University of Washington
Department of Civil and Environmental Engineering

HYDROLOGIC INFORMATION AND ANALYSES REQUIRED FOR MITIGATING HYDROLOGIC EFFECTS OF URBANIZATION

Stephen J. Burges
Bruce A. Stoker
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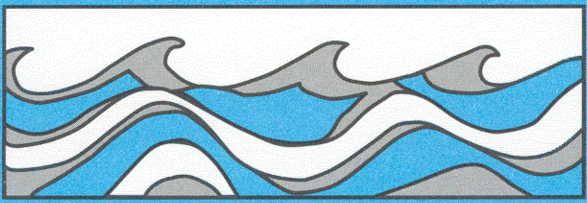

Water Resources Series
Technical Report No.117
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Principal Investigators:	Stephen J. Burges Professor of Civil Engineering Dennis P. Lettenmaier Research Professor of Civil Engineering

TABLE OF CONTENTS

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ABSTRACT

The objectives were to characterize for gauged and ungauged catchments the pre-development hydrology and to determine or estimate the post-development hydrology and develop criteria for runoff control measures to mitigate hydrologic effects of development. Field observations combined with map and stereo aerial photograph interpretation are used to identify catchment features associated with runoff production. From these features the spatial distribution of dominant basin hydrologic processes is estimated. Hydrologic and geomorphic processes, not considered in traditional methods, that are identified by the process zone mapping procedure developed include areas of saturated overland flow, return flow, areas with significant water detention, and channel segments where sediment transport thresholds are likely to be exceeded.

An overlay map of the extent, location, and types of hydrologic process zones is prepared based on interpretation of the field data, aerial photographs, and map information. A similar process zone map is prepared for any proposed development configuration and differences between it and the pre-development conditions are summarized in tables, charts, and maps. Changes in drainage density, water detention volume, and quick storm response areas are associated with their respective downstream channels. Potential impact zones are defined by comparison of the pre- and post-development runoff and channel conditions. Examination of the channel sections bars, and substrate for channel segments draining relatively undisturbed and changed parts of the catchment, respectively, indicate critical channel erosion problems and erosion and deposition potential. These locations dictate the extent of mitigative measures needed upstream; flow released from mitigative schemes must be constrained above the start of first order-channels if channel geometry and stream habitat are to be preserved. The method yields primarily two-dimensional zone maps and channel segments, each having several associated attributes. For file and data keeping purposes the information is stored most conveniently using an appropriate geographic information system (GIS).

A relatively simple spatially-distributed rainfall-runoff model for quantitative decision making was developed using the mapped extent of flow production zones as subareas within subcatchments. Upper soil (and litter) and lower soil depths (attributes determined by direct field measurement) are included explicitly. This type of model shows promise as an important tool for demonstrating relative impacts of land use change at different locations within a subcatchment. The hydrographs determined for subareas provide guidance for the type and location of appropriate mitigative measures to reduce hydrologic impacts from land use change and urbanization in particular. The model needs further refinement and testing before its general applicability can be determined.

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

1.1 HYDROLOGIC EFFECTS OF DEVELOPMENT

Urban, agricultural, and forest development result in land modifications that affect the hydrology of a catchment. Land modifications that change the extent and relative importance of hydrologic processes, such as overland flow, evaporation, infiltration, and water storage, alter the overall storm response and baseflow characteristics of a catchment. The impacts of these changes are not localized to the site where the land was modified and usually have greater impact downstream and downslope of the development.

Stormwater management in developing areas has traditionally been based on prediction of pre- and post-development runoff, coupled with mitigation measures designed to compensate for changes to the natural hydrologic system. Storm runoff prediction is a key element of this overall management strategy. This approach has had limited success for two reasons: either the methods simplify the hydrologic process to the extent that they cannot predict catchment runoff response correctly or the predictive methods require more data than is available, hence they cannot be calibrated and verified properly. Most existing methods (described in Appendix G) use average catchment properties and therefore suffer from an inability to describe the spatial variations in the landscape that determine storm runoff response. These methods do not incorporate the spatial distribution of catchment runoff generating properties directly. Models of catchment rainfall-runoff response should be motivated and constrained by the site features. The work reported here is a logical development from earlier work by Hardt and Burges (1976) and Kemp and Burges (1978) and is an attempt to overcome some of the limitations of present approaches to estimating and mitigating hydrologic effects of land change, notably changes due to urbanization.

1.2 OBJECTIVES

There are two principal objectives:

1. To characterize the pre-development hydrology of a catchment, and
2. To determine or estimate the catchment post-development hydrology and to develop criteria for runoff control measures to mitigate effects of development

The procedures to be developed must be applicable to gauged and ungauged catchments. The spatial scales of concern are small (10 to 50 acre subdivisions) and larger (0.5 to several square miles) for assessing integrated effects of incremental development.

1.3 CRITICAL ISSUES

A major thrust of this work which sets it apart from most work in urban hydrology is the emphasis placed on identification of the spatial locations and forms of flow production within a given catchment. It is this explicit identification which permits estimation of the location, type, and magnitude of change that will accompany land use modification. Such a procedure indicates that parts of a relatively small catchment may need different mitigative measures to minimize deleterious environmental change effects locally, at the heads of the smallest streams (first-order channels), and at the confluence of streams (higher-order channels).

We have considered water as a change agent as it moves over and through mineral and organic substrates (soils, stream channels, and forest and other vegetal litter). Moving water erodes, transports, and deposits organic, inorganic, and biological substances. It provides chemical and biological exchange opportunities with its substrates. Land and vegetation, including stream channels, are the substrates which are subject to potentially dramatic change due to development. While the work we have done has been for catchment conditions found in the forested, glaciated, humid Western United States, the general principles are applicable in all humid climates. Given the principal focus of the work, much of the literature concerning soil, forest litter properties, and evaporation and transpiration is for this region. For the glaciated Western U.S., land sediment production, transport and delivery, and channel scour and deposition give rise to changed channel geometries critical to aquatic habitat particularly fish habitat. Consequently, pre- and post- development flow fluxes must be estimated at many locations within a catchment.

The complexity of the variation in flow production is illustrated in Figure 1.1a for a small catchment whose main channel is second-order at the outlet. Pre- and post-development (no mitigative measures implemented) hydrographs are shown for a relatively high flow state associated with short duration rain falling on a wet catchment.

The input hydrographs to a first order channel (location 1) for pre- and post-development are substantially different. The flow production mechanisms for the developed state are different than for the pre-development state. Critical design control locations, for tributary inputs draining areas on the order of ten to fifty acres, and critical channel locations where slopes change or susceptibility to erosion is likely, are shown. These types of locations and associated fluxes that can be tolerated dictate the form of mitigative measure needed.

The longer term flow hydrograph is illustrated in Figure 1.1b for many storms showing changes in main channel flow rates. The most notable features are increased variability of flow rates and a general reduction in the magnitudes of sustained lower flows. The increased flow rates influence channel degradation (and downstream deposition) and damage aquatic habitat. Lower sustained flows result in lower aquatic biological productivity.

1.4 RESEARCH THRUST

The emphasis here is on ungauged catchments where no measurements of any hydrologic fluxes have been made. Use is made of precipitation recorded in the region and of relatively crude indices of seasonally averaged evapotranspiration. A major part of our work involved integrating what is known about relevant processes by forest hydrologists, geomorphologists, engineering hydrologists, and terrestrial and aquatic ecologists.

By following this integrative approach, we developed a method for plan view mapping of flow production zones throughout any catchment as well as mapping environmentally sensitive channel reaches. Hydrologic process zones are determined largely by field inspection. Digital terrain data is at too crude a scale for other than use in broad feature mapping so it could not be used. The locations where field examination is concentrated are identified initially using topographic information (maps), stereo aerial photographs, and higher resolution county government contour maps.

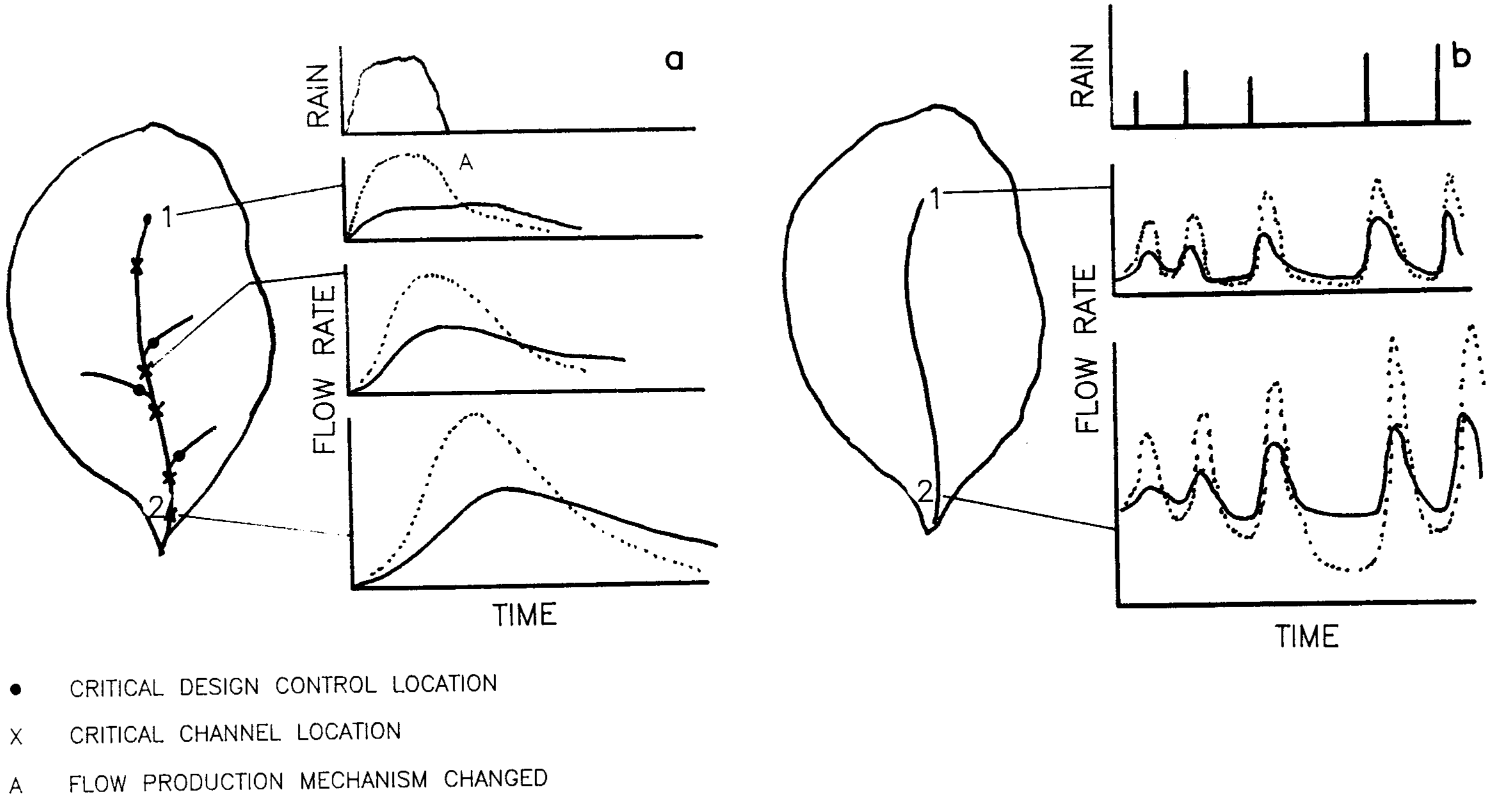


Figure 1.1 Schematic of a catchment showing hydrographs for pre-development (solid) and post-development (dotted) (a) hydrographs at critical locations for a single storm, (b) continuous hydrographs for a longer period of five major storms.

Field mapped zones (vegetation, land form, channel locations and features, etc.) were encoded into a geographic information system (GIS) for ease of updating and providing derived quantities for use in estimating qualitative and quantitative hydrologic catchment responses to precipitation. The GIS adopted is ARC/INFO, an ubiquitous system that is becoming the mapping system of choice in many countries. Field information about channel discharge capacities at various locations throughout the catchment is used to provide qualitative and quantitative measures for post-urbanization maximum discharge rates.

The mapping procedure provides a critical component for management strategies to minimize hydrologic effects of urbanization. The spatial locations of hydrologic process zones is essential information for determing hydrologic impacts at various critical channel sections. We expanded the scope of the originally proposed work to include a continuous simulation, spatiality-distributed, hydrologic model for demonstrating relative hydrologic changes corresponding to changes in flow production zones resulting from urbanization.

A major research activity involved demonstrating the methodology for a catchment in Western Washington. The demonstration follows all steps needed to measure and map relevant quantities, convert these quantities into an ARC/INFO GIS, and to model continuously the spatial hydrologic response of a portion of this catchment to illustrate pre-and post- development hydrographs without any mitigative measures being undertaken. It is the comparison of these estimated continuous hydrographs that provides crucial management information for design of mitigative measures.

1.5 REPORT OUTLINE

Chapter 2 describes catchment flow production processes important to understanding and mitigating hydrologic impacts resulting from changes in vegetation and landform. Chapter 3 details a set of procedures to follow to develop maps of process zones. Chapter 4 shows how these techniques are applied to an ungauged demonstration catchment that has recently undergone light urbanization. Chapter 5 describes and illustrates the geographic information system. Chapter 6 describes a simple continuous spatially distributed hydrologic model we have developed and its application is illustrated for a portion of the catchment described in Chapter 4. Chapter 7 contains a summary and conclusions.

CHAPTER 2 HYDROLOGIC PROCESS ZONES

2.1 INTRODUCTION

Areas of a catchment can be classified by the dominant hydrologic processes occurring there. Catchment areas where processes, such as overland flow, evaporation, infiltration, or water detention storage, is the dominant factor controlling catchment rainfall-runoff response are defined here as a hydrologic process zone. Detailed work on intensively monitored research catchments demonstrate the utility of identifying catchment process zones (Pearce et al, 1986; McColl et al, 1985; Mosley, 1979; Anderson and Burt, 1978; Dunne and Leopold, 1978; Dunne et al, 1975). Without extensive long-term research efforts, the distribution of dominant processes can only be estimated based on observable site features. Interpretation of map, stereo aerial photographs, and field data can provide significant understanding of site processes in a relatively short time. Catchment configuration, materials, and dominant hydrologic processes can be identified and inferred from topographic form, vegetation types and distribution, thickness of forest litter, depth to saturated soil, geological features, channel geometry and channel substrate.

Process zones to consider will vary by climatic and geologic region and by the specific basin characteristics. For example, in humid maritime climates like the Pacific Northwest, the dominant hydrologic process zones include open channels; wetlands; water storage from vegetation, depressions, forest litter, and soils; areas of saturated overland flow (SOF); Horton overland flow (HOF); and return flow. The relative importance of these process zones changes with differing storm distributions and antecedent basin conditions.

Mapping of hydrologic process zones requires stereo air photo and geologic interpretation to identify catchment features and dynamics, a hand auger and shovel to examine soil profiles, a tape and level for measuring channel transects, an inclinometer and compass for preparing cross section and plan view sketches of site features, and a photo or video camera to provide documentation of site features. This chapter provides background information on hydrologic processes and describes field indicators used to identify their areal extent and relative importance.

2.2 STREAMFLOW GENERATION -- PRE- AND POST -URBANIZATION

Precipitation reaching the surface of a catchment follows numerous paths through the catchment. The path water takes and the travel time along each path varies with the basin condition and the nature of the storm. Catchment water dynamics are divided here for convenience into the input, storage, and output of water. This classification provides a simple structure to help visualize what is actually a continuum of interrelated processes that vary in time, location, and magnitude.

Tracing the effects of a rainstorm on a catchment will help in understanding some of the more common runoff-producing processes. Consider the case of a relatively large storm (on the order of 10-centimeters precipitation depth in several days) falling on a forested catchment that has not received any rain for some time.

Before the storm occurs, the stream that drains the catchment receives water from subsurface flow. Water, referred to as baseflow, is seeping from wetlands in the basin and from the subsurface saturated zone of the hillslopes along the creeks. As the storm begins, the vegetation intercepts much of the rain until the leaves and branches are coated. Vegetation interception stores between 2 and 8 mm of water (Zinke, 1965; Hewlett and Nutter, 1969; Helvey and Patric, 1965; Dunne and Leopold, 1978). Once the storage capacity of the vegetation canopy is attained, the trees begin dripping and the continuing rain, though temporally delayed in the vegetation, will fall (throughfall) to the surface. There a mat of partially decayed organic material (forest litter) and loose mineral soil will delay and store additional rainfall. The amount stored in the surface layer will depend on the soil texture, pore spaces, absorbancy of organic material, thickness of the layer, and the number of pores already containing water. The litter zone can store up to 7 centimeters of water in typical Pacific Northwest forests (Balci, 1964). Water in excess of the litter field capacity begins to drain into the loose mineral soil beneath. The intensity of heavy rainfalls commonly exceeds the infiltration capacity of the underlying mineral soil.

Depressions in the surface of the mineral soil fill as water percolates through the litter zone faster than it can infiltrate the mineral soil. The forest litter begins to saturate, and lateral flow along the surface of the underlying mineral soil can occur. Surface depressions will fill as the rainfall continues. They fill, spill over and begin filling the larger topographic lows.

Depressions on this hypothetical catchment are scattered throughout much of the catchment and typically store up to 3 cm of water before they begin spilling over into one another and connect with low rills that connect to the smallest upstream channels. The intense rain rate does not last long enough to fill most of the depressions over most of the forested area of the catchment. The water stored on the surface will soak into the ground as the storm proceeds. In a few areas, especially near the smallest tributaries, the depressions will spill over into channels and begin, along with the rain that has fallen directly on the creek, to increase the stream flow.

Water infiltrating into the soil fills some of the soil pores as it migrates deeper. The amount of soil pore water storage depends, as with the litter storage, on soil texture, the number of pore spaces that the water has access to, the antecedent moisture content, and the thickness of the soil layers. In this hypothetical catchment, the bedrock or other compact relatively impermeable material is between 0.5 and 3 meters below the surface, a typical range of soil thickness over much of the Pacific Northwest. Towards the ridgetops the soil just above this impermeable material is moist but not saturated. Most of the free interpore water has drained or been exfiltrated by the vegetation. Farther down the slopes there is still a zone of saturated soil above the impermeable layer. This interpore water is flowing down slope and contributes to the prestorm baseflow of the creeks.

As the storm water percolates through the soil it encounters the impermeable layer or water table and flows downslope. As time proceeds from the onset of the storm, increasing amounts of water arrive at the subsurface saturated zone. As the water arrives at the saturated zone, the water table typically will rise. In hollows and swales, groundwater flow paths converge. The water table will rise faster in these areas and can rise to saturate the full depth of the soil profile while other areas are still only partially saturated. Rain that falls on these expanding, fully saturated zones will not be able to infiltrate and so will flow as saturated overland flow into channels where it contributes further to the rising stream hydrograph. The saturated soil zones continue to expand with increasing storm duration. Water exiting from below ground onto these zones is known as return flow.

As the storm wanes, trees continue to drip, filled surface depressions drain, and free water (in excess of the litter and soil field capacity) drains to the water table. Over a period of days the free water all drains to the saturated zone, which is still high. Subsurface water continues to flow to the swales and creeks. Gradually the water table drops as the saturated soil drains.

Further rain falling on the catchment, while water storage elements are still undrained and the saturated zone is still expanded, will generate stormflow much faster than with dryer antecedent conditions. A larger percentage of the storm precipitation will make its way to the channels.

Storm response is different for this catchment once it has been urbanized; land modifications have changed the types of runoff-producing processes. As the storm begins there is little vegetation storage. The forest litter has been mixed with mineral soil and compacted, leaving the surface soil with less water storage potential and lower infiltration capacity (Moore, 1986). The grass quickly wets and there are fewer and much smaller soil depressions to store water on the surface. Intense rainfall periods during the storm quickly exceed the soil infiltration capacity and fill depressions over portions of the catchment pastures and lawns. The storm quickly wets and fills depressions of the impervious roofs, roads, and roadsides and produces flow into storm drains that feed directly to the creeks (or indirectly via storage ponds, if the area was developed more recently). Water from the storm drains or ponds discharges into swales or portions of the creek that may never have carried very much water in the pre-developed condition. Channel adjustment results from the new hydrologic conditions.

2.3 WATER INPUTS

Rain and snow are the major water sources to most catchments. Frost and dew are minor sources but can be significant factors in some locations or seasons. For example, when frost restricts rainfall infiltration surface runoff producing areas expand.

The rainfall-runoff response of a catchment is strongly influenced by the antecedent catchment conditions prior to a storm's arrival. The largest rainfall events do not necessarily produce the largest runoff events. Storms arriving in the wet season are more likely to fall on a basin with water storage zones already partly full. Extreme runoff events commonly occur when less intense long duration storms fall on catchments that are still partially saturated from previous storms, because the zones of saturation that contribute to stream discharge are expanded in these circumstances. For example, severe flooding in the King County area (Washington State) caused by the January 18, 1986 storm, resulted from a rainfall peak intensity on the order of 0.3 inches per hour as indicated at the Carnation, Washington gauge (Figure 2.1) which by itself has a recurrence interval of less than 2 years (Appendix D). However, the peak rainfall was preceded by 3.9 inches of rainfall on 12 of the previous 18 days. Rain fell for nine hours prior to the peak intensity at 12 noon on the 18th and was followed by 11 hours of rainfall, all with an average peak intensity of only 0.12 inches per hour (Figure 2.2).

While field evidence of a recent storm is indicated by the general moisture condition of the catchment water storage elements, field conditions do not reveal much about the frequency, intensity, and distribution of storm events. In most cases extrapolation of weather data from established gages, is necessary for estimating hydrologic impacts from small urban development projects.

2.4 EVAPORATION

Evaporation and transpiration constitute a significant fraction of gross precipitation. Kittredge (1948) reports that between 6% and 43% of rainfall is caught by the vegetation canopy and evaporated. Evaporation and transpiration typically removes between 40 and 50 percent of annual precipitation from catchments in the Puget Sound Lowland. This estimate is based on average runoff to rainfall data (Bodhaine and Thomas, 1964), average annual pan evaporation of 31 inches (81 cm)

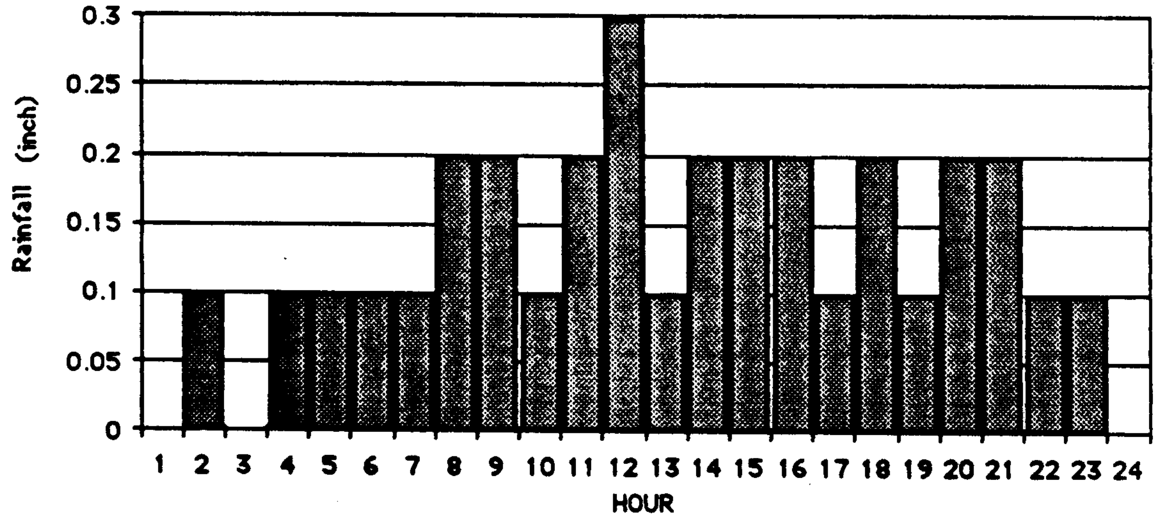


Figure 2.1 Hourly rainfall in inches at Carnation, Washington for January 18, 1986 (National Climatic Data Center, 1986).

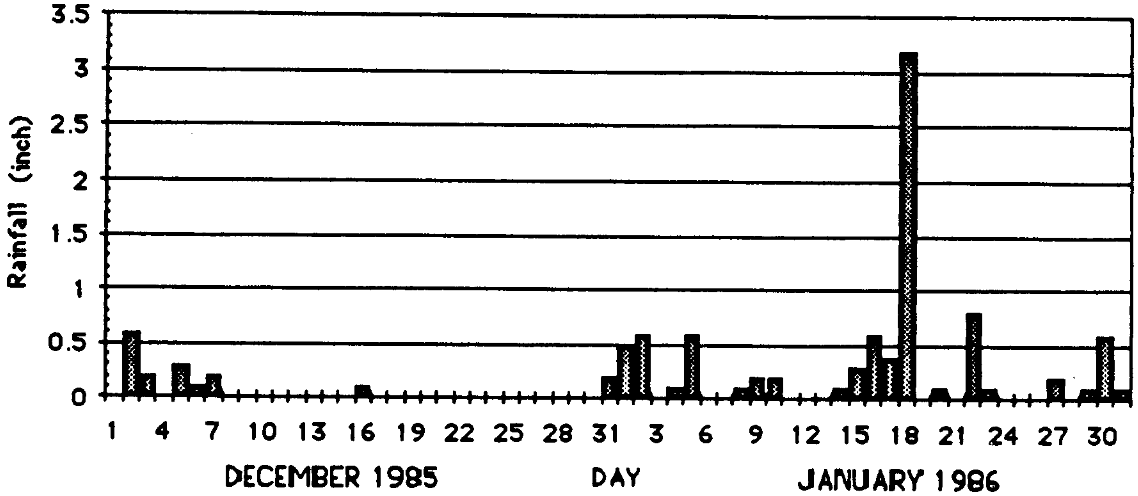


Figure 2.2 Daily rainfall in inches at Carnation, Washington for December 1985 and January, 1986 (National Climatic Data Center, 1985, 1986).

with a standard deviation of 2 to 4 inches (5 to 10 cm) (Dunne and Leopold, 1978) average annual evaporation from shallow lakes of 25 inches (63 cm) (Kohler et al, 1959), and from water balance studies (Swank, 1972). Transport of water to the atmosphere from the catchment occurs as evaporation from open water bodies (including snow), water intercepted on the vegetation canopy and forest litter, bare soil, and transpiration from plants. Vegetation influences evaporation rates by interception of rain, snow or dew, and by the active removal of moisture out of the soil root zone.

Evaporation rates are governed by the annual climatic regime (Swank, 1972). For a catchment in the Puget Lowland, Swank (1972) found that evaporation of water intercepted by the vegetation canopy was the dominant source between October and March (the wet season). In April through September (the dry season), transpiration becomes the dominant evaporative source (Swank, 1972). Total evaporation loss and transpiration varies with changing vegetation surface area, temporal distribution of precipitation, wind speeds, and solar energy.

Effects From Land Modification

Evapotranspiration can remove significant amounts of water from the soil zone (Swank and Miner, 1968; Swank, 1972; McNaughton and Black, 1973; Singh, 1979; Rogerson and Byrnes, 1968; Lewis, 1968). Removal of vegetation and alteration of species makeup reduce the rate water leaves the soil zone by evapotranspiration. Forest removal also results in less canopy interception storage and evaporation. Forest practices, such as burning and forest floor disturbance from logging machinery, tree falling, and removal, reduce litter storage, making more water available to either infiltrate or flow quickly to channels. The combined effects of vegetation changes commonly result in greater antecedent soil moisture levels than for the natural state. Greater portions of the catchment will then become saturated and produce storm runoff. Elevated porewater pressures can in turn increase the frequency of new slope failures and activate dormant ones (Humphrey, 1982; Selby, 1982; Swanston, 1974). During storms saturated overland flow can occur over greater areas and for longer periods of time. Seeps and small drainages experience more frequent and greater flows. The increased flow rates and volumes can impact creek channels and related habitat with increased erosion, deposition, and bank instabilities.

2.5 WATER STORAGE

Water storage is the temporary or permanent delay of water received by the catchment. Storage processes include interception by vegetation and forest litter, depression storage, soil storage, and wetland or pond storage. Areas with sparse vegetation and shallow soils may only have minor amounts of vegetation and soil storage while forested areas can have considerable storage potential with vegetation, forest litter, depressions, and ponds all contributing. Many development-related land modifications remove existing water holding and delaying features of a catchment. Estimates of this loss can be central to deciding the size of detention facilities necessary to mitigate development related change.

VEGETATION INTERCEPTION

Most of the rain falling on vegetation in light storms is intercepted, up to 0.03 to 0.18 cm (0.01 to 0.07 inch) (Horton, 1919; Chowdappa, 1960; Zinke, 1967; Swank, 1972). In larger storms, when the canopy storage capacity is filled, water drips and runs down the vegetation (throughfall). Annual canopy interception loss was estimated at 7.9 inches (20 cm) or 14 percent of the annual rainfall of 55 inches, for 40-year old Douglas-fir in the Puget Lowland of Western Washington (Swank, 1972). Chowdappa (1960) found average total rainfall interception varied by species from 30% to 55%.

Field Indicators

Vegetation type, density, and distribution give an indication of the significance of interception in a catchment. Many empirical equations are available to estimate interception loss for a variety of species types and regions (Helvey and Patric, 1965; Helvey, 1967; Zinke, 1967; Swank, 1972; Dunne and Leopold, 1978). In general the more vegetation that is present the greater canopy interception loss will be. Zinke (1967) indicates that rainfall storage capacity for most grasses, shrubs, and trees can be estimated at 1.3 mm (0.05 inch) and snowfall interception for trees can be estimated at 3.8 mm (0.15 inch).

SOIL WATER STORAGE

The water-holding properties of the litter and mineral soil zones vary depending on the type of soil materials, position on a hillslope, vegetation, local climate, and land-use history. The soil volume (V_t) is made up of water (V_w), mineral and organic solids (V_s), and air (V_a).

$$V_t = V_s + V_w + V_a \tag{2.1}$$

The porosity (N) is the fraction of the soil volume that is pore space.

$$N = \frac{(V_w + V_a)}{V_t} \tag{2.2}$$

If the soil becomes saturated the porosity is equivalent to or slightly greater than the saturated moisture content.

The field capacity of a soil is the moisture content that remains after free draining. The wilting point is the lowest moisture content from which plants can extract soil moisture for transpiration. The maximum water storage potential of a soil prior to rainfall is typically the soil porosity minus the wilting point moisture content. Estimates of potential soil water storage can be based on an assumed initial moisture condition. The moisture detention capacity (soil porosity minus field capacity) provides an estimate of how much water can be stored temporarily in a soil profile.

The greatest impact to soil water storage from land development results from disturbance of the loose surface soil and litter. Litterfall, biological activity, and soil creep produce a relatively loose and porous zone called by various professionals forest floor, duff, forest litter, or organic zone. In Puget Sound wooded areas, forest litter accumulates on the forest floor at rates of 1000 to 3500 pounds/acre/year depending on stand density, age, and species types (Chowdappa, 1960). Water enters the forest floor as rain or throughfall and exits by evaporation, transpiration, drainage, or runoff (Hanks and Ashcroft, 1980). Physical properties of the forest floor control its moisture characteristics and hydrological behavior, and consequently are important in watershed management (Balci, 1964). Forest floor water retention and detention occurs in the voids between organic particles and by absorption into the particles (Grelewicz and Plichta, 1985; Fosberg, 1975; Jackson, 1964). The forest floor remains loose, relative to the mineral soil below, by churning of the soil by gravity, biologic activity, water movement and phase changes, and temperature changes. Loss of forest cover, conversion to different vegetation, topsoil removal, and soil compaction will change soil water detention, retention, and infiltration rates.

The Committee on Forest Floor Classification (Hoover and Lunt, 1952; Balci, 1964) established a classification criteria for forest floor litter. The scheme divides the forest litter into 3 layers that overlie the mineral soil or A_1 horizon:

L layer	(Litter Layer) The surface layer of the forest floor consisting of freshly fallen leaves, needles, twigs, stems, bark, and fruits. In warm climates rapid decomposition results in a thin or absent L layer.
F layer	(Fermentation layer) Layer of partially decomposed but still recognizable litter.
H layer	(Humus Layer) Layer consisting of well decomposed organic matter.
A_1 horizon	The surface mineral soil horizon containing incorporated or infiltrated organic matter.

There are two distinct forest floor types that depend on the absence or presence of a H layer. When there is no H layer (layer of well decomposed litter) and the organic matter is uniformly mixed into the mineral soil, the forest floor is referred to as a mull. When an F and H layer are present over a layer of mull the forest floor type is a mor.

Forest floor properties are extremely variable depending on location, tree species, drainage, climate, and topography. In the Pacific Northwest the cool climate slows the decomposition rate of litter allowing development of mor type litter zones of 7 to 29 cm in depth in old growth forests (Gessel, 1965; Balci, 1964).

Bulk density of forest litter is highly variable, ranging from 0.07 to 1.09 g/cm^3 (Trimble and Lull, 1956). Bulk densities of forest floors in Western Washington coniferous forests averaged 0.13 g/cm^3 (Gessel, 1965; Cooper, 1985). Duff layers in British Columbia and Western Washington can hold from 200% to 300% of their dry weight in water (Wright, 1935, 1967; Balci, 1964). Mor forest floors have porosities in the range of 40% to 80%. Porosity of mull lies between that of mor and mineral soils.

Field capacity (% moisture retained after free draining) was found to be 38% by volume for mors and 41% for mulls (Trimble and Lull, 1956). Balci (1964) measured field capacities in Pacific Northwest old growth forests at 18% to 20%. Detention capacity (difference between saturation capacity and field capacity) was found to be 45% by volume for mor forest floor and 34% for mull (Trimble and Lull, 1956). Balci (1964) measured values of detention capacity of 14% to 20% for old growth mor forest areas.

Forest floor has a very high infiltration capacity (Moore et al, 1986; Balci, 1965). Balci (1965) developed micro-hydrographs (Figure 2.3) to study the hydrologic behavior of mor and mull forest floors under 2.3 cm/hr (0.9 in./hr) rainfall intensities. The durations of the 2.3 cm/hr tests compare to a 50 to 100-year one-hour duration rainfall in Seattle. The area under the curve (B and C in Figure 2.3) is the total discharge through the litter layer. The area above the ascending portion of the curve (A) is the total detention capacity of the litter. Detention slowly decreases to zero at which time water flows into and out of the sample at the same rates. The area under the descending limb (C) represents the release of the temporally detained water. The infiltration capacity of the loose litter is generally greater than the underlying mineral soil so detained water will migrate laterally along their interface in addition to percolating into the mineral soil below.

The large water storage capacity of forest litter means it will have an important role in catchment rainfall-runoff response. Delay from infiltration or lateral migration of 1.5 to 6.5 cm of water for 15 to 60 minutes provides significant moderation of rainfall-runoff response in forested catchment areas. In addition to water detention, forest litter reduces lateral flow velocities below what would occur if flow were on the surface. Clearly, use of overland flow velocities is inappropriate for estimating time of concentration for heavily vegetated areas.

Zone Identification and Field Indicators

Catchment areas where forest floor water storage is important can be mapped based on vegetation types observed in air photos. Typical litter and mineral soil depths are easily obtained with a hand auger. To estimate potential water storage in the litter and soil zones, measurements and estimates of the depth to relatively impervious substrata and to the saturated water table are needed for the seasons of importance to catchment storm response. Water capacities can be measured in the field (Appendix A) or estimated based on typical values in the literature (Balci, 1964; Gessel, 1965; Helvey and Patric, 1965; Zinke, 1965; Dunne and Leopold, 1978). Based on such data a catchment plan view map of potential water storage can be developed. The change from pre- and post-development water storage along the length of the catchment main channel can be used to identify zones that will experience increased runoff and resulting adjustment of downstream channels.

DEPRESSION STORAGE

Topographic depressions provide reservoirs that store water. While held in temporary storage, water has an opportunity to infiltrate or evaporate. Depression storage has a continuum of scales. Depressions on the order of tens of meters in plan dimension with extended periods of saturation and wetland vegetation are treated separately as wetlands. At the other extreme, dimensions for depressions converge to a microscopic size that is better handled analytically as porosity or soil litter storage. The plan dimension scales of centimeters to meters are considered to be depression storage here.

Depressions store return flow (if any) and rainfall (or snowmelt) that has not infiltrated into the soil during intense periods of precipitation or while rapid snow melt occurs. Depression storage zones are difficult to recognize where storage may occur for only a few minutes to several days. Wetland indicators may not be evident when depressions hold water only for short periods during intense rainfalls. Characterization of depression storage is complicated by the variety of patterns and scales. A single wetland can be mapped and the main outlet controls studied to establish the storage potential. A hummocky field with depressions from 1 centimeter to 20 meters in characteristic length with variable water storage volumes below their outlet controls and apparently distributed in a random

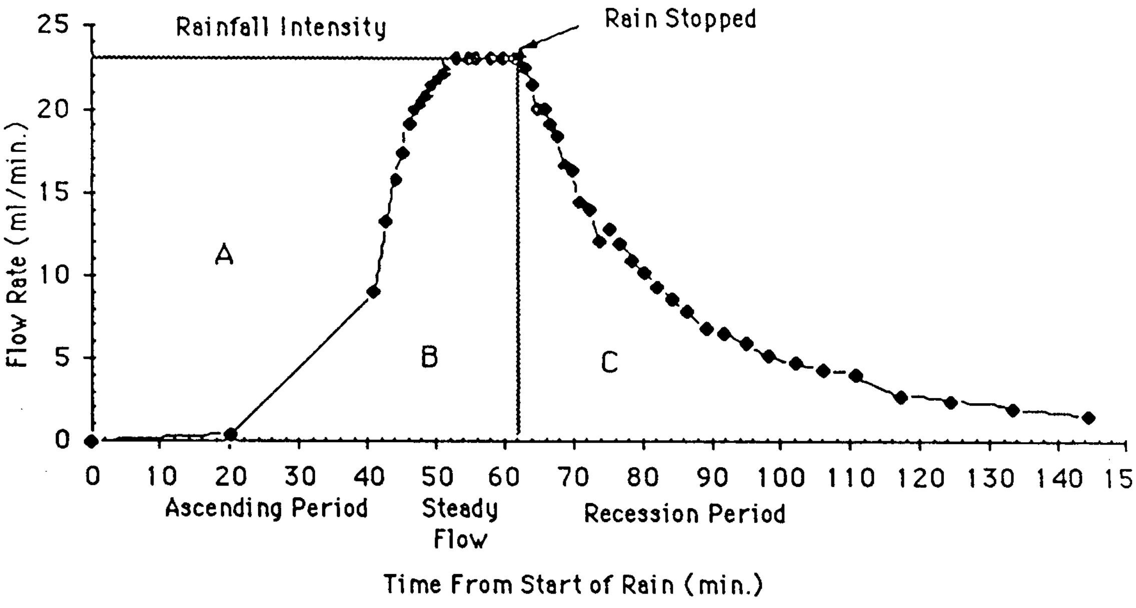


Figure 2.3 Flow characteristics for a sample of mor forest floor under 2.3 cm/hr rainfall. Data are from Balci (1964), for Sample II 1-A. The sample is from an old growth stand of Western Hemlock (Tsuga heterophylla), at an elevation of 915 meters. Total depth of the L, F, and H layers was 19.1 cm, bulk density was 0.124 g/cm^3.

way, does not lend itself well to characterization. However, the potential water storage even for centimeter-size depressions cannot be ignored.

As an estimate of depression-storage potential, some classification scheme should be developed that fits the typical scales of depressions present in the catchment. The levels that may be considered are: large (greater than 1 meter and described by a typical diameter, depth to outlet control and number per unit area) medium (less than one meter); and small (less than 1 centimeter and described by a typical volume and as a continuous distribution) and minimal. Extensive measurement of depressions would not be practical. Observing the depressions qualitatively in each area will provide a ranking of the relative importance of depression storage as significant, significant only in minor storms, or minor. Field notes include statements such as, "14 acres above road hummocky with 3 to 15 meter depressions 0.2 to 1 meter deep, distribution continuous, depression storage potential high".

Field Indicators

Field observation of surface texture and topography in relation to tributary channels will allow estimates of the relative importance of depression storage in representative areas of the catchment. Field inspection in the wet season during an intense storm is probably the best method to assess the importance of depression storage. Field visits conducted in dry weather will allow the depressions to be observed but will not reveal the extent to which the depressions are interconnected and their hydrologic effectiveness in water storage. Many areas with heavy forest cover can infiltrate the highest intensity storms with little or no surface ponding. Surface litter will remain fluffed and well oxidized in these areas indicating there has not been standing water. Depressions that hold water sometimes show a laminated layer of leaves or a black or gray to blue gray color. Water levels from temporary ponding are sometimes observable by vegetation changes, a ring of silt, or different surface litter textures.

WETLAND STORAGE

Wetlands are depressions where, due to the duration of saturated conditions, some wetland plants, soils, and land forms are observed. Wetland plants are also found around seeps and along lower slopes where flow emerges; lacking the land form of a wetland, they are unlikely to be confused with wetlands. If wetlands are modified an estimate of changed storage potential is obtained by mapping the volume of storage and natural outlet controls. Unintentional modification of wetland storage often occurs when the outlet is disturbed. Fill material placed across outlets can cause an increase in storage by restricting outflow. Nearby ditches will reduce wetland storage by increased surface and subsurface drainage. When drainage ditches or subdrains are installed the lost storage includes surface water and the potential water content of the soil above the new water table. Filling in portions of wetlands also reduces the volume of storage.

CHANNEL STORAGE

During floods creek channels store water in side channels and on the flood plain. As water stage increases during a flood the water that flows out over the flood plain is detained and provides a buffering effect to the flood peak. When loss of channel storage could be a concern, as in levee or channel straighting projects, two-dimensional flood routing models are needed to account for flood plain storage through the channel network.

The amount of channel storage can be approximated by measuring the channel geometry at representative locations for each typical reach of the drainage network. An estimated stage-storage relationship is then developed for pre- and post development conditions.

Effects From Land Modification

Channel storage is lost when flood plains are filled. Levees reduce channel storage by preventing water access to the flood plain. Loss of flood plain storage occurs at road fills; however, backwater from culvert restriction of the flow may compensate for some of the lost storage. Dredged or excavated channels have increased channel storage but require regular maintenance because the modified channel is not in balance with the discharge, gradient, and sediment transport. Excavation damages stream banks and stream habitat.

2.6 RUNOFF

Runoff is that portion of the incoming precipitation that moves through the catchment by flowing over the surface or as open channel flow. The well documented mechanisms for surface runoff production are Horton overland flow (HOF), saturated overland flow (SOF), and return overland flow. Storm flow is the fast runoff response to precipitation by these mechanisms. Baseflow results from flow to channels from the gradual subsurface drainage of catchment storage elements.

HORTON OVERLAND FLOW

Horton overland flow occurs when rainfall intensity exceeds the infiltration capacity of the soil long enough to result in flow across the surface. Infiltration capacity was defined by Horton, "as the maximum rate at which a given terrain when in a given condition can absorb rain as it falls" (Horton, 1940). Horton overland flow is the dominant runoff producing process on impervious areas and areas with a low infiltration capacity, because it is on these surfaces that rainfall intensity typically exceeds the infiltration capacity.

Field Indicators

Horton overland flow is common on impervious or nearly impervious surface layers with little or no overlying soil or litter zone. Compact surface layers, pavement, concrete, bricks, and roofs readily generate Horton overland flow. Lawns and play fields can produce Horton overland flow, depending on the soil texture, compaction, and potential depression storage. Undisturbed mor and mull forest floors, with infiltration rates of 10 to 50 in./hr (Moore et al, 1986; Balci, 1964; Trimble and Lull, 1951), will not produce overland flow unless enough rain falls to saturate the soil litter fully (discussed later as saturated overland flow). In undisturbed areas the excess rainfall is detained in the forest litter during intense rainfall periods and later percolates into the soil. The infiltration rate of roads, rock, and exposed till layers are all less than 0.1 in./hr (Snyder, 1973; Freeze and Cherry, 1979). Rainfall intensities commonly exceed these infiltration rates. Pastures and closely mowed lawns have infiltration rates within the range of typical rainfall intensities. Trampled and compacted pastures and playfields will produce overland flow early in a storm. Well maintained pastures and thick lawns generally do not produce Horton overland flow, they can produce saturated overland flow depending on the subsurface soils.

Effects From Land Modification

Production zones of Horton overland flow are created when forest or fields are converted to urban developments. The forest litter and loose upper soil layer are graded and compacted. Impervious or nearly impervious surfaces can cover between 5 and 100 percent of developed areas. Potential water storage on impervious zones is reduced to a small amount of depression storage that is easily filled by all but the smallest storms. Loss of temporary water storage in the litter zone, reduced potential depression storage and changed soil texture of the upper soil layer can reduce infiltration rates sufficiently for Horton overland flow to occur on many lawn and pasture areas. The new areas of overland flow are generally in close proximity to drains and ditches that concentrate the overland flow for quick conveyance away from the area.

RETURN FLOW

Water that infiltrates to the saturated zone flows laterally downhill. At locations where the soil profile thins or the saturated zone thickens, as in swales where considerable subsurface water has converged, the saturated zone can expand to the full depth of the soil profile thereby returning some of the water to the ground surface. Water that infiltrates near to channels can percolate to the saturated zone and migrate laterally to the channel banks or springs in time to contribute to the stormflow.

Water that enters the saturated zone further up slope will need greater time to percolate to the channel and therefore will become part of the post-storm baseflow.

Field Indicators

Locations of return flow are controlled by site topography and geology. Springs are an easily recognized and widely known form of return flow. Return flow also occurs as a slow seeping of water distributed along side slopes and valley edges, especially in hollows and slope concavities. Wet zones along the foot of slopes are often due to return flow. These areas are sometimes identified by wetland plants and small rills or slumps. Impervious layers, joints, and faults will conduct water to the surface and often control the locations of the main ravines and valleys of a catchment (Reneau and Dietrich, 1987; Wilson and Dietrich, 1987; Dunne, 1980).

Effects From Land Modification

Road cuts and ditches create areas of return flow where they intersect seasonal or permanent saturated subsurface zones. Where the saturated zone is exposed, water that would have been stored in the saturated zone and migrate slowly to the creeks to become baseflow now becomes part of the stormflow.

Many wetlands receive water as return flow from the surrounding slopes. The effects on the flow path from alteration of the wetland must be assessed. Land modifications that preserve the infiltration capacity but reduce evaporation such as vegetation removal can increase saturated subsurface flows and result in increased return flows. Piping and slope instability can result from increased subsurface pore pressures (Selby, 1982; Humphrey, 1982). Return flow from subsurface seepage out of reservoirs, infiltration trenches and ponds can lead to damage from soil piping and surface slumps.

SATURATED OVERLAND FLOW

Rainfall that falls on saturated areas can not infiltrate, hence saturated areas are in effect impervious surfaces. Locations where the entire soil profile becomes saturated, either temporally during intense, long duration storms after vegetation, depression, and litter storage is filled, or permanently as in bogs, will generate surface runoff that can flow to the creek channels and contribute to stormflow. Areas that are saturated due to return flow generate runoff consisting of return flow and the rainfall that falls on the saturated area.

Field Indicators

The zone of saturated overland flow expands during storms or in the wet season and gradually recedes after storms or in the dry season. An effective way to identify the extent of ephemeral saturated areas is to mark the edges of the saturated areas during storms. The extent of seasonally saturated zones can be inferred based on topographic position, soils, and in some cases vegetation types. Zones of seasonally saturated ground that give rise to overland flow commonly occur around the edges of bogs, wetlands, and low-order drainages. The saturated zone gradually expands with increasing duration of the storm or wet season. The soil profile in swales and low areas where subsurface flow is converging will saturate before areas where subsurface flow is diverging. Low concave shaped areas on the middle and lower parts of a hillside are areas to search for other confirming evidence of seasonal overland flow. Seasonal overland flow may be expressed in surface features such as tiny rills that are buried beneath last season's litter. Small depressions around surface pebbles can indicate if surface runoff has occurred.

Effects From Land Modification

Removal of vegetation reduces rainfall interception and soil moisture transpiration. The increased rainfall available to infiltrate and reduced soil moisture removal can result in a rise in the shallow subsurface water table. The storm duration needed to saturate the soil profile is lessened so it is more common for storms to encounter an elevated water table. This leads to an increase in the area of the catchment contributing saturated overland flow.

Installation of subsurface drains and ditches reduces the chance that the drained area will saturate and cause saturated overland flow. However, the saturated overland flow is merely replaced by a man-made form of return stormflow. A ditch containing flowing water during a storm is added to the area of direct stormflow runoff.

As areas are urbanized the tendency is to direct subsurface drains and drainage ditches to lower areas, such as swales. Swales tend to have seasonally high water tables from the topographic convergence of shallow subsurface water. When additional stormflow is introduced from upslope drainage, a greater area of the swale will saturate. Increased saturated overland flow will occur and often the increased flow is enough that the low-order channel in the lower portion of the swale will tend to erode upslope by increased soil piping and from overland flow that develops into rilling.

OPEN CHANNEL FLOW

Channels form where water has gained enough energy to overcome the forces that bind soil and rock together. This occurs at locations where water is concentrated by surface or subsurface hollows. The initial hollow or swale is often related to the occurrence of geologic controls such as joints or changes in soil or rock units (Reneau and Dietrich, 1987; Wilson and Dietrich, 1987; Dunne, 1969, 1980). Initiation of channels occurs by subsurface piping, surface rilling, and earth slumps. In glaciated areas the initial channel network results from the interplay of local soil units and the initial glacial landforms.

River channel width, depth, slope, substrate, flow velocity, and discharge are controlled by the combined effects of meteorologic, hydrologic, geologic, and biologic processes in the catchment. Numerous studies have related channel geometry (width, depth, slope, and channel roughness) to measurable catchment parameters; one of the strongest relationships is with discharge (Leopold and Mattock et al, 1953; Dunne and Leopold, 1978).

Channel geometry adjusts to the catchment water and sediment supply. Land modifications that alter water or sediment supply will result in channel adjustments. Observations of gravel-bed channels at low discharge rates reveals there is little or no sediment transport occurring. As flow increases, in a storm or during the wet season, the water has greater energy to overcome the substrate resisting forces in portions of the channel. At channel-full (or bankfull) stage the discharge has sufficient energy to form the channel by erosion and deposition of bank and substrate material. Channel-full stage is indicated by erosional and depositional topographic features and vegetation changes along the channel edges. Bankfull stage has been correlated with discharge rates having recurrence intervals of 1 to 5 years, (Wolman and Leopold, 1957; Richards, 1982; Brown, 1971) with 1.5 years being common in mid-west U.S. sand-bedded rivers. These studies involved low gradient channels from relatively large catchments. Correlations for small high-gradient 1st-order rills and creeks (which are of interest in urban development) can only be assumed.

Land modifications change the frequency, magnitude, and duration of runoff to channels. This results in adjustment of the channel to the new flow regimen which generally means channel changes in the form of increased sediment transport, bank and slope instability, flooding, and damage to aquatic habitat. Limiting post-development peak discharge rates to pre-development levels has been attempted using various schemes based on calculated pre- and post-development conditions. Even if these calculations are correct, changes to channel morphology, sediment transport, and aquatic habitat will still occur because of increased frequency and duration of higher flow rates. When detention structures are used throughout a catchment the duration of peak discharge will be increased as the stored flood runoff is released from each pond. For example, if the long-duration release from a detention structure is at the pre-development peak discharge for a 2 year (or greater) recurrence flood event, it is likely significant sediment transport will be occurring for the duration of this flow rate. To mitigate this, the long-term release rate, once the peak has passed, can be maintained at some fraction below the threshold discharge rate for significant sediment transport, which is typically near to the bankfull discharge.

ESTIMATION OF PRE-DEVELOPMENT CHANNEL CAPACITY

The dimensions of catchment channels prior to land modifications can be used as a baseline indicator of catchment conditions. Pre-development bankfull and flood stages indicated by field evidence can be mapped at representative reaches along a catchment channel network. The natural geometry of channels that have been modified by land use changes can be estimated by correlation with undisturbed tributaries (Medej, 1982). Limiting post-development long duration discharge to a magnitude significantly less than the bankfull capacity of pre-development conditions gives site-specific criteria to limit post-development discharge rates.

To use this method, channel discharge rates must be estimated for the channel bankfull and flood bar levels. The best but not always practical method is to take flow measurements for 3 or 4 flood stages. The stage-velocity measurements can then be used to simulate discharge at a range of stage heights. When flow measurements are not practical, less precise estimates can be made with empirical equations such as Manning's equation (Appendix B, Eq. B4).

Manning's equation provides good results for straight low-gradient channels with uniform flow. It can be used with good results in natural channels with nonuniform flow when used within the range of verified channel-roughness data. When used on boulder and gravel-bed rivers (see Appendix F for the size classification used) with slopes of 0.24 to 2.3 degrees (0.4 to 4%), Bathhurst (1986) reports errors of 9% in surveying the cross section, 25% in evaluation of the roughness coefficient, and 25% from neglecting boulders or logs projecting into the current and in assuming the mean water surface is represented by the water edge elevations. Interpretation error from selecting the level of bankfull and flood stage can be expected to reduce accuracy further. Additional error can be introduced by assuming high flow rate channel cross sections are comparable to those at low flow stages. A final and perhaps the most critical error is introduced in steep (slopes of 0.1 to 4 degrees) and very steep channels (slopes greater than 4 degrees) where energy losses and flow patterns are introduced that Manning's equation does not model well.

Channel roughness factors include cross section irregularities, channel shape, obstructions, vegetation, channel meandering, suspended and bedload material, and channel and flood-plain conditions (Jarrett, 1984). Values of Manning's roughness coefficient from references range from 0.03 to 0.07 for natural streams (Bathurst, 1984; Richards, 1982; Dunne and Leopold, 1978; Chow, 1964). Limerinos (1970) developed an empirical equation for Manning's roughness coefficient, n, based on relative channel roughness. This value of n (eq. 2.3) does not account for section irregularitives, meandering, and vegetation:

$$n = \frac{(0.0926)\, R^{1/6}}{1.16 + 2.0 \log, \frac{R}{d_{84}}} \qquad (2.3)$$

n = Manning's Roughness coefficient
R = Hydraulic Radius (feet) = Area/Wetted perimeter,using mean depth
d_{84} = Intermediate particle diameter (feet) that equals or exceeds that of 84% of the particle diameters determined by the method of Wolman (1954).

Jarrett (1984) provided an empirical equation to estimate the roughness coefficient, n, for steep channels (slope greater than 0.002 or 0.1 degrees) that extends the utility of Manning's equation up to slopes of 0.04. or 2.3 degrees for channels with gravel, cobble and boulder beds. Jarrett's data indicate the Manning's roughness coefficient decreases with flow depth and increases with friction slope (Jarrett, 1984) i.e.

$$n = 0.39\, S^{0.38}\, R^{-0.16} \qquad (2.4)$$

n = Manning's Roughness coefficient
R = Hydraulic Radius (feet) = Area/Wetted perimeter,using mean depth
S = Friction Slope (ft/ft) or Channel Slope for fairly uniform channels.

2.7 RUNOFF PRODUCING ZONES

Dominant runoff producing process zones, common to many catchments in humid temperate areas, include open channels; water storage from vegetation, depressions, and soil zones; saturated overland flow (SOF); Horton overland flow (HOF); and return flow. Areas of a catchment can be classified by the dominant processes occurring there. Consideration of how these processes may vary, by seasons, during a storm, and by areal distribution, is vital to understanding the catchment dynamics. Without extensive long-term data gathering efforts the distribution of dominant processes can only be estimated based on the observable site features. Interpretation of map, aerial photograph, and field data can yield some understanding of the site processes. Dominant process zones to consider in catchment analysis will vary by region and by the specific basin characteristics. For example, in regions with a freezing winter season, snow and frozen ground will need to be considered. In dry regions the distribution of rainfall and slope exposure is important. In humid temperate areas, vegetation and forest litter take on added significance. Humid tropical regions may have greater vegetation storage.

2.8 BASIN RESPONSE TIME

The speed with which water flows from a basin in relation to the occurrence of rainfall will vary depending on the basin configuration, the antecedent conditions when a storm arrives, the locations of flow production zones, and on the spatial distribution and intensity of the storm. The basin lag time is usually defined as the time from the centroid of the rainfall hyetograph to the centroid of the runoff hydrograph. Basin response time will be different for each subbasin in a catchment. The hydrograph from each subbasin combines to generate the downstream hydrograph. Estimating the dominant processes in each portion of a catchment allows the runoff response to be classified as quick-stormflow or slow-baseflow. Quick storm response can be inferred for areas with high drainage density, shallow soils that saturate quickly, impervious surfaces, and steep slopes. Slow response can be inferred for those areas with dense vegetation, depression, litter, and soil storage, low drainage density, and gentler slopes. Using a baseflow-stormflow criterion to map a catchment separates those areas where a significant volume of precipitation can contribute to the storm hydrograph and those portions of the catchment that have delayed runoff because of water storage and long travel times.

Basin lag times may be known for a few catchments in the region where both rain and stream gauges are present. These are generally for larger basins and are of little use in estimating response time for the small areas generally considered in land development proposals. Installation of rain and stream gauges for 1 or 2 years should provide adequate data on the basin response time for typical flows. During a short record period a catchment may experience an extreme event but the record is not adequate to assess fully the recurrence frequency of extreme floods or droughts. Short term gauge records of basin lag time, interpreted in context with the antecedent basin conditions, can provide verification of estimated catchment process zones and are essential for checking storm routing calculations. Measuring the catchment response for even one flow producing storm provides a quantitative estimate of the dynamics of the catchment in its pre-developed state. This helps identify what possible effects proposed land modifications might have. For example, a catchment where throughflow is the dominant runoff process could be distinguished from one where overland flow dominants by the general characteristics of the hydrographs and basin lag times. Differences in lag time of 3 times or more can be expected for catchments of the same area but dominated by different runoff processes (Dunne and Leopold, 1978; Anderson and Burt, 1978; Rantz, 1971). Measurement of lag time for one storm event is relatively easy to accomplish (Dunne and Leopold, 1978, page 339 and 388).

When actual catchment processes are considered lag times will need to account for flow velocities of surface and subsurface water flow paths. Water flow velocities of surface and subsurface water can differ by orders of magnitude as shown in Figure 2.4.

Overland flow velocities can be less than 0.15 cm/sec (0.06 ft/sec) in low gradient (< 3 degrees) vegetated areas and up to 15 cm/sec (0.5 ft/sec) on 22 degree slopes (Dunne et al, 1975; U.S. SCS, 1975). Open channel flow can range as high as 400 cm/sec (13 ft/sec) but more typically is in the range of 7 to 150 cm/sec (0.2 to 5 ft/sec).

Subsurface flow velocities can range as high as 10 cm/sec (0.3 ft/sec) for open joints or openwork gravels but typically are in the range of 10^{-1} to 10^{-3} cm/sec (10^{-3} to 10^{-5} ft/sec) for silts, sands and gravel-sand mixtures and less than 10^{-5} cm/sec (10^{-7} ft/sec) for clays (Freeze and Cherry, 1979; U.S. SCS, 1975; Peck, et al, 1974). Subsurface water flow velocities are generally orders of magnitude slower than surface flow velocities.

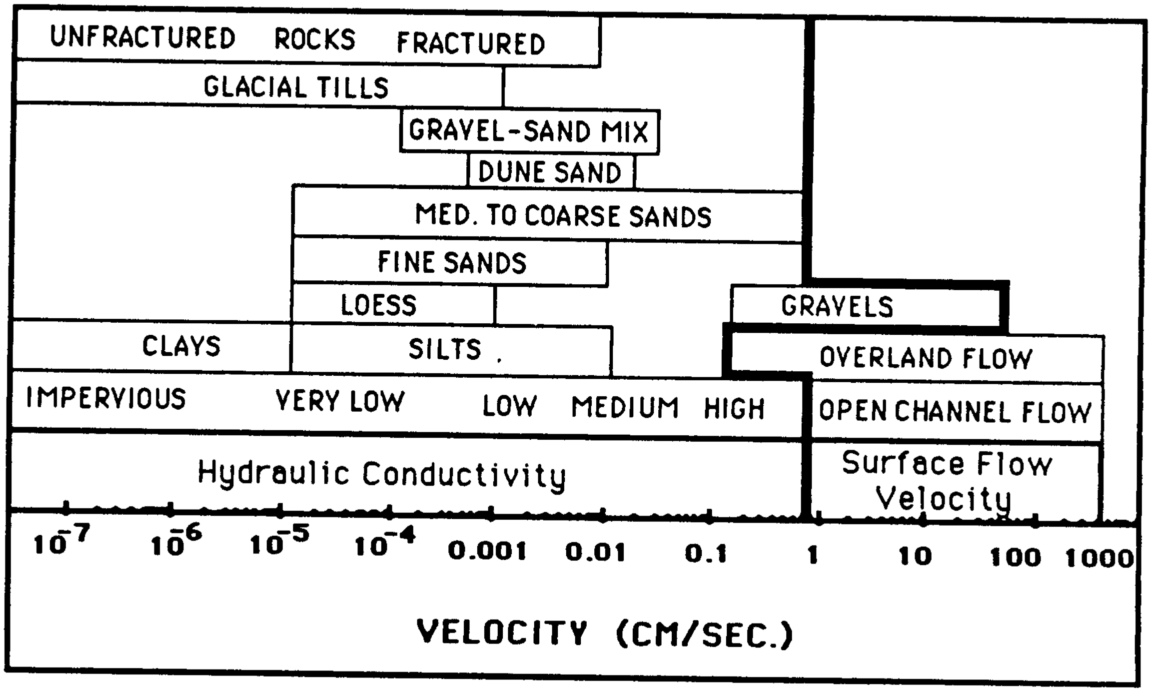


Figure 2.4 Typical surface water flow velocities and subsurface hydraulic conductivity for various materials (After Freeze and Cherry, 1979; U.S. SCS, 1975; Dunne et al, 1975; and Peck, et al., 1974).

2.9 SUMMARY

Processes, field indicators of processes, and effects on processes from land use change have been described together with ranges in relevant rate limiting fluxes and schemes for estimating quantitatively particular process parameters. The processes can be categorized as land form, vegetal, and channel. The capacity of the channel system at various locations becomes the limiting consideration for urbanization hydrologic impact mitigation. A systematic scheme for determining hydrologic process zones is given in Chapter 3.

CHAPTER 3 PROCEDURES TO DETERMINE CATCHMENT HYDROLOGIC PROCESSES

3.1 INTRODUCTION

The following sections outline steps needed to characterize pre- and post-development catchment features and hydrologic processes. Basin configuration, materials, and hydrologic processes (typically water storage and runoff) can be identified and inferred from site features by use of aerial photographs, maps, and field interpretation. Hydrologic processes estimated from basin features can be used to estimate basin response, constrain rainfall-runoff estimates, and identify areas in need of mitigative measures.

Field investigations are necessary to identify the features associated with dominant hydrologic processes. A data base of site features is developed for natural or existing conditions and various proposed development options. The data base need be no more than a set of overlays on a base map, which show forested areas, impervious zones, seasonally saturated areas, permanent wetlands, and channels. The base map and overlays can be digitized at needed resolution levels for use in an interactive database or geographic information system (GIS).

3.2 INFORMATION SOURCES

For the small scale catchments where change is to take place the following information is likely to be available.

1. a. Ungauged Catchments: Hourly rainfall, and possibly pan evaporation data, within about 20 miles.

   b. Gauged Catchments: at best one raingauge and one streamgauge that has been operated for a short time as well as the data in 1a.
2. Stereo aerial photographs from about 1935.
3. 7 1/2 minute quadrangle topographic maps with 25 feet contour intervals.
4. Broad scale county or U.S. Dept. of Agriculture, Soil Conservation Service, soil survey maps.
5. Broad scale vegetation cover maps.
6. County maps of land surface -- contour interval five feet, not available generally in Geographic Information System (GIS) format.
7. Approximate delineation of wetland areas.
8. Approximate mapping of fish habitat zones.
9. Broad scale geological maps.

10. Miscellaneous non-stereo photographs of parts of the catchment.

11. Maps of planned (or existing) municipal infrastructure utilities.

3.3 BASIN CHARACTERIZATION

Field data should be gathered for the catchment within which change is anticipated and those areas that can affect or be effected by that change. In general, the study area will include all of the subbasin in which the project is proposed. Inclusion of nearby basins may be needed for comparative purposes. Catchments that will undergo change may be at various stages of development. Consequently our information sources and mapping details include natural and man made features.

Data Accuracy

Accuracy of measurements, such as areas of various process zones or depth of the litter layer, will vary depending on available resources, data needs, time constraints, and the size of the catchment. Some data can be obtained from topographic maps where contour accuracy commonly ranges from 25 to 100 feet. Aerial photographs are produced at a scale of 1:12,000 to 1:20,000. Unrectified distortions of scale, tilt, and parallax errors, along with measurement and interpretation errors, will limit accuracy to at best % 20 feet with 1:20,000 scale photographs and % 10 feet on 1:12,000 imagery (Stoker, 1977). Field mapping of hydrologic process zones, based on a limited number of field visits, involves considerable interpretation of some of the process zones, therefore, map and air photo limitations may not be the limiting factors to the accuracy of hydrologic process zone mapping. Detailed map contours are of less importance than the changes in slope, location of swales and other critical features that divide geomorphic and hydrologic zones.

Topographic Map

The topographic map provides initial orientation to the area. The boundary of the catchment of interest is estimated from this map and verified later. Estimated subbasin boundaries within the catchment should be drawn.

Base Map

A base map, including the catchment drawn to an appropriate scale, will be used for compiling field data and for representation of each process zone. On large catchments, to show relevant detail, subbasins may need to be drawn separately at different scales. If a computer data base is created the size of the base map is controlled by the data input scheme. Base maps include: changes in slope, surface water features, swales, slope failures, subbasin boundaries, storm water systems, drain fields, roads, and other existing developments.

Drainage Network

A drainage network map is prepared by drawing the surface water features of the catchment on a copy of the base map . This includes all lakes, streams, creeks, ditches, wetlands, swales, and storm drains. Topographic maps, stereo aerial photographs, field notes, and proposed development drawings are used in preparing drainage nets. Depending on objectives, separate drainage nets for the wet, average, and dry season, may be needed. For example, if base flow in the dry season is a critical concern for habitat, a dry and wet season drainage net for pre-development conditions will be needed. A separate drainage net is drawn for the pre-development condition and each development option that is being considered.

Subbasin Boundaries

Verify basin boundaries estimated from topographic maps for the existing catchment conditions using stereo photo interpretation and follow-up field observations. The subbasin boundaries prepared for each proposed development option and identified or estimated hydrologic and geomorphic process zones are superimposed on the subbasin maps.

Cross-Sections

Cross-sections of soil profiles, ground surface and subsurface longitudinal profiles, channel longitudinal profiles, and channel transect features are measured in the field and drawn. Soil profiles are drawn for each representative area of the catchment. Profiles are divided into sections having similar characteristics. Typical thickness of soil layers, texture, moisture condition, organic content, and grain sizes are described for each unit of the soil profile.

The channel network is divided into segments based on similar channel slope, pattern, form, substrate features, and catchment area. Channel reaches determined from field observation to have features typical of most of the segment are selected as being representative of the entire segment. For each representative reach cross-sections are prepared showing low-, bankfull-, and flood-flow stages. Discharge stages are identified using flood bar heights, substrate features, height of overbank deposits, vegetation types and ages, and water or litter marks. Substrate is classified by particle size distribution for the surface pavement and subsurface material for each reach. The substrate data are used to estimate the bankfull discharge and for designating potential erosion or deposition locations.

3.4 DETERMINATION OF HYDROLOGIC PROCESS ZONES

Overlays of the relevant process zones are prepared for existing conditions and each development option being considered. For example, catchment areas with thick vegetation and forest litter could be interpreted as an infiltration process zone because quick surface runoff will not occur there. At the other extreme areas that are impervious or are estimated to have very low infiltration rates can be identified as Horton overland flow process zones because precipitation in excess of the infiltration capacity will be the dominant hydrologic response. The water flow paths for each part of the catchment are estimated from the process zone maps, typical slope profiles, and channel cross sections. Process zone and water flow path estimation involve an assessment of the topographic, vegetation, geomorphic, and geologic features.

Vegetation Zones

Vegetation can be classified into as many categories as needed. Examples might be forest, brush, and grass, or 100 to 60 percent cover, 60 to 30 percent cover and 0 to 30 percent cover. For the pre-development condition vegetation zones are determined from stereo aerial photographs and field inspection. Post-development vegetation types can be assumed based on proposed zoning and local land use practices. Vegetation zones are closely related to litter types. They both are associated with areas of higher infiltration, interception, and detention of rainfall. Because of this close association classification of vegetation and infiltration process zones can be combined.

Infiltration Zones

Zones of infiltration will vary depending on the season and duration of storms. The infiltration capacity of each representative soil profile in the catchment is classified. Classification of approximate infiltration capacity is based on surface condition, soil profile, slope, and position on the hill slope. Given the costs and difficulties of measuring infiltration rates (Hewlett and Nutter,1969), it is unlikely extensive infiltration measurements will be undertaken for each development project. The exception has been percolation tests for sanitary drain fields. Standard percolation tests give some indication of the response of the soil profile but generally do not represent the full soil profile adequately. Percolation tests conducted in the dry season will miss the relevant wet season soil response. In addition, percolation tests do not account for significant surface effects on infiltration. Therefore, only a general classification of infiltration zones will be possible. Areas of the catchment where overland flow is unlikely, due to highly porous soil, vegetation, and surface conditions such as a deep litter, are classified as infiltration zones. This classification is broken down further to areas that are likely to contribute to subsurface stormflow and those that would only contribute to long term baseflow.

Estimating the path of infiltrated water is complicated by the multiple paths it can take. Some will evaporate, much of it will percolate to the first low permeability layer where a portion will flow laterally and some will infiltrate into cracks and macro-pores to the regional ground water table. Where these waters will emerge and the travel time along each of these flow paths is difficult to estimate without extensive geochemical tracer investigations. Base flow discharge can be estimated when subsurface flow is restricted by a shallow nearly impervious unit, such as bedrock or compact till, the geometries of the surface and the subsurface impervious layer are known, and soil porosity, field capacity, and hydraulic conductivity are known (Dunne, 1975; Iida, 1984). The effort and accuracy of modeling multiple subsurface flow paths for the full range of geometries encountered in most catchments is needed principally at locations where road cuts may intercept a substantial quantity of slow subsurface flow important to aquatic habitat maintenance.

Impervious Zones

Areas where infiltration capacity is limited are mapped for existing and post-development options. Two categories are considered. The first category is for quick response impervious zones where infiltration capacity is essentially zero and there is only minor depression storage, including compacted earth along road sides and in playgrounds, as well as roads, parking lots, roofs, and bedrock. The second category includes delayed response impervious zones where infiltration capacity is commonly exceeded in storms but there is some delay before surface runoff occurs. Included in this category would be many lawns, pastures, and impervious areas with considerable depression storage. Impervious zones connected to channels and drains, must be distinguished from areas that drain onto adjacent pervious land surfaces where water can infiltrate.

Effective Storage

Field studies of the soil strata and measurements or estimates of the potential storage in the vegetation, depressions, litter layer and soil layers are combined to estimate the amount and areal distribution of effective storage in the catchment. This is an important process for most areas and is one of the aspects of basin dynamics that has received little attention in existing methods. Estimates of lost effective water storage need to be used in sizing retention or detention ponds if replacement of lost storage from land use changes is to be achieved.

Stormflow Response Time

The hydrologic process zones are classified in terms of zones with quick rainfall-runoff response and those with slow stormflow response. Quick stormflow is generated from areas of the catchment where overland flow is generated; slow stormflow response is generated from areas of the catchment where runoff follows subsurface flowpaths or long and slow surface flowpaths. Flow velocities of surface and subsurface water differ by orders of magnitude as indicated in Figure 2.4.

Subsurface flow contributes to quick stormflow when shallow subsurface water arrives from areas near to surface channels and from piping which involves longer distance, high, subsurface flow velocities through macro-pores. Catchments where throughflow of shallow subsurface water is a significant process experience flood peaks from overland flow and a delayed peak from throughflow.

3.5 INDICES OF PRE- AND POST-DEVELOPMENT HYDROLOGIC PROCESS ZONES

Before any mitigative measures are considered, comparison of pre-and post-development catchment features identifies locations where critical mitigative control decisions are required. Graphs that show the cumulative area of each process zone for both pre- and post-development situations as a function of position provide one measure of the influence of change. Starting at the catchment boundary in the subbasin of interest, proceed to the head (furthest upstream portion) of the main channel, keeping track of the areas of the relevant process zones along the way. The distance from the catchment boundary along this path is defined here as the Watershed Distance (WSD), with WSD 0.0 being at the catchment boundary and the basin outlet being the largest WSD value. Plotting the resulting tables of WSD vs. process zone area as cumulative curves (see Chapter 4 for examples) or as percent change identifies locations where impacts will occur. The same process is repeated for tributaries.

Graphical presentation of the drainage density (channel length per unit area) vs. WSD for pre- and post-development conditions qualitatively indicates areas that will experience less water detention and storage, increased storm runoff, and reduced baseflows. WSD vs. infiltration area for pre- and post-development conditions shows downstream areas where altered runoff and baseflows occurs. Comparison of the percentage change in area producing quick storm response vs. WSD and the estimated bankfull discharge vs. WSD identifies locations where the existing channel will be impacted by a changed flow regime.

Many county and city governments require retention structures to maintain stream flows at or below pre-development or existing levels. If the purpose is to reclaim lost habitat, the original natural state of the catchment should be the basis of the pre-conditions. This can be estimated with historical aerial photographs and maps, and field investigation of erosional and depositional features. If the goal is to maintain the existing conditions prior to a proposed change, field data for current conditions are used.

A map of effective storage, created by combining the estimated storage potential from the dominant storage elements on the catchment, can be summarized in a plot of WSD vs. maximum potential water storage. The difference between the pre- and post-development effective storage curves indicates the magnitude of storage needed to be replaced if pre-storm response is to be approximated.

Constraints on Mitigative Measures

Constraints on release location and rates from retention facilities should be based on the WSD vs. channel-full capacity curves. Standard engineering practice for down-stream analysis is to calculate if the channel capacity is adequate to carry additional flow. This does not address the potential response of the channel to a changed flow regime. An extreme, but all too common example, is the introduction of surface flow into areas where only subsurface flow and perhaps sheet flow previously existed. Such areas require infiltration systems or construction of adequate channels or pipes to avoid potential rapid or catastrophic incision of new drainage routes.

Effects of altered flow regime on channel erosion, deposition, bank stability, and habitat is assessed by comparing existing channel conditions with the estimated increase in flow rate and potential channel changes. The return frequency, duration, and magnitude of flood peaks should remain comparable to a natural or baseline level. When the intent is to preserve or restore habitat, peak flood frequency, duration and magnitude must not be allowed to exceed the natural flood pattern. When quick stormflow is detained in ponds it is common to release it at the maximum allowable release rate. The peak release rate is maintained near the estimated pre-development level but the duration is greatly extended. If the allowable release rate is above the threshold of significant sediment motion, channel scour, transport, and deposition of sediment will be active far longer than in the pre-development case, thus channel pattern and form will be changed. The long duration release of the stored flood flow should be maintained at a discharge rate that does not cause significant sediment erosion and transport. The sediment motion equations in Appendix B can be used to estimate a threshold discharge above which significant sediment motion will occur. Discharges for each channel segment that minimize channel morphology impacts can be estimated using these equations.

3.6 PROJECT IMPACT AND MITIGATION ZONES

Impact zones are those areas that will change as a result of development within the catchment. They include both the development site and downstream areas that will experience hydrologic changes because of the project. The pre- and post-project process zone maps help determine the location and types of hydrologic impacts. For example, diversion of subsurface flow to surface flow and discharging it into a swale that previously experienced only subsurface flow will be classified as an impact zone.

The limited hydrologic analysis which usually accompanies individual building permits is not adequate to address basin-wide cumulative effects. Cumulative effects to main channels need to be assessed based on proposed zoning densities.

Impact zones are used to identify potential project mitigation options; design safety factors must be adjusted to reflect how well catchment dynamics have been quantified. For example, if the estimated threshold discharge for significant sediment transport is poorly defined the allowable release rate should be set at a lower rate. Project impacts may be categorized simply as: high, moderate, or low, if extensive data have not been collected for the catchment. When potential impacts from a project are considered high more restrictive designs must be used than for projects considered to have little potential impact. Considerable research is needed to determine appropriate safety factors.

3.7 AUTOMATION TOOLS

Overlays of basin attributes collected from field surveys, maps, and stereo aerial photographs are needed for analysis and presentation of catchment conditions. For small projects, direct use of field notes and a few sketches and overlays may be adequate. Use of computer graphics and design systems can be helpful for large or complex catchments requiring numerous overlays. Because of the rapid development of systems for observing, recording, and digitizing data, we mention here broad features rather than specific systems.

Stereo aerial photographs provide valuable historical and current information on catchments. Aerial photograph interpretation is assisted by interfacing the drawing of stereo image overlays with a computer drawing and graphics program. Input is handled in several ways depending on available equipment. Available methods include digitizing tablets, scanners, and video cameras. Trials with each of these methods indicate that video camera input with a digitizing graphics board is the least time consuming and most adaptable to the variety of scales and graphic media used in hydrologic and geomorphic studies. Video images of field features, maps or photographs can be digitized directly in seconds (Weissman, 1986).

Image processing adjusts contrasts, enhances or removes image features, and provides intensity levels for each digital image pixel that can be utilized as arrays of catchment features. Active cursors, now available in many commercially available graphical software packages, are used to draw overlays directly from the video images. The introduction of area, length, centroid, and area moment calculations for polygons and irregular lines is now being added into drawing programs for advanced personal computers and work stations. This upgrades a computer into a planimeter system. Planimetering of lengths and areas is done on the digitized images and data stored in files for use in graphics programs. These systems make image processing easier than drafting and in some systems link image processing to the image data collection.

Low level aerial and ground video or photographic images provide a convenient way to measure and analyze catchment terrain. A photographic or video camera mounted on a helicopter, truck tower, or hand held, can record, for example, the entire length of a rugged mountain stream in a matter of minutes. Field observations and placement of scale markers prior to the photo run provides essential ground truth information for the area. Stop-action video images allow assessment of geomorphic, physical, and habitat characteristics at selected locations along the route (Barclay, 1987).

3.8 SUMMARY OF METHOD FOR DETERMINING HYDROLOGIC PROCESS ZONES

The following 7 steps are needed for mapping hydrologic process zones in both gaged and ungaged catchments:

Pre-development assessment

1. Identify existing catchment features (Section 3.3).
    - A. Obtain available topographic, soil, geologic, and land use maps and at least one set of stereo aerial photographs for the catchment.
    - B. Combine information from each source in Step 1.A. onto one preliminary base map. The base map includes major breaks in slope, existing and abandoned roads, creek channels, vegetation boundaries, fence lines, and existing structures. The base map or maps are prepared at a scale sufficient to portray site features in a clear and readable manner (minimum of 1 inch = 2000 feet).
2. Estimate the location and extent of dominant hydrologic process zones (Section 3.4).
    - A. Prepare a preliminary overlay map for the base map showing estimated hydrologic process zones based on interpretation of the information available at Step 1.
    - B. Visit the catchment, add to and modify the base map geographic, hydrologic, and geomorphic information. Classify vegetation, forest litter, and soil materials. Measure cross sections and sample substrate materials of channels. Identify and map catchment features such as swales, steep slopes, wetlands, and landslides.
    - C. Prepare a final overlay map of the extent, locations, and type of hydrologic process zones. Include areas of infiltration, detention storage, return flow, Horton and saturated overland flow, and open channel flow.

Post-Development Assessment

3. Select proposed project configuration
4. Prepare a post-development hydrologic process zone map
    - A. Identify areas and types of topographic, vegetation, soils, and channel modifications that project development will create.

B. Based on the proposed post-development site conditions draw an overlay map of estimated hydrologic process zones. Include areas of infiltration, detention storage, return flow, Horton and saturated overland flow, and open channel flow.

Comparison of Pre- and Post-Development Process Zones

5. Compare pre- and post-development catchment conditions in summary tables, charts, and maps (Section 3.5) including:

    A. Watershed distance (WSD) vs. pre- and post-development drainage density.

    B. WSD vs. lost detention storage.

    C. Overlay map of incremental change in quick storm response area.

    D. Map of channels associated with changed quick storm response area.

    E. WSD vs. pre- and post-development quick storm response area

    F. Basin lag times at potential channel impact locations using actual water flow paths.

    G. Site processes and relative influence project development will have.

6. Define potential impact zones (Section 3.5). Define areas of the catchment where potential impacts would occur. Include areas of lost water detention storage, surface landslide potential, sediment erosion potential, and sediment deposition potential.

7. Propose mitigative measures

CHAPTER 4 EXAMPLE BASIN CHARACTERIZATION

4.1 INTRODUCTION

An application of the method of hydrologic assessment developed in Chapter 3 is presented. The catchment selected for this example has characteristics typical of many developing areas in Western Washington. There is no rain or stream gage in the catchment, therefore, stormwater mitigation design must rely on information gathered from the site. A nearby rain gage and a recently recorded approximately 25 year return period 24-hour duration rainfall provide some additional information for use in quantitative calculation of catchment hydrologic response.

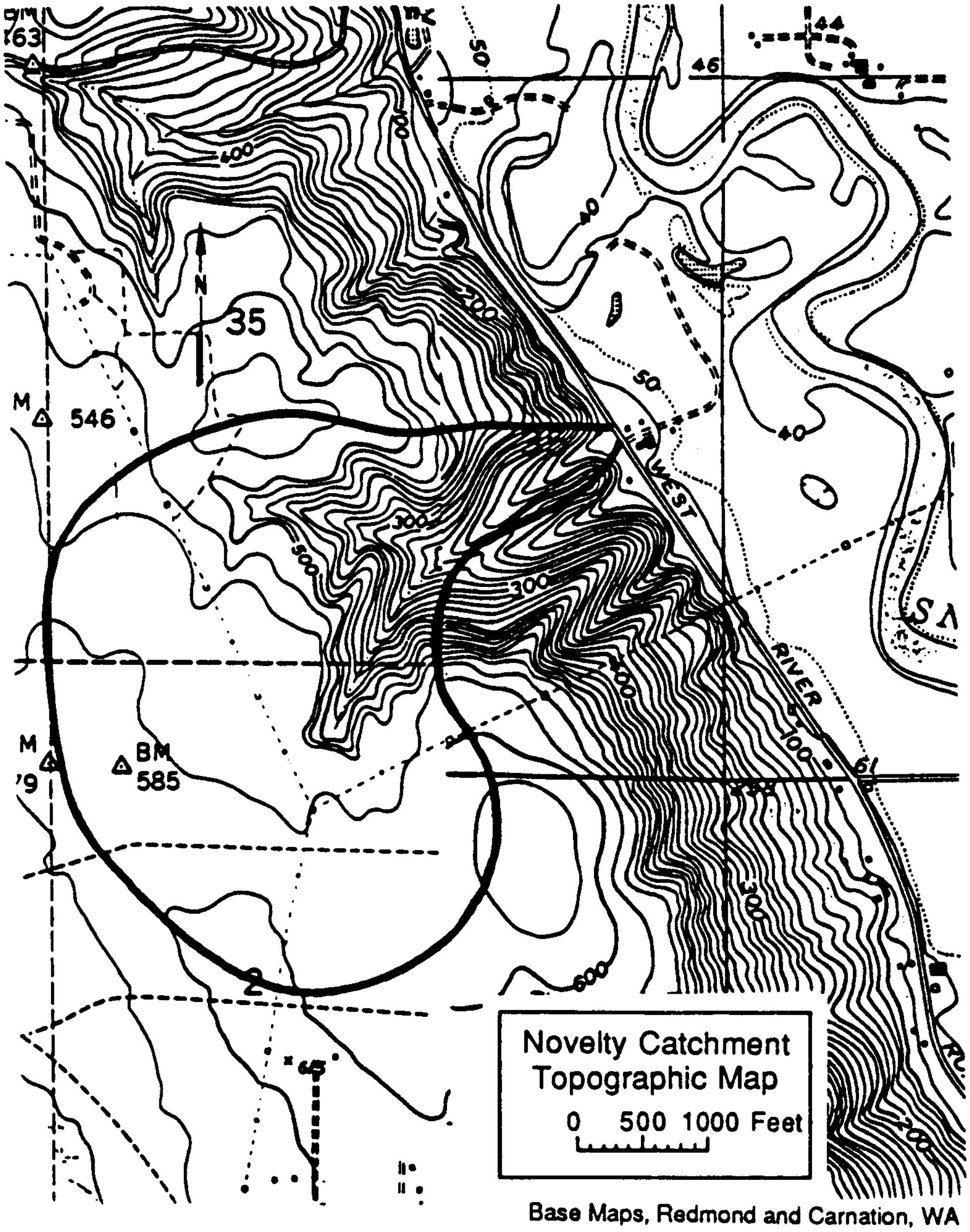
4.2 CATCHMENT LOCATION

The approximately one-half square mile catchment (1.3 km^2) is located 3.7 miles (6 kilometers) southwest of Duvall, Washington in Sections 35 and 36, T26N, R6E, and Section 2, T25N, R6E as shown in Figure 4.1. The catchment is called "Novelty" hereafter because of its proximity to the town of Novelty. The unnamed outlet creek crosses West Snoqualmie Valley Road N.E., 0.9 miles south of Novelty Hill Road shown at the extreme top of Figure 4.1. The catchment contains a plateau region between elevation 500 and 600 feet and falls steeply towards the east to the Snoqualmie Valley flood plain. Part of the Snoqualmie River is shown in the northwest quadrant of Figure 4.1. Access to the upper Basin is from Novelty Hill Road. The study area includes the entire drainage, with emphasis being placed on comparison of modified areas to those that are relatively undisturbed.

4.3 DATA SOURCES FOR HYDROLOGIC CHARACTERIZATION OF THE NOVELTY CATCHMENT

Hydrologic characterization of the Novelty catchment is based on analysis of field observations, topographic maps, and aerial photographs. Of these the field observations and stereo aerial photographs provided the most detailed information on hydrologic process zones.

The Novelty base map was prepared from 1985 aerial photographs with limited corrections for the scale differences between the plateau and Snoqualmie River Valley (elevation difference approximately 500 ft). The main and tributary ravines were mapped from stereo photographs using a mirror stereoscope. Portions of these photographs have been reproduced, with some loss of image quality and range of view, for use with a pocket stereoscope (Figures 4.2 and 4.3). Only the major topographic features are apparent in the aerial photographs because of the dense catchment vegetation. Field studies were preceded by review of maps and aerial photographs available for the site. Site access and accessibility to various parts of the catchment were identified from stereo photos, saving considerable field time that could be wasted in impassable or impractical routes across the catchment. Preliminary work with the maps and aerial photographs permitted identification of the basic terrain units including major ravines, some of the minor swales, abandoned but still passable logging grades, and vegetation zones. Field data gathering was greatly simplified because base maps with identifiable features were prepared in advance. These maps provided reference locations for terrain features as they were encountered in the field.



Base Maps, Redmond and Carnation, WA

Figure 4.1 Novelty catchment topographic map.

The dominant catchment hydrologic process zones were estimated based on data gathered during five field visits, and interpretation of the 1965 and 1985 aerial photographs (Figure 4.2 and Figure 4.3). The second-growth forest conditions prior to 1978 are used here as the basis for hydrologic comparison. The extent of forest, wetlands, and natural drainages at that time were estimated from historical photographs and field studies of undisturbed areas.

Field work began with a reconnaissance walk throughout the catchment to observe major drainage features. Features previously mapped from aerial photographs were confirmed and those too small or obscured in the air photos were noted. It was at this stage that two wetland areas (not identifiable from the air photos) were discovered. Notes were made of the channel gradients, floodway dimensions, channel substrate, bank stability, and bankfull geometry. Ditch geometry and flow directions along with culvert slopes and sizes were established. Zones along the channels that were low or showed signs of saturation based on vegetation, seeps or wet conditions were noted so the area of quick runoff response could be calculated. Estimated subbasin boundaries were confirmed; corrections and additional details were sketched on the base map.

Subbasin boundaries and the overall catchment boundary were difficult to identify on the flat thickly vegetated plateau. The first estimate of total catchment area, based on the topographic maps, was between 400 and 500 acres. This value was refined to between 280 and 320 acres based on the stereo aerial photographs and field visits. Road cuts and stream channels were convenient places to observe soil units. Once the basic geomorphic features of the site had been mapped more detailed data on the ravine channels and forest floor litter were gathered to provide estimates of water channel capacities and detention.

4.4 REGIONAL SETTING

The Snoqualmie River meanders through a glacially modified valley in northeast King County, Washington. Forested slopes along the valley edge lead up to a rolling upland plateau that is typical of many areas to be developed in the Puget Sound area. Valley slopes consist of glacial and proglacial deposits of outwash, till, fine-grain river flood deposits, and lake sediments (Figure 4.4). The upland edges are dissected by small post-glacial first to third-order creeks that are eroding into the glacial deposits of the plateau.

The entire area has been logged, probably around the beginning of this century, and now contains an extensive cover of second-growth Douglas Fir (*Pseudotsuga menziesii*), Alder (*Alnus rubra*), Cottonwood (*Populus trichocarpa*), Western Red Cedar (*Thuja plicata*), Big Leaf Maple (*Acer macrophyllum*), and Vine Maple (*Acer circinatum*). The basin has a network of old logging grades. Two major power lines cross the upper catchment. Starting in about 1978, portions of the catchment were cleared for low-density housing. In the last decade the uplands have experienced second growth logging, new logging roads, several miles of improved roads have been built, and a number of 5-acre home sites have been cleared. At the end of 1987 the majority of the area was covered with second growth forest.

4.5 GENERAL GEOLOGY

The catchment can be divided into three general zones: a gently rolling upland plateau, steep ravines, and an alluvial fan that has formed over the Snoqualmie River floodplain. Starting from the

Figure 4.2a Stereophotographs of Novelty catchment taken July 6, 1965. The channel and ravine areas is left of center in the middle photo large plateau area is to the right where the photo scale is approximately 1:10,000. Photo identification: left K-SN-65 25A-62, center K-SN-65 25A-61, right K-SN-65 25A-60.

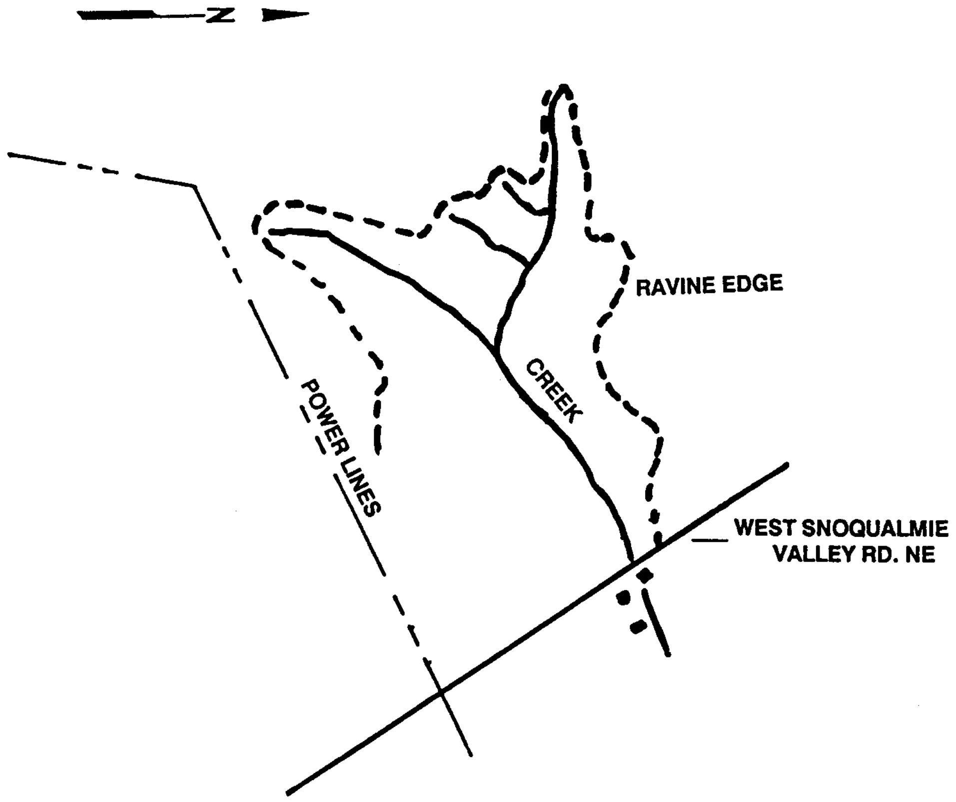


Figure 4.2b Example of catchment features that can be identified from stereo examination of Figure 4.2(a).

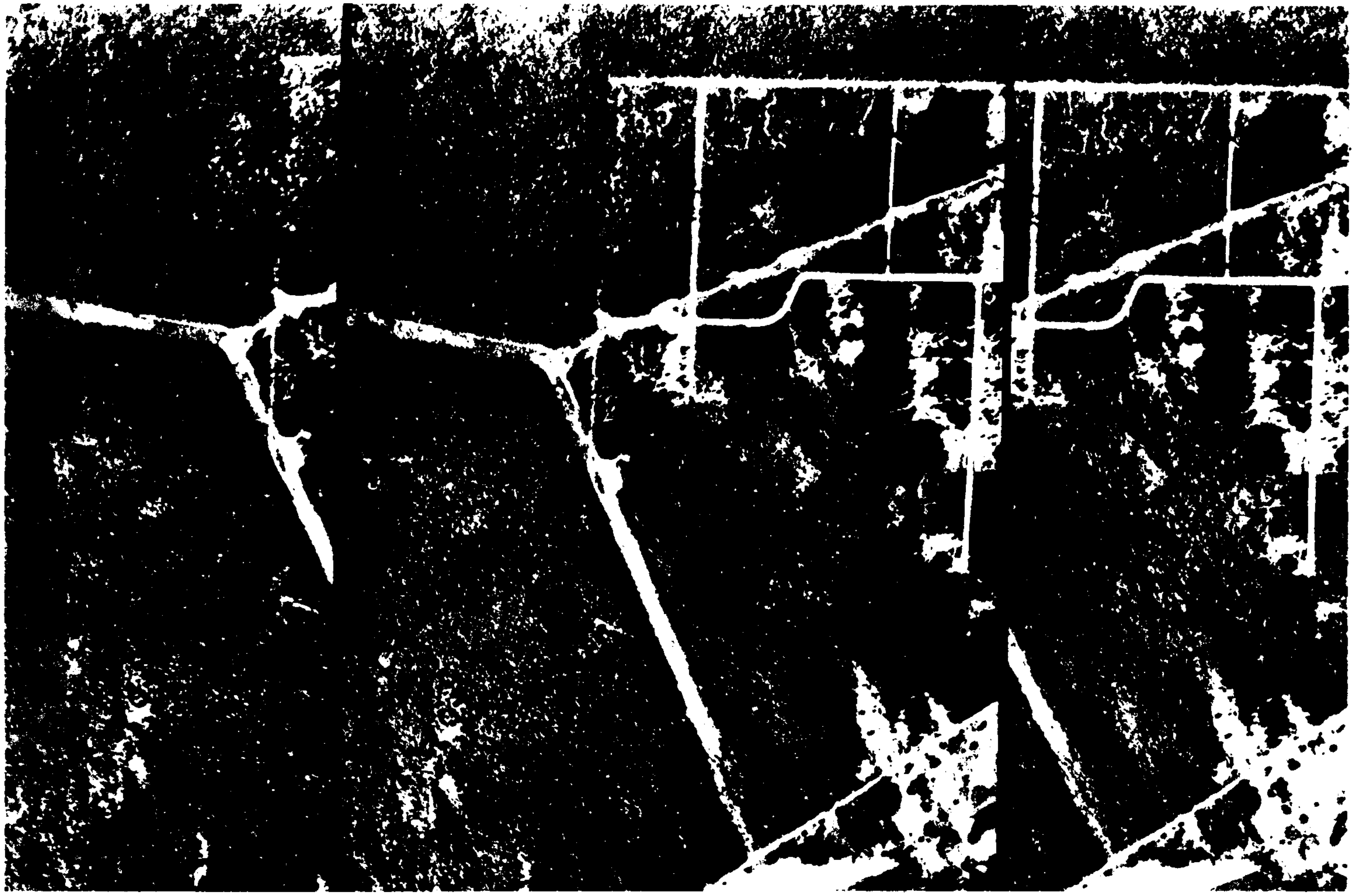


Figure 4.3a Stereophotograph of Novelty catchment taken July 3, 1985. The photo scales are the same as Figure 4.2(a). Photo identification: left SP-85 26-071-235 7-3-85, center SP-85 26-071-234 7-3-85, right SP-85 26-071-233 7-3-85.

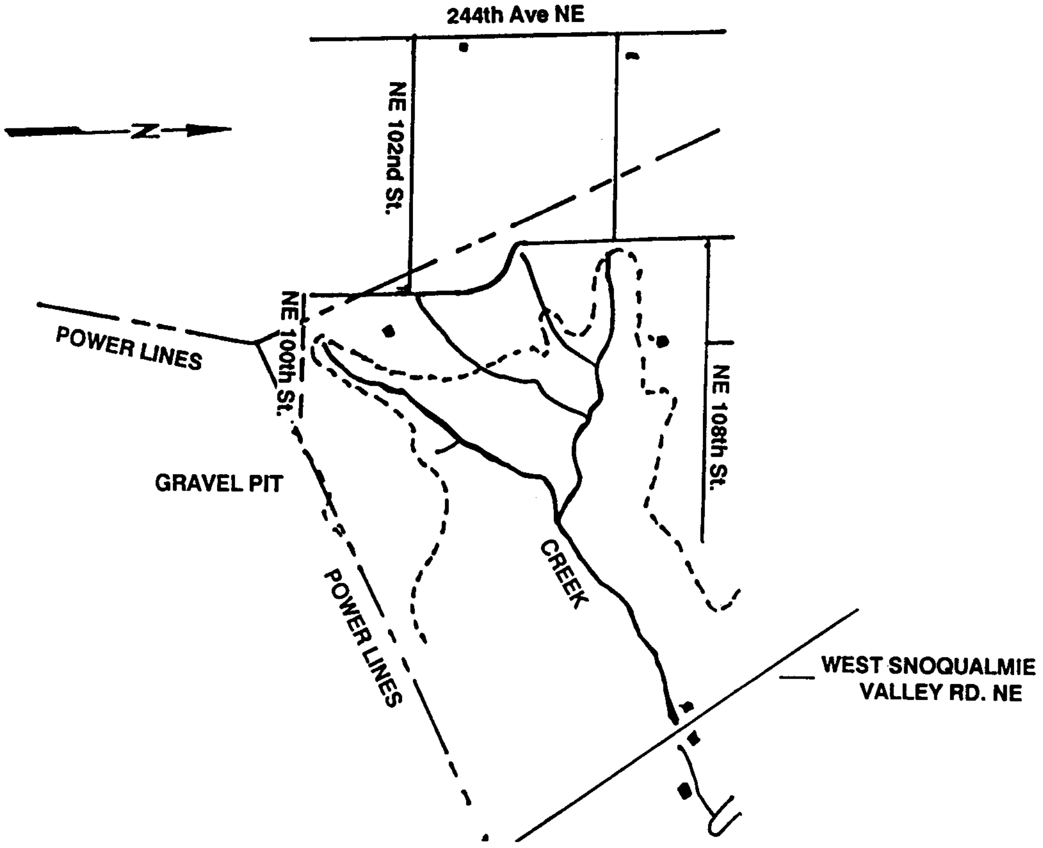


Figure 4.3b Catchment features identified from stereo examination of Figure 4.3b. Note the extension of channels from those identified in Figure 4.2b.

plateau (Figure 4.4) at between 500 and 600 feet elevation (above mean sea level), small creeks expose a glacial sequence of till over an advance outwash, with fine-grained overbank and lake sediments at the bottom (Booth, 1984). In some areas a thin loose recessional outwash overlies this sequence. In normal application of the analysis method a general section similar to Figure 4.4 may not be available from inspection of channel banks or excavated areas.

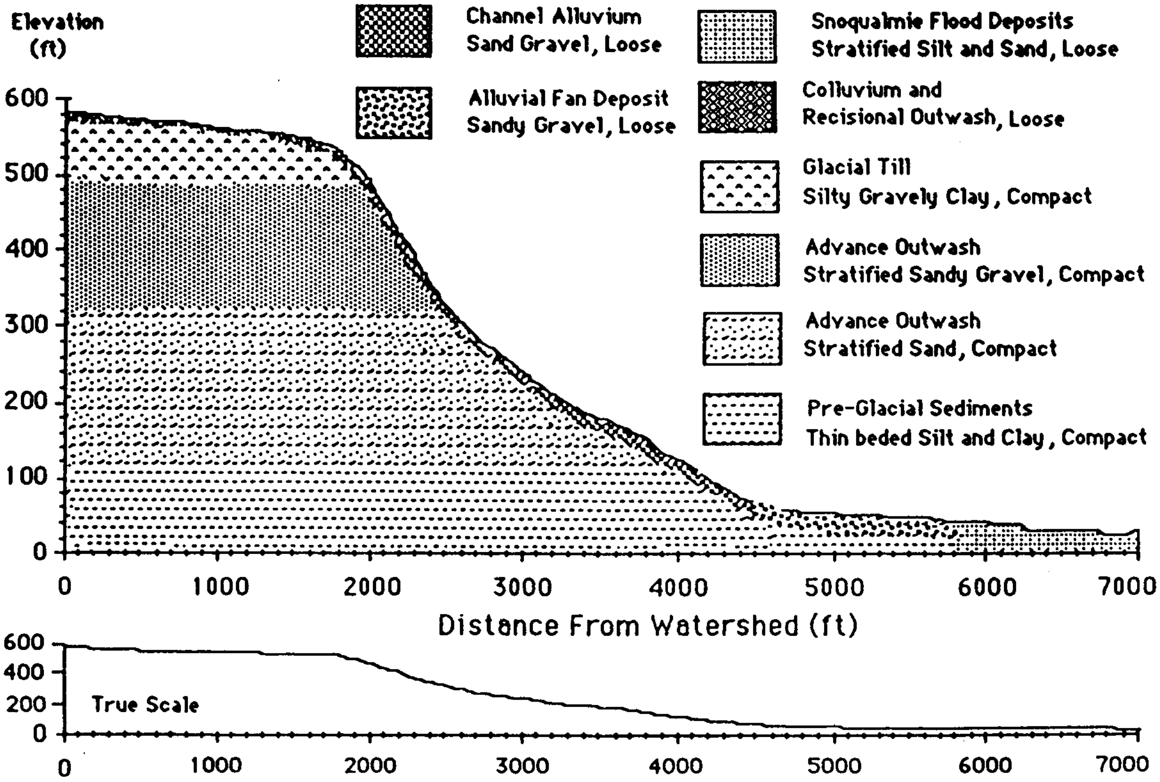


Figure 4.4 Catchment longitudinal profile along the main catchment channel (Channel A in Figure 4.8a) and generalized stratigraphic cross section.

4.6 PRECIPITATION

Average annual precipitation is between 46 and 51 inches based on the Duvall and Carnation weather station records from 1931 to 1954 and 1941 to 1961, respectively (Cooperative Extension Service, 1968). The Duvall gage is 5.5 miles (9 km) northeast of the catchment at an elevation of 814 feet, which is 200 feet above the upper portion of the study catchment. The Carnation gage is 0.6 miles (1 km) southeast at an elevation of 50 feet above mean sea level. Average, greatest, and least monthly precipitation data are shown in Figure 4.5. Average monthly snowfall is shown in Figure 4.6. The greatest daily precipitation for the 23 years of record at the Duvall station (Figure 4.7) was 2.6 inches (6.6 cm). During the course of this investigation a large, infrequent storm (January 18, 1986) deposited 3.2 inches over a 24 hour period at the Carnation gauge. The catchment was wet when the storm arrived; 3.9 inches of rain had been recorded at Carnation in the preceding 18 days. The 24 hour

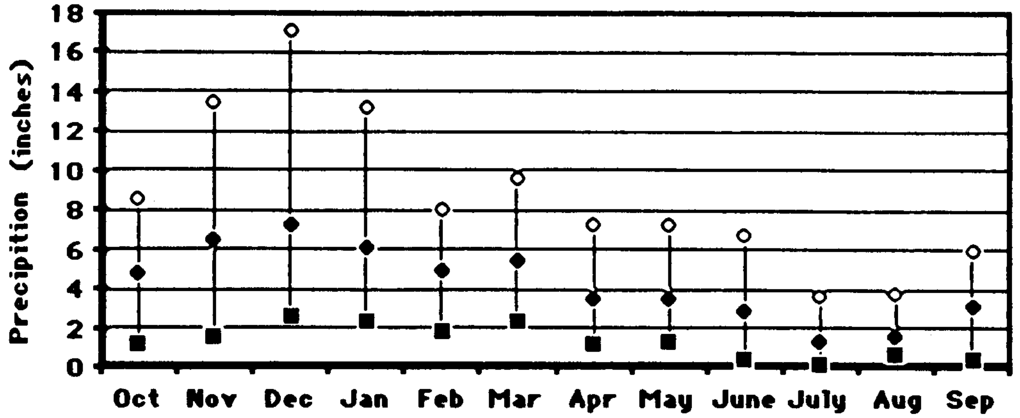


Figure 4.5 Average, greatest, and least monthly precipitation at the Duvall, Washington, 3NE weather station from 1931 to 1954. The station is located 5.5 miles (9 kilometers) northeast of the catchment at an elevation of 814 feet, which is 200 feet higher than the catchment plateau.

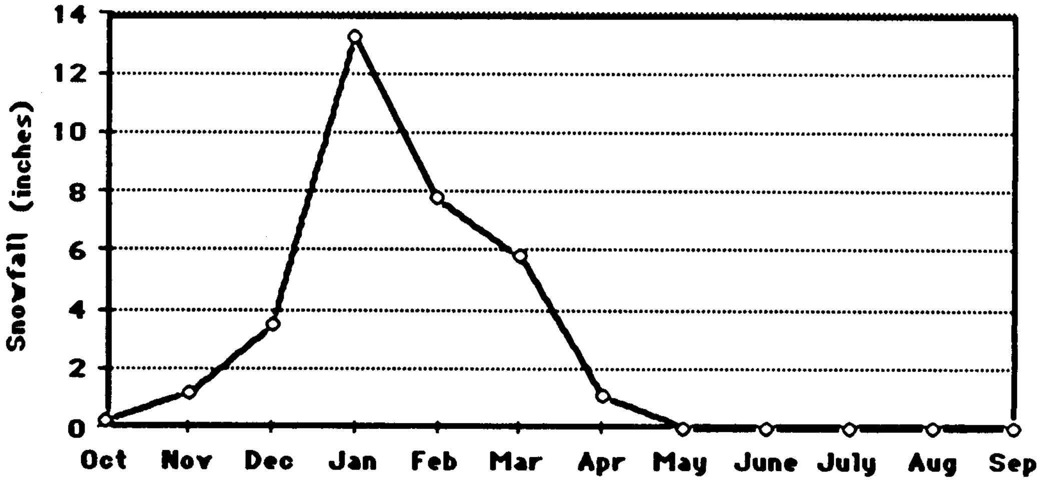


Figure 4.6 Average monthly snowfall at the Duvall, Washington 3NE station from 1931 to 1954.

rainfall total appears to have a recurrence interval on the order of once in 25 to 50 years. Reference to this storm is made in subsequent sections.

4.7 SURFACE WATER FEATURES

Upland surface-water features prior to development (Figure 4.8a) included wetlands, swales, and creeks. (Before and after development figures are shown at small scales for convenience; larger scale maps are used for all analyses). The areal extent of forest, wetlands, and natural drainages were estimated from historical aerial photographs (Figure 4.2 and 4.3) and by field observations. Several wetlands lie in northeast-trending low areas between low broad ridges of ground moraine. Soil sampling using a hand auger in the wet areas indicated 0.5 to 2 feet of loose organic-rich soil over very compact glacial till. Water depths in the wetlands vary from about 1 foot of water in the wet-season to a few inches of saturated soil at the bottom of the soil profile by the end of a dry summer.

Alders and vine maples are present throughout all but the central portions of the wet areas. Consequently, air photo identification of the full extent of the seasonal wet areas is not possible. These wet areas had not been identified on the SCS soils maps (Snyder,1973) or in the King County Wetlands Survey. They were identified by field observation during and after storms. In summer and early fall the only surface indicator of wet-season standing water is the layered texture of the leaf litter, the black soil, and presence of moisture-tolerant plants.

Plateau water is concentrated by lowlands and swales that change to ravines with open channels below the plateau edge. It is estimated, based on wet weather observations in disturbed and undisturbed catchment swales, that prior to road construction, drainage from the wet areas was predominantly by subsurface flow in broad low gradient (slopes of 1 to 2 degrees) swales. Based on the observed shallow depths to the impervious till layer, it is estimated that in larger storms drainage from the wetland swales would have saturated the full depth of the soil in the low gradient swales and flowed slowly overland amongst the litter, roots, logs, and vegetation. At the edge of the plateau the swales are more pronounced, having been modified from their original glacial form by headward erosion of

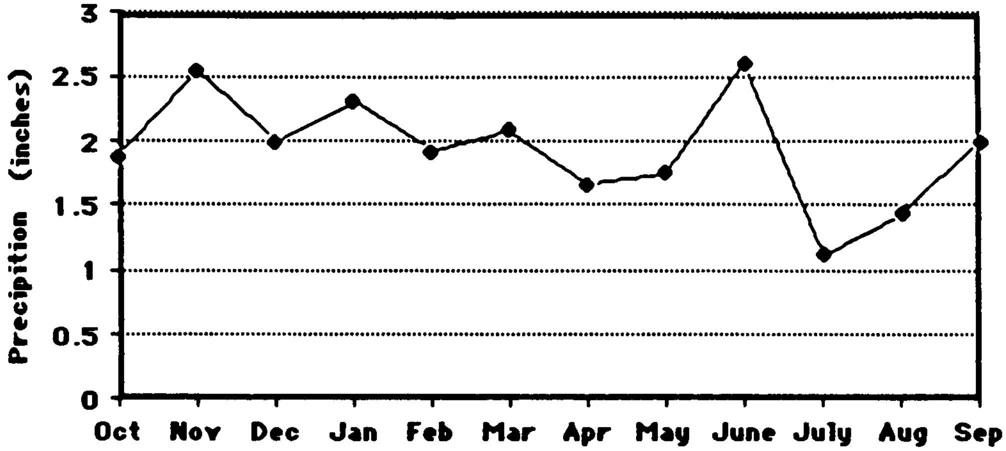


Figure 4.7 Greatest one-day rainfall depth by month at the Duvall, Washington 3NE station from 1931 to 1954.

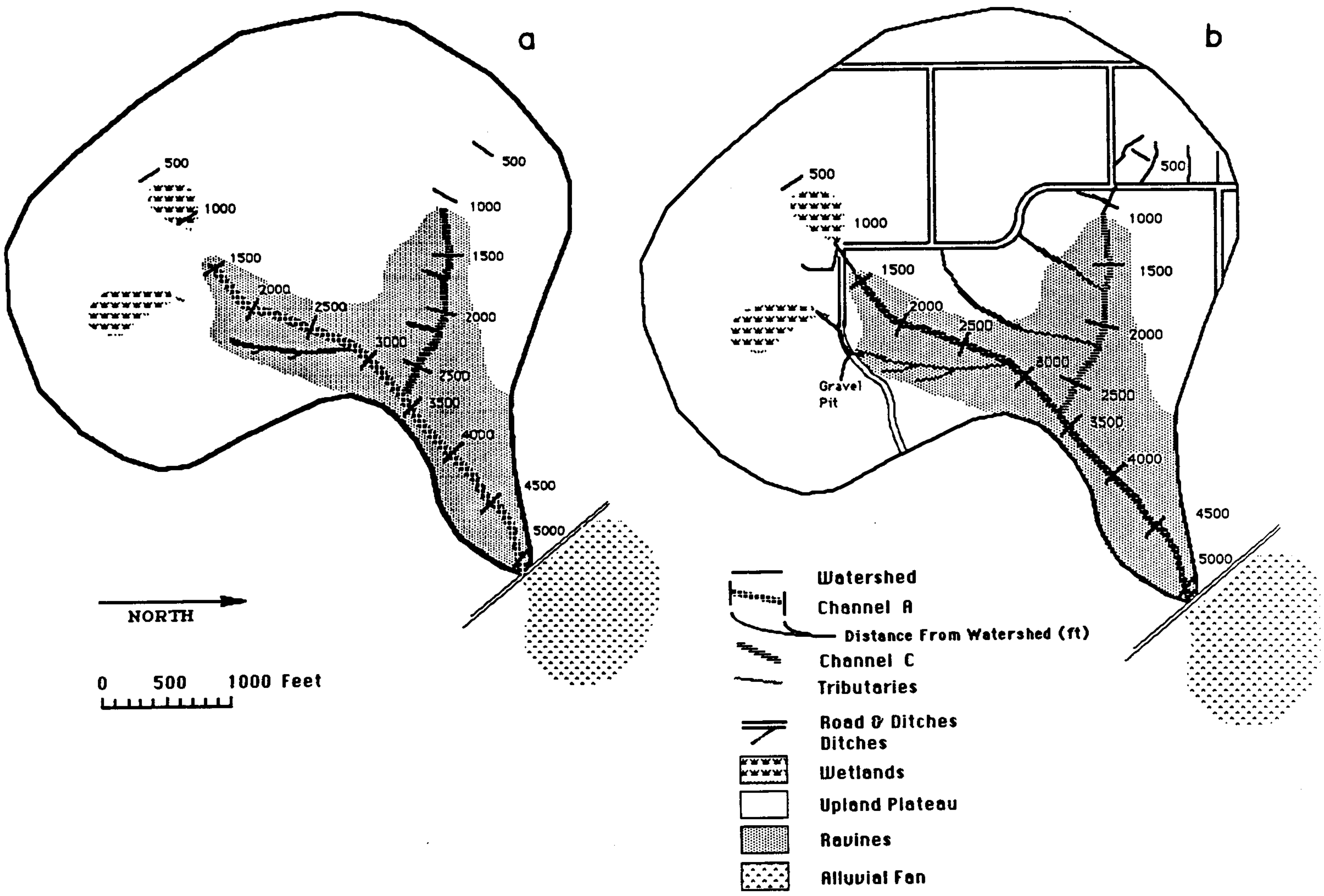


Figure 4.8 Drainage net and catchment features at watershed distance (WSD) 1200 A and C (corresponds to Points #1, station 0 + 00 A and C, respectively, King County, (1987)) (a) pre-development, (b) post-development (Autumn, 1987).

the ravines. The location of the open-channel heads varies with subbasin area and conditions. Channel heads typically have numerous springs. Headward erosion occurs by rilling of the compact soils that become exposed by piping and sloughing of the overlying loose soils along the edges of the channel.

Upland drainage enters five 1st-order channels (smallest upstream tributaries), the largest of which are labeled Channel "A" and Channel "C" in Figure 4.8a (as designated in the King County Survey (1987)). Channels A and C join as one channel with wide terraces at WSD 3427A. The creek remains a single channel until the start of the alluvial fan at WSD 4900A where the creek would, under undisturbed conditions, shift location as sediment is deposited on the low gradient alluvial fan. At present the creek has been excavated 5 to 6 feet below the gradient of the fan surface for 300 feet above the road crossing of West Snoqualmie Valley Road NE; the channel above the road culvert fills with sediment in storms causing the channel to shift and divide along and below the road in a manner typical of alluvial fans.

Upland surface water features after 1978 (Figure 4.8b), when low density residential development began, include the introduction of new 1st-order channels in the form of field drains and ditches. Road construction has increased open channel density 62 percent (Figure 4.9); ditches from the roads and pastures now direct flow into the upper ends of swales and 1st-order channels. The upper portions of all the swales, except two of the smaller ones, have been altered by road and powerline construction. Several 1st-order channel heads were filled with dirt and wood debris. Channel erosion has since removed the fill leaving behind large wood debris. Swales with drainage areas of about 20 acres and greater break into open channels near the plateau edge. Swales draining areas of 5 to 10 acres do not develop open channels until farther down the ravine slopes, typically about mid-slope.

First-order channels erode into compact to very compact proglacial gravels and sands. First-order channels and the upper part of second-order channels are constrained by narrow ravines. They have limited room to meander and have narrow, 5 to 20-feet wide flood bars. The advance glacial outwash unit coarsens upwards to a cap of cobbles to large boulders. This resistant cap creates a high-

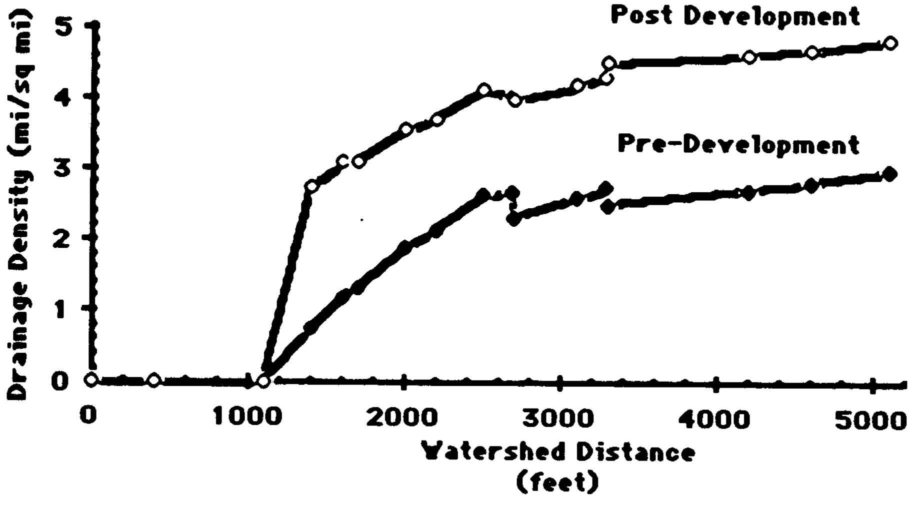


Figure 4.9 Watershed distance vs. open channel density along channel "A" (Fig. 4.8).

gradient section or waterfalls in the 1st-order channels. Channel C (King County, 1987) encounters the cap of the outwash at watershed distance 1650C (Station 4+50). The bed is paved with cobbles and boulders that originate from the outwash deposit. Below the start of the 3rd-order channel, WSD 3427A, the creek is no longer constrained in a narrow valley. Terraces are from 40 to 100 feet wide with several old terrace levels visible. Nineteen channel cross sections throughout the catchment were measured (See Appendix C in Stoker, 1988). Observation of vegetation, litter thickness, sediment deposits, and estimation of channel flood stages indicate the channels have eroded 4 to 6 feet below the channel flood plain to form paired terraces along Channel C and Channel A below the Gravel Pit tributary (WSD 2800A in Figure 4.8b).

Terrace formation reflects either of two processes, relative base level changes or changes in the discharge/sediment yield ratio imposed by the catchment (Richards, 1982). Most of the creek length has experienced terrace formation related to the new (post 1978) catchment hydrologic condition. Inspection of the channel cross section at WSD 2775A (Station 15+75A) (Figure 4.10) indicates the degree to which channel change has occurred. An old growth cedar tree stump is located approximately fifteen feet upstream from the section shown in Figure 4.10 about 20 to 25 feet from the left bank of the old channel. Its location indicates the channel must have previously been on the other side of the valley. An old channel on the opposite side from the stump, has a smaller discharge capacity than the new channel that has eroded around the old growth stump.

The estimated discharge capacity shown in Figure 4.11 for the old channel compares closely with the range of predicted flood flows by several regional regression equations for discharge in relatively undisturbed catchments (Dunne and Leopold, 1978, page 616; Cummans, et al 1975; Bodhaine, 1964).

Channel capacities within Novelty catchment were estimated using Manning's equation (Appendix B, Eq. B(4)) in conjunction with one flow measurement and measured cross section data for selected locations along Channels A and C (Figure 4.10, 4.12, and Appendix C in Stoker (1988)).

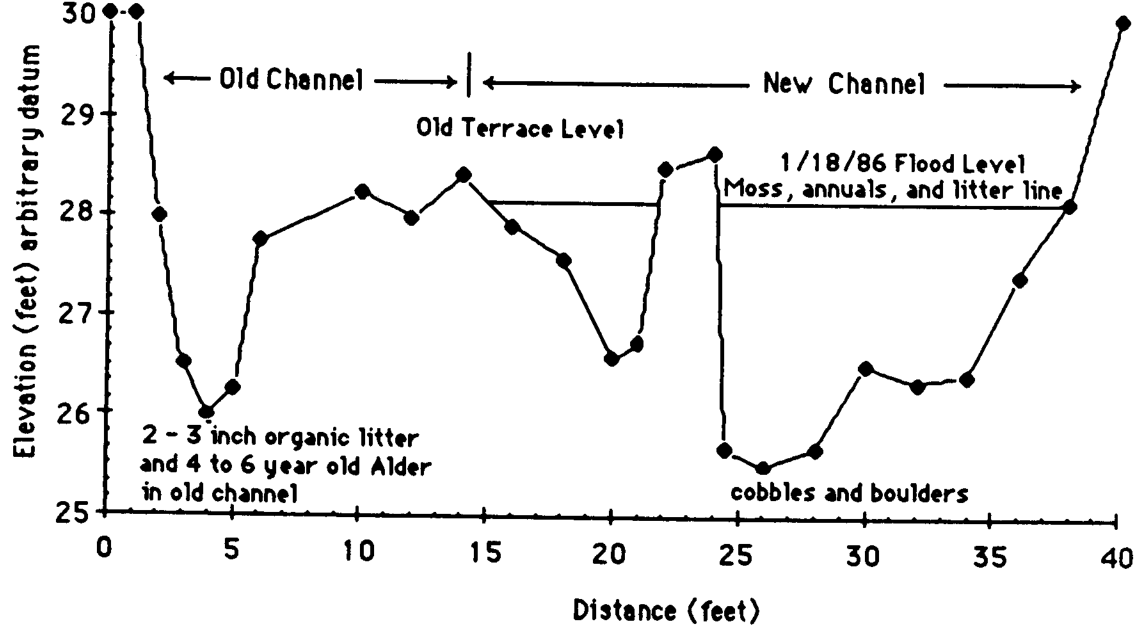


Figure 4.10 Channel cross section at station 15+75A (WSD 2775A, Fig. 4.8) in 1987.

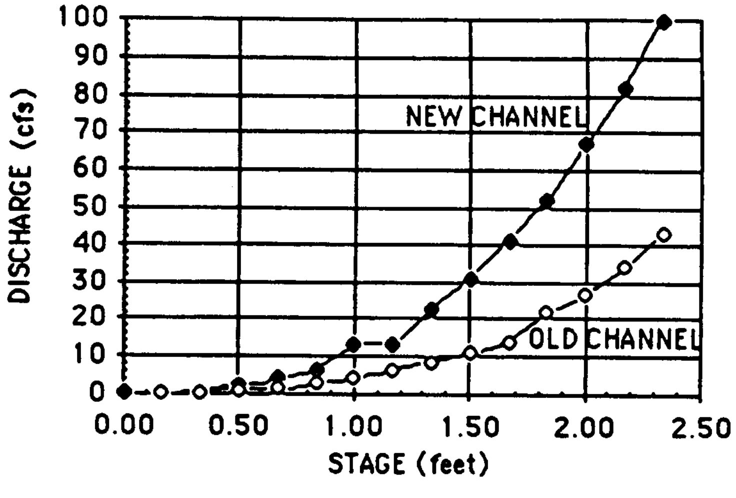


Figure 4.11 Stage discharge relationships for the old and new channels at station 15+75A (Watershed Distance 2775A) determined from Manning's Equation and Equation 2.4 to estimate the roughness coefficient.

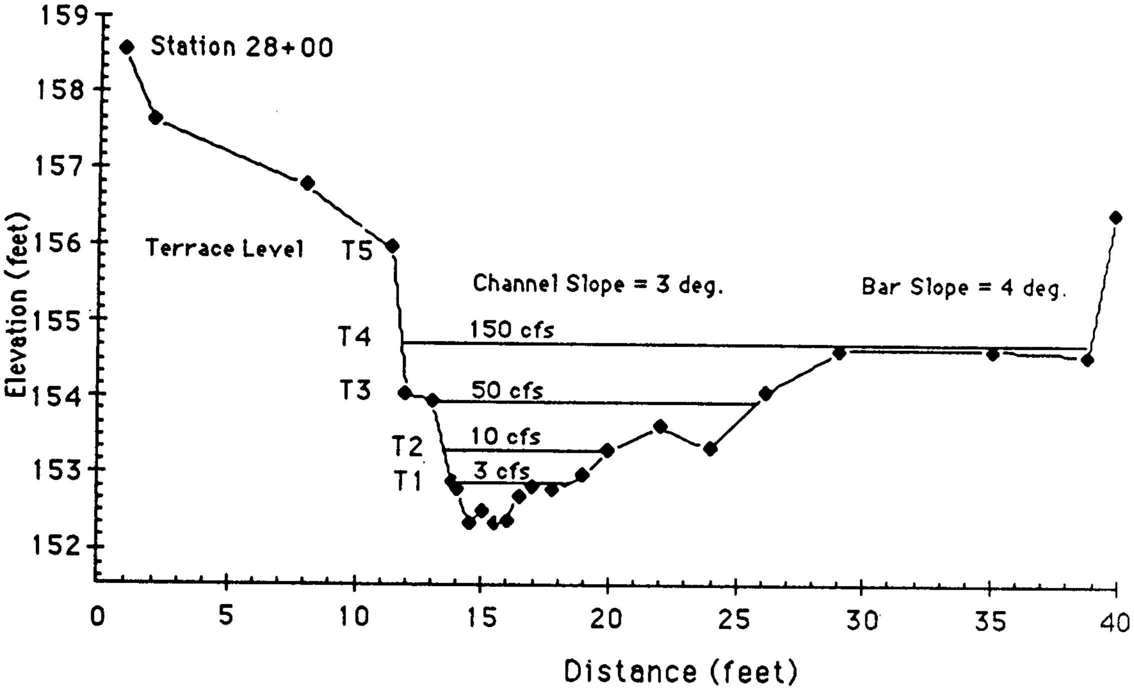


Figure 4.12 Channel cross section at station 28+00A, (WSD 4000A, Fig. 4.8); elevations from King County Survey (1987).

Channel features recorded include: flood bar and terrace levels (labeled T 1-5), channel bank stratigraphy, substrate composition, vegetation types and ages; and indicators of water stage (washed substrate, watermarks, and debris lines).

Most of Channel A above WSD 3500A and Channel C have channel slopes of 5 to 10 degrees, with isolated reaches behind log jams in the range of 2 to 3 degrees. Downstream of WSD 3500A the channel slope flattens from 4 degrees to 3 degrees on the alluvial fan. Most of the channel length is defined here as very high gradient (slopes greater than 0.069 or 4 degrees). Manning's equation was used at selected cross sections along the entire channel, including slopes up to 10 degrees, to show the general pattern of discharge. The values must be interpreted in the context of the broad range of potential errors discussed in Chapter 2. The scatter in the values indicates only a very rough discharge value can be estimated from the equations outside their verified range. Despite the inherent problems, calculated discharge rates for the very steep reaches (greater than 4 degrees) are comparable with those of the steep reaches (1 to 3 degrees). Several low flow measurements (2 to 3 cfs) at Station 28+00A and 37+00A were used to calculate Manning's roughness coefficient (n). The calculated n value was found to be 0.06 to 0.07. Figure 4.13 compares roughness values for Station 28+00A (WSD 3800A) with estimates using Limerinos (1970) (Eq. 2.3), and Jarrett (1984) (Eq. 2.4).

Discharge rates are estimated for the prominent flood bar and terrace levels along Channels A (Figures 4.14 and 4.15) and Channel C (Figures 4.16 and 4.17). A constant roughness value of 0.07, based on agreement of estimated n with Limerinos's (Eq. 2.3) was used in channel capacity calculations

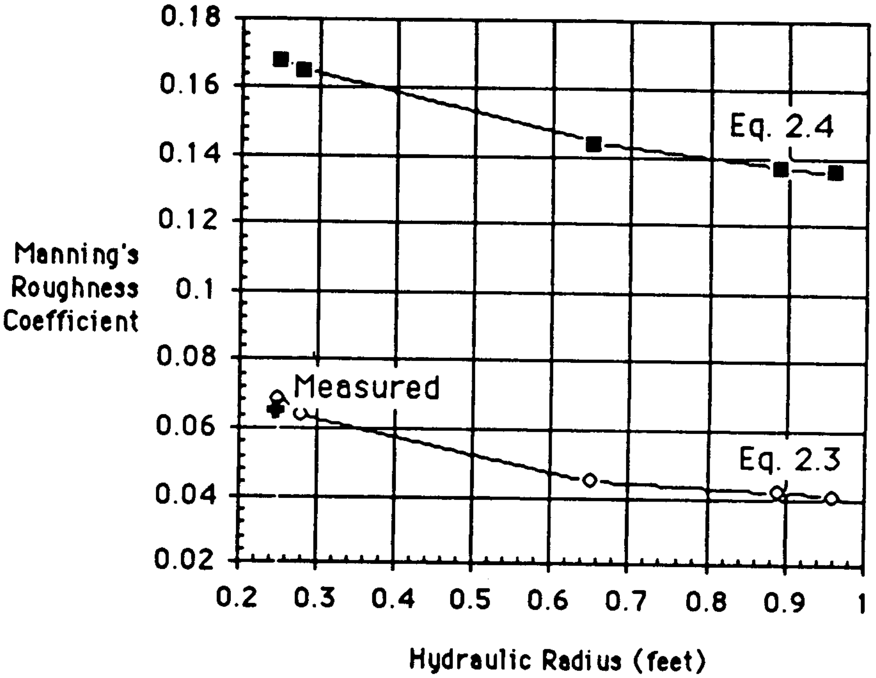


Figure 4.13 Comparison of Manning's roughness coefficient determined from the empirical equations of Limerinos (1970) (Eq. 2.3) for straight reaches in natural channels with some gravel and Jarrett (1984) (Eq. 2.4) for high-gradient boulder-bed streams (slopes greater than 0.002), and from measured low flow velocities and Manning's equation.

in Figure 4.14 and 4.16. Jarrett's Equation 2.4 is used to estimate channel capacity in Figures 4.15 and 4.17. The range of discharges for these sections is likely to fall within the estimates in Figures 4.14 and 4.16, and Figures 4.15 and 4.17.

The highest flood flows estimated for the main terrace along Channel "A" (for example T5, Figure 4.12), with discharges in the range of 200 to 300 cfs (not shown in Figures 4.13 - 4.17) reflect channel incision and not actual channel flood rates. The T5 terraces are commonly paired and are well vegetated with brush and 2nd-growth trees, giving further indication that the main channels have abandoned the T5 terrace by channel incision. Flows estimated for the lowest flood bars, T1, correspond to fairly common storms. There is a lack of perennial vegetation on the T1 flood bars, annual plants are very sparse, and a lack of accumulated leaf and twig fall indicates regular inundation. Typical winter floods as indicated by the T1 level range from 3 to 10 cfs in the main channel (Figures 4.14 and 4.15).

The 2nd bar stages, T2, are roughly comparable with bankfull discharge, typically assumed to be between a 1.5 to 5-year recurrence interval flood. Annuals are present along with sparse rapid growing brush at the bar edges. A matt of leaf and twigs is present but there is little organic soil development. The bankfull discharge is estimated to range from 10 to 40 cfs (Figures 4.14 and 4.18).

The T3 and T4 levels correspond to floods capable of moving large amounts of sediment stored along the channel. Some of the measured channel cross sectional areas may correspond to recent channel erosion and thus make the discharge estimates high. At the T1 and T2 flood level sediment transport is occurring, however, sediment discharge capacity is less likely to exceed sediment supply. The large amount of scatter in the T3 and T4 calculations could reflect differential erosion rates among the measured cross sections and likewise the consistent downstream increase in calculated discharge in the T1 and T2 levels may reflect stable channel conditions at these discharge rates.

The information contained in Figures 4.10 to 4.17 is representative of that which can only be gathered from field measurements and inspection and interpretation of strata and vegetation. Possible field visits during high flow provide opportunities for additional dischange measurements. The information is typical of what can be obtained with limited streamflow gauging and geomorphological observation and measurements at times convenient to the observer.

4.8 HYDROLOGIC PROCESS ZONES

The dominant hydrologic processes active in the Novelty catchment include direct rainfall onto flowing channels and wetlands, infiltration with resulting water storage by forest litter and soil, return flow from infiltrated water, saturated overland flow, water losses due to soil and vegetation evapotranspiration, and Horton overland flow. These processes are common to many temperate areas. Figures 4.18 a and b, showing the estimated extent of these process zones, is based on interpretation of aerial photographs (larger scale versions of Figures 4.3 and 4.4) and field observations. Errors of interpretation of the extent of process zones that change by season or during storms limit the map accuracy. Additional ground truth during storms and different seasons might refine process zone boundaries. The presence of roads and cleared right of way for power lines (Figure 4.18b) introduces fast responding Horton overland flow areas. The channel network in Figure 4.18b is more extensive than in Figure 4.18a. The influence of flow redistribution to the channels is explored quantitatively in Chapter 6.

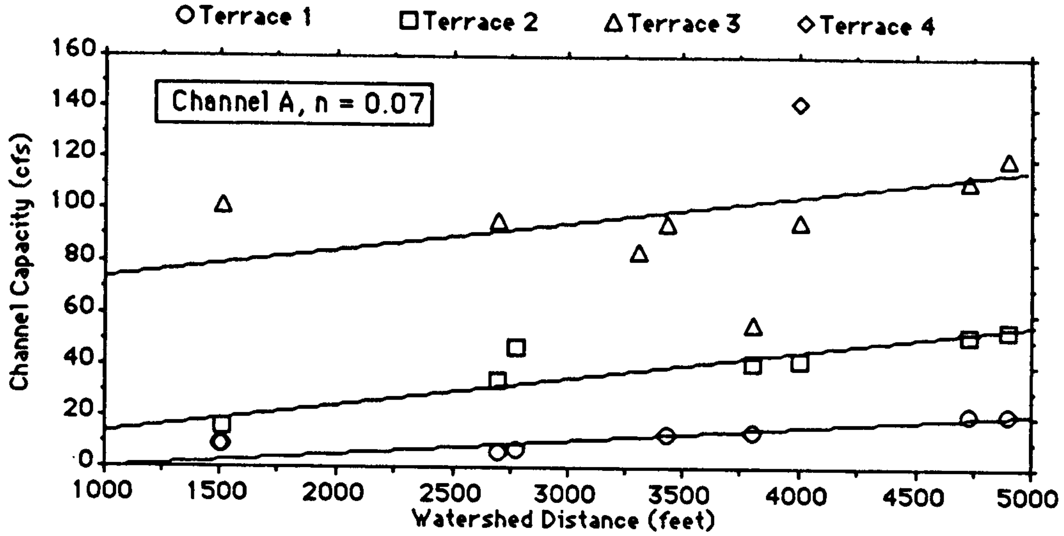


Figure 4.14 Watershed distance along channel "A" vs. channel capacity, based on measured cross sections and Manning's equation using n = 0.07. Terrace levels T1 through T4 start at the lowest pronounced flood bar level and proceed to the highest as in Figure 4.12.

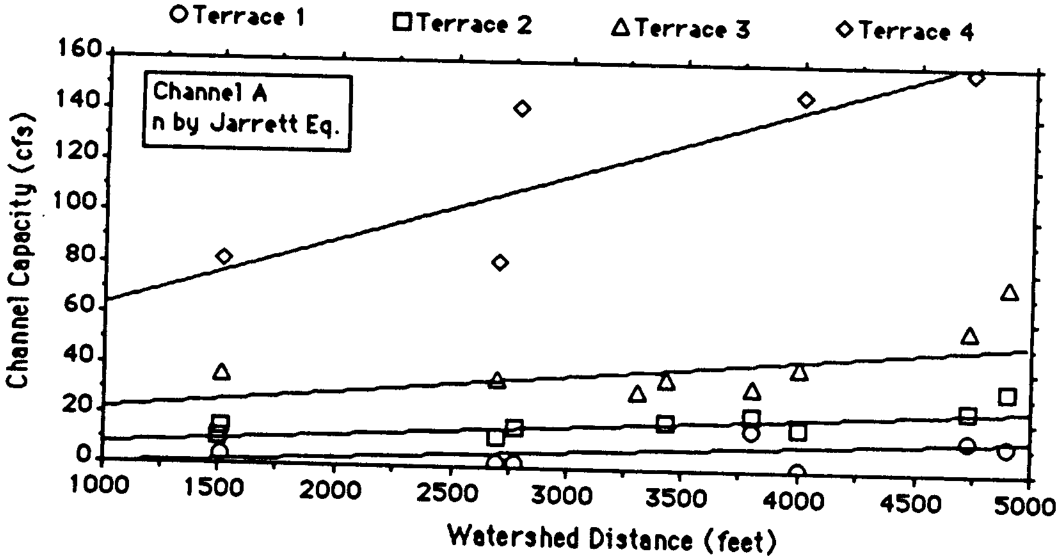


Figure 4.15 Watershed distance along channel "A" vs. channel capacity channel capacity is based on measured cross sections and Manning's equation using n values from Jarrett's equation (Eq. 2.4). Terrace levels are defined in Figure 4.12.

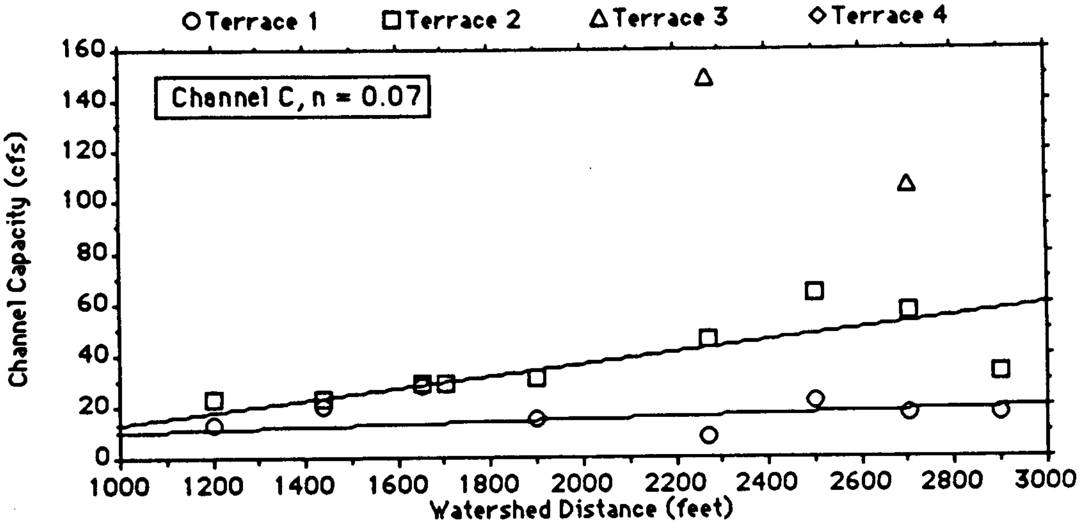


Figure 4.16 Watershed distance along channel "C" vs. channel capacity. Channel capacity is based on measured cross sections and Manning's equation using n = 0.07. Terrace level T1 through T4 start at the lowest pronounced flood bar level and proceed to the highest.

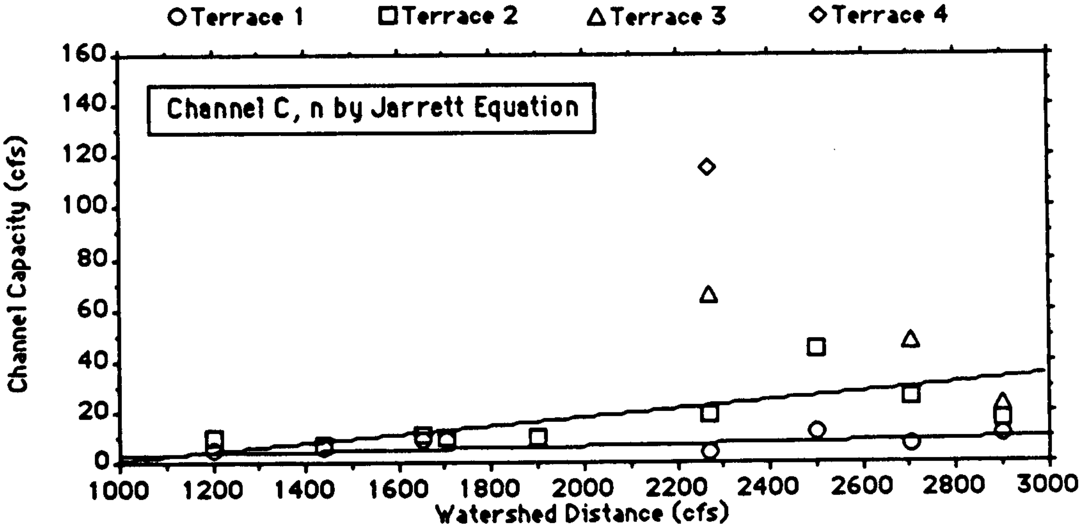


Figure 4.17 Watershed distance along channel "C" vs. channel capacity. Channel capacity is based on field cross sections and Manning's equation using n values from Jarrett's equation (Eq. 2.4).

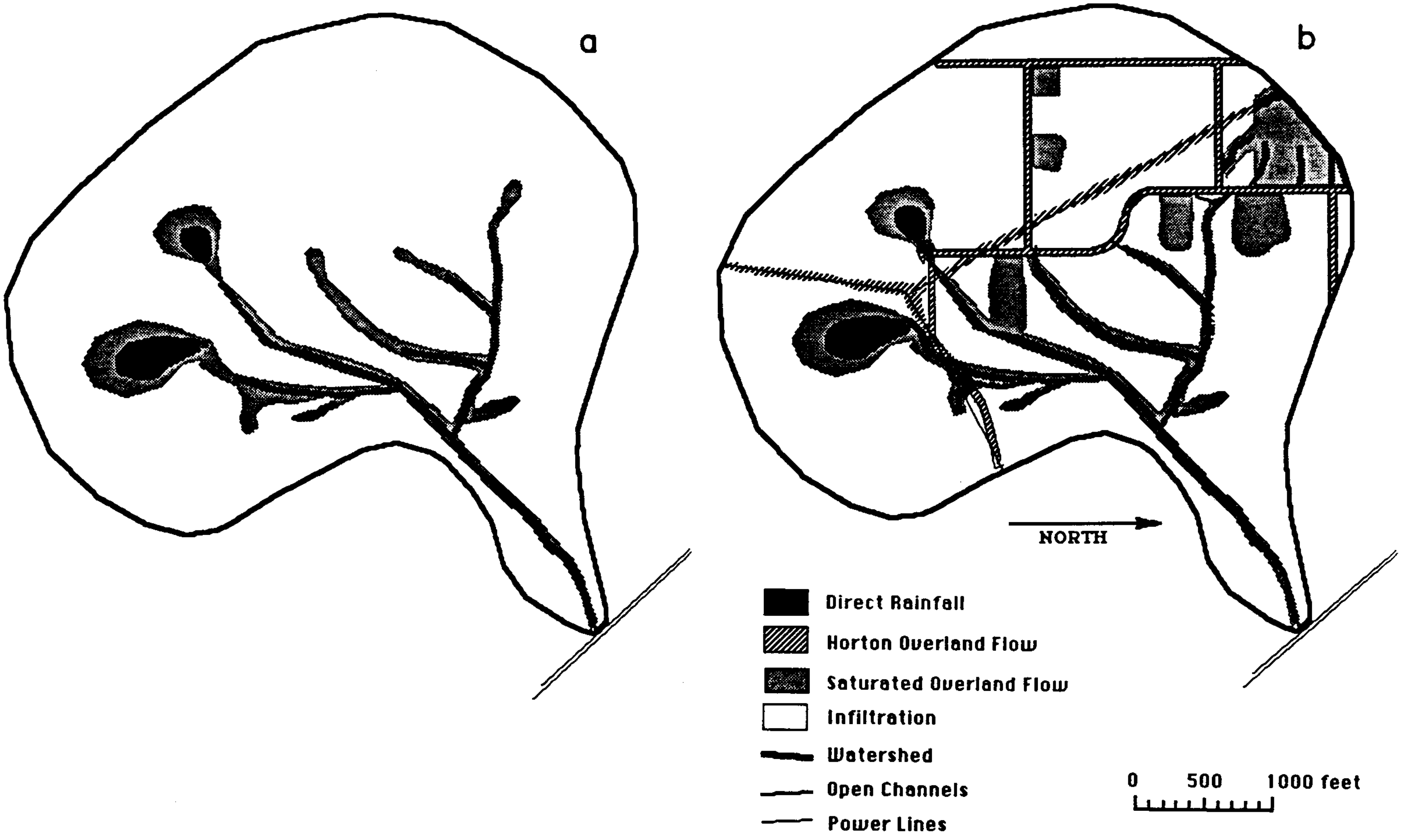


Figure 4.18 Estimated hydrologic process zones for a moderate to large storm and wet antecedent catchment conditions, (a) pre-development, (b) conditions in Autumn 1987.

Direct Rainfall Onto Channels

Estimated direct rainfall areas were mapped on aerial photograph overlays (Figures 4.2b and 4.3b) and verified during field visits. Catchment areas where direct rainfall occurs include 1st through 3rd-order open channels and upland wetlands connected to channels. The direct rainfall process zone area varies on a seasonal basis and during storms. In the dry season, after groundwater flow has diminished, the only channels with surface flow are the stream sections with thin or no alluvium. Dry season flow is subsurface in creek segments with thick alluvium, such as the upper and lower alluvial fan. In the wet season the direct rainfall area expands to include the entire channel network (Figures 4.18b). While the area of direct rainfall onto open channels is small relative to the total catchment area, hydrograph response to direct rainfall upstream is almost immediate.

Infiltration

Catchment areas where infiltration is the dominant hydrologic process are mapped based on a lack of surface channels, presence of vegetation, and forest litter condition. The infiltration process zone (Figure 4.18) covers the greatest percentage of catchment area of all the main process zones. Near channels, infiltrated water can flow via subsurface paths in time to contribute to a storm hydrograph. The ravine slopes are covered by 1 to 5 feet of loose sandy colluvium with permeability rates of 2 to 6 inches per hour (Snyder et al, 1973). Subsurface water could arrive from 10 to 20 feet away from the channels in a storm that lasts for several days. Piping from macro-pores such as root and animal holes could deliver subsurface water from greater distances. Infiltrated water, from areas further inland from channels, flows slowly toward the channels and contributes to a delayed baseflow hydrograph response, or is lost to litter, soil, and vegetation storage and evaporation.

Catchment Water Storage and Detention

Typical catchment soil profiles used to estimate potential water storage and detention are based on examination of exposures along roadcuts, ditches and channels, hand auger tests, and 3 test pits. On the plateau, loose to medium compact colluvium and recessional outwash varies in thickness from zero to 5 feet (1.5 meters) but typically is loose and only 1 to 2 feet thick (0.3 to 0.6 meters). In the undisturbed 2nd-growth woods on the Novelty catchment (the majority of the catchment) the forest floor was a mor type that varied from 3 to 12 inches (7 to 30 cm) and up to several feet at infilled low areas. Along the power lines, roads, pastures, and lawns the floor type was a Mull from 0.2 to 2 inches (0.5 to 5 cm) deep. Forest litter porosity and field capacity were 0.6 and 0.2, respectively, for a typical mor litter sample from the Novelty catchment. The upper portion of the underlying loose mineral soil has a porosity of 0.45 and field capacity of around 0.25.

Forested areas on the Novelty catchment have a loose textured surface soil with a well developed organic litter and no development of surface rills. This indicates rainfall intensity does not exceed the rate of infiltration. A sample calculation of potential soil and litter water detention indicates 7 cm (2.8 inches) of rainfall can be delayed in typical forested areas of the Novelty catchment. The length of the ascending period would be 27 to 30 minutes based on Balci's empirical equation (Balci, 1964). Even if the forest soils were to saturate fully, local depression storage in the hummocky terrain will prevent rapid runoff of precipitation. Based on a simple sponge analogy of potential water detention capacity and the lack of observable open channels in the upland forest it is concluded surface runoff was rare in the upland parts of the undisturbed catchment.

A similar estimate for the amount of water detention that is lost when the 2nd growth forest areas of the Novelty catchment are developed indicates less than 4 cm (1.6 inch) of potential water detention remains. Reduced infiltration rates, caused by destruction of the forest litter and soil compaction, combined with reduced soil and litter water detention and storage, accounts for the observed overland flow on the power lines, road sides, pastures, and lawns of the Novelty Catchment.

In the pre-development Novelty catchment depression water detention includes two wetlands (one permanent, the other seasonal) and area-wide detention of water in low areas of the forest floor. In the developed parts of the catchment, surface depression storage occurs in the pastures and lawns during storms. Wet areas are typically 1 to 3 cm deep and 2 to 10 meters across. They are sparsely distributed in the low areas. Depression storage areas interconnect, by tiny rills or areas of sheetwash, to other depressions and the ditch system. Development of these rills and overland flow network was observed on newly cleared (and bare) fields during rainstorms. With time, grass conceals the tiny network, though it can still be felt through the grass and observed during storms.

Evaporation

Evaporation throughout the catchment varies with differing soil, vegetation, and exposure conditions. Seventy acres or 22% of the catchment has been cleared; 20 acres for road right of way and 50 acres for lawns, pastures, powerlines, and logging. First-year increase in water yield from forest clearing based on the data of Hibbert (1967) and others are presented in Hewlett and Nutter (1969) and Dunne and Leopold (1978). Increased water yields of 2 to 4 inches (5 to 10 cm) could be expected if the 70 acres had all been cleared at once. Only the road area of 20 acres was cleared initially; home sites have been slowly cleared in the last 7 years. As more of the catchment is cleared for lawns and pasture additional reduction in evaporation can be expected.

Return Flow

Three typical geometries dominate return flow areas. In the developed state, return flow is intercepted by roadside and field ditches. In the ravines, return flow occurs along the base of plane slopes, and is concentrated in swales and concave hollows. Return flow locations included topographic breaks in slope where sloughing has removed loose surface colluvium, exposed soils from sheets flow, wet surface soils even at the end of a 3-month drought (summer of 1987), presence of Devil's Club (*Oplopanax horridum*), and the presence of springs.

The catchment area contributing to subsurface storm flow has been altered in several ways. The introduction of roads and ditches quickly removes rainfall (via overland and return flow) that originally would have soaked in the ground and contributed to subsurface flow and evaporation at a later time. the predominance of shallow soils on the upland results in subsurface storm flow along most if not all of the ditch length during extended storm events. Reduced interception and evapotranspiration results in increased return flow because the saturated soil zone is greater. Finally, deeper incision of the creeks creates deeper seepage faces that can deliver return flow to the channel. There is an increased catchment area delivering shallow groundwater return flow to the channels via the ditch and field drain systems. This combines with the new overland flow sources to increase catchment storm response.

An accurate assessment of return flow contribution to the channels cannot be made without extensive field measures of the saturated soil wedge geometry and saturated hydraulic conductivity. The return flow estimation method outlined by Dunne et al (1975) considers straight portions of slopes in a general way. The spatial contribution of return flow along the ravine portions of the catchment will vary because the observed distribution of soils varies greatly within short distance (see also Snyder et al, 1973, page 10), soil drainage and permeability vary, and topography of the slopes and low permeability till concentrates water in hollows. Application of the method of Dunne et al (1975) to the ravines indicates return flow contributions along the creek channels of 1 to 3 cfs based on saturated hydraulic conductivities for the mineral portion of the soil of 0.17 to 0.5 feet per hour (snyder at al, 1973) a hydraulic gradient of 20 to 30 degrees and saturated soil wedge along the creeks of 2 to 3 feet depth

Saturated Overland Flow (SOF)

Saturated overland flow occurs in areas where soil water storage capacity is filled resulting in a saturated surface condition. On the Novelty catchment pastures and lawns with zero to 1 ft (30 cm) of loose soil (porosity ≃ 0.4) and minimal litter are likely to saturate in extended storm events. Depression storage and saturated overland flow will result.

Only areas where saturated overland flow has access to channels via ditches, field drains, and existing channels were included on the process zone maps. Saturated overland flow occurs along the edges of wetlands and channels where return flow prevents rainfall from soaking into the ground. Overland flow on catchment lawns and pastures is partly due to saturated overland flow and partly to Horton overland flow.

Horton Overland Flow (HOF)

Horton overland flow is assumed for areas with impervious or nearly impervious surface layers including roads, houses, and some pastures. Only those areas producing Horton overland flow that connect to open channels were considered. The Horton overland flow process zone is insignificant in the pre-development catchment. It consists of small areas of exposed glacial deposits along channel banks. The width of this relatively minor HOF process zone varies from 0 to 5 feet along either side of the channel. Channel banks are also a common location for return flow to occur resulting in Saturated and Horton overland flow occurring in the same area.

Pre-development and undisturbed channels have dense vegetation along their banks. Channels from the developed sub-basins have lost bank vegetation and colluvium because of bank erosion. This exposes a greater area of compact material along the channels where HOF (and SOF) has direct access to the channel. HOF areas with direct access to the channel network are greatly expanded in the developed condition by the introduction of roads, cutslopes along ditches and roads, and pastures or lawns where the loose soil has been removed or compacted. The road surfaces are the most significant contribution to the HOF process zone area.

4.9 HYDROLOGIC EFFECTS OF DEVELOPMENT

Table 4.1 outlines qualitatively the dominant catchment processes and the relative direction that development (up to 1987) has changed the frequency of occurrence, extent, duration, or magnitude of the process.

Water Interception and Detention Storage

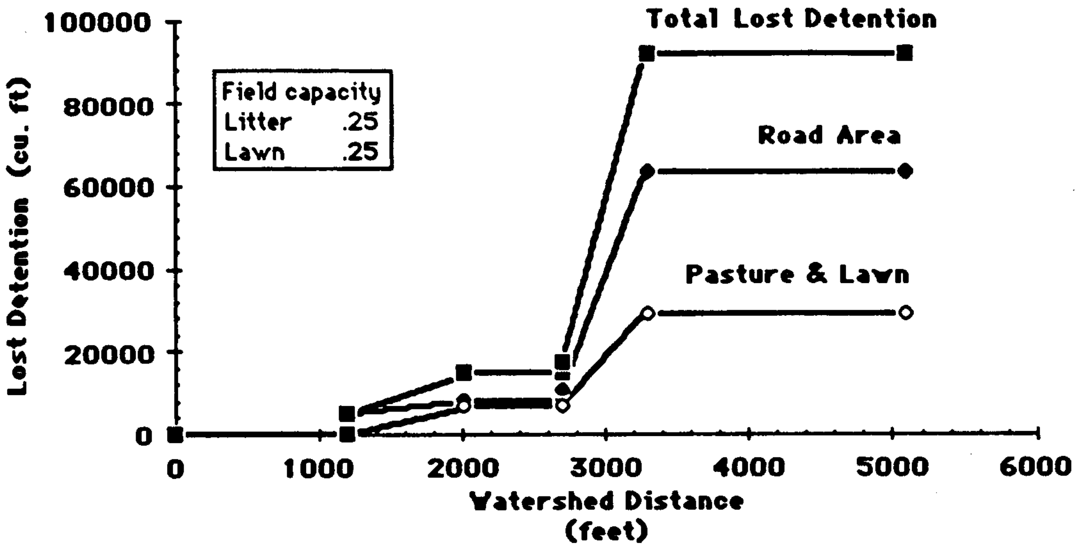
Interception storage and potential evapotranspiration has been reduced by replacement of 2nd growth forest with roads, ditches, houses, lawns, and pastures. Soil water detention is reduced in graded areas. Water detention has been altered at the two main wetland areas (Figure 4.8a and b) by altering the hydraulic control of the wetland outlets.

Logging disturbs the litter zone by mixing it with soil, compaction, and by reducing litter production. The hydrologic response of the soil is altered (Moore et al, 1986). Clearing for pasture and building construction completely removes the litter zone and disturbs the loose upper portion of the underlying soil horizons. Road construction destroys the loose soil zone and covers it with a compact surface. Ditches along the roads drain the surface and subsurface water from the surrounding area. The zone of influence of the ditches varies with the nature of soil material, slopes, and ditch depth.

With only roads added to the catchment a minimum of 65,000 to 120,000 cubic feet of potential water detention has been lost by replacement of forest litter with roads and ditches (Figure 4.19). The loss of 120,000 cu. ft. of potential water detention is equivalent to an average depth of

Table 4.1 Development Effects on Dominant Catchment Processes

PROCESS	RELATIVE CHANGE
Direct Rainfall onto Channels	Increased
Interception	Reduced
Evaporation	Reduced
Infiltration	Reduced
Water Storage	Reduced
Return Flow	Increased
Saturated Overland Flow	Increased
Horton Overland Flow	Increased
Channel Density	Increased
Discharge Rate and Volume	Increased
Quick Storm Response Area	Increased
Erosion, Transport, and Deposition of Sediment	Increased
Slope Stability	Reduced



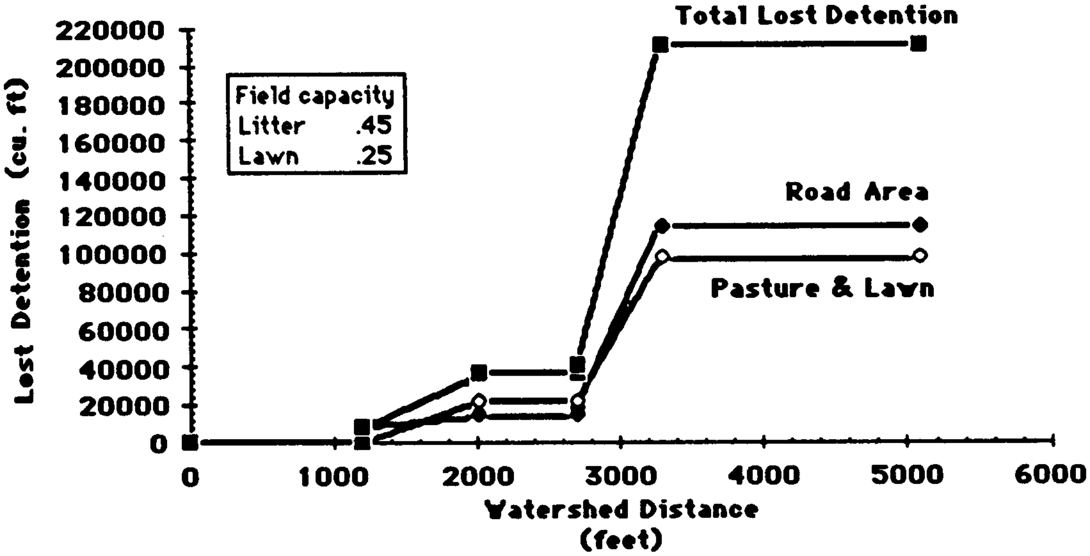


Figure 4.19 Watershed distance along channel "A" vs. minimum lost water detention. A forest litter depth of 6 inches (15 cm) and field capacities of 0.25 and 0.45 are used in the computations. Litter thickness of lawns and pastures that replace forest litter in all but the road areas is estimated conservatively at 3.5 inches thick with a field capacity estimated to be 0.25.

only 0.1 inch over the entire catchment. The 120,000 cubic feet is equivalent to lost detention of 3.3 inches averaged over the 10 acres where significant change has occurred. These 10 acres connect directly to the channel network. This is considered a minimum lost detention because only field capacity of 0.25 to 0.45 for a litter depth of 6 inches (15 cm) was considered lost for the width of roads and ditches. Additional losses to soil water detention resulting from vegetation clearing, grading of depressions, and soil compaction were observed but not considered for calculation of minimum lost detention. Minimum potential water detention loss is estimated between 100,000 to 200,000 cubic feet when litter detention loss for the 22 acres of existing pastures and lawns are also considered (Figure 4.19). Lawn and pasture litter depths were observed to range from 0.6 to 3 inches (1.5 to 7.6 cm); field capacity for pasture and lawns was assumed to be 0.25.

Overland Flow

The roads and ditches create new overland flow areas that have direct access to the catchment channels. Overland flow was observed during rain storms and is further indicated by field evidence of sheetwash, rilling, and depression ponding. Rilling and sheetwash patterns observed along the shoulders of the paved and gravel roads indicate Horton overland flow from the roads is entering the ditches. Horton and saturated overland flow are both present over portions of the pastures and lawns. Much of this water accumulates in 1 to 3 inch (2.5 to 7.5 cm) deep depressions on the pastures. For moderate to large storms depressions fill and connect to the road ditches. Tiny rills can be observed along the ditch cutslopes where pasture overland flow enters the channel system. Existing lawns have been graded more than the catchment pastures. Tiny sheetwash patterns of sand and organic material indicate overland flow occurs on the lawns. Pastures and lawns on the upland are wet and often saturated if field drains and ditches are not added. People do not like wet yards and pastures so additional drainage facilities are being added to existing fields, yards, and pastures. This will further increase the area of quick response overland flow that has access to the catchment channels.

Channel Density

Road construction has increased open channel density (Figure 4.9). The typical flow path distance from the catchment boundary to an open channel was 600 to 1200 feet in the undeveloped state. It is now 200 to 600 feet because of the addition of road and field drains (Figure 4.8b). The increased channel and subsurface drains provide direct access to the channel system for a greater proportion of the subsurface and overland storm flow.

Quick Storm Response Area

Prior to road development the area of quick storm response is estimated to have included the wetlands and areas that saturated along the channels (Figure 4.20a). Removal of vegetation and forest litter, surface grading, field drains and ditches, roads, creek bank slumping, and removal of hydraulic controls of wetlands have all combined to increase the area of quick storm response (Figure 4.20b). Quick runoff response from the addition of 10 acres of roads and ditches (3% of the catchment) has direct and rapid access to the main channels. Surface runoff observed from portions of lawns, pastures, and powerlines during rain storms takes longer to reach channels because of longer, less direct overland flow paths, and runoff volumes are reduced by depression and soil water storage and

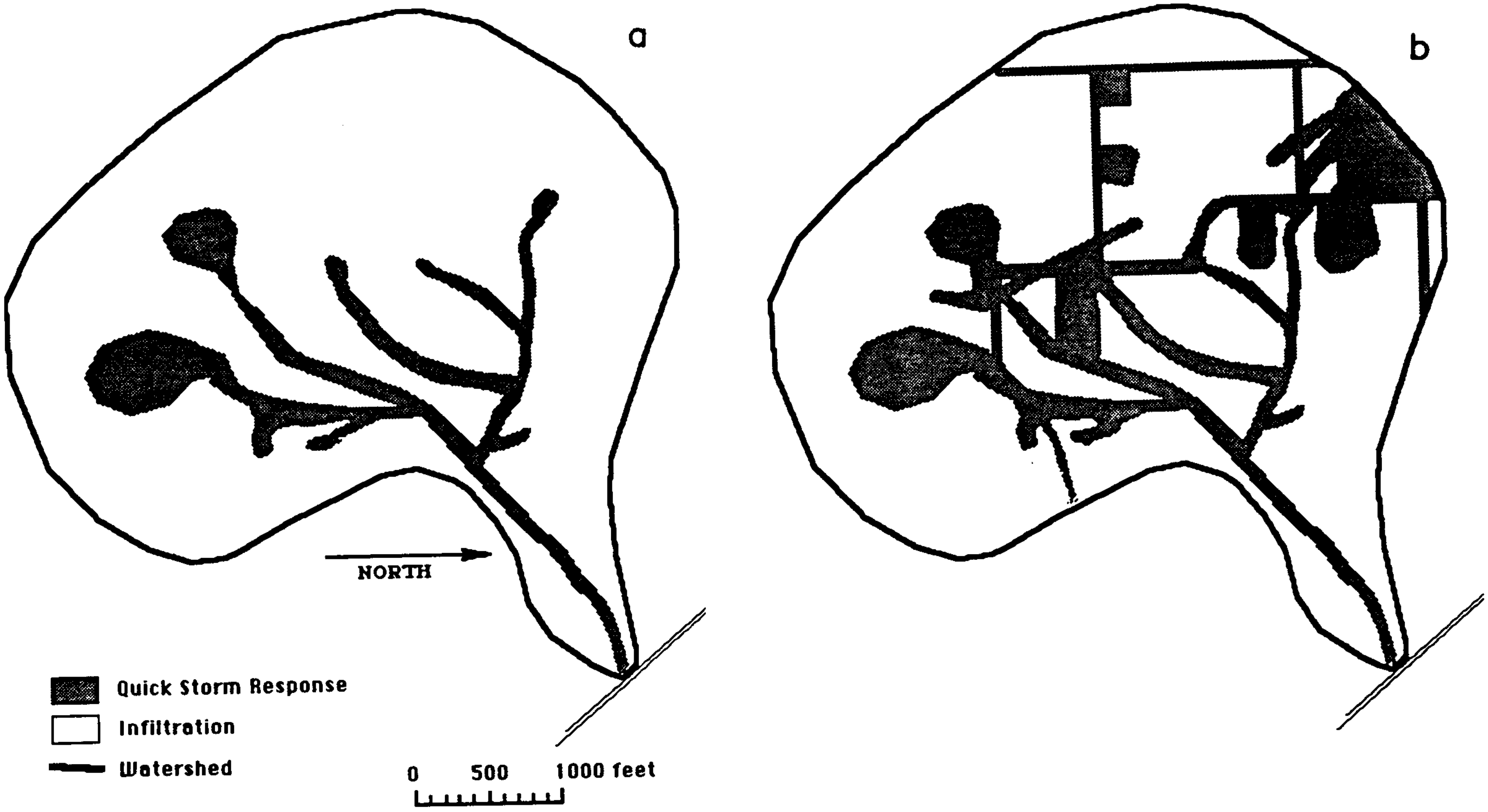


Figure 4.20 Quick storm-response zones, (a) pre-development, (b) conditions in Autumn, 1987.

detention. The estimated pre-development quick storm response zone of 30 acres (9.6% of the catchment) has been increased to 60 acres (19% of the catchment), based on the areas of lawns, pasture, power lines, and a ditch/road width of 50 feet (Figure 4.21). Most of the developed area is in the Channel "C" drainage which enters the main channel at WSD 3400A.

Approximate Unverifiable Estimates of Flood Discharge Rates

Vegetation clearing, grading, and construction of roads increased drainage density, reduced areas of infiltration, reduced evaporation, and decreased potential water detention. Field evidence and use of four different relatively crude rainfall/runoff estimation methods indicate catchment modification have resulted in increased peak flow rates. These unverifiable estimated flood discharge rates are summarized in Table 4.2. Peak flood rates estimated from the channel capacities, partial area rational (Dunne and Leopold, 1978, page 304), and SCS methods are comparable, given the accuracies of the methods, and indicate peak flows considerably greater than estimates from the regional regression and simple rational methods.

While the regional regression does not give a pre- and post-development condition for comparison, it provides some indication of the general magnitudes to be expected in the region. The water flow path assumed in the rational method incorrectly presumes the dominant flow path of the catchment to be Horton overland flow and is therefore inappropriate to model all but small impervious areas of the catchment.

The partial area rational method applies the rational method to the identified zones of the catchment where overland water flow paths are most likely. It does not account for throughflow, which is an important and possibly the dominant runoff process in the pre-development catchment. Runoff peaks are assumed by this method to result only from rainfall on all impervious and saturated areas. These peaks should be combined with a significant but unquantified throughflow hydrograph contribution.

The channel capacity method applies an hydraulic equation, typically Manning's equation with an estimated roughness coefficient, to calculate an average channel velocity for relevant stages identified at channel cross sections. Accuracy is limited by the interpretation of channel-full stage, in the selection of an appropriate roughness coefficient, and to the applicable range of the slope-area equation. For the present catchment condition, discharge was estimated for three flood bar levels: the lowest bar, bank-full level, the January 18, 1986 flood bar, and for the terrace level that was abandoned by channel incision. One estimate for pre-development discharge based on channel capacity was made for an abandoned old channel (Figure 4.10). Channel-full stage is assumed to approximate the 0.5 to 2-year recurrence interval peak flow event, based on the condition of substrate, on leaf litter and vegetation on the bankfull flood bars, and by comparison with studies and reviews by Pizzuto (1986), Richards (1983), Dunne and Leopold (1978), Shen (1971), and Wolman and Miller (1960). The discharges estimated for the largest catchment floods are based on channel sections corresponding to gravel flood deposits, silt and litter marks, and vegetation lines. The January 18, 1986 storm (Figures 2.1 and 2.2) is the largest recent storm in the area. In the catchment area the January storm was approximately a 25-year, 24-hour duration, recurrence interval rainfall (Appendix E, Albright, 1986; Krogh, 1986). The recurrence interval of the runoff from this storm is a function of rainfall and antecedent catchment conditions, therefore, it can not be assumed equivalent to rainfall recurrence interval. If the recurrence interval of the rainfall and runoff are assumed to be equivalent, as is done

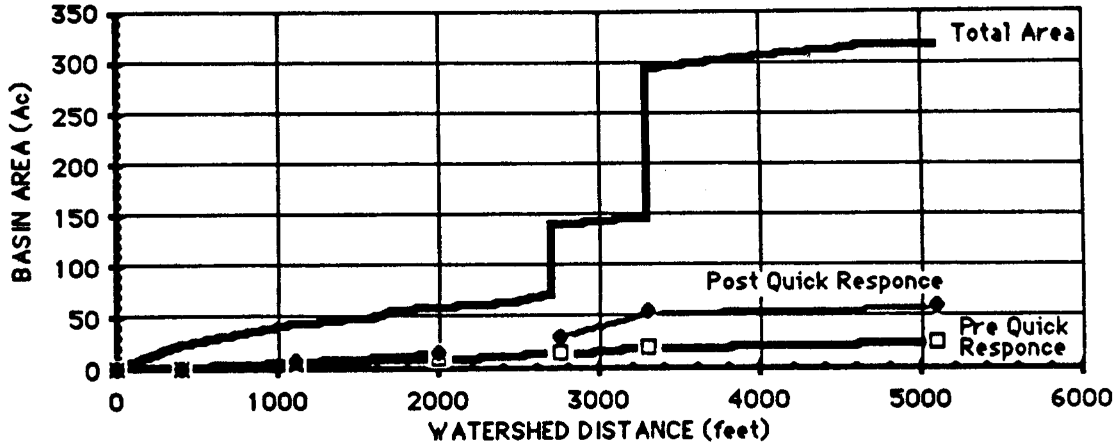


Figure 4.21 Watershed distance vs. total basin area and quick stormwater response area for pre- and post-development conditions.

with the rational and SCS method, the 25-year, 24-hour duration recurrence interval peak runoff is estimated to be around 60 to 150 cfs, based on estimates of channel capacity for several channel cross sections.

Increased peak discharge rates have caused the formation of larger capacity channels by eroding compact glacial material, channel alluvium, and colluvium from the steep first order valleys and channel alluvium and bank material from the 2nd and 3rd order channels. Channel enlargement is indicated by comparison of a remnant of old channel on the terrace with present channel dimensions. Channels with increased drainage density are actively incising into the compact glacial deposits and channel alluvium. Channel C and Channel A below the tributary at WSD 28+00A (Gravel Pit Tributary) has incised 2 to 5 feet into the valley alluvium. Paired terraces; stratigraphy of channel alluvium; new slumps; vegetation ages on the terraces, floodway, and slumps; and calculation of very high and unlikely flow rates of 200 to 400 cfs at channel-full stage to the upper terrace are the basis of concluding that channels have undergone accelerated expansion in the last decade. The number and condition of tree falls and the degree of rill development in the compact glacial deposits suggests that the tributary starting at the gravel pit (Figure 4.8b) has been rapidly expanding. Disturbance causing increased discharge in the Gravel Pit Tributary catchment includes, channelization and lowering of the hydraulic control at the outlet of the wetland, exposure of the water table in the gravel pit, vegetation removal along the power lines (Figure 4.18b), and concentration of the wetland, powerline, and gravel pit water via a 4 ft. deep ditch to the tributary head.

Valley terrace alluvium along Channels A and C represents a large supply of stored sediment that can be eroded and transported to the alluvial fan and Snoqualmie River. Incision of the channel has eroded approximately 2000 to 4000 cubic yards of stored alluvium (4500 ft. long, 2 ft. deep, 6 ft. wide). Additional sediment is introduced by channel bank slumping and erosion of the compact valley walls of sandy outwash.

The slope of the main channel flattens from 5 to 10 degrees (8% to 18%) in the ravines to 1.5 to 3 degrees (2.6% to 5%) on the alluvial fan. Sand and gravel are deposited on the upper and central portion of the alluvial fan. Sand and silt are deposited on the lower fan and the Snoqualmie River

Table 4.2 Estimation of Maximum Flood Discharge (cfs) at West Snoqualmie Road (WSD 5000)

Method	Type	Accuracy		Flow Rate Recurrence Interval					
				Q_2	Q_5	Q_{10}	Q_{25}	Q_{50}	Q_{100}
Magnitude[1] and Frequency of Floods	Regional Regression	Standard Error of Estimate 42% to 61%	Pre[2]	9	13	16	19	22	25
			Post[3]						
Rational Method	General Empirical Range	Mean Absolute Deviation 34% 17 to 55%[4] -46% to 61%[5]	Pre	5	6	7	9	10	11
			Post	7	10	12	14	15	18
Partial Area Rational Methods[6]	General Empirical	Can not assume any better than rational until tested	Pre	11	15	18	21	24	27
			Post	30	42	50	60	72	84
Channel Capacity[7]	Manning's	25 to 60% error[8]	Pre	Channel-full			Flood Stages		
			Post	10 to 30			70 to 150		
SCS TR55 Graphical (Tc) Method	General Empirical[9]	Sensitive to curve number[10]	Pre	10	15	21	34	42	55
			Post	14	22	31	48	51	75

[1] Cummans et al (1975)

[2] Pre-condition refers to 2nd growth forest prior to road development

[3] Post-catchment condition refers to 1987 condition

[4] Chow (1964), calculated values were consistently low

[5] Schaake et al (1967) (urbanized catchments, Baltimore, Maryland area)

[6] Dunne and Leopold (1978, page 304)

[7] Use of channel morphology from field cross sections

[8] Bathurst (1986) reports average error of -19% and up to -60% in boulder bed rivers with slopes of 0.4%. Here greater error can be expected because of interpretation errors of stage elevation and use of slopes up to 7%

[9] Based on agricultural catchments

[10] Runoff depth is sensitive to curve number (Hawkins, 1984, 1975; Bondelid et al, 1982) and to time of concentration (McCuen et al, 1984.

flood plain. The channel on the upper and middle alluvial fan has been channelized and excavated to a grade that is below the natural grade of the fan. Flood flows deposit alluvium to the natural grade of the fan, moving the channel regime towards the classic shifting and braided channel form of an alluvial fan deposit and placing public and private structures on the alluvial fan at risk of damage.

Erosion, Transport and Deposition of Sediment

Sediment processes were investigated to evaluate possible effects to the stream from land use changes occurring in the upper catchment. In the high-gradient upper channel reaches, flow is, unsteady, and non-uniform. The longitudinal profiles of first order channels are characterized by a very steep step-pool structure (overall slopes of 10 to 90 degrees) and substrate ranging from boulders to cohesive silt and clay. These conditions can not be modeled adequately with existing analytic or numerical methods. There are currently no models, theoretical or empirical, that have been widely used in very high gradient streams. Therefore, this assessment makes extensive use of field observations of recent and historical fluvial deposits along the channels.

Commonly used equations of sediment transport rates (Meyer-Peter and Muller, 1948; Yalin, 1977; and Parker and Klingeman, 1982) are semi-empirical equations. Sediment transport rates are estimated, based on basal shear stress and density, together with empirically derived coefficients. The Meyer-Peter and Muller equation is commonly used in coarse bedded streams because its coefficient was derived from data sets including coarser materials, up to 2 cm, and for rivers of steeper slope, up to 3.5 degrees (6%). These sediment transport equations will not be used here because the creeks on the Novelty catchment do not fit within the proper range of application of these transport equations.

The channel system was divided into four segments based on similarities of channel form, slope, substrate, and bank materials (Figure 4.22). Changed hydrologic response to catchment modifications on the upper plateau affects sediment supply and transport potential differently in each of these channel segments.

Pre-developed drainage from the plateau segment was limited to small unchanneled valleys (zero order basins) at the heads of each of the ravines. Sediment supply from the land would have been small because of dense vegetation, low gradient (0.25 to 2 degrees), and lack of concentrated discharge. In the post-developed condition an extensive network of 1st order channels concentrate discharge into the ravines. Increased overland flow sources (roads, ditches, lawns, pastures, and the gravel pit) are potential sources of clay to sand size sediment, especially during construction periods. Post-development sediment transport from the plateau is limited to fine grain sediment because of the low gradient and low water discharge.

The second channel segment, the very steep channels (4 to 90 degrees) on the ravine slopes, were formerly zero and 1st-order channels that received flow from the wetlands and swales of the plateau. They are now 1st to 2nd-order channels receiving flow from wetlands and road ditches. Only three of the smaller ravine swales remain relatively undisturbed, giving some indication of the catchment pre-development conditions. Water moving down these very high-gradient channels has considerable energy to erode and transport sediment.

Discharge was limited in the pre-development condition, at most of the ravines, by small subbasin areas and the large percentage of precipitation that was stored and slowly released. Sediment transport was limited because pre-development runoff did not contact the loose colluvium of the

Channel Segment	1	2	3	4
Sediment Sources	Sheet erosion of bare soil.	Channel incision into compact till and outwash. Bank slumps	Channel incision into loose channel alluvium and bank slumps	Transport From Upstream
Range of Grain Sizes Available	Clay Silt Sand	Clay Silt Sand Gravel Cobbles Boulders	Sand Gravel Cobbles Boulders	Silt Sand Gravel
Sediment Transport Driving Force	Low Limited by discharge and graident.	High Discharge Limited	Very High	Medium Limited by gradient
Sediment Transport Rate	Low Limited by discharge.	High Limited by supply of loose sediment and high critical sheer stress of compact units	Very High	Medium Limited by gradient

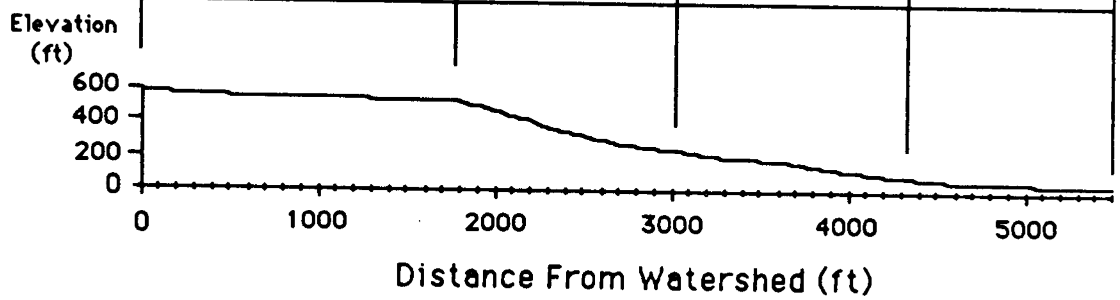


Figure 4.22 Sediment transport potential along the catchment longitudinal profile. Segment 1 includes the upland plateau, Segment 2 includes the 1st and upper reaches of the 2nd order creeks, Segment 3 includes the lower portions of the 2nd order channels and the 3rd order channel, and segment 4 is the alluvial fan.

channel banks (the channel banks were armored with vegetation), and because of the high critical shear stress (see Appendix B) needed to erode the compact glacial units of the ravine channel beds. Channel enlargement and bank instability are apparent in the ravines where road and ditch construction has concentrated and redirected increased discharge. Sediment is now supplied by erosion and slumping of bank colluvium and by channel incision into the compact glacial units. The drainage basin north of the Novelty Catchment provides a dramatic demonstration of this; a 60 ft. deep chasm has been carved into the compact outwash by the concentration of road and ditch runoff.

The third channel segment includes Channel "A" from below the Gravel Pit Tributary (WSD 2800A) to the start of the alluvial fan around WSD 4700A. The channel gradient changes from 10 to 3 degrees along this segment. This is a transitional zone between the very high-gradient 1st-order channels and the lower gradient alluvial fan. There is sufficient storm water discharge to transport an abundant supply of sediment stored in alluvial bars and terraces along the channel. Sediment deposition occurs at the mouths of tributary creeks at lower flows; transport occurs at flood flows.

The fourth channel segment starts around WSD 4700A where sediment discharge from the catchment has built an alluvial fan onto the Snoqualmie River flood plain. On the upper and mid-portions of the alluvial fan, decreasing basal shear stress due to decreasing stream gradient, loss of discharge to infiltration, and channel division reduces the ability of the creek to continue moving larger sediment. Deposition of gravel and sand results in channel shifting and over time builds the classic form of an alluvial fan. On the lower fan, flood waters from the Snoqualmie River modifies the alluvial fan deposits.

Effects of the introduction of increased flows on sediment motion can be assessed by considering the threshold of sediment motion for the existing substrate and channel conditions. Knowing the approximate discharge for each representative or critical reach at which significant sediment transport will begin to occur will help assess the sensitivity of each creek segment to altered discharge frequencies and magnitudes (as estimated by qualitative mapping of changes in the hydrologic process zones or semi-quantitatively with rainfall/runoff models).

Potential channel impact zones will be those down-stream channel segments where the frequency and magnitude of runoff is expected to increase above the threshold level of significant sediment transport of observed and potential new sediment sources. Limiting the frequency of peak discharges that are above the estimated threshold of sediment motion to a level comparable to the estimated pre-development frequency provides a constraint to allowable release rates of any post-development mitigation facilities; the long duration discharge from detention ponds can be held at or below this limiting transport level.

The threshold of sediment motion was assessed at Station 28+00A ,WSD 4000A, using the methods outlined in Appendix B. Relevant grain size distributions are given in Appendix C. The commonly used Shields criteria (Shields, 1936) for initial bedload motion is compared with the equation of Wiberg and Smith (1987a,b) (Figure 4.23 and Figure 4.23 and+4.24). Based on the Shields curve, fine sand to very fine gravel will move as bedload at a discharge as low as 3 cfs. It indicates the d_{50} grain size (3.5 cm) in the central channel will not move until well above 100 cfs (Figure 4.23). Field observations at 3 cfs indicate fine sand is not moving; gravel deposits along the channel indicate gravel and cobbles regularly move at higher flow rates.

The discrepancy between theory and observation arises because the Shields curve results from an empirical equation based on initiation of movement of well sorted (uniform sediment size) sediment

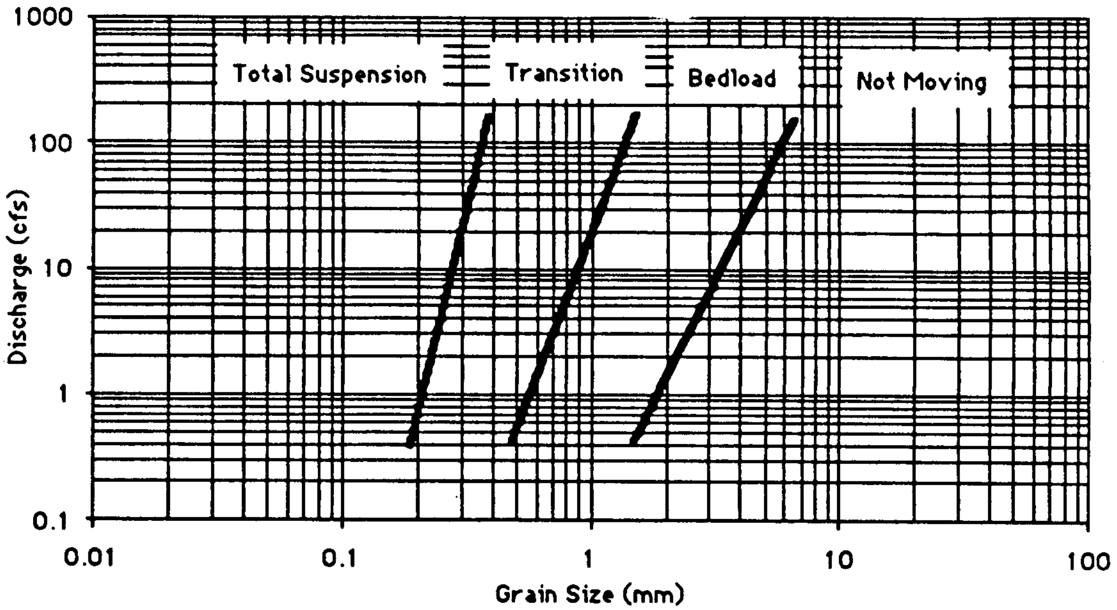


Figure 4.23 Sediment motion for uniform sediment in the main channel at station 28+00 based on Shield's relation. The suspension criterion is given in Figure 4.25.

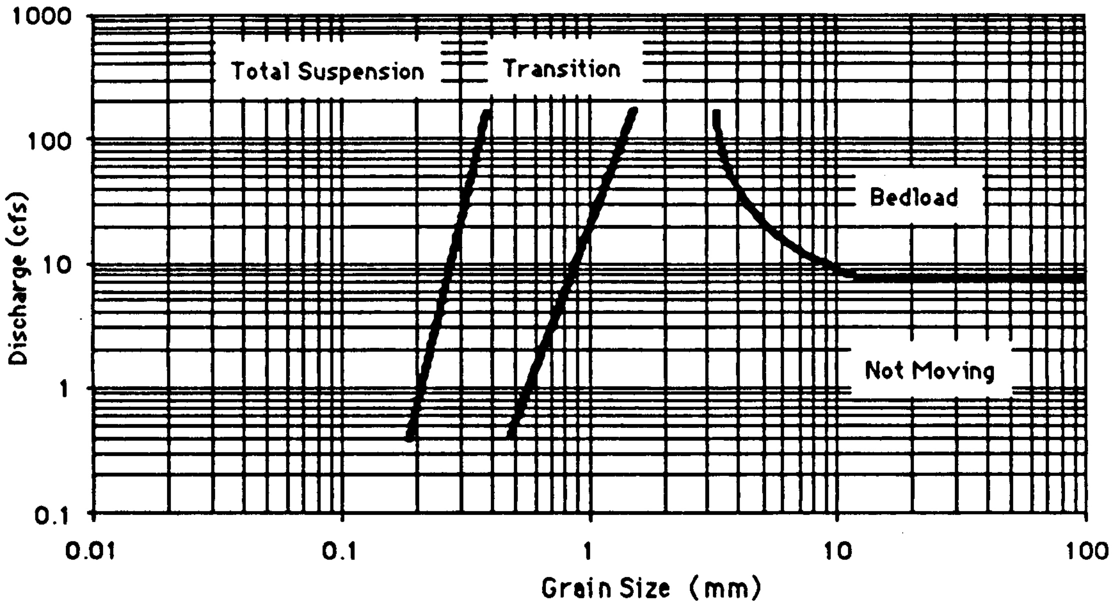


Figure 4.24 Sediment motion for poorly sorted sediments at station 28+00A, based on Wiberg and Smith (1987). Critical bottom shear stress for sediment motion is calculated using d_{50} as the length scale of the bed roughness (k_s). The sediment suspension criterion is given in Figure 4.25.

whereas the channel deposits are a poorly sorted mix of many sediment sizes. Studies by Parker and Klingeman (1982), Andrews (1983), and Wiberg and Smith (1987b) indicate that for poorly sorted sediment, gravels move long before Shields criterion indicates they would; the small grain sizes do not move until the coarse pavement begins to move. In poorly sorted substrate, large grains protrude farther into the flow and will roll or lift out of their pocket easier than a small grain that is sheltered from the current amongst the coarser bed material. The sediment motion equation of Wiberg and Smith (1987b) (Eq. B(7), Appendix B) accounts for this hiding factor in sediment motion and indicates the full range of gravel sizes will begin to move at about 7 to 10 cfs (Figure 4.24). The sand to fine gravel which is sheltered beneath the channel bed's coarse grained "pavement" will not move until the pavement begins to move. Equation B(13) (Appendix B) is used to determine what grain sizes are transported as suspended load in the interior of the flow, as bedload saltating and rolling on the bed, or is in the transition between these transport mechanisms (Figure 4.23 and 4.24).

Substrate along the main channel floodway of Channels A and C consists of a pavement of gravel, cobbles, and boulders. Below the surface pavement is a mixture of sand, gravel, and cobbles. At low stages (for example less than 3 cfs at cross section 28+00, bar level T1, Figure 4.12) flow is contained within the cobble/boulder portion of the cross section. The flow does not have access to the sand and gravel mixture of the bar deposits or the sand and silt of the channel banks. Only silt and fine sand less than 0.25 mm would be transported as suspended load if introduced from upstream (Figures 4.24 and 4.25). Grains less than 0.7 to 0.25 mm would be in transition between suspended and settling, they lodge in the cobbles and tend not to be resuspended. The Wiberg-Smith equation indicates the full range of pavement material will begin to move at 7 to 20 cfs, which corresponds to the channel full stage of the second flood bar level (T2, Figure 4.12). The second bar level was estimated to correspond to the bankfull discharge for the catchment based on vegetation and bar top condition. Based on the sediment motion equations, channel shape, and bar top conditions, the formative stage of the 2nd bar

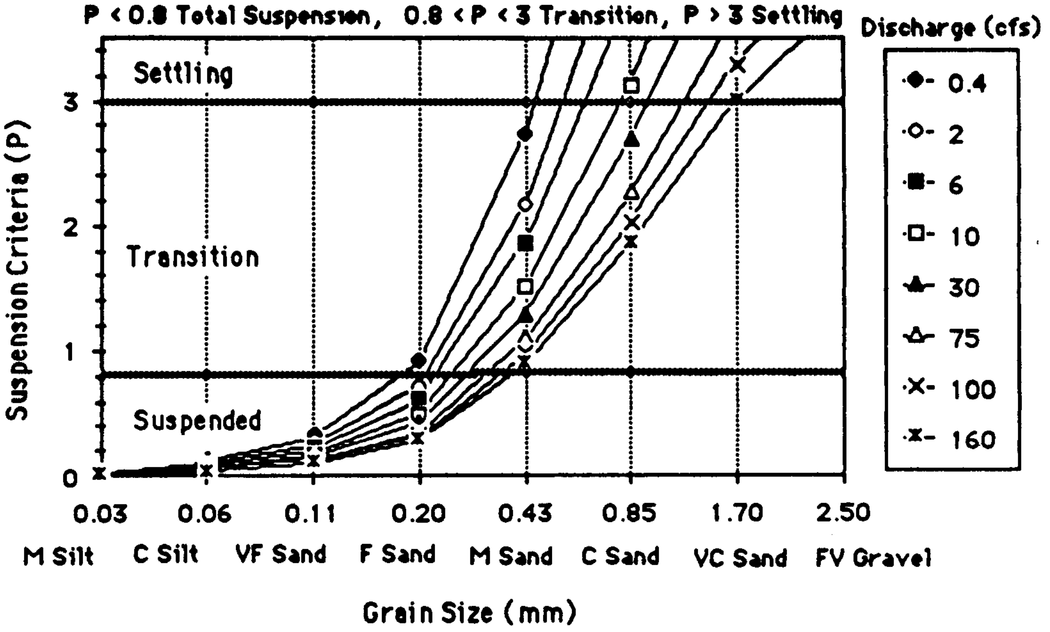


Figure 4.25 Suspended sediment at station 28+00A (WSD 4000A) for a range of discharges based on equation B(12), Appendix B.

level roughly corresponds to the 2 to 5 year recurrence interval flood event with a discharge rate of 7 to 20 cfs.

Initiation of sediment motion will occur sooner in the upper portions of main channels where discharge is similar to that at Station 28+00 (WSD 4000A) but slopes have increased from 3 degrees up to 10 degrees. Sediment sizes that are easily eroded in the upper channel segments will be less mobile on the upper alluvial fan (starting at WSD 4700A).

Both field observations of the channel deposits and the sediment motion calculations indicate silt, sand, and gravel-size sediment is very mobile in the upper and lower main channel at typical flood flows. Cobbles and boulders are mobile at the higher flood flow rates. Mobility decreases on the alluvial fan causing channel infilling and shifting. Channelization of the creek on the alluvial fan, to allow for public and private structures, virtually guarantees regular excavation maintenance of the channel will be needed. Increased transport rates that can be expected from unmitigated development will increase the channel maintenance requirements. Small storms can easily fill the culvert at West Snoqualmie Road with sediment. (Only 6 feet of infilling in the excavated channel is needed to bring the bed to the natural terrace level of the alluvial fan, resulting in the natural shifting channel of an alluvial fan.) At bankfull discharge and greater, the sediment discharge rate is controlled by the hydraulic conditions in the channel. This differs from the lower flow rates where sediment discharge rate is limited by the upstream supply. This indicates that sediment discharge can be controlled at lower flows by land erosion control measures but at flows above 7 cfs sediment discharge can only be controlled by controlling discharge.

Slope Stability

Slope stability is a concern along the plateau edges. King County ordinances require a minimum 25-feet setback to steep slopes. At most sites along the ravine this will keep the building footings in the compact till. However increased runoff created from clearing and drainage increases the potential for surface slides on the ravine hillslopes and edges of the 1st and 2nd-order channels. Three general cases of slide initiation were observed in the catchment: slides caused by channel incision, by point discharge of water onto the ravine slopes, and by debris from land clearing being pushed over the edge. Incision of the channels results in bank slumps and resulting loss of support of the slope surficial soil. With support at the base of the slope removed a translational slide can occur. The surficial material slides into the channel creating a low gradient fill of sediment and logs. Three low gradient fills of this type are present along Channel C. Two are related to translational bank slides; the third appears to be the remnants of an old crib dam. During the initial slope failure a temporary debris and log dam can form. The debris dam overtops and can result in a torrent. The Novelty channel is not steep enough to sustain a debris torrent but the resulting flood peak will be added to the ongoing flood flow resulting in bank erosion and increased sediment deposition on the alluvial fan. Residents have reported surges of increased discharge.

The building site at the east end of NE 102nd Street (Figure 4.3b) provides a good example of the effects of clearing along the ravine edges. The 5 acre lot was cleared to the edge of the ravine. The natural grade lines that remain around trees indicate that 1 foot of forest litter and the upper portion of loose soil has been removed. The loose soil was only 1 to 1.5 feet thick over the compact till unit. Cleared stumps and debris were pushed over the steep ravine edge. In storms the lawn water detention potential is quickly filled and water flows overland to the ravine edge. Yard drains were installed in an attempt to drain the standing water. As a result a 30 by 100 feet area of surface colluvium slid into the channel. When this slide was first observed in 1986 the freshly exposed till surface was rough. By 1987 a central rill had formed and will continue to erode from the surface runoff concentrated in the slide scar. Tension cracks in the loose surface colluvium and sidecast material indicate additional slumps are forming along the ravine edge. The material that slides and washes from this slope constricts the creek channel until floods erode the channel fill of sediment and logs. Trees from the slumps tend to jam up, causing stream sediment to fill in behind forming a wedge of temporarily stored sediment that is 4 to 6 feet deep by 50 to several hundred feet long. The elevated base level of the channel in this section brings flood flows into contact with new banks and leads to additional bank slumping.

4.10 IMPACT ZONES

Potential development related impact zones (Figure 4.26) are defined based on interpretation of the pre- and post-development process zones and quick storm response zones. The potential impact zones must be considered in the formulation of development guidelines, project designs, and mitigation options.

Lost potential water detention includes those areas where increased runoff can be expected because of clearing, grading, and drainage. Development related surface landslide potential occurs along the channels and plateau edges. At the plateau edge clearing of vegetation, grading, destruction of the litter zone, and point source discharge of water results in translational slides of the steep surface colluvium that overlies the compact glacial deposits. Slides along the channels occur when channel incision and bank erosion remove support at the base of slopes. In either case the resulting slide material that enters the channel forms a wedge of sediment and trees which is eroded gradually during floods. Additional erosion and bank slides occur because the elevated channel level exposes the banks to increased erosion. Development-related surface landslide potential results along the channels because increased peak discharge erodes steep channel banks, resulting in an increased frequency of slumping.

Sediment erosion and deposition potential is indicated for the entire channel system including the swales where ditches or clearings discharge. Increased sediment deposition is greatest on the alluvial fan where the transporting power of the creek is reduced.

4.11 INCORPORATION OF HYDROLOGIC PROCESS ZONE INFORMATION INTO IMPACT MITIGATION

Application of the method for identifying hydrologic process zones and estimating channel discharge and stability characteristics has been demonstrated in the previous sections. This information is used now to identify physical measures that would help to mitigate impacts of the changed catchment conditions. Mitigation measures are needed for urban, agriculture, and forest practices if undesirable downstream effects, as have occurred on the Novelty Catchment, are to be mitigated.

Stormwater detention ponds are one of the more common hydrologic mitigation measures used to control increased catchment flow production. Placement of detention/retention ponds on the plateau would mitigate increased runoff peaks and volumes, if detention volume and outlet controls are

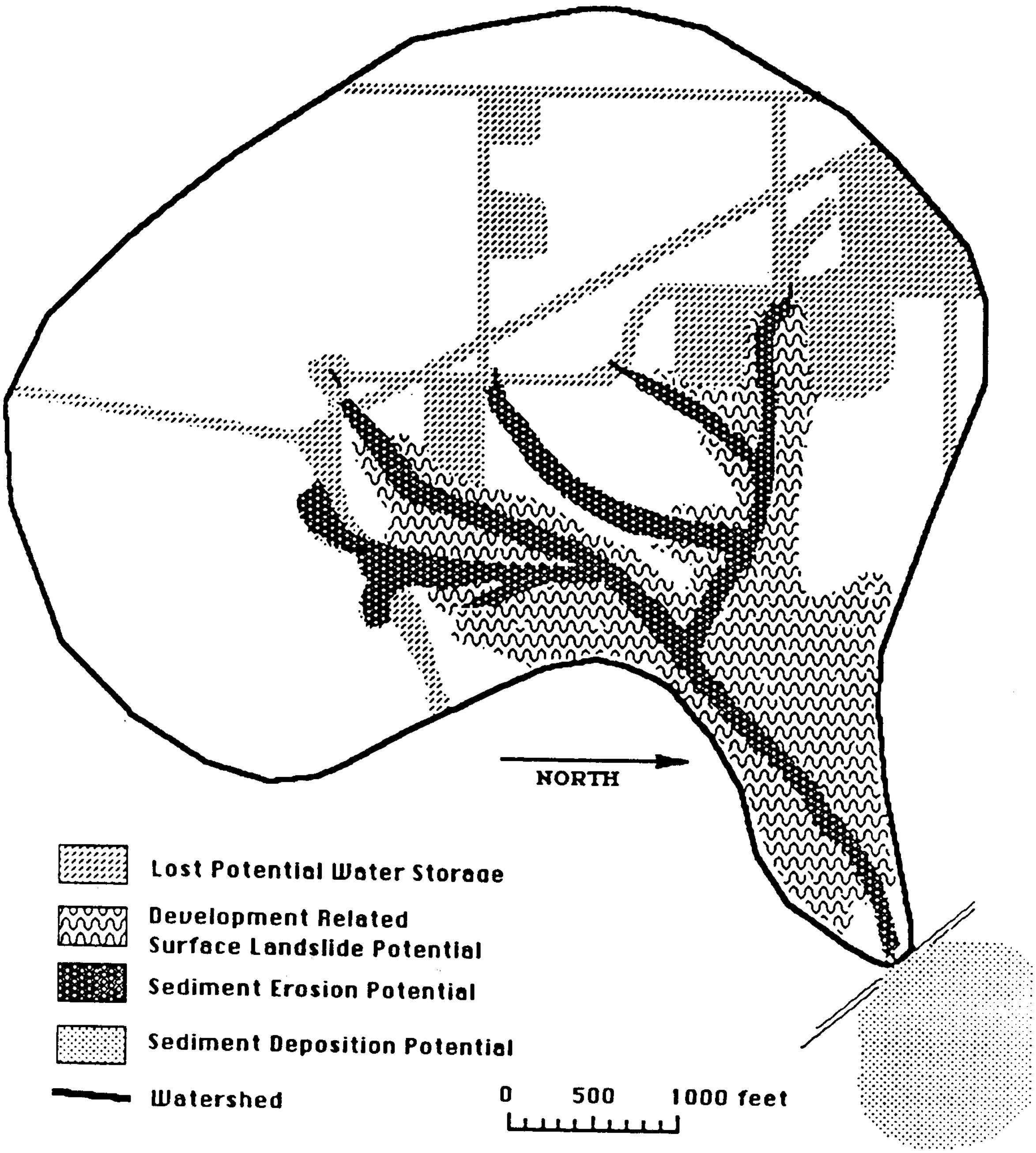


Figure 4.26 Development related impact zones.

adequately designed. Detention pond storage volume is usually sized to facilitate an allowable release rate. The allowable release rate is commonly based on estimates of pre- and post-runoff volumes. The accuracy of all known methods of estimating changes in runoff from ungaged basins is poor. Therefore, conservative sizing of detention/retention facilities should be used on catchments of this type because potential for channel erosion and downstream deposition is great and risks to downstream public safety and public works are present. Detention pond sizing for the Novelty Catchment should include the effective lost water detention because storage lost through development on the catchment's typical plateau soil profile is 4 times greater than the required detention storage volume calculated using existing county government surface water management guidelines. Based on lost water detention volume the pond for a typical 5-acre apartment complex would need to be 93 feet square by 5 feet deep (3.9% of the 5-acre lot) rather than 42 feet square by 5 feet deep (0.8% of the lot) as required by King County guidelines (Stoker, 1988). The required detention volume based on the King County guidelines (King County, 1979a,b) is equivalent to 0.5 inch (1.2 cm) spread over the 5-acre area, required storage is equivalent to 2.4 inches (6 cm) spread over the development if based on the estimated lost soil water detention volume alone. In addition to lost litter and soil water detention, catchment development results in reduced evapotranspiration. Rainfall that would have been stored in the forest litter and soil, in the pre-developed condition, no longer has the opportunity for removal by evapotranspiration because it quickly runs off.

Even when estimated by the simple and conservative methods utilized here, it is apparent that requiring replacement of lost water detention volume may involve a considerable increase in land area devoted to runoff mitigation. Larger detention facilities will allow for hydrologic uncertainty and potentially remove more pollutants by longer retention times.

A down-stream analysis is essential to determine if the channel network is adequate to convey additional runoff from development projects. Stability of the channel must also be assessed. Channel incision and increased sediment transport will result if discharge rates exceed the threshold of sediment motion for the channel. The frequency of peak discharges that are above the estimated threshold of sediment motion should be limited to a level comparable to the estimated pre-development frequency. Determining the spatial extent and locations of hydrologic process zones assists in selection of the most appropriate model to use and facilitates selection of appropriate parameter ranges and modifications. For example, the dominant processes on the pre-development Novelty Catchment indicate the partial area rational formula (Appendix G) may be appropriate because quick response runoff is only produced from rainfall on the saturated areas of the catchment.

Long duration cumulative discharge to a channel from all feeder detention ponds should be limited at or below the limiting threshold flow rate that causes sediment motion. Estimated allowable discharge rates for Channel "A" of the Novelty Catchment are given in Figure 4.27. These rates are based on estimated pre-development channel capacities from Table 4.2, present channel cross-sections, the estimated threshold of sediment motion calculated using the method outlined in Appendix B, and by assuming the bankfull discharge is near the sediment motion threshold.

The allowable release rate for the sum of all plateau releases into the main channel, based on estimated pre-development conditions, is 5 cfs. Based on the 1987 channel dimensions the allowable release rate is 9 cfs. Detention/retention ponds at each point discharge from developed areas are needed to reduce quick runoff peaks. Outlet control should maintain long-duration cumulative pond releases to below the indicated channel sediment motion threshold.

Baseflow discharge peaks generated from an earlier portion of a storm can coincide with later high intensity rainfall periods giving rise to the largest storm peaks from the catchment. In a similar manner delay of quick response storm runoff by detention facilities can delay the hydrograph peak to coincide with the basin return flow peak and result in a larger peak flow than estimated (Hardt and Burges, 1976). Several detention ponds feeding on the same channel, if not designed in an integrated manner, can also result in increased peaks.

Flood routing and estimates of channel capacities based on flood bar and terrace levels can be improved by measuring channel geometry and discharge and back calculating the roughness coefficient. This roughness value is used to guide selection of the roughness value for unobserved stages.

Several new home sites in the Novelty catchment demonstrate the need for enforceable buffer zones along the plateau edge. Home builders clear the trees, brush, and forest litter to make graded lawns to the ravine edges. Resulting overland flow and loss of soil stability cause small slumps and washouts that can grow into damaging hillslope failures. Locations where surface runoff is created and in particular areas where surface discharge did not previously exist need some form of channel armor or conduit to prevent erosion. Point discharges from 4 inch diameter yard drains onto the steep ravine slopes cause washouts and further aggravate channel sedimentation. Point discharges on steep slopes requires flexible pipe or channel armor extended beyond the base of the slope or should be made into retention or infiltration facilities that can reduce discharge below the erosion threshold of the channel or slope.

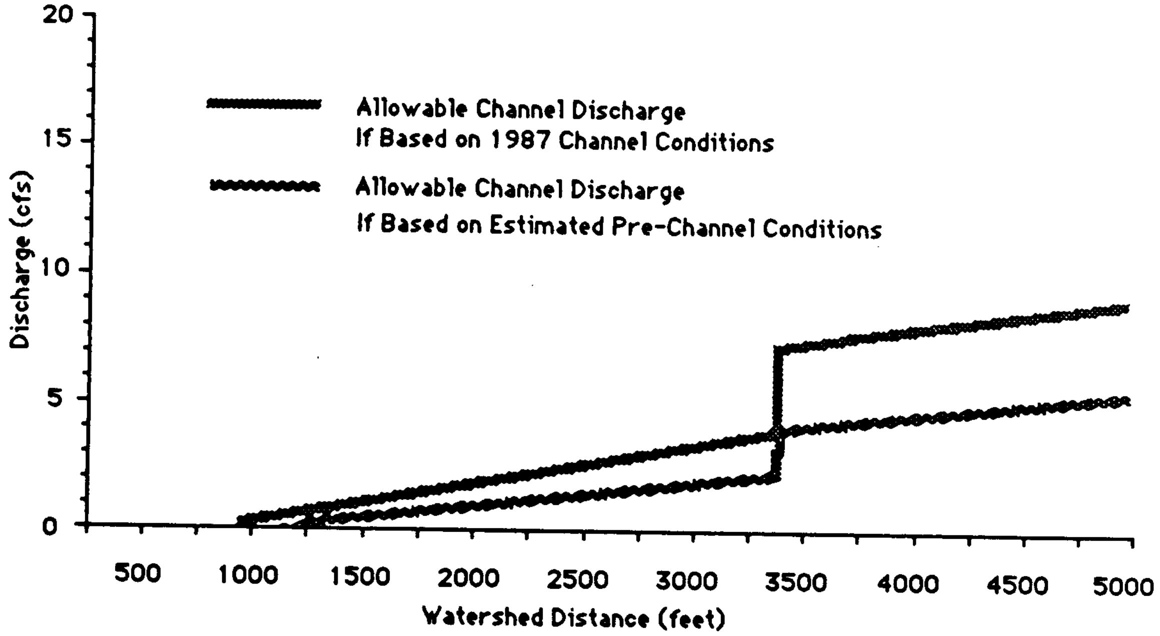


Figure 4.27 Estimated discharge rates for channel A vs. watershed distance for which erosion of channel substrate and banks is minimized .

Side casting of material into swale heads and over the edge of the steep ravine slopes has occurred in several locations, resulting in erosion and slumping directly into the channel. Silt fence construction can provide a clear visual barrier for equipment operators as well as potential erosion protection during construction.

Vegetation buffer strips, that are adequate to maintain slope stability, prevent surface erosion, and disperse water concentrated in developed areas are needed along creek channels, swales, and steep slopes. In some cases a minimum undisturbed vegetation buffer of 50 feet or more from steep slopes may be appropriate to absorb post-development overland runoff from yards and pastures.

4.12 SUMMARY

We have demonstrated how a catchment can be described hydrologically to ensure that after it is urbanized the spatial sources of channel flow remain largely as they would have been in the unchanged state. Apart from limited use of some rainfall data observed at nearby stations, all data for relevant mitigation measures are determined from maps and field measurements. Land surface hydrologic process zones indicate where channel flow originates in the catchment. Limited measurements of channel properties (sections, strata, and grain size distributions) indicate the magnitudes of design flow rates to be maintained throughout the channel system to avoid changes to sediment movement, channel degradation and deposition.

The maps, graphs, and quantitative analyses were all done manually. The information used in constructing process zone maps and various graphs can be systematized and stored in a more accessible fashion and be amenable to updating as more detailed examinations of the catchment are made preparatory to change. In Chapter 5 we report on aspects of a Geographic Information System (GIS) used for this purpose.

The most quantitative aspects of the hydrologic flux rates in this chapter are found for channel flow. We pursue land aspects of flow production quantitatively with a simple spatially distributed model in Chapter 6. This spatial model of process zones uses information developed from the GIS data base.

CHAPTER 5 A GEOGRAPHIC INFORMATION SYSTEM FOR HYDROLOGIC ANALYSIS

5.1 INTRODUCTION

A geographical information system (GIS) is a computerized graphics and data base system (hardware and software) for the storage and analysis of land-related information. It is most often characterized as a combination of computer aided drafting (CAD) and database management system (DBMS). The differences between a GIS and CAD system are worth noting, however.

The main difference between CAD and GIS lies in their different approaches to data structure. Both CAD and GIS drawings are made up of primitive graphical elements which can be grouped into logical blocks. Both have data base capabilities, that is, the elements or blocks can be given data attributes. What separates GIS from CAD is that the GIS keeps track of containment and connectedness of the graphical elements (Dangermond, 1986). Simply put, a GIS has a topological data structure, while CAD does not. By generating topology, a GIS is able to perform complex relational operations on and between separate maps.

We elected to use a commercial GIS (ARC/INFO) after exploring attributes and limitations of CAD and GIS systems as well as recently developed software for analyzing digital terrain data for certain hydrologic applications. The dominant advantage of GIS structures lies in their relational forms which permit ready creation of maps (coverages) that are the intersections or unions of many other attributes. CAD systems have much less flexibility in this important feature. The limitations we identified have been described recently for land use and building inventories (Tyson, 1989) and for transportation planning (Simkowitz, 1989). In the latter instance, Simkowitz emphasis the value of the multi attribute storage and map creation capabilities of a GIS. What is true for transportation planning is more so for urban hydrology where spatial representation of structures, vegetation, soil types, etc. is crucial to hydrologic analysis and design of mitigative measures.

In the remainder of this chapter we describe salient features of a GIS (ARC/INFO) and procedures used to create relevant maps for hydrologic analysis. Use of ARC/INFO is illustrated by creating maps for the example catchment described in Chapter 4. Additional information was used to define elevations and road locations more precisely and to delineate subcatchment boundaries. Typical maps of feature coverages are provided to illustrate some of the capabilities of the GIS. The maps were created after expending the considerable effort needed to develop the data bases from which they are constructed.

5.2 FUNDAMENTAL OPERATIONS OF A GIS

Geographical information systems are, for the most part, general-purpose systems. They offer procedures for use in land-use planning, resource planning, and facilities inventory and management, to name a few (Dangermond, 1988). The most basic graphical GIS operations, length and area calculations, are fundamental to hydrologic analysis. The database management facilities of a GIS are also useful for keeping track of tables of land-based information needed for hydrologic analysis (Rennick, 1986). Other GIS procedures that are useful in hydrologic analysis include interactive query, overlay map generation, map matching, interactive editing, and map updating. Each of these procedures is defined and described below; we have chosen to use general rather than software specific terms.

Interactive Query

Interactive query involves identifying the feature of interest on the display and asking the system for the desired information related to that feature (Burrough, 1987). For example, one might give a command, point to a polygon, and receive the area of that polygon. In a more complicated (and more useful) example, one might issue a command, point to a polygon describing a subbasin, and receive a table of slope ranges and the areas represented by each range. Alternatively one might point to a stream reach or a graphic screen display and receive tabular information describing that reach including length, slope, roughness, bank-full cross-sectional area, and subbasin area. All these data must be collected in the field, verified, added to the data base, and the data base checked for entry and classification accuracy.

Overlay Map Generation

Map overlay operations are the dominant reason for existence of geographical information systems. These operations include procedures from McHargian overlay analysis to set theory. McHarg developed procedures in the 1960's for graphical land use suitability analysis (McHarg, 1969). In the most basic example, the proposed use might be a new county fairgrounds. Thematic maps of interest might include soil types, slopes, vegetative cover, and land use. Each map is shaded on clear drafting film, the lightness of the shading being directly related to the proposed use's suitability based on that map's theme. A clear area represents no constraint, while a black area represents absolute unsuitability. When all of the maps are prepared they are laid on each other, and the light areas are examined in further detail for the possibility of development into a fairgrounds. (A CAD system could prepare each map; a GIS scheme provides the integrated single desired composite overlay).

Set theory includes Boolean operations between entities. These include the "and" (intersection), "or" (union), and "not" functions of symbolic logic. Venn diagrams provide a simple way of visualizing these functions. These functions are applied in various forms and combinations in GIS overlay generation (Robinove, 1986).

Map Matching

Map matching is the joining of two separate, adjacent maps at the edges. This is a much more complicated task than it may seem. The problem of map matching has received much attention since the widespread automation of mapmaking. A human can lay two U.S. Geological Survey (USGS) quadrangle maps side by side and easily reconcile the differences between the two at the edges. One simply matches the corresponding feature lines on the two maps and averages the differences, if any. This kind of spatial averaging is easy for a human, but very difficult to program into a machine. Automated map matching is a necessity, or the benefits of automated mapping and overlay analysis may be defeated by conflicting information (discontinuities) at map edges (Burrough, 1986).

Interactive Editing

Interactive editing is a mode of changing or updating map information that appears on an existing digital map. Typically this involves having the map drawn on a video screen and adding or moving graphical elements (Burrough, 1986).

Map Updating

Map updating entails extracting an area of interest, refining its features, and putting it back in its original place. In a system of overlay maps, some information may be contained in more than one map. The propagation of changes through the overlay hierarchy should be as automatic as possible. Batch processing capabilities are helpful in automating often-used strings of operations.

5.3 DATA NEEDS, SOURCES, AND QUALITY

For hydrologic analysis data needs generally include maps of topography, soils, hydrography, geodetic control, and land cover. Data sources, described in Section 3.2, include aerial photo surveys, field work, USGS quadrangle maps, "as-built" construction documents, and Soil Conservation Service publications. Geodetic control should be based on control points that can be located in the field. Section and quarter-section corners, which are part of the Public Lands Survey System, are convenient control points (Bauer, 1987). County Assessor's maps usually contain distances and bearings of dwellings between section and quarter-section corners.

Digital topographical data are becoming more readily available, useful, and complete. US Geodata, a branch of the USGS Mapping Division that distributes digital quadrangle maps, has digital elevation data, hydrography, roads, and political boundaries at several scales: 1:24,000; 1:100,000; 1:250,000; and 1:2,000,000 (Jannace, 1987). Unfortunately, not all themes are available yet. The digital elevation data is in a grid format, while the other data is in vector format. A GIS requires most of its data base to be in polygon (topological) format, so considerable translation is needed to convert digital elevation data to formats useful with a GIS.

Information quality is important in any kind of mapping scheme. It is of special importance in a GIS because a user may need to zoom in on any portion of a map, regardless of the original scale of the work. National map accuracy standards call for an accuracy of one fiftieth of an inch at map scale, for map scales of 1:20,000 and smaller (NRC, 1983). For example, features drawn on a map at a scale of 1:24,000 (1 inch = 2000 feet) have a positional accuracy of plus or minus 40 feet. On a paper map the user cannot zoom in to take a closer look at an area of a map, so accuracy can be assumed from the size of the map. A computer map, however, can be printed or perused at almost any scale, so it is important to know the effective original scale of the map.

The Canadian Council on Surveying and Mapping breaks information quality into 5 categories (Lodwick and Feutchwanger, 1987). These are accuracy, precision, resolution, up-to-dateness, and completeness.

Accuracy:	Accuracy is the degree of exactness of the data or feature positions.
Precision:	Precision deals with the degree of exactness with which the data are expressed.
Resolution:	Resolution is the smallest distance two entities can be separated and still be identified as individual entities.

Up-to-dateness:	Up-to-dateness is the degree to which the data represent the current state. (A temporal hierarchy in the GIS is a convenient way to record data age).
Completeness:	Completeness is the degree to which the data have been collected.

5.4 APPLICATION OF ARC/INFO TO MAPPING FEATURES OF NOVELTY CATCHMENT

In ARC/INFO the spatial and thematic data are organized into layers called coverages (ESRI, 1988 a,b). Each coverage contains information on one or several themes, for example, roads or streams. A coverage can be combined with other coverages in many ways -- by union, intersection, and updating, to name a few -- to produce a new coverage.

There are three basic coverages in the ARC/INFO system: point, line, and polygon. Point coverages are for things that require only a set of coordinates to describe their spatial position and extent. Line coverages represent things that are best represented one-dimensionally, centerlines for example. The lengths of features are automatically calculated for line coverages. Polygon coverages are for things that require an areal extent for their depiction. Feature areas and perimeters are automatically calculated for polygon coverages.

5.4.1 Organization of Coverages

Coverages were organized in this example to make any changes or updates as easy as possible to propagate through the other coverages that may be affected by such change. The coverages developed include the base map, basin boundary, stream centerlines, wetlands, subbasin boundaries, soils, lawn and pasture areas, road centerlines, and powerline centerlines. These coverages are independent, self-contained representations of one feature class. Coverages derived from these basic coverages include streams, slopes, surface cover, roads, powerlines, and composite. The organizational hierarchy reflects the steps needed to develop derivative coverages that are needed for hydrologic mapping, modeling, and mitigation scheme development.

Most conventional mapping systems use topography and hydrography as the base map. An alternative and better scheme for digital mapping of base map information is geodetic control. The base map for this example is simply the set of quarter-section corners contained in the immediate area of the novelty catchment. The catchment is only half of a square mile, yet portions of it fall into six quarter-sections, thus there are 12 points that make up the base map. Assessor's maps were the source of the bearings and distances of the quarter-section lines. One corner was chosen arbitrarily as the origin, and the coordinates for the other corners were calculated using plane geometry.

Streams

The stream channel network was broken into reaches and entered as a line coverage and then transformed into a polygon coverage. A stream reach is defined by endpoints or confluence points. Reaches were broken up further based on differences in gradient. Attributes for this coverage include length, width, slope, stream type (natural, altered, constructed), roughness, and an estimate of bankfull capacity. All these attributes were obtained from the field mapping described in Chapter 4.

The GIS generated the stream polygons based on the table of widths in the stream centerline coverage. The stream polygon coverage was used only for generation of the surface cover and composite coverages. The stream centerline coverage was still useful because the connectivity of the stream network is encoded in the line coverage better than in the polygon coverage.

The post-development streams coverage includes two new stream types, "ditch" and "culvert". The post-development coverage was generated in interactive edit mode, with the ditches added parallel to the roads. Feature attributes such as slope and width were taken from the "as built" construction documents and entered manually. A polygonal stream coverage was then generated in the same way as in the pre-development case.

Wetlands

Wetlands areas were identified and mapped in the field (Chapter 4). The wetlands were entered into a separate polygonal coverage. The surface-type of "wetland" was assigned to each of the wetland polygons.

Subbasins

Subbasins were delineated for each reach of stream channel (Chapter 4). More detailed delineations were based on conventional map analysis where detailed surveying information was available. The 1:2400 scale, 5-ft contour interval, "as-built" County construction documents for the plat were used to refine subbasin boundaries for most of the plateau area. As the plat did not cover the entire basin, the next best available topographic maps, the USGS 7 1/2 minute quadrangle maps (1:24,000, 20, and 25 ft. contour intervals), were used. (The basin is about one half square mile and occupies part of two quadrangles. One quad's contour interval is 20 feet, while the other's is 25 feet.) The paper subbasin map was then digitized into the "subbasins" coverage. Each of the eight subbasins delineated was assigned a subbasin identification number .

The subbasins were redefined by the road layout, causing the post-development coverage to differ from the pre-development condition. Some road high-points were not located at the original ground high-points, causing some redirection of any surface flow. This is most obvious in the two subbasins located in the North-West portion of the catchment as indicated in Figure 5.1. Three derivative maps are presented in this chapter. In each instance the pre- and post-development case is shown for immediate comparison of changes in the catchment.

Soils

There are two soil types present in the vicinity of the novelty catchment. Soils were entered as a polygon coverage and each polygon was assigned its soil type. Other soil attributes include soil thickness and litter zone thickness. The soil polygons were made to extend far beyond the actual study basin boundary. There is no reason to include the basin boundary in more than one coverage. When necessary, the surplus can be trimmed with a simple intersection ("and") command.

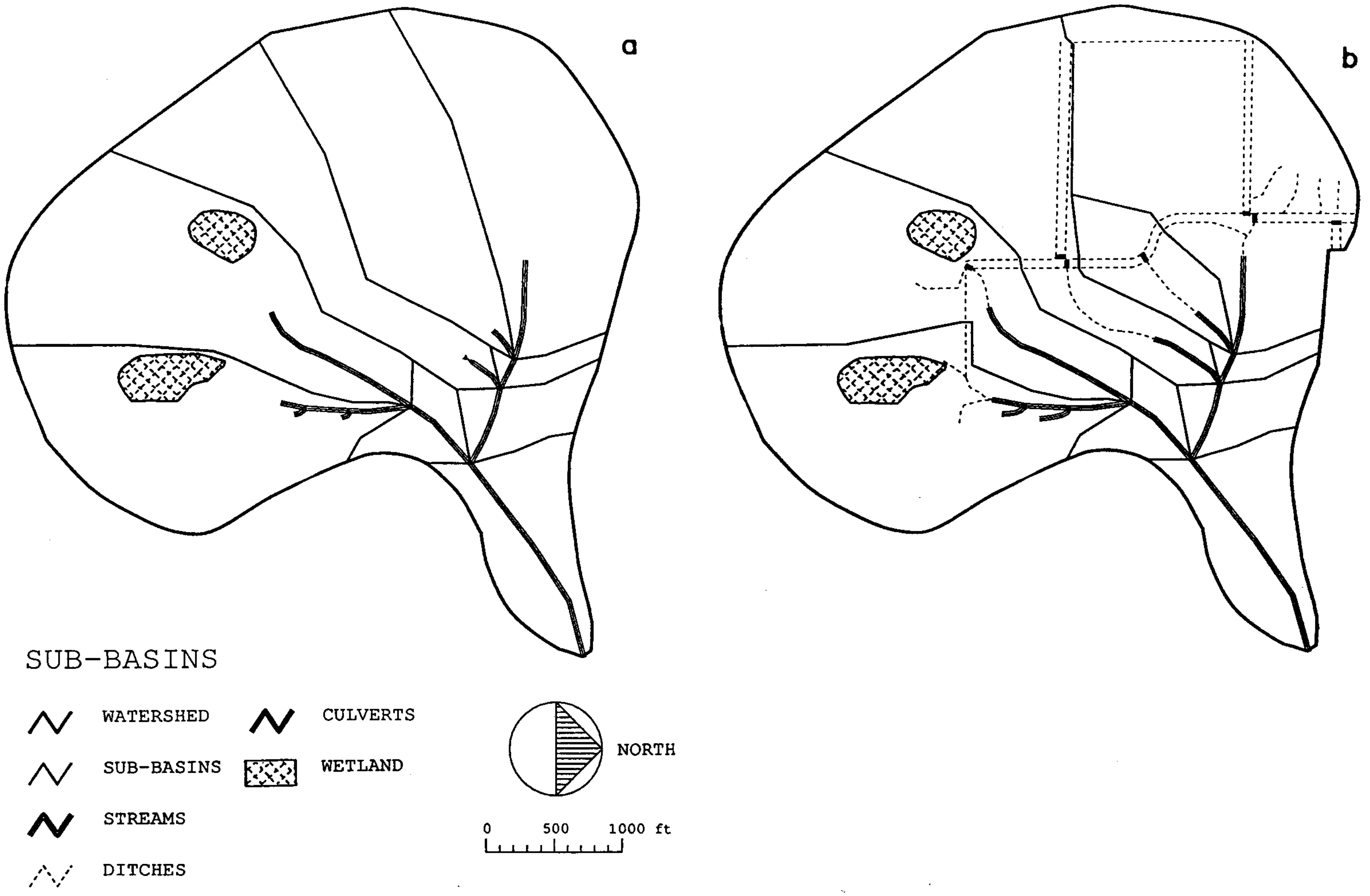


Figure 5.1 Subbasins created using ARC-INFO (a) pre-development, (b) post-development.

Lawn and Pasture

Aerial photography and field work were used to derive vegetative cover type. The County Assessor's maps helped to locate the lawn and pasture areas because these areas tended to be bound by property lines. These features were input to a polygon coverage and assigned the surface-type of "lawn/pasture."

Roads

The "as-built" construction documents were used to locate the correct map positions of the roads in the catchment. Digitizing the road locations from Figure 4.8b would have been much faster and easier, but it would have caused a degradation in positional accuracy. Furthermore, the accurately surveyed road layout served as a convenient positional backbone for the whole catchment, due to its high positional accuracy. Attributes assigned to road segments include width, road-type, surface-type, and name.

The road centerlines coverage was used to generate a polygonal road coverage much as the streams coverage was generated. The other attributes associated with the road centerlines were transferred to this coverage, making previous coverages obsolete. The roads vary from 10 feet wide gravel logging roads to paved two-lane streets of 38 feet width (including shoulders). Pavement and shoulder were lumped together as "impervious" for simplicity.

Powerlines

Powerline centerlines were entered in the same way the road centerlines were. The powerlines represent a wide swath of grassy surface (the forest litter has been removed) through the forest. The powerline easement was assigned a surface type of "lawn/pasture" because the well-maintained grassy vegetation functions hydrologically similarly to lawn or pasture.

Slopes

To display pre- and post-development "slopes coverage", the hierarchy of coverages described previously had to be created before "slopes" could be created. Attributes from "streams", "wet lands", "subbasins", "lawn/pasture and "road" coverages are needed to generate "slopes".

Newer versions of ARC/INFO have a triangulated irregular network package for the modeling of elevation information. This was not available when we made our maps so a similar type of elevation model was improvised. The surface of the catchment was broken into flat polygons, much like the faceted surface of a cut gemstone. Each polygon has two attributes: gradient, and direction.

The slopes coverage was crafted so subbasins could be extracted easily; the subbasins coverage represented the finest step in the derivation of the slopes coverage, since subbasin boundaries represent breaks in grade. Other convenient breaks in grade include the stream channel and the ravine edge. First a copy was made of the basemap, then subbasins and stream centerlines were copied onto the map and the ravine edge was digitized. The resulting polygons were further subdivided to fit the faceted model surface to the catchment topography.

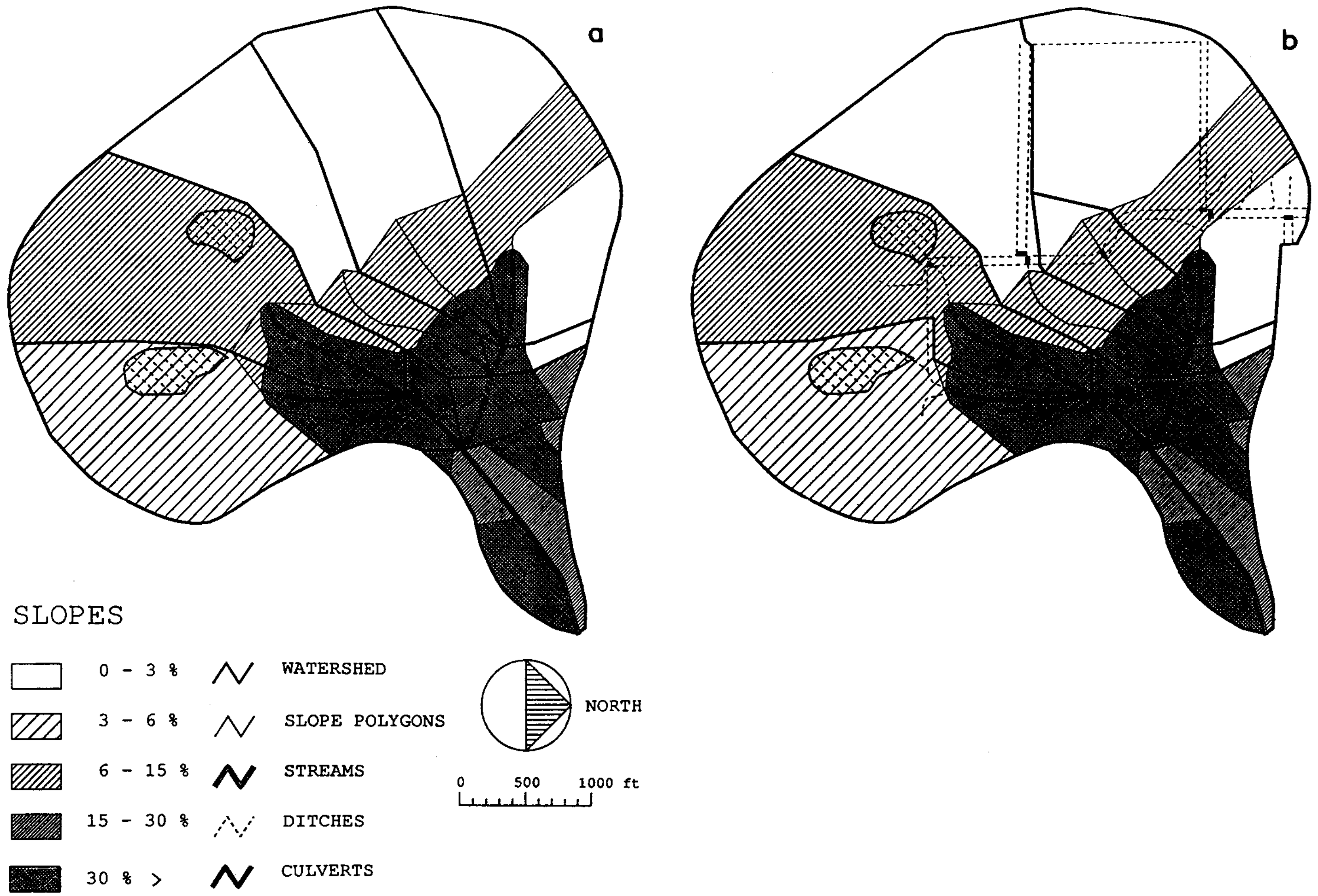


Figure 5.2 Slopes coverage (with "wetlands" superposed) (a) pre-development, (b) post-development.

The original subbasins coverage is now obsolete because all of the information in it is now in the slopes coverage as well. Since each slope polygon has a subbasin identification number, the GIS can treat this coverage as either a collection of eight subbasin polygons or 44 slope polygons, depending on the intents and purposes of the user. The slopes for the pre-development catchment are shown in Figure 5.2. Relatively coarse ranges of slope are used; higher resolution would result in many more than 44 polygons for this 320 acre catchment. If detailed representation of a subcatchment is needed, more polygons for the subcatchment can be created in a new coverage which supersedes the previous coverage for that subcatchment because all previous information is contained in the latest coverage.

The post-development slopes coverage differs from the pre-development coverage in that some of the subbasin boundaries are different in the post-development case. The post-development coverage was generated in interactive edit mode with the post-development case subbasins in the background. A few nodes and vertices were moved around and "snapped" to the background coverage. If ARC/INFO understood English the "snap" command would have been, "move these vertices on the slopes coverage to the exact positions of those vertices on the subbasin coverage."

Surface Cover

The surface cover coverage is the final derived coveraged we illustrate. The basin boundary, streams, powerlines, wetlands, lawn/pasture, and roads coverages were combined to make this coverage. The derivation followed seven steps.

1. The entire catchment was taken to be forested. The coverage had just one polygon, described by the basin boundary, and this polygon was assigned a surface type of "forest".

2. The powerline swath was superimposed on the forest. Now there are several forest polygons and a lawn/pasture polygon.

3. Wetlands were superimposed next.

4. Lawn and pasture areas from residential development were superimposed next. There were no intersections of lawn and pasture with wetland. Which type would dominate in a map intersection would depend on map usage.

5. The stream polygons were superimposed next. In the pre-development case there were no intersections of stream with anything but forest, but in the post-development case, roadside ditches intersected powerline and lawn/pasture areas. In such cases the "ditch" surface type takes precedence, so the stream coverage was overlaid after the others.

6. Roads were superimposed last, because they take precedence over all other surface-types. For example, the intersection of a road area with the powerline area results in a road surface type, and the intersection of a road and stream (actually a culvert) results in a road surface type.

7. Finally, any areas falling outside the basin boundary were trimmed by using the slopes coverage boundary (intersection) much as a pastry chief uses a cookie-cutter.

A distinct hierarchical organization of coverages is used to make the surface cover coverage. At each step the evolving coverage was updated by a more strongly expressed (user defined) surface type. The GIS operations used to make this coverage are different from those used to generate the slopes coverage. The only manual activity required in this operation was in making sure the data files associated with the coverages were in identical format so the GIS could merge them. The resulting surface cover maps are shown in Figure 5.3.

Composite

We developed a final coverage (maps are not included here because of size limitations) which is a composite of everything else. Surface cover, slopes, and soils were combined into a final coverage of hundreds of polygons, each with its attributes of area, slope, surface-type, soil-type, and subbasin identification number. The only manual work involved here was in ensuring that the data files associated with the coverages were in a compatible format.

5.4.2 Data Input and Output Considerations for Hydrologic Modeling

Data tables were generated for input into a simple distributed hydrologic model (Chapter 6). Areas, slopes, surface types, soil types, and channel characteristics were compiled automatically by the GIS. Surface flow path lengths were determined in interactive query mode, and manually compiled. The output was directed to a file which was transferred to a personal computer and imported into a spreadsheet program for a slight modification in format before input into the computer model. At present the GIS is not structured for developing output files for use with hydrologic models. Each hydrologic model has a particular input data format, hence the need for intermediate steps in data manipulation.

There are many ways the data associated with the study catchment could have been entered into ARC/INFO and analyzed. This example was developed using five guidelines:

1. Keep it simple
2. Avoid redundancy
3. Make the computer do as much of the work as possible
4. Make the data base and maps easy to revise or update
5. Make it modular -- based on hydrologic units (subbasins)

In the interests of numbers 2 and 4, the study basin's boundary was stored in only one of the basic coverages, the slopes coverage. the soils, roads, and powerlines coverages were made to extend beyond the limits of the watershed. Derived coverages were trimmed of areas outside the watershed by a simple command. There are two important benefits of this approach. First any revisions to the basin boundary need to be performed on only one coverage -- slopes. Secondly the annoying insidious problem of "slivers" is avoided. Slivers are long, skinny, anomalous polygons that occur in overlays when two lines from different coverages that should be coincident are not. There are procedures designed to expunge slivers; however, the simplest approach is to prevent their occurrence.

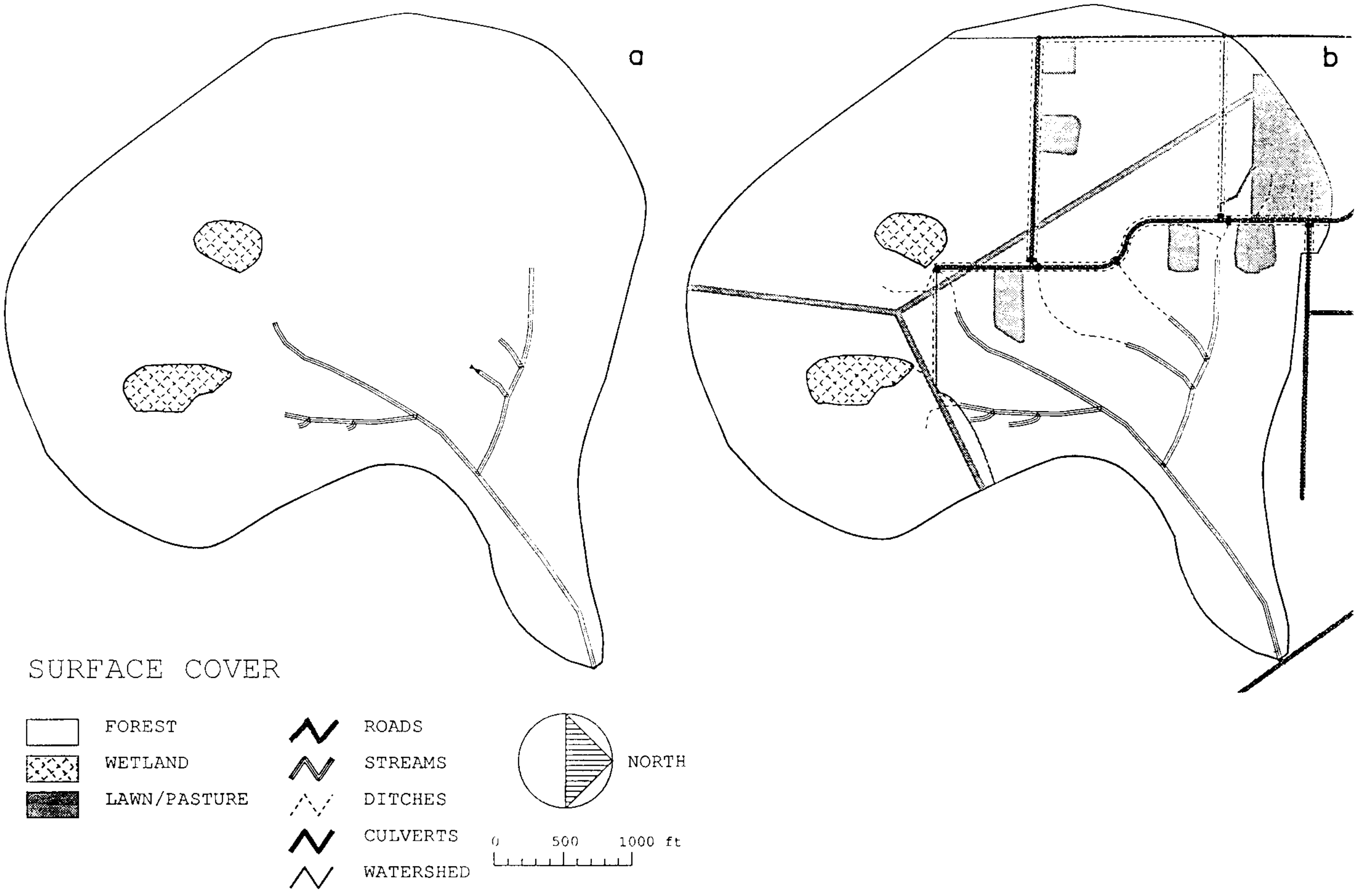


Figure 5.3 Derivative map of land surface cover (a) pre-development, (b) post-development.

This system is set up so refinements can be made to, say, the wetlands, coverage for example, without requiring extensive manual work to propagate those changes down to the composite coverage. Although there are several steps involved in making the surface cover and composite coverages, these steps can be automated by using macro files. A macro file is much like a batch file. It is nothing but a line-by-line series of commands just as they would be entered in the usual prompt mode. Propagation of changes to the wetland coverage can be carried out in just three steps. First make the changes to the wetlands coverage. Then run the macro file to regenerate surface cover. Finally run the macro file to regenerate the composite coverage. The last two steps could be combined into one macro if desired.

5.5 SUMMARY OBSERVATIONS

Besides learning how to use the software the most difficult parts of this exercise were in the operations that had to be done manually. There was considerable manual work involved in generating the pre-development slopes coverage. Some kind of automated digital elevation scheme would be preferable. For maximum usefulness in hydrologic analysis, though, the digital elevation scheme should provide for extraction of whole subbasins. That is, slope polygons, if used, should be bound at subbasin divides.

Like any powerful computer software package, ARC/INFO takes a great investment of time to learn to use with confidence and efficiency. Using either the tutorial examples or a short course introduction, an experience computer user might achieve a useful understanding of the command syntax of ARC/INFO in about two weeks of full-time study. As a starting point, an understanding of what the software can and cannot do is essential. If one knows what one wants to do, and knows that the software can do it, one can figure out how to get the software to do it. At the present state of rapid development of GIS schemes, there are still limitations on what they can do. They have enormous power in ordering information hierarchically and permitting it to be blended with other coverages developed for other land use and inventory purposes. Some specific purpose programs will be needed for extracting information for other than thematic purposes.

CHAPTER 6 DEVELOPMENT AND APPLICATION OF A SPATIAL MODEL FOR EVALUATING HYDROLOGIC CHANGE

6.1 INTRODUCTION

Field mapping delineates the average areal extent or wet condition extent of flow production zones. Identification and quantification of flow rates from production zones and the locations where flows are delivered to channels is critical to understanding catchment dynamics from the point of mitigating the hydrologic impacts of urbanization.

To our knowledge, there is no readily available model that can incorporate all relevant hydrologic processes when catchment development is to be evaluated. We have developed an approximate model for use in such circumstances to demonstrate relative impacts. The model simulates flux rates and spatial distributions of evapotranspiration, Horton (infiltration excess) overland flow, saturated overland flow, subsurface storm flow, and dry weather base flow. It is continuous, allowing changes in mass balance to be estimated. The model is for use in both ungauged and gauged catchments, and has parameters that are readily measured or estimated.

A brief description of the general model structure and its major components is given. The complete structure and equations are given in Appendix H. The model is then applied to an example subbasin within the Novelty catchment to illustrate it's use in a catchment undergoing land use change. Of particular importance is the model's spatial (and temporal) representation of runoff mechanisms and the physical basis of input parameters which allow application in ungauged catchments. This is followed by a discussion of simulation results, including model use in hydrologic design and land use planning.

6.2 MODEL STRUCTURE

A schematic representation of the model is given in Figure 6.1. The model structure allows explicit use of readily obtainable field measurements (e.g. litter zone depth, soil depth, water table elevations, extent of saturated zone, etc.) for input and calibration. The model consists of a rainfall preprocessor and seven components which simulate canopy interception; evapotranspiration; infiltration; and surface, litter, unsaturated, and saturated flow dynamics.

In application, the catchment to be modeled is divided into subareas based on soil type and depth, vegetation type, topography, and field mapped hydrologic process zones. Within each subbasin the quantities and areal locations of Horton, subsurface, and saturated overland flow are simulated. An approximate calibration is achieved by comparing the location of simulated runoff production zones against the field mapped locations. Each subbasin is modeled separately as a single plane surface and the results from all subbasins are combined using a simple physically-based routing scheme.

Rainfall is processed one month at a time, allowing a variable time-step to be used based on rainfall intensity and a corresponding antecedent precipitation index. The use of six time-step lengths, ranging from 6 minutes to 24 hours was found to produce satisfactory results. Our choice of 6 minutes during storms is based on hillslope simulations conducted by Gan (1988) where various surface flow mechanisms occur. Interception loss is simulated by an interception storage capacity based on canopy type. All rainfall is assumed to enter interception storage until it is full. Interception storage is depleted by evaporation at the potential rate until reduced to zero.

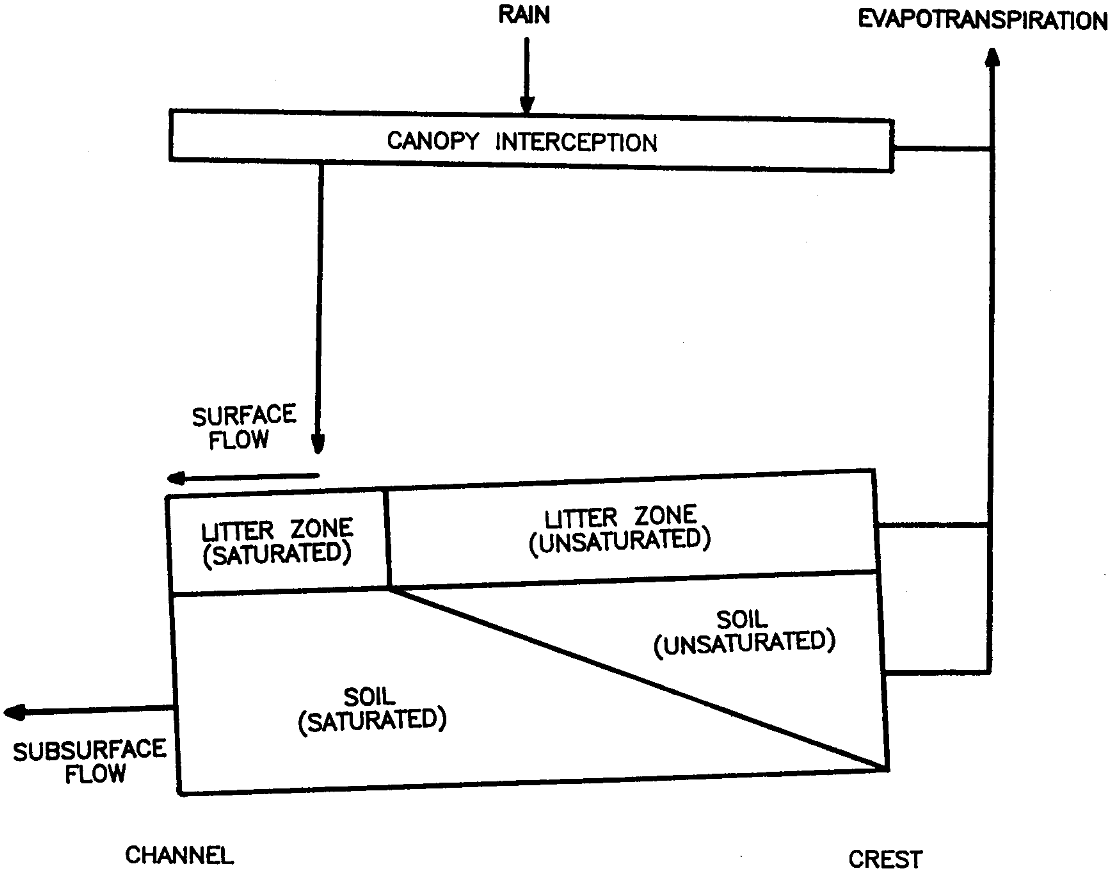


Figure 6.1 Schematic showing model representation of hillslope profile, which includes components for canopy interception; evapotranspiration; and surface, litter, unsaturated, and saturated flow dynamics.

Rainfall which is not intercepted (throughfall) may fall either on litter or directly on soil. The impact of various forms of land use can be simulated by completely removing the litter zone or changing its thickness. Throughfall which enters the litter zone is temporarily detained, increasing the average moisture content. Percolation from the litter zone increases with moisture content. The model allows formation of a saturated litter zone extending upslope from the channel.

The amount of direct throughfall or litter zone percolation which enters the soil profile is estimated by Philip's (1957, 1969) equation. When available input to the soil zone exceeds the infiltration capacity, percolation from the litter zone is restricted, or when no litter is present, Horton overland flow is generated (once surface detention has been exhausted). The modeled soil zone extends from the base of the litter zone to the first relatively impermeable layer (determined by field measurements). Infiltrated water is routed through the unsaturated zone at a rate proportional to the soil's hydraulic conductivity (a function of moisture content). The affect of near surface soil crusting or compaction may be simulated by reducing the infiltration capacity (while unsaturated zone parameters remain unchanged).

Flow dynamics within the saturated zone are simulated using a kinematic storage model based on Darcy's Law. The slope of the phreatic surface is taken as constant, and the potential gradient is set equal to the slope of the impermeable layer. When the water table intersects the soil surface, a saturated zone forms. No litter zone percolation enters the soil through the saturated zone. In the absence of litter, any throughfall landing on the saturated zone produces saturated overland flow. Infiltrated water is still supplied to the soil profile upslope from the saturated zone. It is possible to generate both saturation and Horton overland flow simultaneously. Surface flows are routed down the hillslope via a kinematic routing scheme. Water is removed from canopy interception and surface detention by evaporation at the potential rate. Evapotranspiration extracts soil and litter zone water at the potential rate when moisture contents are equal to, or above field capacity. When moisture content is below field capacity, the rate of evapotranspiration is reduced, going to zero at the wilting point.

6.3 MODEL APPLICATION

Example Basin

A second-order, 97-acre basin located in the northwest corner of the Novelty catchment was chosen to illustrate the relative hydrologic affects of light urbanization. The drainage consists of two main subbasins (Figure 6.2), each containing a gently rolling upland plateau drained by broad swales. At the edge of the plateau the swales are more pronounced, changing downslope into steep ravines incised by narrow channels.

Prior to 1978 (pre-development) the entire drainage contained an extensive second growth forest cover (Figure 6.3a). The undisturbed forest floor was covered by a litter zone 3 to 12 inches thick. From 1978 to the present (post-development) the basin has undergone light density urbanization (Figure 6.3b). About 15% of the forest has been replaced by lawn and pasture, and 3% by gravel roads with drainage ditches in subbasins 1 and 2. Figure 6.3 is derived from Figure 5.3 and subelements of Figure 5.1 using overlay features of the ARC/INFO GIS for the catchment.

On the plateau, loose-to-medium compact colluvium and recessional outwash varies in thickness from zero to 5 feet, but is typically loose, and only 1 to 2 feet thick. Water is concentrated by lowlands and swales, discharging to the steep ravines downslope. Prior to road construction, plateau drainage was predominantly by subsurface flow, some of which reemerged in the lower gradient swales. Roadside ditches now intercept most of this flow. In places the roads and ditches go against the natural grade and the resulting redirection of flows substantially increases the drainage area of subbasin number 2 at the expense of subbasin 1. Prior to development subbasins 1 and 2 had similar areas (43.7 and 53.1 acres respectively). After road construction, the area of subbasin number 2 has increased to 74.9 acres, while the area of subbasin number 1 is reduced to 14.7 acres (Table 6.1). Road construction in the southwest region of the basin diverts some flows out of the catchment, reducing the total drainage area by 7 percent.

The ravine slopes are covered by 1 to 5 feet of loose sandy colluvium with permeability rates of 2 to 6 inches per hour (Snyder et al., 1973). While drainage is predominantly by subsurface flow, saturated zones form in swales and adjacent to the stream channels during many storms.

Clearing for lawn and pasture completely removed the litter zone and most or all of the topsoil (down to the till layer). These areas generate a combination of Horton and saturated overland flow during moderate to large rainstorms.

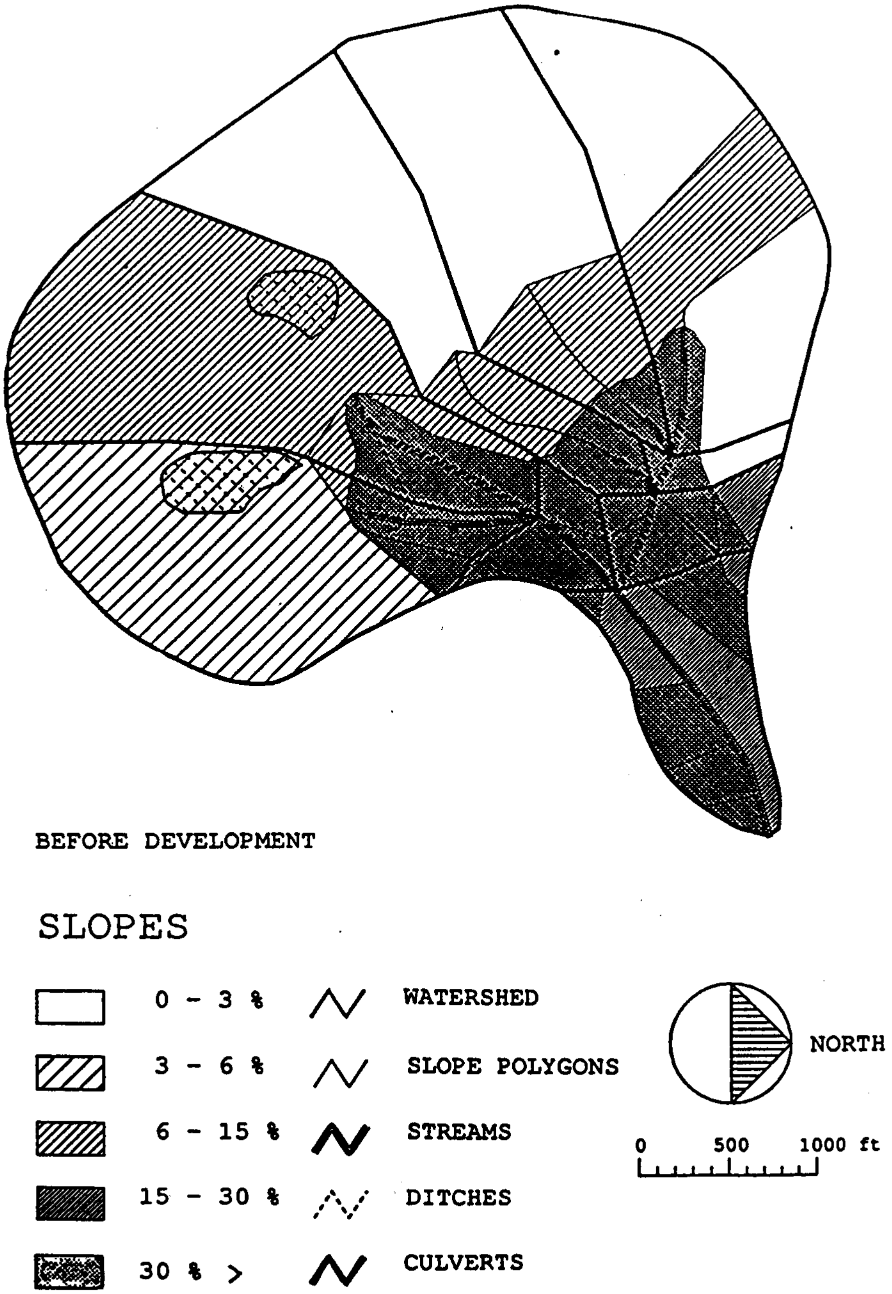


Figure 6.2 Plan view of pre-development Novelty Hill drainage; the two subcatchments modeled are in the North West corner.

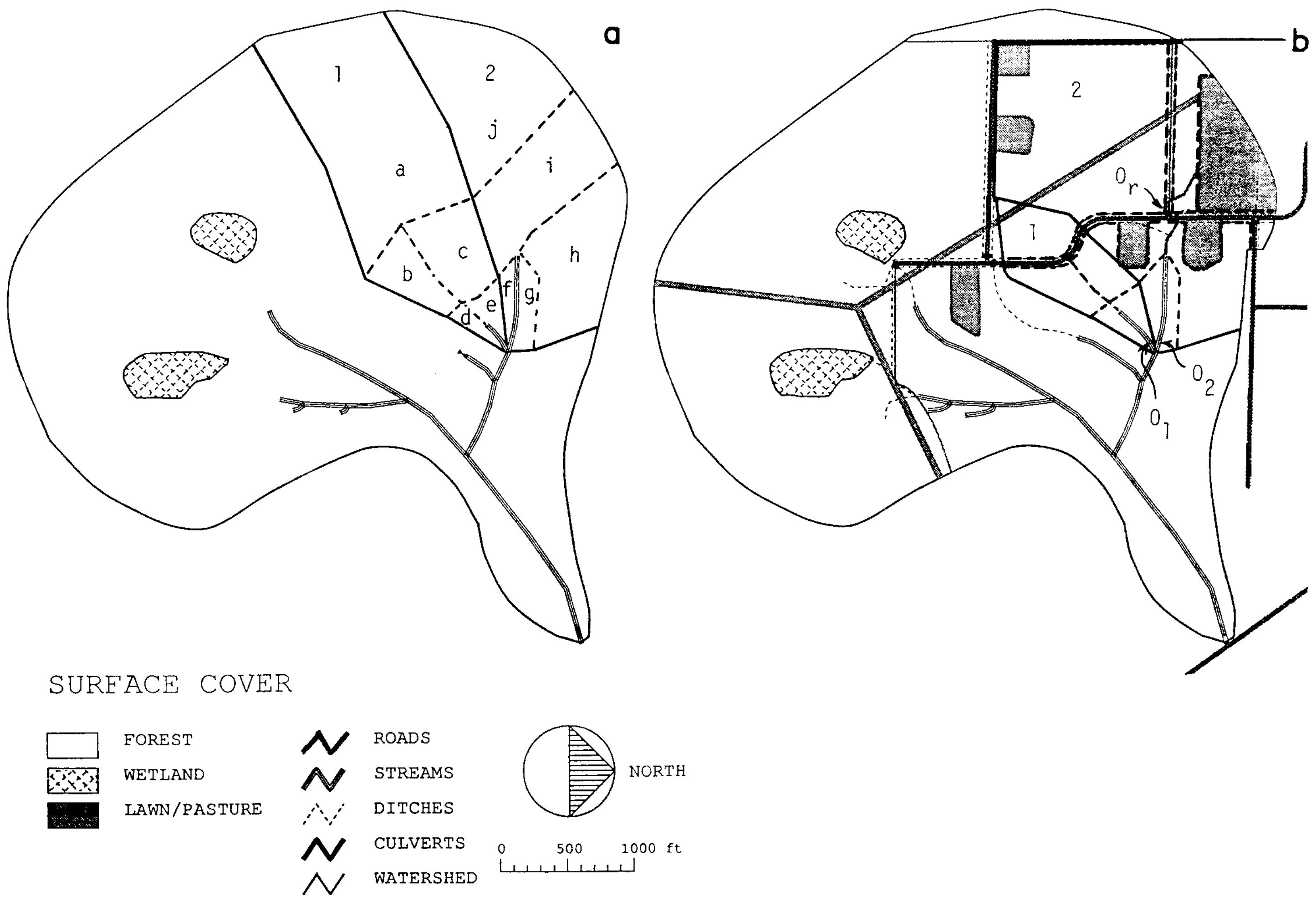


Figure 6.3 Land use and configuration of catchment elements for subbasins 1 and 2 used in model application for (a) pre-development (elements a to j) and (b) post-development conditions.

Table 6.1 Eleven-Year Mean Annual Mass Balance for Subbasins 1 and 2

Location	Land Use	Pre	Post
Subbasin Number 1	Forest	43.7	14.0
	Pasture	------	------
	Road	------	0.7
	Total	43.7	14.7
Subbasin Number 2	Forest	53.1	59.7
	Pasture	------	13.0
	Road	------	2.2
	Total	53.1	74.9

Furthermore, the estimated increase in surface runoff (from 11.7 to 19.8 percent of rain, Table 6.2) means less rainfall enters the soil column. The reduced infiltration also causes a decrease in the amount of post development subsurface flow.

As would be expected in this temperate humid climate, under natural conditions and light density urbanization, the majority of precipitation falling on the catchment is removed by ET (63 and 59 percent respectively). (These fractions would be smaller if actual catchment rainfall was available for model input). Under pre-development conditions, subsurface flow is the dominant runoff mechanism. Volumes of surface and subsurface flow are nearly equal with light urbanization.

Selected Storm Hydrographs: Temporal Effects of Land Use Change

Three storms, occurring March 3, 1972, November 28, 1973, and October 10, 1981, were selected for detailed study based on simulated antecedent soil moisture, and rainfall intensity and duration. During the storm, a uniform time step of 6 minutes was used. The impact of antecedent conditions on basin response soon became apparent. This effect is best illustrated by comparing model output from the March 5, 1972 and October 10, 1981 storms.

The March 1972 storm generated 2.70 inches of rainfall in 24 hours. This 24-hour depth has a regional return period of about 10 years. Rainfall intensities were relatively low, with a peak of only 0.22 in/hr (Figure 6.5a). However, the storm occurred when the catchment was wet, having received 5 inches of rainfall in the preceding 10 days. This depth is close to the available litter and soil (field capacity) storage of 5.3 inches at locations where the soil and litter are thin.

The October 1981 storm was of similar duration, producing 2.72 inches of rainfall in 24 hours. Peak rainfall intensities were higher, reaching 0.42 in/hr (Figure 6.5b). However, the basin was dryer prior to the storm, with a 10-day antecedent rainfall of 3.88 inches. The 30-and 60-day cumulative rainfalls were also much lower for the October 1981 storm (5.62 and 5.92 inches respectively versus 8.77 and 15.91 inches for the March 1972 storm).

Average hydrologic litter zone parameters were taken from Balci's (1964) work on the properties of certain Western Washington forest floor types. Hydrologic soil parameters were estimated from soil texture based on the findings of Rawls et. al. (1981). Of the soil types considered in their study, the loamy sand, having a mean saturated hydraulic conductivity of 2.4 in/hr provides the closest match to soil textures and estimated infiltration rates in the example catchment. Additional field measurements would allow more accurate representation of soil parameters.

Model output for the pre-development case was compared to field mapped hydrologic process zones. Soil depth was adjusted within measured values to achieve the best correspondence with mapped process zones. In addition, a lateral saturated conductivity of 1.64 ft/hr was used for the loose colluvium and outwash in subbasins representing the plateau region. This is within the range of relevant published values (Beven, 1981). In the remaining subbasins, the vertical and lateral conductivities remained equal at 2.4 in/hr.

Land Use Change

Roads were modelled as impervious with no surface detention. At many locations all of the litter zone and most of the topsoil was removed (down to the till layer) when clearing for lawn or pasture. These locations were modelled as having no litter zone and a 4 inch soil depth. The limiting value for Philip's infiltration equation was reduced to 0.04 in/hr. This value is in agreement with Snyder's (1973) regional estimated infiltration rate of less than 0.06 in/hr for the underlying glacial till. All other model parameters remained unchanged.

6.4 MODEL RESULTS

Annual Mass Balance

There are no rain or streamflow gauges in the catchment. Consequently we demonstrate relative influences by using the Seattle-Tacoma airport weather station records. We chose arbitrarily to operate the model continuously with an 11 year rainfall record. Eleven-year means for monthly precipitation, modeled evapotranspiration (ET), surface flow and subsurface flow are presented in Figure 6.4 and Table 6.2. Total annual precipitation for the eleven years averaged 36.53 inches. (Actual catchment rainfall should be larger than that recorded at Sea-Tac based on the Carnation and Duvall weather stations (Section 4-6). Our objective is to demonstrate relative hydrologic influences if this catchment experienced the Sea-Tac rainfall and ET patterns). Simulated ET under pre-development conditions averaged 23 inches annually. ET was low early in the year (Figure 6.4a), when potential ET is low. Estimated ET increased with potential evapotranspiration to its peak in May. Although potential evapotranspiration is high in the summer months, soil moisture is low, and simulated ET decreased through the summer and fall.

Estimated annual ET under post-development was 21.5 inches, a decrease of 6.5 percent (Table 6.2). The monthly pattern remained similar to that for pre-development conditions. A decrease in post-development ET would be expected, resulting from vegetation and litter removal.

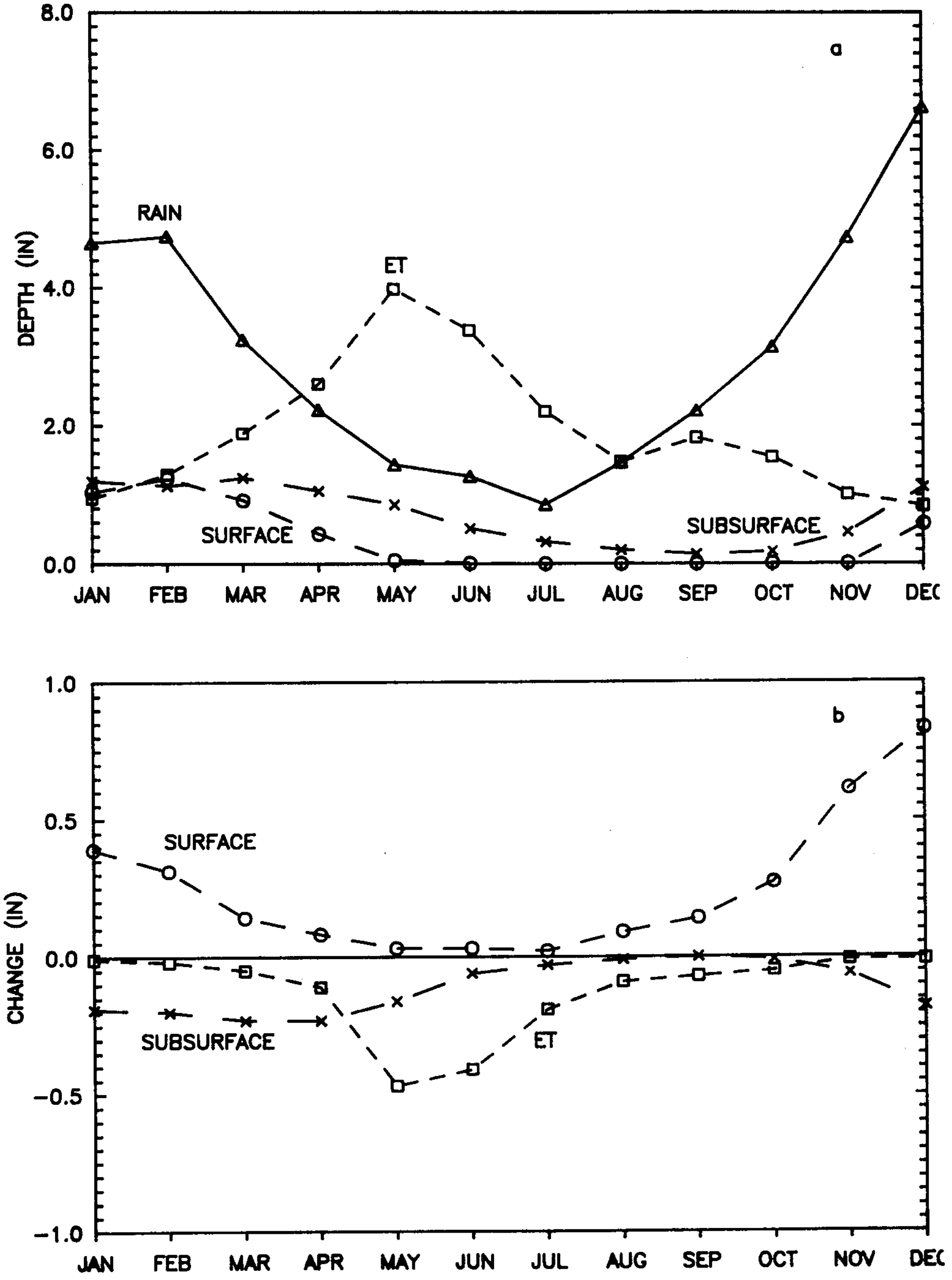


Figure 6.4 Eleven-year mean annual mass balance for (a) pre-development and b) post-development minus pre-development flow and ET.

Table 6.2 Eleven-Year Mean Annual Mass Balance for Subbasins 1 and 2

	Pre-development		Post-development	
Flux	Depth (in)	Percent of Rain	Depth (in)	Percent of Rain
Rain	36.53	------	36.53	-------
ET	22.95	62.8	21.46	58.7
Surface Flow	4.26	11.7	7.22	19.8
Subsurface Flow	8.37	22.9	7.01	19.2
Soil Storage	+0.95	+2.6	+0.84	+2.3

Furthermore, the estimated increase in surface runoff (from 11.7 to 19.8 percent of rain, Table 6.2) means less rainfall enters the soil column. The reduced infiltration also causes a decrease in the amount of post development subsurface flow.

As would be expected in this temperate humid climate, under natural conditions and light density urbanization, the majority of precipitation falling on the catchment is removed by ET (63 and 59 percent respectively). (These fractions would be smaller if actual catchment rainfall was available for model input). Under pre-development conditions, subsurface flow is the dominant runoff mechanism. Volumes of surface and subsurface flow are nearly equal with light urbanization.

Selected Storm Hydrographs: Temporal Effects of Land Use Change

Three storms, occurring March 3, 1972, November 28, 1973, and October 10, 1981, were selected for detailed study based on simulated antecedent soil moisture, and rainfall intensity and duration. During the storm, a uniform time step of 6 minutes was used. The impact of antecedent conditions on basin response soon became apparent. This effect is best illustrated by comparing model output from the March 5, 1972 and October 10, 1981 storms.

The March 1972 storm generated 2.70 inches of rainfall in 24 hours. This 24-hour depth has a regional return period of about 10 years. Rainfall intensities were relatively low, with a peak of only 0.22 in/hr (Figure 6.5a). However, the storm occurred when the catchment was wet, having received 5 inches of rainfall in the preceding 10 days. This depth is close to the available litter and soil (field capacity) storage of 5.3 inches at locations where the soil and litter are thin.

The October 1981 storm was of similar duration, producing 2.72 inches of rainfall in 24 hours. Peak rainfall intensities were higher, reaching 0.42 in/hr (Figure 6.5b). However, the basin was dryer prior to the storm, with a 10-day antecedent rainfall of 3.88 inches. The 30-and 60-day cumulative rainfalls were also much lower for the October 1981 storm (5.62 and 5.92 inches respectively verses 8.77 and 15.91 inches for the March 1972 storm).

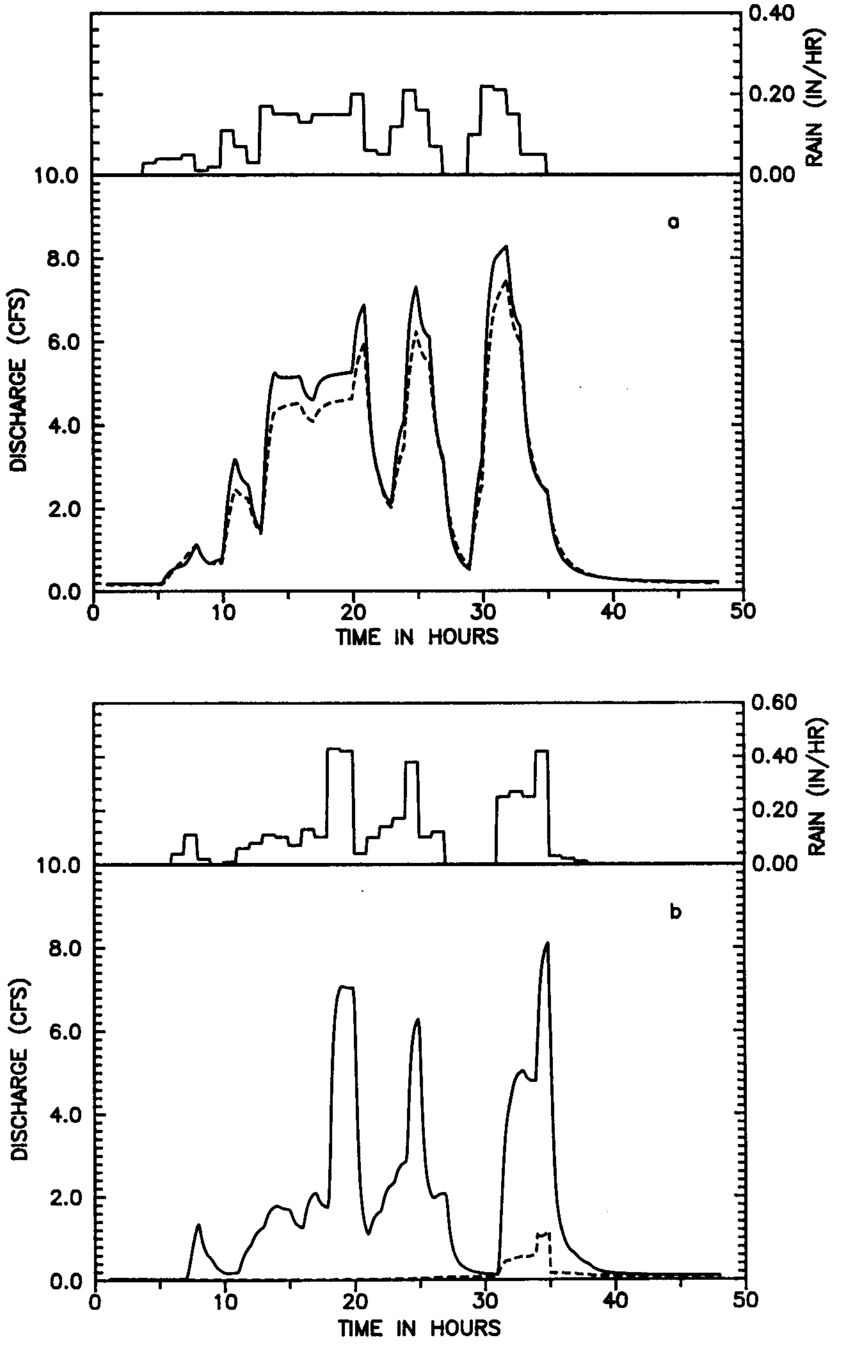


Figure 6.5 Hyetographs and hydrographs at the confluence of subbasins 1 and 2 for the (a) March 3, 1972 and (b) October 10, 1981 storms; solid line post-, dashed line pre-development conditions.

For nearly the same 10-year, 24-hour rainfall, the two storms generate very different results (Figure 6.5). Basin response to the March 1972 storm is similar under both pre- and post-development conditions. Development causes only a slight increase in peak discharge (7.5 to 8.3 cfs) and runoff volume (374,000 to 417,000 ft^3). In contrast, the October 1981 rainfall produces vastly different pre- and post-development responses. Peak discharge increases from 1.2 to 8.1 cfs and runoff volumes from 17,000 to 254,000 ft^3.

A review of stream gauge records from basins in the surrounding area lends credibility to model results. Although these catchments are larger than the example basin, the relative effects of antecedent conditions and storm characteristics should be similar. As would be expected based on model simulation, records from mostly undeveloped catchments generally show a large increase in discharge during the March 1972 storm and little or no discharge increase for the October 1981 storm. Records from lightly urbanized basins show large discharge increases for both storms.

The impact of land use change is highly dependent on antecedent conditions, and rainfall intensity and duration. This can be explained in terms of runoff mechanisms. Under pre-development conditions, no Horton overland flow (HOF) is generated, and saturated overland flow (SOF) dominates the storm hydrograph. Wet antecedent conditions promote this type of flow production. Development, through litter and soil removal (and soil compaction), introduces HOF into about 18 percent of the basin. This mechanism is less dependent on antecedent conditions and more on rainfall intensity.

Wet antecedent conditions prior to the March 1972 storm resulted in a large SOF response in the pre-development case. Under post-development conditions the road and ditch system provides more efficient soil drainage by intercepting subsurface flow. This results in a reduction of saturated areas and a damped post-development SOF response. Although HOF is generated in the developed case, the relatively low rainfall intensities do not cause it to dominate the hydrograph (Figure 6.6a). As a result, for the March 1972 storm, the large pre-development SOF response is nearly equal to the combination of moderate intensity HOF and relatively damped post-development SOF.

In contrast, the lower rainfall prior to the October 1981 storm results in lower soil moisture and very little SOF production under either pre- or post-development conditions. However, the high rainfall intensities allow HOF to dominate the Hydrograph after development (Figure 6.6b) In this case the great difference between pre- and post-development response can be attributed almost entirely to HOF.

The greatest post-development peak discharge (10.0 cfs), which occurred during the November 28, 1973 storm, resulted primarily from HOF. This high peak flow was generated by a single one-hour burst of rainfall totaling 0.61 inches. The short duration storm occurred for a relatively dry catchment, producing almost no pre-development response, and 68,000 ft^3 of post-development flow.

The effect of antecedent conditions is further illustrated by the flow duration curves presented in Figure 6.7. This figure shows the percent of time a given daily flow volume is equaled or exceeded. Figure 6.7a shows for a wet year (1974) the pre- and post-development curves are nearly identical. In contrast, during the dry year of 1977 (Figure 6.7b) there is a significant difference 30% of the time, and some difference about 80% of the time.

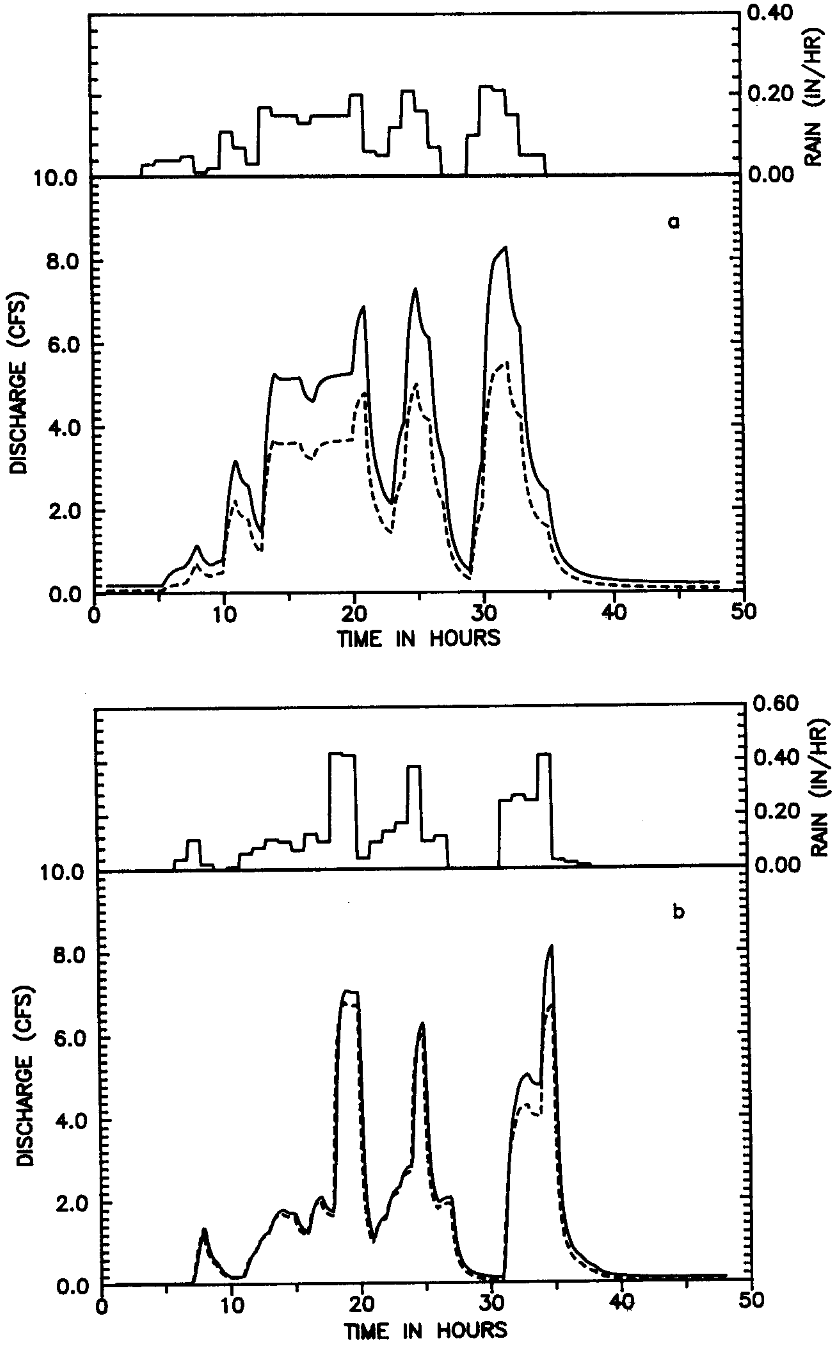


Figure 6.6 Hyetographs and hydrographs at the confluence of subbasins 1 and 2 for the (a) March 3, 1972 and (b) October 10, 1981 storms; solid line total post-development hydrograph, dashed line hydrograph for areas of land use change.

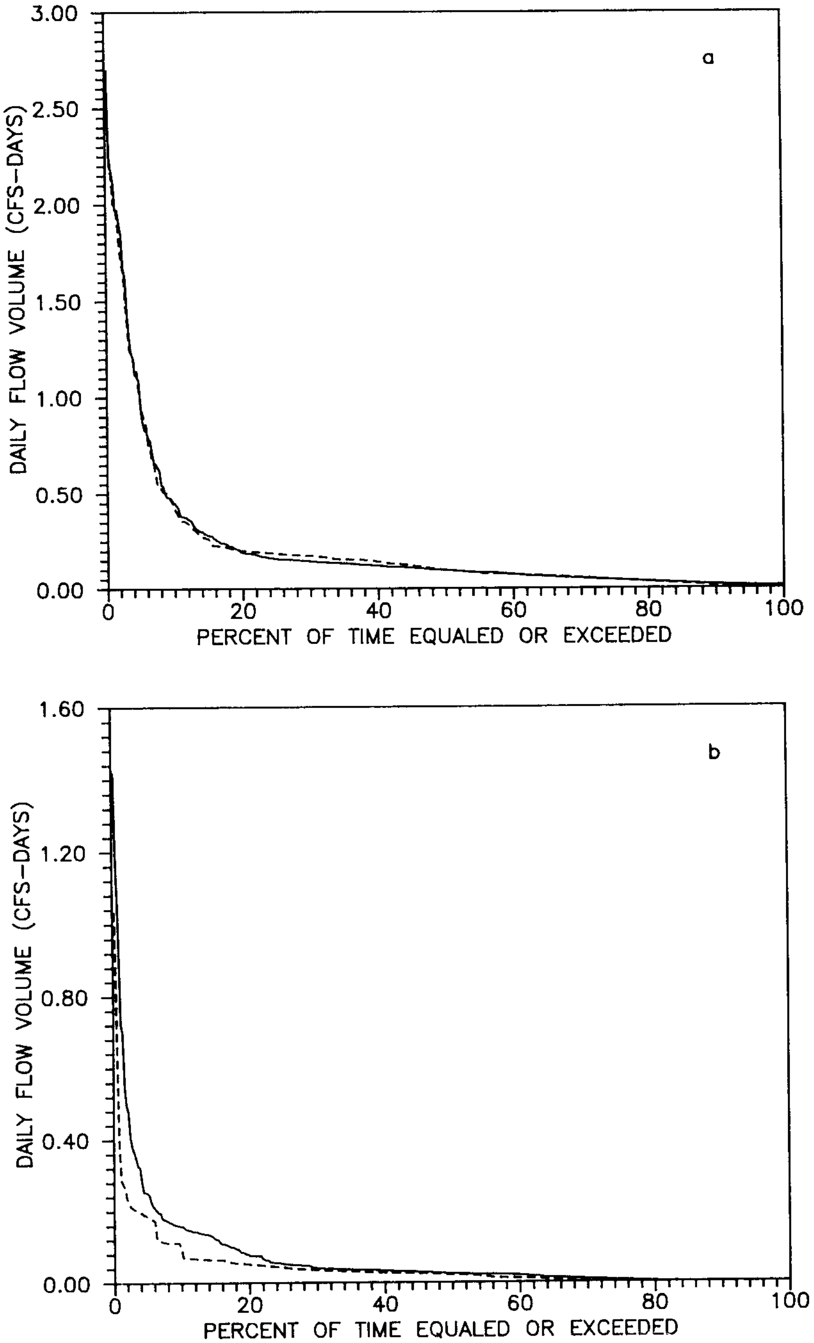


Figure 6.7 Flow duration curve at the confluence of subbasins 1 and 2 for (a) the wet year of 1974 and (b) the dry year of 1977; solid line post-, dashed line pre-development conditions.

The effect of antecedent conditions and rainfall patterns on runoff mechanisms has an important impact on detention facility design. This is particularly true, if for ecological considerations it were desirable to match pre- and post-development hydrographs throughout the year. For example, both the March 1972 and October 1981 storms have regional 10-year, 24-hour return periods. The March 1972 storm would require 43,000 ft^3 of available storage to match pre- and post-development hydrographs. In contrast, the October 1981 storm would require a storage volume of 273,000 ft^3.

Selected Storm Hydrographs: Spatial Effects of Land Use Change

Land use change influences hydrologic response at specific catchment locations. When the whole example catchment (97 acres) is considered only about 17 percent of the area has been developed. However, impact on subbasin 2 alone is more significant; the drainage area has been increased by 42 percent (from 53 acres to 74.9 acres), of which 64 acres (84 percent) drains to the road network. All of the developed areas drain to roads or road ditches. The March 1972 storm will be used to illustrate land use change spatial influence on hydrologic responses. This storm produces the largest pre-development flow response. Therefore, the impact of land use change will be greater in many other storms (eg. October 10, 1981).

Pre- and post-development hydrographs derived for the total catchment (subbasins 1 and 2) are similar in shape and volume. However, the spatial effects of land use change become apparent when flows from subbasin 2 alone are considered. As can be seen in Figure 6.8a and Table 6.3, development increases both peak discharge and flow volume by about 50 percent at the outlet of subbasin 2. Peak discharge increases from 4.3 to 6.4 cfs and flow volume increases by 105,000 ft^3.

Table 6.3 Flow Peaks (cfs) and Volumes (ft^3), March 3, 1972

Location		Pre	Post	Change
Total Basin	Qpk	7.5	8.3	0.8
	Volume	374,000	417,000	43,000
Subbasin 2 (Confluence)	Qpk	4.3	6.4	2.1
	Volume	214,000	319,000	105,000
Subbasin 2 (Road)	Qpk	3.3	5.5	2.2
	Volume	169,000	279,000	110,000

Runoff from the 64 road-drained acres enters the 1st-order channel at a single location (O_r in Figure 6.3b). Simulated hydrographs at this location (Figure 6.8b and Table 6.3) show that development produces a volume increase of 110,000 ft^3 and a peak discharge increase of 67 percent (from 3.3 to 5.5 cfs). The flow duration curve at this location for 1972 (Figure 6.9) shows development has caused a significant increase in flow volumes over about 25 percent of the year.

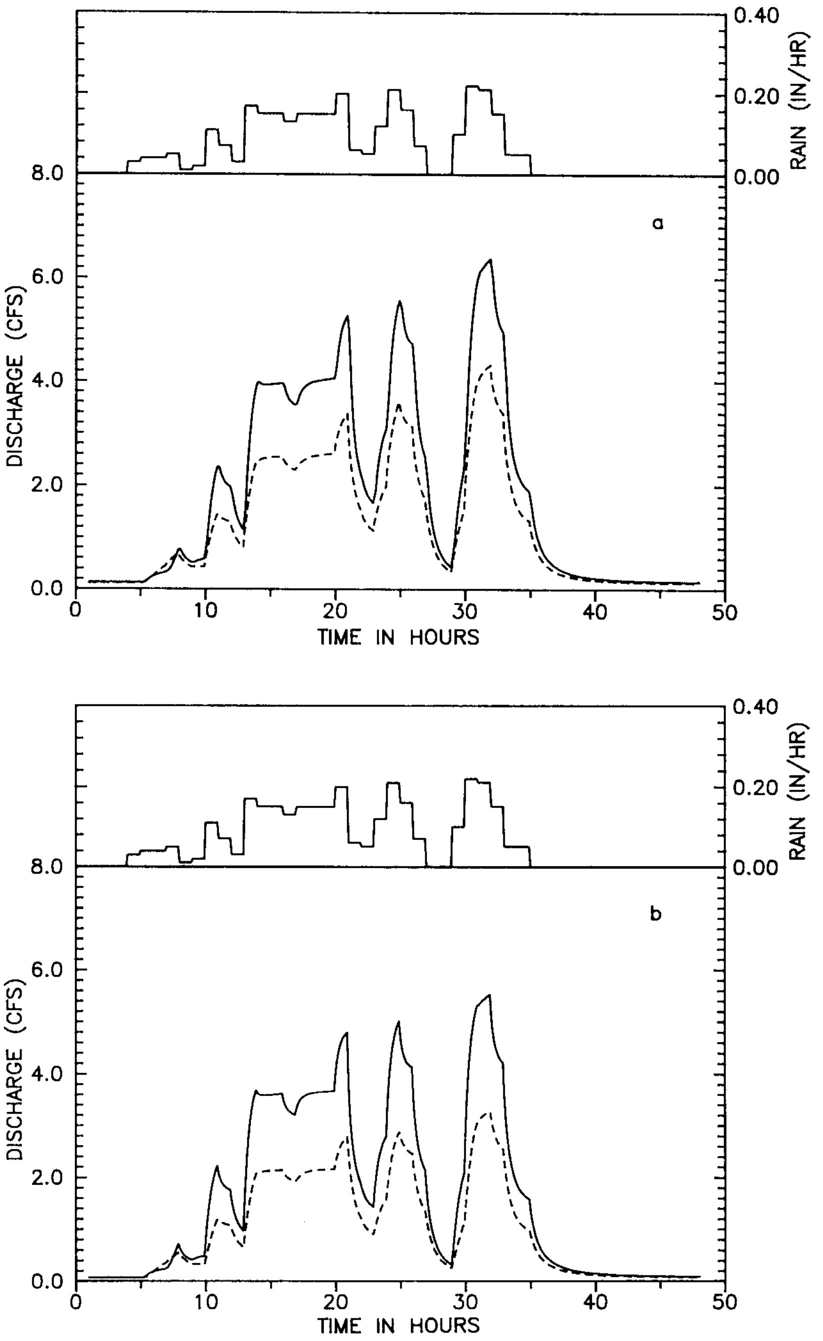


Figure 6.8 Hyetographs and hydrographs for the March 3, 1972 storm at (a) the outlet of subbasin 2 (O_2, Fig. 6.3(b)) and (b) upslope at the road-channel junction (O_r, Fig. 6.3(b)); solid line post-, dashed line pre-development conditions.

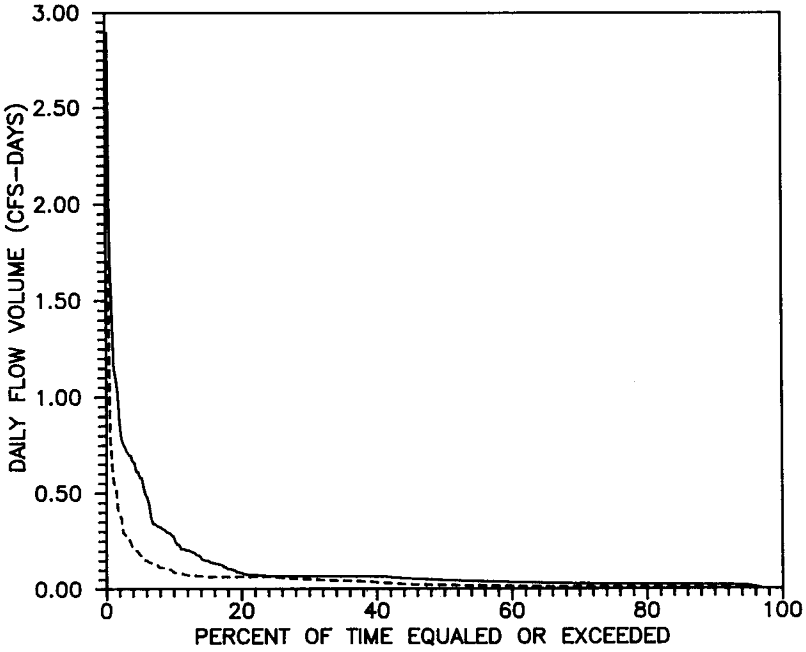


Figure 6.9 Flow duration curve at the road channel junction in subbasin 2 (Or, Figure 6.3(b); solid line post-, dashed line pre-development conditions.

Under natural conditions, the drainage network is in "quasi-equilibrium" with pre-development flows. The significant increase in flow peaks and volumes described above indicates a potential for channel degradation. One mitigative strategy is detention. The obvious location for detention is where the road-drained discharge enters the channel system. A review of Figure 6.8 and Table 6.3 shows that most land use impact occurs above this location and is translated down channel to the subbasin outlet. This would suggest little additional storage would be required at the outlet.

6.5 SUMMARY

We have demonstrated the importance of using field mapped process zones for disaggregating a catchment into elements for modeling pre- and post-urbanization hydrologic responses. The significance of antecedent conditions is emphasized in Figure 6.5. The significance of modeling the spatial location of flow production and the need for this information for effective design of mitigation measures is emphasized in Figure 6.8. The form of the model developed and illustrated here stresses the need for further model development and testing in appropriately instrumented small catchments. This class of model can and will make use of traditionally measured hydrologic fluxes (rainfall, ET, and stormflow) as well as ancillary measures of field observable moisture states. We are continuing development and testing of such models.

CHAPTER 7 SUMMARY AND CONCLUSIONS

7.1 SUMMARY

An approach for identifying hydrologic process zones throughout a catchment has been developed for determining locations for various forms of flow production that will be modified when catchment land use is changed. It is applicable to both gauged and ungauged catchments and provides guidance for any subsequent hydrologic observations, measurements, and modeling. Field observations combined with map and stereo aerial photograph interpretation are used to identify catchment features associated with runoff production. From these features the spatial distribution of dominant basin hydrologic processes is estimated. Places that will experience hydrologic impacts resulting from potential development are identified by comparison of the spatial extents of pre- and post-development hydrologic process zones. Use of the location and extent of hydrologic process zones allows important hydrologic and geomorphic processes that currently are not included explicitly in rainfall-runoff models to be considered in design and management decisions. Hydrologic and geomorphic processes, not considered in traditional methods, that are identified by the process zone mapping procedure developed here include areas of saturated overland flow, return flow, areas with significant water detention, and channel segments where sediment transport thresholds are likely to be exceeded.

The method provides information (at an appropriate scale) about the influence of catchment topography, materials, vegetation, and land use on runoff production processes. Existing catchment features are drawn on a preliminary basemap developed from available maps and aerial photographs. Catchment features shown on the basemap include major breaks in slope, existing and abandoned roads, swales, creek channels, wet areas, vegetation boundaries, fence lines, and existing structures are identified first for pre-development conditions. A preliminary overlay map for the basemap is prepared showing the estimated hydrologic process zones including areas of significant water infiltration and detention, saturated overland flow areas, Horton overland flow areas, wet areas, and open channels. Field inspections of the catchment provide relatively complete information on vegetation, forest litter, soils, channel geometry, and topography that are not obtainable from maps and aerial photographs. A final overlay map of the extent, location, and types of hydrologic process zones is prepared based on interpretation of the field data, aerial photographs, and map information. A similar process zone map is prepared for the proposed development configuration and compared with the pre-development conditions in summary tables, charts, and maps. Changes in drainage density, water detention volume, and quick storm response area are associated with their respective downstream channels. Potential impact zones can then be defined by comparison of the pre- and post-development runoff and channel conditions.

The method is illustrated by estimating the type, location, and extent of hydrologic process zones for an ungaged developing area in King County, Washington. The approximately one-half square mile (1.3 km^2) catchment is located 14 miles east of Seattle, Washington. Two thirds of the catchment is a forested relatively flat upland plateau (0 to 3 degree slopes) (Figure 4.1). Swales from the plateau concentrate surface and subsurface runoff into very high gradient channels (4 to 90 degrees) that form ravines along the plateau edge. Field observations in the catchment indicate rural low density development practices (5 to 10 acre lots) can change catchment hydrologic response noticeably and result in damage to stream habitat and civil works. Increased channel density in the form of ditches and associated creation of new areas of quick response overland flow from roads, pastures, and lawns are the main cause of down-stream channel changes in the catchment. Road construction has introduced 10 acres of quick response overland flow area that is directly connected to the natural channel system via ditches. An additional 20 acres of land has lost over 50,000 cubic feet of potential water detention volume with resultant quick storm runoff in the form of Horton and saturated overland flow. The bulk of these influences are experienced by the northwestern one third of the catchment. Examination of the channel sections, bars, and bedforms for channel segments draining relatively undisturbed and changed parts of the catchment, respectively, indicate critical channel erosion problems and erosion and deposition potential. These locations dictate the extent of mitigative measures needed upstream. Such locations indicate flow released from mitigative schemes must be constrained above the start of first order-channels if channel geometry and stream habitat are to be preserved.

The method yields primarily two-dimensional zone maps and channel segments. Each zone and channel segment has several associated attributes. For file and data keeping purposes the information gathered from maps, stereo aerial photograph interpretation, and field observations can be stored most conveniently using an appropriate geographic information system (GIS). We explored several systems and found ARC/INFO (or an equivalent system) to be a suitable hierarchical scheme for storing and displaying map information relevant to catchment hydrology. The relative ease with which derivative maps (overlays of processes or "coverages") can be constructed with this system makes it a preferred scheme. Moreover, its compatibility with other land use and cadastral inventorying needs facilitates incorporation of hydrologic description and analysis into land use decision making.

The mapping methodology developed and illustrated here emphasized the need for a rainfall-runoff model that can be used at all spatial scales (from a few acres to hundreds of acres) relevant to land use characterization or land use change decision making. We could not find nor adapt an existing model that incorporated the types of information yielded by our mapping approach so we developed a relatively simple spatially-distributed model that can represent the mapped process zones. This model uses the mapped extent of flow production zones as sub-areas within subcatchments. Upper soil (and litter) and lower soil depths (attributes determined by direct field measurement) are included explicitly. We have demonstrated qualitatively that this type of model has promise as an important tool for showing relative impacts of land use change at different locations within a subcatchment. The hydrographs determined for sub-areas provided guidance for the type and location of appropriate mitigative measures to reduce hydrologic impacts from land use change and urbanization in particular.

7.2 CONCLUSIONS

Management and design decisions that profoundly change catchments will continue to be made with very limited data collection. The purpose here was to describe an approach to conducting a basin study that makes use of readily obtainable field observations. Field studies identify what materials and processes are present in the basin. Field mapping of catchment features associated with hydrologic processes allows basic information on the dynamics of a catchment to be read from static and limited dynamic field observations. Comparison of the pre- and post-development hydrologic process zones allows site specific hydrologic and geomorphic processes to be included in project design and mitigation decisions.

Identification and mapping the spatial location and size of hydrologic process zones provides significant and relevant information for division of the catchment into subbasins for modeling and decision making purposes. Field investigation provides critical information for identifying channel reaches susceptible to degradation from changed flow patterns. These details can not be inferred from topographic maps; they are crucial for determining where hydrologic flow control points will be beneficial. Delineation of catchment process zones does not provide complete quantitative information needed for development design and mitigation. Field mapping of hydrologic process zones in conjunction with precipitation and runoff measurements and runoff modeling is required to quantify catchment rainfall-runoff response.

The model developed here is capable of representing all major flow production mechanisms throughout a subcatchment at any spatial scale needed for decision making involving mitigation of hydrologic impacts. The model is constructed to take advantage of subcatchments, subareas, and channel segments, and their attributes (slopes, soil types, soil depth, stable channel discharge rate, etc.) stored within a GIS framework. The importance of the model structure lies in its ability to represent changes that occur in a catchment (forest cover removal, regrading, litter zone removal, etc.). For example, in the demonstration application two subcatchments having a combined area of 97 acres were modeled using ten subareas in the pre-development state. For the post-development state (moderate development level) seventeen subareas were used to model the hydrologic response to reflect the changes in mapped flow production zones. While the model has not yet been tested against quantitative measurements, it has provided hydrographs consistent with flow production mechanisms observed during storms. Moreover it indicates where within a subcatchment changed response is most significant. For example, in Figure 6.3, the storm hydrograph at location O_r is almost identical to that at O_2 indicating O_r is the critical control point for this branch of the stream system. O_2 drains a substantially larger area than drains to O_r.

The model developed is being refined and will be subject to rigorous testing against measured rainfall and streamflow in a variety of very small subcatchments. The inclusion of process zones in models of the hydrology of catchments provides an impetus for additional measurements as well as more traditional measurements of rainfall and streamflow. Only when such measurements are made to test the appropriateness of this type of model will there be sufficient information for quantitative modeling of changes at scales on the order of 10 acres that contributed to deleterious hydrologic impacts. We anticipate that limited duration, spatially extensive measurements of hydrologic fluxes and the location and extent of hydrologic zones combined with a model built along the lines of the one we have developed will provide the most satisfactory approach for quantitative design to mitigate hydrologic impacts from urbanization.

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APPENDIX A. MEASUREMENT OF POTENTIAL WATER STORAGE CAPACITY

The following method can be used to obtain field measures of the porosity and field capacity of forest litter and soil samples.

1. Clean and weigh the sampler (W1).
2. Push sampler full depth of loose upper soil zone. The sample edges may need to be cut in advance.
3. Measure height of sample in tube and calculate the volume of the sample (V_t).
4. Dig out one side of sampler and slide a plate under tube. Remove the sampler and place a watertight cap on the base of the tube.
5. Weigh the sampler with the sample in it (W2) and subtract the weigh of the sampler (W1) to get the weight of the sample (W_{sample})
6. Determine the bulk density (q_b) of the Sample

$$q_b = \frac{Wsample}{V_t}$$

7. Pour a known volume of water into the sample until the sample is saturated to the surface.
8. Weigh the saturated sample ($W_{saturated}$) and note if the volume has changed in the wetting process ($V_{t\ saturated}$). Calculate the Saturated Bulk Density ($q_{saturated}$).

$$q_{saturated} = \frac{W_{saturated}}{V_{t\ saturated}}$$

9. Remove the water tight cap and allow the sample to drain. Weigh the drained sample after no more water is freely flowing from it ($W_{field\ capacity}$) and check the volume ($V_{field\ capacity}$). Calculate the field capacity ($q_{field\ capacity}$). The sample may need to be carefully removed and placed in a container so that it can drain while other samples are taken.

$$q_{field\ capacity} = \frac{(W_{field\ capacity})}{(V_{field\ capacity})}$$

10. Calculate the unit volume of water stored in the sample between the saturated and freely drained condition.

$$\text{Volume Stored} = \frac{(q_{\text{saturated}} - q_{\text{field capacity}})\ (\text{Sample Volume})}{(\text{Density of Water})}$$

or the depth of water that the soil column will hold is:

$$\text{Water Depth} = \frac{(q_{\text{saturated}} - q_{\text{field capacity}})\ (\text{Sample Area})}{(\text{Density of Water})}$$

A slightly quicker method is to weigh the sampler with the saturated sample and subtract the weight of the sampler with the drained sample and calculate the volume of the water.

APPENDIX B SEDIMENT MOTION

Sediment will move when the local bottom shear stress s_b (Dynes/cm^2) exceeds the critical shear stress for sediment motion s_c (Dynes/cm^2).

$$s_b > s_c \qquad \textbf{B(1)}$$

The total bottom shear stress $(s_b)_t$ can be used as a simple approximation of the bottom shear stress s_b.

$$(s_b)_t = q_f \, g \, h \, s \qquad \textbf{B(2)}$$

$(s_b)_t$ = Total Bottom Shear Stress (Dynes/cm^2)

q_f = Fluid Density (grams /cm^3)

g = Acceleration of Gravity (980 cm/sec^2)

h = Depth of Flow (cm)

s = Slope of channel (cm/cm)

Total resistance to flow is created by the form drag of the channel, skin friction of the bed roughness elements, and fluid viscosity. To determine what size grains move on a channel bed, the local shear stress at any given or typical location in the channel is required; the skin friction shear stress s_{sf} (Dynes/cm^2), not the total shear stress $(s_b)_t$, is needed. The total shear stress $(s_b)_t$ has commonly been used in sediment transport studies because it is relatively easy to obtain.

The skin friction shear stress (s_{sf}) can be calculated by using the vertical velocity profile at the site. It is not practical to measure velocity profiles at every stage and location of interest so a typical velocity profile is fitted to a given flow and channel geometry. The following vertical velocity profile is fitted to the low, intermediate, bankfull, and flood stage flows in representative creek cross sections.

$$u = \frac{U^*}{j} \, \mathrm{Ln} \left(\frac{Z}{Z_o} \right) \qquad \textbf{B(3)}$$

u = Velocity (cm/sec.) at z

U_* = Shear Velocity (cm/sec.) = s_b/q_f

j = von Karmann's Constant = 0.407

z = Depth (cm)

z_o = Roughness Length (cm) = $\frac{k_s}{30}$ for hydraulically rough flow ($R_* > 100$) See Eq. B(8) and Wiberg and Smith (1987b)

k_s = Scale length of the bed roughness (cm)

Manning's equation was used in Chapter 4 to estimate the mean flow velocity (<u>) at relevant flow stages. Flow stages are selected based on observed channel features.

$$<u> = \frac{1}{n} R^{2/3} S^{1/2} \qquad \text{B(4)}$$

$<u>$ = Mean Channel Flow Velocity (cm/sec)

n = Manning's Roughness Coefficient

R = Hydraulic Radius (cm) = Area/Wetted Perimeter, using mean depth <h>

S = Channel Slope (cm/cm)

The logarithmic velocity profile, Eq. B(3), is fitted to the channel using the mean velocity <u> yielding Eq. B(5). A convenient form of the boundary shear stress is given by Eq. B(6).

$$<u> = \frac{U_*}{j} \text{Ln}\left(\frac{<h>}{Z_o} - 1\right) \qquad \text{B(5)}$$

$$s_b = (U_*)^2 q_f \qquad \text{B(6)}$$

The critical shear stress for the initial motion of sediment on poorly-sorted beds has been found to differ from that on a well-sorted bed (Baker and Ritter, 1975; Andrews, 1983; Carling, 1983). Shields empirical criterion (Shields, 1936) for initial movement of well-sorted uniform grain size sediment was compared with the equation of Wiberg and Smith (1987b) that accounts for well- and poorly-sorted substrate. The critical shear stress required to move a grain (s_{cr}) is a function of grain size (d), grain density (q_s), grain shape as reflected in the drag coefficient (C_d), the velocity profile across the grain, and geometry of the pocket where the individual grain is located.

The sediment motion equation of Wiberg and Smith (1987a,b) (Eq. B7) can be used to calculate s_c on mixed grain size substrates. For consistency their notation is used here.

$$(S_*)_{cr} = \frac{2}{c_d a} \, \frac{1}{< f^2 (\frac{z}{z_o}) >} \, \frac{(\tan U_o \cos b - \sin b)}{[1 + (\frac{F_L}{F_D}) \tan U_o]}$$

$(s_*)_{cr}$ = Nondimensional critical shear stress = $\frac{s_{cr}}{(q_s - q_f)gd}$

q_s = Sediment Density (grams /cm^3)

C_d = Drag Coefficient

a = (Area of Grain)(d)/Vol. Grain = 1.5 for a sphere

d = Diameter of Grain (cm)

$<f2(\frac{z}{z_o})>$ = Velocity Profile (User specified, a logarithmic profile Eq. B3 is used here)

F_L = Lift Force (Dynes/cm^2)

F_D = Drag Force (Dynes/cm^2)

b = Bed Slope (degrees)

uo = Bed pocket particle angle of repose (degrees)

A full discussion of this equation is given in Wiberg and Smith (1987b). This equation, which is derived from an analysis of the balance of forces occurring at the substrate surface, indicates what grain sizes can be transported with a given flow rate and substrate size distribution.

The term ($<f2(\frac{z}{z_o})>$) is the two dimensional water velocity profile which is a function of the roughness Reynolds number (R_*),

$$R^* = \frac{U_* k_s}{m} \tag{B(8)}$$

k_s = Scale length of the bed roughness (cm)

m = Kinematic fluid viscosity (cm^2/sec)

The scale length of the bed roughness (k_s) is represented by various authors as the d_{50}, d_{65}, or d_{84} particle diameter (intermediate particle diameter that equals or exceeds 50, 60 or 84 percent of particle diameters). For hydraulically rough flow ($R_* > 100$), as is the case for open channel flow in high and very high gradient creeks, the logarithmic velocity profile of Eq. B(3) applies for $z > 3k_s$ and is approximated as logarithmic from $z = 3k_s$ to the bed. The areal extent of the bed roughness elements becomes important when dealing with boulder or debris filled reaches. The velocity profile needs to be modified to allow for the additional momentum extracted from the flow when the diameter of the bed elements (d) are large relative to the depth of the flow, h (i.e. d > 0.2, Wiberg and Smith (1987b)).

The lift force (F_L) acting on a grain at the bed is calculated as,

$$F_L = \frac{1}{2} C_L \, s_b \, [f2(\frac{z_t}{z_o}) - f2(\frac{z_b}{z_o})] \tag{B(9)}$$

C_L = Lift Coefficient = 0.2 as suggested by Wiberg and Smith (1987b, 1985)

z_t = Height above the bed to the top of the grain (cm)

z_b = Height above the bed to the bottom of the grain (cm)

The drag force acting on a grain on the bed (F_D) is calculated as,

$$F_D = \frac{1}{2} q_f C_D < f2(\frac{z}{z_o}) > A_x \qquad \text{B(10)}$$

C_D = Drag Coefficient

z_t = Height above the bed of the top of the grain (cm)

z_b = Height above the bed of the bottom of the grain (cm)

A_x = Cross-sectional area of the grain (cm^2)

The drag coefficient (C_D) is a function of the particle Reynolds number, Re, and particle shape, and is estimated using data for spheres given in Rouse (1961).

$$Re = \frac{<u>\ d}{m} \qquad \text{B(11)}$$

$<u>$ = Average Water Velocity Across the Grain (cm/sec)

d = Nominal Grain Diameter (cm)

m = Kinematic Fluid Viscosity (cm^2/sec)

The bed pocket particle angle of repose (u_o) can be estimate using data from Miller and Byrne (1966) and is expressed by,

$$u_o = \cos^{-1}\left[\frac{D/k_s + z_*}{D/k_s + 1}\right] \qquad \text{B(12)}$$

The term z_* represents the level of the bottom of an almost moving grain and is a function of the particle sphericity and roundness. The value of z_* is - 0.02 for natural sand with sphericity of 0.7 and roundness of 0.5 (Russell and Taylor roundness grades) (Wiberg and Smith, 1987b).

The ratio of downward advection to upward diffusion of sediment is used to calculate whether a grain size is transported as suspended load in the interior of the flow, as bedload saltating and rolling on the bed, or is in the transition between these transport mechanisms (Rouse, 1937; Middleton and

Southard, 1984). These classification depend on the Rouse number P in Eq. (B13)

$$P = \frac{W}{a\, j\, U_*} \qquad \mathbf{B(13)}$$

W = Settling Velocity of the Grain (cm/sec.)

a = 1.35 (range for a is $.74 < a < 1.35$, Middleton and Southard (1984))

j = von Karmann's Constant = 0.407

U_* = Shear Velocity (cm/sec.) = $\frac{s_b}{q}$

Sediment will be suspended totally when $P < 0.8$, in transition between suspension and settling to the bed for $0.8 < P < 3$ and settling to the bed for $P > 3$.

APPENDIX C. SUBSTRATE PAVEMENT GRAIN SIZE DISTRIBUTION

Channel substrate pavement was characterized for two locations in the Novelty catchment channel system by measuring the intermediate axis of about 100 randomly selected grains across the channel or bar top. Substantial differences in grain size distributions exist at the two locations.

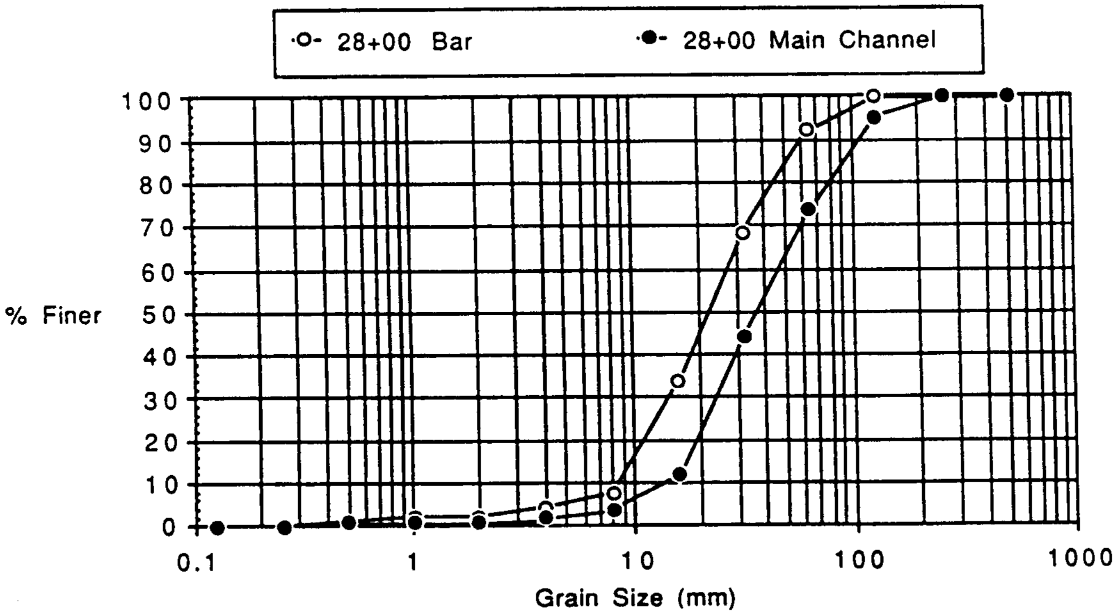

Figure C.1 Substrate pavement pebble count at station 28+00A.

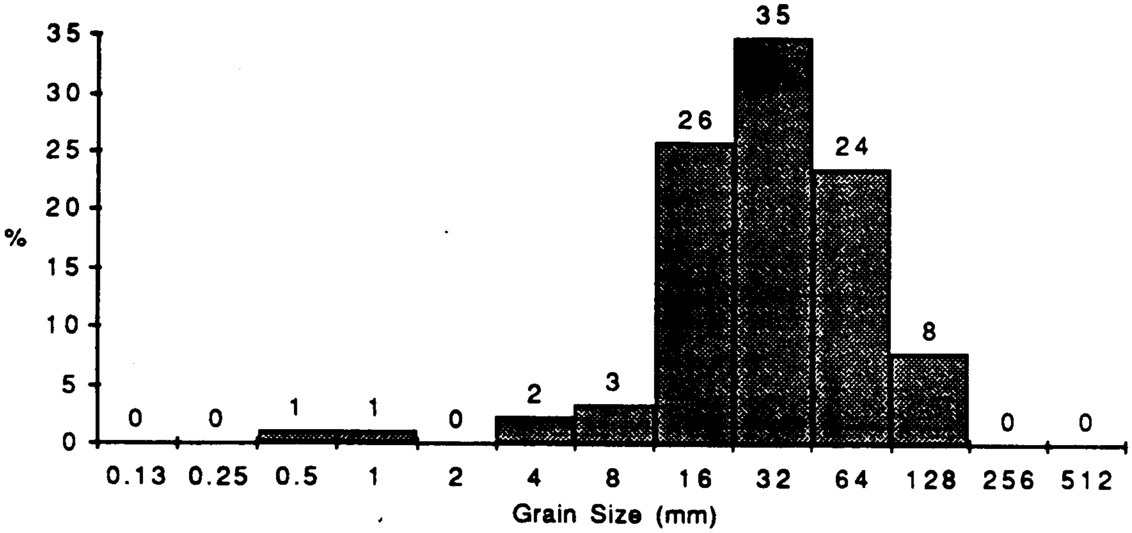

Figure C.2 Histogram of substrate pavement pebble count at station 28+00A, bar top.

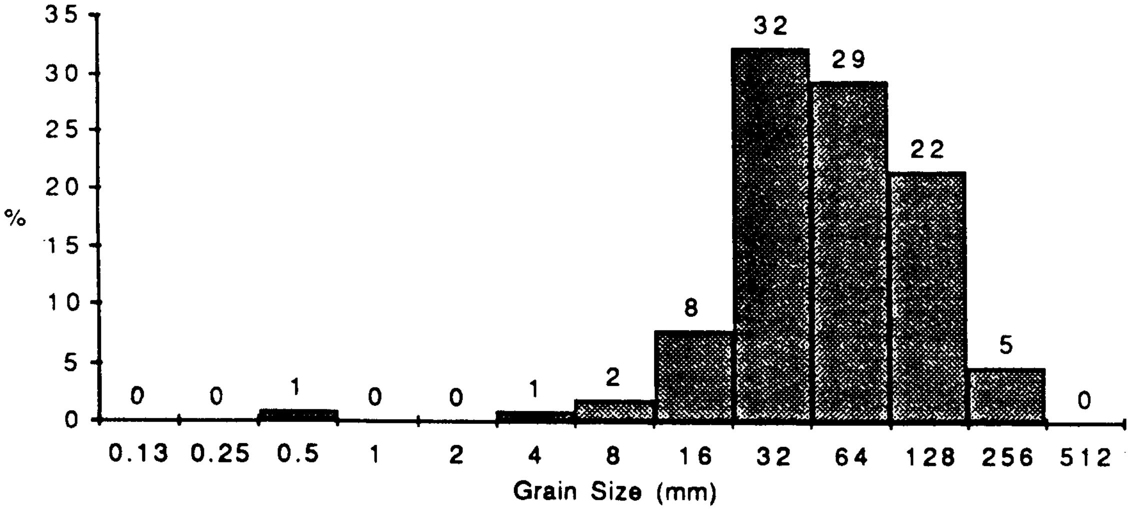

Figure C.3 Histogram of substrate pavement pebble count at station 28+00A, main channel.

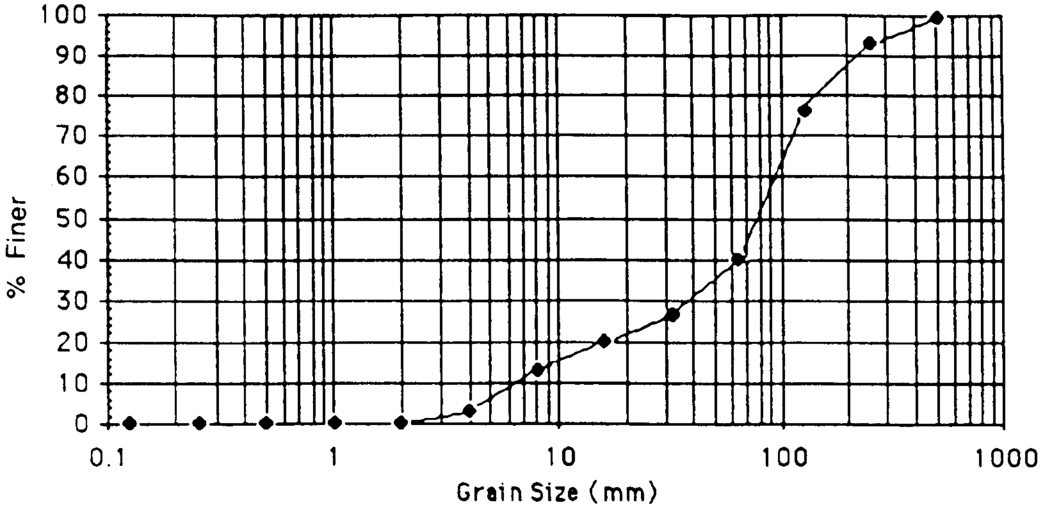

Figure C.4 Substrate pavement pebble count at station 15+00A.

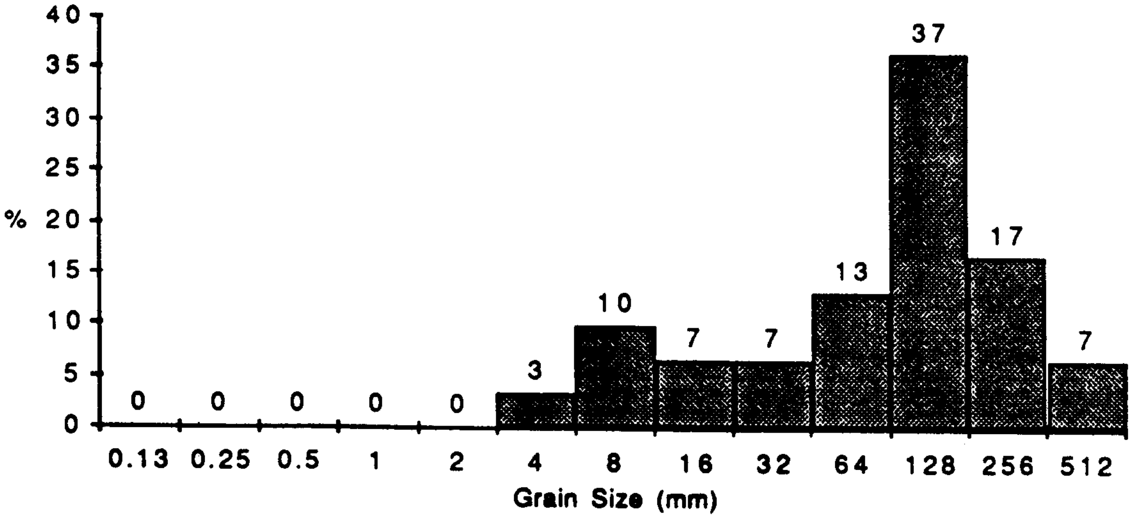

Figure C.5 Substrate pavement pebble count at station 15+00A.

APPENDIX D. RAINFALL INTENSITY - DURATION - FREQUENCY

Reference is made throughout the text to approximate recurrence intervals for storm rainfall. Figure D.1 shows the approximate relationship for Seattle, Washington and the January 1986 storm recorded at Carnation, Washington.

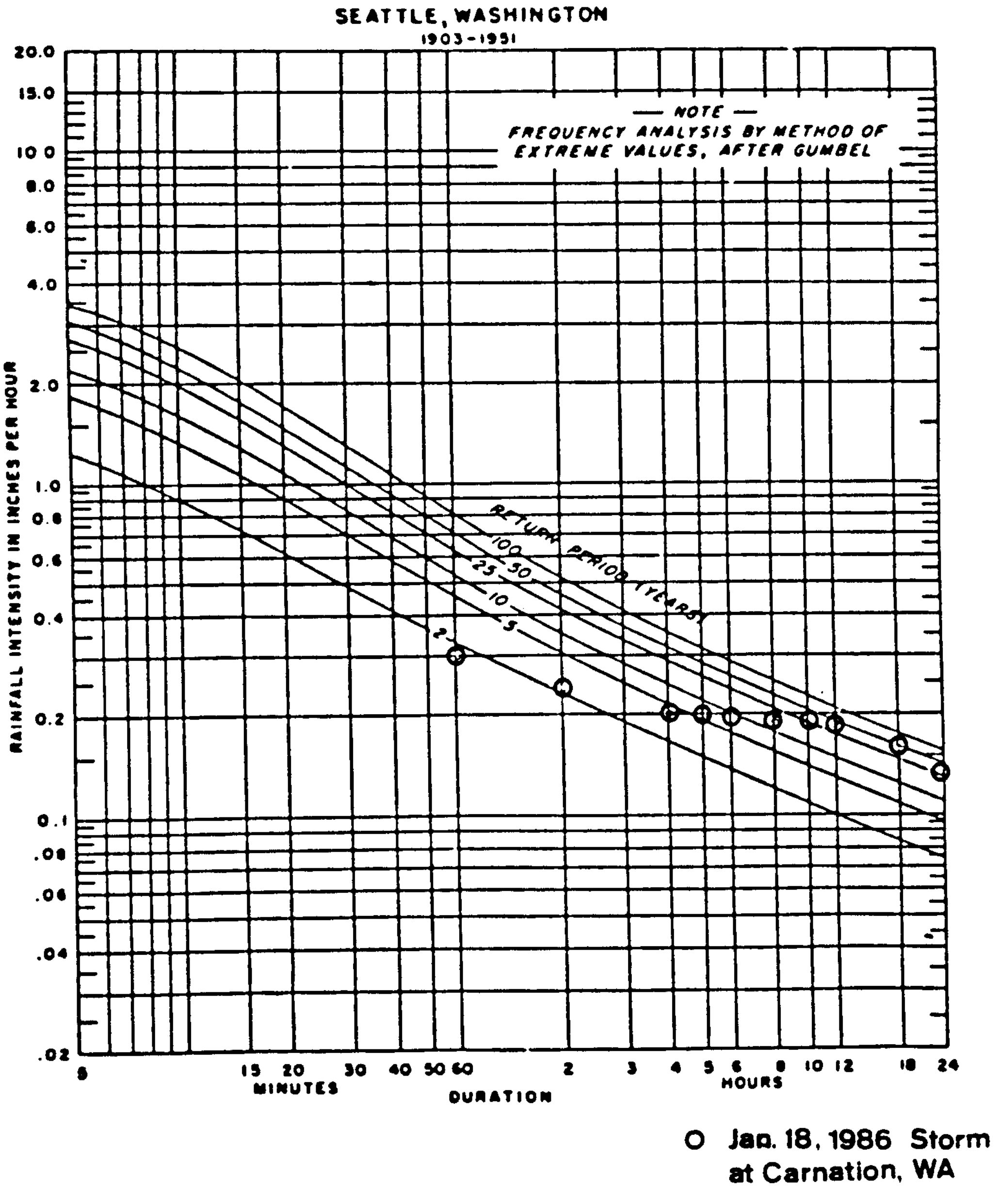

Figure D.1 Rainfall intensity - duration - frequency data for Seattle, Washington, (King County, 1979, Figure 3, page 8).

APPENDIX E. 24-HOUR RAINFALL AND RETURN PERIOD, JANUARY 18, 1986 STORM

Table E.1 Twenty-four Hour Rainfall Depth and Return Period, Jan. 18, 1986 Storm

*STATION	AMOUNT INCHES	PRECIPITATION-FREQUENCY IN YEARS	SOURCE
DARRINGTON	6.8	50	NWS #
CUSHMAN	9.4	100	NWS
SNOQUALMIE FALLS	3.7	2	NWS
LANDSBURG	2.4	< 2	NWS
FRANCES	5.2	5	NWS
MONTESANO	3.4	2	NWS
CENTRALIA	2.4	2	NWS
QUILCENE	4.5	5	NWS
MCMILLIAN	1.8	< 2	NWS
MUD MOUNTAIN	1.4	< 2	NWS
MARBLEMOUNT	4.6	10	NWS
ABERDEEN	6.2	50	NWS
PORT ANGELES	3.8	25	NWS
QUINALT RS	5.5	< 2	NWS
EVERETT	2.6	25	NWS
CARNATION	3.4	25	NWS
SANDPOINT/SEA	4.56	>100	NWS
MOUNTLAKE/SEA	4.43	>100	NWS
SEATAC	3.13	25	NWS
QUILCEDA	1.59	2	USGS *
SILVER LAKE	3.42	> 50	USGS
LYNNWOOD	3.16	> 50	USGS
LAKE LEOTA	4.56	>100	USGS
BLACK DIAMOND	1.93	< 2	USGS
LAKE MORTON	2.48	5	USGS
1 MI. N OF GREEN RIVER COMMUNITY COLLEGE	2.40	5	USGS

Data were obtained from NWS Fisher Porter recording rain gage tapes with preliminary analysis by Lee Krogh, Hydrologist NWS. Final analysis will be made and published by the NWS Climatic Center in about 6 months.

* Data were obtained from USGS/Tacoma from their rain gages and analysis by Rick Dinicola USGS/Tacoma for the maximum 24 hour amounts.

Precipitation-Frequency was determined using:
NOAA ATLAS 2
Precipitation-Frequency Atlas of the Western United States
Volume IX-Washington

APPENDIX F. CLASSIFICATION OF STREAM SUBSTRATE

The classification of stream channel substrate materials by particle size used in this report follows Lane (1955) and Platts (1983). The size distribution is given in Table F.1.

Table F.1 Classification of Stream Substrate.

	Size Range		Approximate sieve mesh openings per inch	
Class name	**Millimeters**	**Inches**	**Tyler Screen**	**United States Standard**
Very large boulders	4,096-2,048	160-80		
Large boulders	2,048-1,024	80-40		
Medium boulders	1,024-512	40-20		
Small boulders	512-256	20-10		
Large cobbles	256-128	10-5		
Small cobbles	128-64	5-2.5		
Very coarse gravel	64-32	2.5-1.3		
Coarse gravel	32-16	1.3-0.6		
Medium gravel	16-8	0.6-0.3	2.5	
Fine gravel	8-4	0.3-0.16	5	5
Very fine gravel	4-2	0.16-0.08	9	10
Very coarse sand	2.000-1.000		16	18
Coarse sand	1.000-0.500		32	35
Medium sand	0.500-0.250		60	60
Fine sand	0.250-0.125		115	120
Very fine sand	0.125-0.062		250	230
Coarse silt	0.062-0.031		270	
Medium silt	0.031-0.016			
Fine silt	0.008-0.004			
Very fine silt	0.008-0.004			
Coarse clay	0.004-0.0020			
Medium clay	0.0020-0.0010			
Fine clay	0.0010-0.0005			
Very fine clay	0.0005-0.00024			

APPENDIX G. EXISTING HYDROLOGIC METHODS FOR STORMWATER MITIGATION DESIGN

Three different approaches are in general use for estimating what changes to rainfall-runoff response might result from catchment land modifications. In the United States the rational and SCS methods are the most used methods to estimate rainfall-runoff response for small development projects in ungauged catchments. Continuous simulation models are often used on larger catchments where adequate gauge data are available for model calibration. A fourth method, catchment gauging, is generally only used for research projects. It involves the placement of both rain and stream gauges within the catchment. Regression equations are then derived relating the rainfall to runoff.

Rational Method of Runoff Estimation

With the rational method a rainfall intensity is multiplied by the subbasin area and a coefficient representing a fixed percentage of rainfall, to obtain a peak runoff rate. The rainfall intensity is selected from rainfall intensity-duration-frequency curves, based on the time period of the longest flow path to the basin outlet.

Thomas Mulvany (1851) first proposed using "the time necessary for the rain which falls on the most remote portion of the catchment, to travel to the outlet," for use as "the time which a flood requires to attain to its maximum height, during the continuance of a *uniform rate of fall* of rain." (Italics are the emphasis of the original author.) Kuichling is credited with the introduction of the Rational method in the United States in 1889 (Schaake et al, 1967). " Despite the complex nature of the rainfall-runoff process, the practice of estimating runoff as a fixed percentage of rainfall is the most commonly used method in design of urban storm-drainage facilities, highway culverts, and many small water-control structures" (Linsley et al, 1982, page 242). At best, the method may be correct when dealing with a smooth surface which is completely impervious, so that the runoff coefficient is near 1.0 (Linsley et al, 1982).

In the 1930's, Robert Horton's studies introduced the first widely accepted explanation for overland flow production. "Since the 1930's the Horton (1933) infiltration approach to runoff production has dominated hydrology and its applications to the prediction of river discharges" (Dunne et al, 1975). The Horton overland flow concept was easily incorporated into the rational method. In the 1960's hydrologists observed that for some landforms storm runoff is only produced from a limited and variable portion of the catchment (US Forest Service, 1961; Betson, 1964; Tennessee Valley Authority, 1965; Hewlett and Hibbert, 1967; Hewlett and Nutter, 1970; Dunne, 1969; Dunne et al, 1975). Recognition of this "variable source area" concept for storm runoff production violates the basic assumptions and therefore limits the range of applicability of the rational method. Another important runoff-producing process, not accounted for by the rational method, is throughflow discharge (water that enters the channel system by shallow groundwater flow paths) (Anderson and Burt, 1978; Sklash et al, 1986).

The rational method utilizes rainfall volumes and intensities from regional rainfall records. The unwarranted assumption is made that rainfall and runoff recurrence intervals are both equivalent; variability in antecedent catchment conditions virtually guarantee rain and runoff recurrence intervals will vary. The same rainfall on a wet catchment will generate a different runoff response than it does on a dry catchment.

A comparison of measured peak discharges with those calculated by the rational method for 66 catchments, located in eastern, middle, and western United States, and England, showed the calculated values were consistently low (Chow,1964). The mean absolute deviation for all 66 catchments was 34% with a range from 17% to 79%. Schaake et al (1967) reported percentage errors that ranged from -46% to +61 obtained by comparing calculated peak flow values by five different agencies using the Rational Method for 6 different urbanized catchments in the Baltimore area.

Soil Conservation Service Method of Runoff Estimation

Paragraph one, page 1-1 of the Soil Conservation Service (SCS) TR-55 manual reminds us that, " At this time only general empirical relationships between the parameters that affect runoff and peak rates of discharge can be developed" (U.S. SCS, 1975). The manual follows with a detailed summary of measurable watershed characteristics utilized by the method. "An understanding of these characteristics is required for judging how to alter parameters to reflect changing watershed conditions" (U.S. SCS, 1975, page 1-2). These volume and time parameters are an incomplete characterization of some aspects of runoff production and give the unwary practitioner the impression model results accurately reflect response for any catchment changes, when in fact basin conditions could respond quite differently. The method is an empirical estimation based on small agricultural catchments. Universal use of the method is similar to using an uncalibrated instrument: results could be accurate but there is really no way to assess the accuracy without some calibration to the site. Rough calibration of the existing catchment conditions can be accomplished with estimates of channel capacities if the basin is in equilibrium or by use of a gauging network. The gauging is rarely conducted, and channel capacity estimates are rough at best and only reflect catchment conditions of the present and recent past. The SCS parameters, though important, are by no means a complete characterization of catchment processes. Estimates of future catchment response using the method can not be calibrated without a complete accounting of catchment processes.

Changes to catchment hydrologic response resulting from landuse modifications is related to changes to basin features such as swales, hollows, 1st order channels, areas of infiltration, and zones of return flow. These features are not well represented on 1:24,000 (1" = 2000') scale maps. Yet this is the common scale of county soils maps. Hydrologic soil groups are commonly selected based solely on soils maps. Many site conditions, such as soil compaction and disturbance of the litter layer, as suggested in SCS TR-55 (page 2-4, paragraph 4) will alter the hydrologic soil group. General soils maps and broad classifications of hydrologic soil groups will not adequately characterize the actual catchment rainfall-runoff response. Field mapping could provide a more detailed classification of catchment hydrologic soil groups but it is uncertain if parameter adjustments based on greater catchment detail are of any value in a general empirical method.

The SCS method is based on overland flow paths; areas with no overland flow, and areas of return flow are not accounted for in parameter adjustments. Time of concentration (t_c) is the greatest length of time it takes water to flow overland to the point of interest on the catchment. Basin lag time is defined as the period of time between the centroid of the rainfall and runoff mass curves. The SCS method is sensitive to both time of concentration and basin lag. Despite this, actual travel times are rarely measured in the field; estimates are based on charts that may not correctly reflect the characteristics of the actual flow paths. Runoff depth is also sensitive to the estimated curve number (Hawkins, 1975, Bondellid, 1982). Hawkins (1984) found the correlation between curve numbers calculated from hydrologic analysis and curve numbers estimated from soil and vegetation groups is not significantly different from zero, (Hawkins, 1984). In an analysis of 110 cases he reports, " In general, there is a discouraging lack of correspondence between the handbook-predicted and the hydrologic data-observed curve numbers" (Hawkins, 1984). Agriculture watersheds led to the most accurate estimates, which is to be expected given the origins of the empiricism. Forested watersheds were found "almost entirely unrelated to observed reality" (Hawkins, 1984). He concludes that the routine application of the curve number method "may lead to variable, inconsistent, or invalid results" (Hawkins, 1984).

Continuous Simulation Models for Runoff Estimation

Continuous simulation computer models, used to estimate runoff from rainfall, provide a detailed hydrologic accounting of rainfall, water losses, and runoff contributions from both surface and sub-surface flow paths. Parameter adjustments, though named for some of the more important runoff processes, are not necessarily consistent with the actual catchment dynamics. The models rely on calibration of the rainfall-runoff relationship with nearby rainfall and runoff gauge records. Typically 6 to 10 years of data are needed for calibration and verification. Most catchments with more than 6 to 10 years of stream gauging are many square miles in area, rather than the small subbasins being analyzed in most hydrologic studies for development permits. Often the rain gauge is some distance from the catchment, making calibration difficult over the full range of encountered weather and catchment conditions. Calibration of computer models with on-site gauge data is useful for present conditions, but the results say nothing about changed conditions unless the functional relationships of the model accurately represent catchment dynamics. Inclusion of catchment hydrologic process zones along with gauge data has received little attention.

Catchment Gauging for Runoff Estimation

Measured catchment rainfall and runoff provide useful data for present catchment conditions. Estimation of future catchment response after development would be facilitated but by no means fully represented by gauge data for a catchment undergoing change. While expressions of rainfall-runoff response can be developed, the expressions say little about what causes the response but rather what the response was and how close the functional expressions mimic the numbers. Prediction of future response, once the catchment has been changed, can not be modeled by an expression unless the main parameters are based on the changing catchment features and the relationships between catchment features and rainfall-runoff response are known. This level of basin characterization has rarely been approached even in intensively monitored areas. There is little hope of this level of study being available for the majority of building decisions. Short-term gauging can provide information on basin lag and response for typical storms; however, it is unlikely a "25 to 100 year" event, upon which mitigation designs are based, would be observed.

Appendix H SPATIALLY DISTRIBUTED RAINFALL-RUNOFF MODEL INTRODUCED IN CHAPTER 6

H.1 MODEL STRUCTURE

The model consists of a rainfall preprocessor and seven components which simulate canopy interception; evapotranspiration; infiltration; and surface, litter, unsaturated, and saturated flow dynamics (Figure 6.1). In application, the catchment to be modeled is divided into subareas based on soil type and depth, vegetation type, topography, and field mapped hydrologic process zones. Within each subbasin the quantities and areal locations of Horton, subsurface, and saturation overland flow are simulated. An approximate calibration is achieved by comparing the location of simulated runoff production zones against the field mapped locations. Each subbasin is modeled separately and the results from all subbasins are combined using a simple physically-based routing scheme. The model differs from numerous others in its representation of upper forest litter and soil layers that are modified when catchment land use changes.

H.2 RAINFALL AND INTERCEPTION

Rainfall is processed one month at a time, allowing a variable time-step to be used based on rainfall intensity and a corresponding antecedent precipitation index. The use of six time-step lengths, ranging from 6 minutes to 24 hours was found to produce satisfactory results (see Chapter 6). Interception loss is simulated by an interception-storage capacity based on canopy type. All rainfall is assumed to enter interception storage until it is full. Interception storage is depleted by evaporation at the potential rate until reduced to zero.

H.3 LITTER ZONE REPRESENTATION

Rainfall which is not intercepted (throughfall) may fall either on litter or directly on soil. The impact of various forms of land use can be simulated by completely removing the litter zone or changing its thickness. The model allows development of a dynamic saturated zone. Throughfall landing on the saturated zone generates saturation overland flow. Throughfall which enters the litter zone is temporarily detained, increasing the average moisture content. Percolation from the litter zone is assumed to be a function of moisture content. The continuity equation for this zone can be written in finite difference form as

$$S_l^{t+\Delta t} - S_l^t = r^{t+\Delta t} X^{t+\Delta t} \Delta t - p^t X^t \Delta t \qquad \text{(H.1)}$$

where S_l is the volume of water stored, r is the rate of throughfall, X is the downslope distance to the water table - soil surface interface (Figure H.1), p is the percolation rate from the litter zone, and the superscripts t and $t+\Delta t$ refer to the beginning and end of the time period respectively.

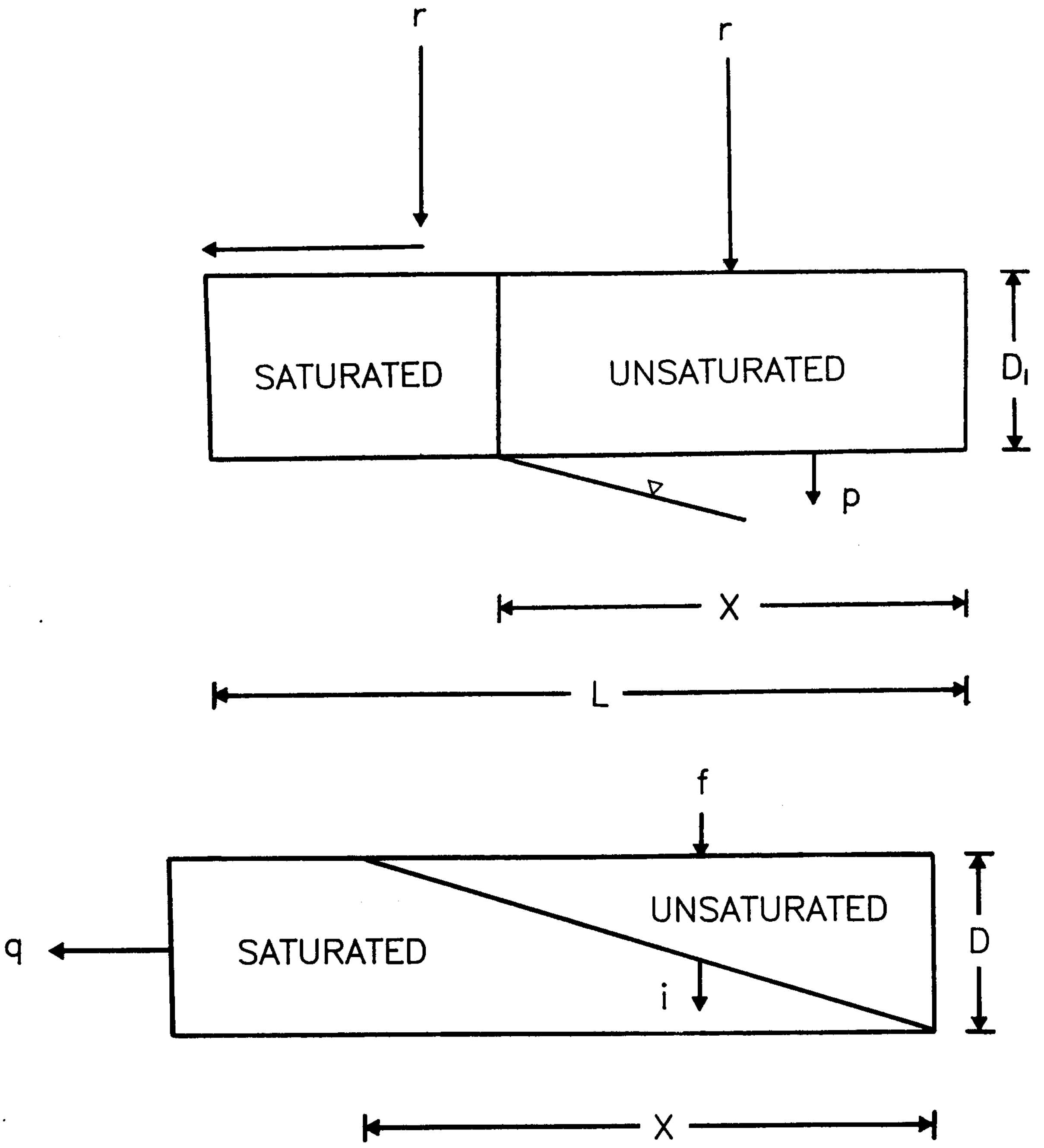

Figure H.1 Schematic of model of two-zone subsurface structure. The litter zone has depth D_l, and the soil has depth, D.

The volume of stored water in the unsaturated litter zone is given by

$$S_l = \phi X D_l \qquad \text{(II.2)}$$

where ϕ is the average volumetric moisture content and D_l is the litter zone depth. Combination of equations (H.1) and (H.2) allows the moisture content at the end of the time period to be calculated as

$$\phi^{t+\Delta t} = \frac{\phi^t X^t D_l + r^{t+\Delta t} X^{t+\Delta t} \Delta t - p^t X^t \Delta t}{X^{t+\Delta t} D_l} \qquad \text{(II.3)}$$

The functional relationship between percolation and moisture content used in this model component is based on the work of Balci (1964). In his work, Balci used a rainfall simulator to study the hydrologic behavior of mor and mull type litter under uniform rainfall intensities of 2.3 and 15 cm/hr. Balci's data allow percolation to be calculated as

$$p = 0, \qquad \phi \leq \phi_{fc} \qquad \text{(H.4a)}$$

$$p = 2.3\left[\frac{(\phi - \phi_{fc})}{(\phi_{2.3} - \phi_{fc})}\right] \qquad \phi_{fc} < \phi < \phi_{2.3} \qquad \text{(II.4b)}$$

$$p = 2.3 + 12.7\left[\frac{(\phi - \phi_{2.3})}{(\phi_{15} - \phi_{2.3})}\right] \qquad \phi_{2.3} \leq \phi \leq \phi_{15} \qquad \text{(II.4c)}$$

where ϕ_{fc} is the volumetric litter zone moisture content at field capacity and $\phi_{2.3}$ and ϕ_{15} are equilibrium moisture contents (a function of litter type and depth) under steady percolation rates of 2.3 and 15 cm/hr respectively.

II.4 SOIL INFILTRATION

The amount of direct throughfall or litter zone percolation which enters the soil profile is estimated by Philip's (1957, 1969) equation modified for variable rainfall intensity

$$f^{t+\Delta t} = K_s + G\left[\frac{G + \sqrt{G^2 + K_s F^{t+\Delta t}}}{4 F^{t+\Delta t}}\right] \qquad \text{(II.5)}$$

where f is the infiltration rate, K_s is the vertical saturated hydraulic conductivity, F is the cumulative infiltration, and G is the soil sorptivity. Antecedent conditions are imposed through the sorptivity term which is a function of soil type and soil moisture at the start of a storm.

Sorptivity is updated prior to a storm using the average moisture content in the unsaturated zone. Sorptivity is then assumed to remain constant during a storm. Cumulative infiltration is reset to zero between storms. This method is consistent with the hydrologic concept of time condensation (Milly, 1986), assuming that the infiltration capacity depends only on cumulative infiltration during the event and on initial conditions at the start of the event. When the available water input exceeds the infiltration capacity, percolation from the litter zone is restricted, or when no litter is present, Horton overland flow is generated (once surface detention has been exhausted).

H.5 UNSATURATED ZONE DYNAMICS

The model's subsurface components (Figure H.1) are based on the work of Sloan and Moore (1984) and Sloan et al. (1983). Infiltrated water is routed through the unsaturated zone at a rate equal to the soil's hydraulic conductivity

$$i = K(\theta) \tag{H.6}$$

where i is the unsaturated discharge to the water table, K is the soil's hydraulic conductivity, and θ is the average volumetric moisture content in the unsaturated zone.

As for the litter zone, moisture content is updated via the continuity equation

$$S_u^{t+\Delta t} - S_u^t = f^t X^t \Delta t - i^t X^t \Delta t \tag{H.7}$$

The volume of water stored in the unsaturated zone (S_u) is given by

$$S_u = \tfrac{1}{2} X D \theta \tag{H.8}$$

where D is the soil depth. Substitution of equation (H.8) for storage in equation (H.7) allows soil moisture at the end of the time period to be calculated as

$$\theta^{t+\Delta t} = \frac{\tfrac{1}{2} X^t D^t \theta^t + (f^t - i^t) X^t \Delta t}{\tfrac{1}{2} X^{t+\Delta t} D} \tag{H.9}$$

The Brooks-Corey (1964) relation is used to determine hydraulic conductivity as a function of moisture content

$$K(\theta) = K_S\left[\frac{\theta - \theta_r}{\theta_s - \theta_r}\right]^{\frac{2+3\lambda}{\lambda}} \tag{H.10}$$

where θ_r equals the residual soil moisture, θ_S is the saturated soil moisture, and λ is an empirical constant relating effective saturation to the soil capillary suction.

H.6 SATURATED SUBSURFACE FLOW

Flow dynamics within the saturated zone are simulated using Sloan and Moore's (1984) kinematic storage model. The slope of the phreatic surface is taken as constant, and the potential gradient is set equal to the slope of the impermeable layer. The continuity equation within this zone may be written as

$$S^{t+\Delta t} - S^t = i^t X^t \Delta t - \tfrac{1}{2}(q^t + q^{t+\Delta t})\Delta t \tag{H.11}$$

where

$$S = \gamma\left[(L - X)H + \tfrac{1}{2}HX\right]$$

$$q = K_l H \alpha$$

and γ is the drainable porosity (assumed equal to the difference between saturation and field capacity volumetric moisture contents), L equals the total slope length, H is the water table height at the down slope boundary, K_l is the lateral saturated hydraulic conductivity, and α is the slope of the impermeable bed.

When the water table remains below the soil surface, H at the end of the time period is computed as

$$H^{t+\Delta t} = \frac{2S^t + 2i^t X^t \Delta t - q^t \Delta t}{L\gamma + K_l \alpha \Delta t} \tag{H.12}$$

If the water table intersects the soil surface, $X^{t+\Delta t}$ is calculated by

$$X^{t+\Delta t} = \frac{DL\gamma - (S^t + i^t X^t \Delta t) + q\Delta t}{\tfrac{1}{2}D\gamma} \tag{H.13}$$

No litter zone percolation enters the soil through the saturated zone. In the absence of litter, any throughfall landing on the saturated zone produces saturation overland flow. Infiltrated water is still supplied to the soil profile upslope from the saturated zone. It is possible to generate both saturation and Horton overland flow simultaneously.

H.7 OVERLAND FLOW

A kinematic storage model was developed for overland flow routing (Figure H.2). This scheme allows a variable rainfall intensity and a time variant saturated zone. The method simulates Horton overland flow and saturation overland flow separately or simultaneously. If the flow is steady and uniform, Manning's equation can be used to compute discharge (q_s) as a function of flow depth

$$q_s = kY^{\frac{5}{3}} \tag{H.14}$$

where

$$k = \frac{1.49}{n}\sqrt{\beta},$$

Y is the flow depth, β is the surface slope, and n is a roughness coefficient.

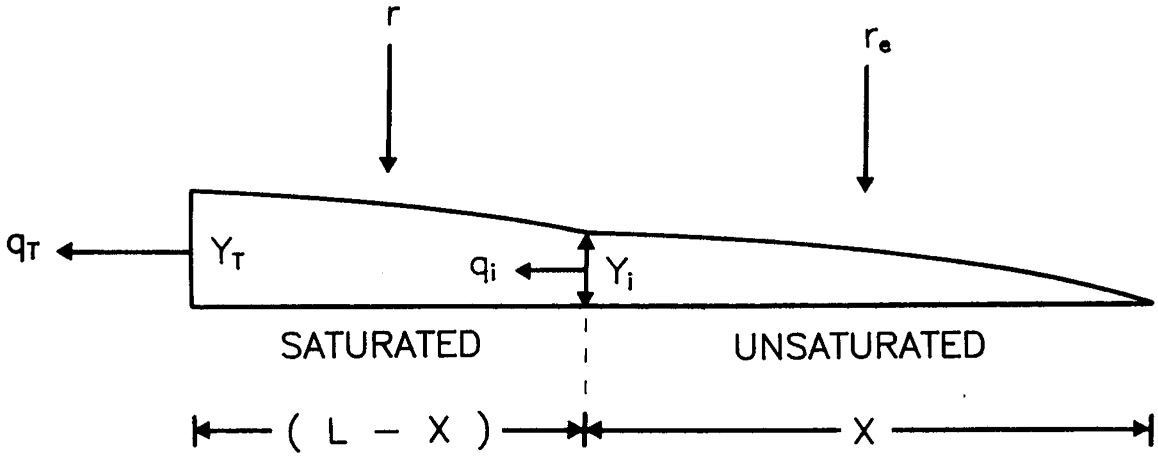

Figure H.2 Definition sketch for surface flow above saturated (L-X) and unsaturated (X) ground.

For steady state conditions, discharge from the infiltration excess zone (q_i, Figure H.2) is given by

$$q_i = k(Y_i)^{\frac{5}{3}} = r_e X \tag{H.15}$$

where Y_i is the flow depth at the downslope end of the zone of infiltration excess, and r_e is throughfall less infiltration. Under these conditions, the total hillslope discharge (q_T) is

$$q_T = r_e X + r(L - X) = k(Y_T)^{\frac{5}{3}} \tag{H.16}$$

where Y_T is the flow depth at the base of the hillslope.

Combining equations (H.15) and (H.16) allows Y_i to be determined as

$$Y_i = \left[\frac{r_e X}{r_e X + r(L - X)} \right]^{\frac{3}{5}} Y_T = A Y_T \tag{H.17}$$

The total volume of water stored on the hillslope (S_o) equals

$$S_o = B Y_i + C Y_T \tag{H.18}$$

where

$$B = \tfrac{5}{8} X Y_i$$

and

$$C = \frac{5}{8} \left[L - \frac{X^{\frac{8}{5}}}{L^{\frac{8}{5}}} \right] Y_T$$

Combining equations (H.17) and (H.18) allows S_o to be computed in terms of Y_T

$$S_o = (AB + C) Y_T \tag{H.19}$$

The continuity equation may be written as

$$S_o^{t+\Delta t} - S_o^t = r_e X \Delta t + r(L - X) \Delta t - q_T \Delta t \tag{H.20}$$

If the time step is small enough that the steady state relationships developed are a good approximation under transient conditions and

$$q_T \simeq k(Y_T^t)^{\frac{5}{3}},$$

the downstream flow depth at time t+Δt can be calculated as

$$Y_T^{t+\Delta t} = \frac{r_e^{t+\Delta t}\, X^{t+\Delta t}\, \Delta t + r^{t+\Delta t}(L - X^{t+\Delta t})\,\Delta t - k(Y_T^t)^{\frac{5}{3}} + S_o^t}{(AB + C)^{t+\Delta t}}, \qquad \text{(H.21)}$$

allowing the new total hillslope discharge to be calculated.

H.8 EVAPOTRANSPIRATION

Actual evapotranspiration (ET_a) is calculated as a function of potential evapotranspiration (ET_p). For the litter and soil zones this relationship is expressed as

$$ET_a = cET_p \qquad \text{(H.22)}$$

where

$$c = 1, \qquad \theta' \geq \theta'_{fc}$$

$$c = \frac{(\theta' - \theta'_{wp})}{(\theta'_{fc} - \theta'_{wp})}, \qquad \theta'_{wp} < \theta' < \theta'_{fc}$$

$$c = 0, \qquad \theta' < \theta'_{wp}$$

where θ' is the average moisture content, θ'_{fc} is the field capacity moisture content, and θ'_{wp} is the moisture content at the vegetation wilting point.

Water is extracted by evapotranspiration in the following order:

1) Interception Storage	potential rate
2) Surface Detention	at potential rate
3) Litter Zone: $\theta' \geq \theta'_{fc}$	eqn (H.22)
4) Soil: $\theta' \geq \theta'_{fc}$	eqn (H.22)
5) Litter Zone: $\theta' < \theta'_{fc}$	eqn (H.22)
6) Soil: $\theta' < \theta'_{fc}$	eqn (H.22)