commonly are used to support different theories. Modeling methods also are used, but modeling methods commonly are based on initial assumptions and commonly simplify complex processes. The same data and models may be used to support different theories because available data do not provide a unique solution. Furthermore, there is much variability and different mechanisms may be predominant between basins, within basins, among storms, and within storms.



Infiltration Excess (Hortonian) overland flow

Occurs on impervious surfaces and occurs in pervious areas, where and when precipitation intensity or runoff from adjacent impervious areas exceeds the infiltration capacity of these areas.

Throughflow

Occurs in sloped areas near dry or wet streambeds. Water infiltrates the surface and travels through macropores or is directed by anisotropy in the soil column down-slope to a surface-water discharge area. Throughflow is not dependant on infiltration excess.

Saturation overland flow

Occurs in pervious areas where the ground-water table rises to the land surface so that precipitation and groundwater flow into the stream network. The contributing area grows and shrinks with fluctuations in groundwater levels. Infiltration, throughflow, and temporary bank storage may contribute to saturated riparian areas.

Near-stream ground-water ridging

Occurs in zones of flow convergence as a rapid response to infiltration and throughflow. The local increase in the water-table gradient increases groundwater discharge to the stream.

Explanation: P precipitation; I infiltration; Q_o overland flow; Q_t through flow; Q_g groundwater flow

Figure 4-1. Schematic diagrams illustrating several conceptual models of rainflow-runoff transformation mechanisims that explain the quickflow response of streams during precipitation events (modified from Ward, 1984).

Infiltration excess overland flow is commonly defined as surface runoff that occurs when precipitaion rates exceed the infiltration capacity of soils and depression storage (**Table 4-1**). Infiltration excess overland flow commonly is associated with arid and semiarid areas where soil-crusts, which substantially reduce infiltration rates, form. Infiltration excess overland flow occurs on anthropogenic impervious areas and natural (such as bedrock outcrops). Infiltration excess overland flow may occur on other pervious or semi-pervious areas that receive overland flow from impervious adjacent areas. Infiltration excess overland flow also may occur on nominally pervious areas (such as residential lawns) that have been compacted as a result of development. The concept of infiltration excess overland flow, its application in curve-number models, and its limitations for characterizing small-storm hydrology in natural basins in humid areas is discussed further in **Appendix 5**. Variations in infiltration excess overland flow are thought to occur as the infiltration capacity and depression storage of a basin varies with antecedent conditions between storms.

Saturation overland flow is commonly defined as surface runoff that occurs when the water table rises to the land surface preventing infiltration and conveying precipitation and ground water to the stream network as surface runoff (**Table 4-1**). Saturation overland flow is assumed to occur in areas adjacent to ephemeral, intermittent, and perennial stream channels (riparian areas) within the stream network. Saturation overland flow commonly is associated with riparian wetlands in humid regions. Variations in saturation overland flow are thought to occur as saturated areas expand and contract seasonally and with variations in antecedent conditions between storms.

Throughflow is commonly defined as sub-surface runoff that occurs when precipitation induces ground-water and soil-water stormflows down-slope to a discharge area (**Table 4-1**). Various throughflow mechanisms (including steep gradients, permeable soils, and perennial, intermittent and ephemeral soil pores) are assumed to occur in steep-slope headwater basins in humid areas. The predominance of ground-water or soil-water stormflows are thought to be controlled by the slope of the underlying impervious surface (bedrock or an impervious soil layer), the permeability and anisotropy of the soil, and the presence and extent of macropores. Throughflow also may contribute to saturation overland flow as it emerges at the base of the slope in source areas adjacent to the drainage network. Variations in throughflow are thought to occur with variations in soil moisture and the hill-slope water table both seasonally and with variations in antecedent conditions between storms.

Near-stream ground-water ridging is commonly defined as stormwater discharge that occurs when the capillary fringe is rapidly saturated by precipitation in areas to ephemeral, intermittent, and perennial stream channels, where the depth to ground water is small (**Table 4-1**). The localized, rapid increase in the hydraulic head of the ground-water table is thought to induce ground-water discharge to the stream. Near-stream ground-water ridging also may contribute to saturation overland flow as it emerges in source areas adjacent to the drainage network. Variations in stormflow from near-stream ground-water ridging are thought to occur because of variations in the depth to ground water and the saturation of the capillary fringe that occur both seasonally and with variations in antecedent conditions between storms.

Direct precipitation is another source of storm-event flows that occurs throughout the storm as precipitation falls directly on the streams and lakes within the drainage network (Mockus, 1972; Ward 1984; Roulet, 1991). Direct precipitation is included in each schematic diagram on **figure 4-1** because it occurs concurrently with each runoff mechanism. Direct precipitation is conveyed to the basin outlet as runoff. Direct precipitation commonly is considered to be negligible (Mockus, 1972). However, direct precipitation may be a substantial proportion of storm flow for small storms in natural basins with on-stream lakes and riparian wetlands. For example, Roulet (1991) studied a low-slope natural basin and found that runoff coefficients were proportional to the channel area, indicating the influence of precipitation falling directly on stream channels.

Development activities in urban and suburban areas may increase the prevalence of infiltration excess overland flow in pervious areas by limiting other runoff generating mechanisms (**Table 4-1**). Development activities reduce infiltration rates in nominally pervious areas because construction and landscaping tends to compact soils and reduce depression storage. For example, Felton and Lull (1963) measured infiltration rates for forest soils and lawns to indicate a potential 80 percent reduction in infiltration as a result of development activities. Similarly, Taylor (1982) did infiltrometer tests in areas before and after suburban development and noted that topsoil alteration and compaction by construction activities reduced infiltration rates by more than 77 percent. Gregory and others (2006) did infiltration tests at different sites and found that construction activity reduced soil infiltration rates by 70 to 99 percent. Construction and landscaping also can reduce vegetation and natural plant litter, thereby reducing absorption and interception. Reductions in infiltration, compaction of soils, and removal of natural vegetation also may reduce soil structures necessary for throughflow. Reductions in surface infiltration, dewatering by sewers and underdrains, and stream-channel alterations associated with development may lower ground-water levels. These changes may reduce contributing areas for saturation-overland flow and other ground-water components of runoff that are more prevalent in less developed basins.

Urban-runoff field studies and computer models are based on the concept of infiltration excess flows (for example Dawdy and others, 1978) because the initial storage and continuous loss rates on impervious areas are small. As such, total impervious area (TIA) (or mapped impervious area, MIA) is commonly used to characterize rainfall-runoff transformation processes. In some urban-runoff studies, however, almost all of the stormflow is attributed to impervious areas that drain to the stream network, which are commonly described as effective impervious area (EIA) or directly connected impervious area (DCIA). This conceptual model works well in developed areas because of the uncertainties in the difference between TIA and DCIA and the effect of development on basin characteristics and riparian areas (**Appendix 1**). Assumptions inherent in hydrograph separation methods for identifying the overland flow component also may support DCIA as the sole source of storm flows in urban-runoff studies (**Appendix 1**). This may occur if slower storm flows from pervious areas are lumped with baseflow.

SELDM users may want to refine estimates of runoff-coefficient statistics using information about other basin characteristics and associated stormflow generation mechanisms. The multi-segment nonparametric regression lines developed with statistics from 167 sites in the database that have nine or more storm events provide an initial estimate of runoff-coefficient statistics from the TIA in a basin, but there is considerable scatter in the statistics. Some of this scatter may be caused by systematic and random errors in measurements of basin characteristics, precipitation, and runoff (Appendix 1), but the scatter probably reflects real differences among basins. Examining basin characteristics with knowledge of runoff mechanisms may help refine initial estimates. For example, if a basin in a humid region is relatively undeveloped and contains a large percentage of perennial headwater wetlands, thus user may want to select a higher average runoff coefficient than would be predicted using TIA-based regression equations. The regression equations for the average and skew of the runoff coefficient statistics (**fig. 30 main report**) have steeper slopes if TIA is greater than about 55 percent. Users may want to more carefully consider other basin characteristics and potential effects of other mechanisms below this development threshold. Runoff-processes from undeveloped areas have a substantial effect on stormflows in many basins throughout the Nation because more than 97 percent of the Nation has anthropogenic TIA values that are less than 50 percent of ground cover and more than 75 percent TIA values that are less than one percent of ground cover (Homer and others, 2007).

References Cited

Abdul, A.S., and Gillham, R.W., 1989, Field studies of the effects of the capillary fringe on streamflow generation: Journal of Hydrology, v. 112 p. 1-18.

Bay, R.R., 1969, Runoff from small peatland watersheds: Journal of Hydrology, v. 9, no. 1, p. 90-102.

Berris, S.N., 1995, Conceptualization and simulation of runoff generation from rainfall for three basins in Thurston County, Washington: U.S. Geological Survey Water-Resources Investigations Report 94-4038, 149 p.

Booth, D.B., and Jackson, C.R., 1997, Urbanization of aquatic systems--degradation thresholds, stormwater detection, and the limits of mitigation: Journal of the American Water Resources Association, v. 33, no. 5, p. 1077–1090.

Boyd, M.J., Bufill, M.C., and Knee, R.M., 1994, Predicting pervious and impervious storm runoff from urban drainage basins: Hydrological Science Journal, v. 39, no. 4, p. 321-332.

Bullock, A., and Acreman, M., 2003, The role of wetlands in the hydrological cycle: Hydrology and Earth System Sciences, v. 7, no. 3, p. 358-389.

Burns, D.A., McDonnell, J.J., Hooper, R.P., Peters, N.E., Freer, J., Kendall, Carol, and Beven, Keith, 2001, Quantifying contributions to storm runoff through end-member mixing analysis and hydrologic measurements at the Panola Mountain Research Watershed (Georgia, USA): Hydrological Processes v. 15, no.10, p. 1903-1924.

Chow, V.T., 1964, Section 14--Runoff: *in* Chow, V.T. (ed.), Handbook of applied hydrology--A compendium of water-resources technology, New York, McGraw-Hill Book Co., p. 14.1-20.54.

Chow, V.T., Maidment, D.R., and Mays, L.W., 1988: Applied Hydrology: New York, McGraw-Hill Inc., 572 p.

Cordery, Ian, and Pilgrim, D.H., 1983, On the lack of dependence of losses from flood runoff on soil and cover characteristics, *in* Keller, Reiner (ed.), Hydrology of Humid Tropical Regions with Particular Reference to the Hydrological Effects of Agriculture and Forestry Practice International Association of Hydrological Sciences Report 140, p. 187-195.

Dawdy, D.R., Schaake, J.C., Jr., and Alley, W.M., 1978, Users guide for Distributed Routing Rainfall-Runoff Model: U.S. Geological Survey Water-Resources Investigations Report 78-90, 146 p.

Descroix, L., Viramontes, D., Estrada, J., Gonzalez Barrios, J.-L., and Asseline, J., 2007, Investigating the spatial and temporal boundaries of Hortonian and Hewlettian runoff in Northern Mexico: Journal of Hydrology, v. 346, no. 3-4, p. 144-158.

Dinicola, R.S., 1990, Characterization and simulation of rainfall-runoff relations for headwater basins in western King and Snohomish Counties, Washington: U. S. Geological Survey Water-Resources Investigations Report 89-4052, 52 p.

Dunne, T., 1983, Relation of field studies and modelling in the prediction of storm runoff: Journal of Hydrology, v. 65, p. 25-48.

Dunne, Thomas, and Black, R.D., 1970, Partial area contributions to storm runoff in a small New England watershed: Water Resources Research, v. 6, p. 1296-1311.

Easton, Z.M., Gerard-Marchant, P., Walter, M.T., Petrovic, A.M., Steenhuis, T.S., 2007, Hydrologic assessment of an urban variable source watershed in the northeast United States: Water Resources Research v. 43, no. 3, Article number W03413

Felton, P.M., and Lull, H.W., 1963, Suburban hydrology can improve watershed conditions: Journal of Public Works, v. 94, p. 93-94.

Fennessey, L.A.J., and Miller, A.C., 2001, Hydrologic processes during non-extreme events in humid regions: in Re-thinking comprehensive stormwater management--integrating quality, volume and peak controls, Proceedings of the 2001 Pennsylvania Stormwater Management Symposium October 17-18, 2001, Villanova, PA, 11 p.

Freer, J., McDonnell, J., Beven, K.J., Brammer, D., Burns, D.A., Hooper, R.P., and Kendall, C. 1997, Topographic controls on subsurface storm flow at the hillslope-scale for two hydrologically distinct small catchments: Hydrological Processes, v. 11, no. 9, p. 1347-1352.

Freeze, R.A., 1974, Streamflow generation: Reviews of Geophysics and Space Physics, v. 12, no. 4, p. 627-647.

Gillham, R.W., 1984. The capillary fringe and its effect on the water-table response: Journal of Hydrology, v. 67 p. 307-324.

Gregory, J.H., Dukes, M.D., Jones, P.H., and Miller, G.L., 2006, Urban soil compaction and its effect on stormwater runoff: in Rushton, Betty, and Livingston, Eric ,(eds.), Eighth Biennial Stormwater Research & Watershed Management Conference, Tampa, Florida, April 27-28, 2005, p. 146-155.

Gremillion, Paul, Gonyeau, Allison, Wanielista, Martin, 2000, Application of alternative hydrograph separation models to detect changes in flow paths in a watershed undergoing urban development: Hydrological Processes, v. 14, no. 8, p.1485-1501.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J., 2007, Completion of the 2001 National Land Cover Database for the conterminous United States: Photogrammetric Engineering and Remote Sensing, v. 73, no. 4, p. 337-341.

Jones, J.A.A., 1997, The role of natural pipeflow in hillslope drainage and erosion--Extrapolating from the Maesnant data: Physics and Chemistry of the Earth, v. 22, no. 3-4, p. 303-308.

Kim, H.J., Sidle, R.C., Moore, R.D., 2005, Shallow lateral flow from a forested hillslope--Influence of antecedent wetness: Catena, v. 60, no. 3, p. 293-306.

Latron, J., and Gallart, F., 2007, Seasonal dynamics of runoff-contributing areas in a small mediterranean research catchment (Vallcebre, Eastern Pyrenees): Journal of Hydrology, v. 335, no. 1-2, p. 194-206.

Leaney, F. W., Smettem, K. R. J., and Chittleborough, D. J., 1993, Estimating the contribution of preferential flow to subsurface runoff from a hillslope using deuterium and chloride: Journal of Hydrology, v. 143, p. 83–103.

Linsley, R.K., Jr., Kohler, M.A., and Paulhus, J.L.H., 1975, Hydrology for engineers 2nd Ed.: New York, McGraw-Hill Book Company, 482 p.

McDonnell, J.J., 1990, A rationale for old water discharge through macropores in a steep, humid catchment: Water Resources Research, v. 26, no. 11, p. 2821-2832.

McGlynn, B.L., and McDonnell, J.J., 2003, Quantifying the relative contributions of riparian and hill slope zones to catchment runoff: Water Resources Research, v. 39, no. 11, p. 1310-1330. doi:10.1029/2003WR002091

McGlynn, B. L., McDonnell, J. J., Seibert, J., and Kendall, C., 2004, 2004, Scale effects on headwater catchment runoff timing,flow sources, and groundwater-streamflow relations, Water Resources Research, v. 40, W07504, doi:10.1029/2003WR002494

McKillop, R., Kouwen, N., and Soulis, E.D., 1999, Modeling the rainfall-runoff response of a headwater wetland: Water Resources Research, v. 35, no. 4, p. 1165–1177.

Meyles, E., Williams, A., Ternan, L., and Dowd, J., 2003, Runoff generation in relation to soil moisture patterns in a small Dartmoor catchment, Southwest England: Hydrological Processes, v. 17, no. 2, p. 251-264.

Mockus, Victor, 1972, Chapter 10. Estimation of direct runoff from storm rainfall: Natural Resources Conservation Service, *in* National Engineering Handbook, Part 630 Hydrology, 24 p.

Mosley, M.P., 1979, Streamflow generation in a forested watershed, New Zealand: Water Resources Research v. 15, no. 4, p. 795-806.

Nathan, R.J., and McMahon, T.A., 1990, Evaluation of automated techniques for base flow and recession analysis: Water Resources Research, v. 26, no. 7, p. 1465-1473.

O'Brien, A.L., 1980, The role of groundwater in stream discharges from two small wetland controlled basins in Eastern Massachusetts: Groundwater, v. 18, p. 359-365.

Ogunkoya, O.O., and Jenkins, A., 1993. Analysis of storm hydrograph and flow pathways using a three-component hydrograph separation model: Journal of Hydrology, v. 142, p. 71-88.

O'Loughlin, E.M., 1986, Prediction of surface saturation zones in natural catchments by topographic analysis: Water Resources Research, v. 22, no. 5, p. 794-804.

Pearce, A.J., Stewart, M.K., and Sklash, M.G., 1986, Storm runoff generation in humid headwater catchments, 1 Where does the water come from: Water-Resources Research, v. 22, no. 8, p. 1263-1272.

Peters D.L., Buttle J.M., Taylor C.H., LaZerte B.D., 1995, Runoff production in a forested, shallow soil, Canadian Shield basin: Water Resources Research, v. 31, no. 5, p. 1291–1304.

Peters, N.E., Freer, J., and Aulenbach, B.T. 2003, Hydrologic dynamics of the Panola Mountain Research Watershed, Georgia, USA: Ground Water, v. 41, no. 7, p. 973-988.

Pilgrim, D.H., 1983, Some problems in transferring hydrological relationships between small and large drainage basins and between regions: Journal of Hydrology, v. 65, no. 1-3, p 49-72.

Roulet, N.T., 1991, Stormflow production in a headwater basin swamp: Nordic Hydrology v. 22, no. 3, p. 161-174.

Sklash, M.G. and Farvolden, R.N., 1979, The role of groundwater in storm runoff: Journal of Hydrology, v. 43, p. 45-65.

Sklash, M.G., Stewart, M.K., and Pearce, A.J., 1986, Storm runoff generation in humid headwater catchments 2--A case study of hillslope and low-order stream response: Water-Resources Research, v. 22, no. 8, p. 1263-1272.

Sloto R.A., and Crouse, M.Y., 1996, HYSEP: a computer program for streamflow hydrograph separation and analysis: U.S. Geological Survey Water-Resources Investigations Report 96-4040, 46 p.

Tarboton, D.G., 2003, Rainfall-runoff processes--a workbook to accompany the rainfall-runoff processes web module: Utah State University, 159 p. available at: http://hydrology.neng.usu.edu/RRP/userdata/4/87/RainfallRunoffProcesses.pdf

Taylor, C.H. 1982, The effect on storm runoff response of seasonal variations in contributing zones in small watersheds (Ontario): Nordic Hydrology, v. 13, no. 3, p. 165-182.

Tromp-Van Meerveld, H.J., and McDonnell, J.J., 2006, Threshold relations in subsurface stormflow--1. A 147-storm analysis of the Panola hillslope: Water Resources Research, v. 42, no. 2, article W02410, 11p.

Uchida, T., Kosugi, K., and Mizuyama, T., 1999, Runoff characteristics of pipeflow and effects of pipeflow on rainfall-runoff phenomena in a mountainous watershed: Journal of Hydrology v. 222, no. 1-4, p. 18-36.

Uchida, T., Kosugi, K., Mizuyama, T., 2001, Effects of pipeflow on hydrological process and its relation to landslide--A review of pipeflow studies in forested headwater catchments: Hydrological Processes, v. 15, no. 11, p. 2151-2174.

Waddington, J.M., Roulet, N.T., and Hill, A.R., 1993, Runoff mechanisms in a forested groundwater discharge wetland: Journal of Hydrology, v. 147, no. 1-4, p. 37-60.

Ward, R.C., 1984, On the response to precipitation of headwater streams in humid areas: Journal of Hydrology, v. 74, p. 171-189.

Wigmosta, M. and S.J. Burges, 1997, An adaptive modeling and monitoring approach to describe the hydrologic behavior of small catchments, Journal of Hydrology, Vol. 202 Issue (1-4), 48-77.

Wolock, D. M., 1993, Simulating the variable-source-area concept of streamflow generation with the watershed model TOPMODEL: U.S. Geological Survey Water-Resources Investigations Report 93-4124, 33 p.