Appendix B

HMP Literature Review

- **Executive Summary**
- **Full Document**

Santa Clara Valley
Urban Runoff Pollution Prevention Program

Hydromodification Management Plan
Literature Review

EXECUTIVE SUMMARY

Background

The California Regional Water Quality Control Board (RWQCB), San Francisco Bay Region, issued a Permit Amendment revising Provision C.3 to the Santa Clara Valley Urban Runoff Pollution Prevention Program on October 17, 2001. The Program's NPDES Permit is jointly issued to thirteen Cities in Santa County, Santa Clara County, and the Santa Clara Valley Water District, all of which are Co-permittees.

A literature review was prepared in response to the NPDES Permit requirements to address the impacts from new and redevelopment projects on stream morphology, habitat, and erosion potential. Permit Provision C.3 requires the Co-permittees to address these impacts through the creation and implementation of a Hydromodification Management Plan (HMP).

The purpose of the literature review was:

1) To meet the permit requirement (Provision C.3.f.viii.2);
2) To provide technical information to assist in the development of the Plan; and
3) To educate stakeholders and regulatory staff.

Articles included peer reviewed journal articles and local and regional sources. Topics included physical processes that influence stream channel characteristics, effects of urbanization on channel stability, thresholds of channel stability, assessment methods, guidance on watershed management strategies, control measures, and habitat quality. Most of the research has been conducted in regions with different climatic, geologic and physiographic conditions than those found in the Bay Area. Reports on local streams conducted by professionals in the Bay Area were also included. The potential list of literature grew to about 80, of which about 50 were ultimately used in this literature review.

Problem Statement (Chapter 1)

Hydromodification refers to the effects of urbanization on runoff and stream flows that in turn may cause erosion and/or sedimentation in the stream channels. Figure E1 presents a *Conceptual Model* of the hydrologic and geomorphic processes that influence the condition of streams and can be affected by hydromodification. Climate, geology, and landscape affect runoff and sediment discharged to stream channels. Land use, soil and vegetation characteristics affect the proportion of rainfall that infiltrates the ground or runs off the surface. Urbanization increases the peak flow and volume of surface runoff by adding impervious surfaces and drainage facilities. Stream flow energy imposed on the stream channel may also be increased due to urbanization, causing erosion of the streambed and banks, sediment transport, and deposition.

HMP Goals and Objectives (Chapter 2)

The primary goal of the HMP and the RWQCB is to protect and restore the physical, chemical, and biological functions of stream systems in urban areas. A top priority is protecting existing healthy stream systems with a goal that urbanization will not result in a net loss of ecological functionality. For impaired streams, the goal is to achieve the maximum attainable practical restoration of functions.

In order to meet these goals the following objectives were defined:

a) Develop a watershed-based HMP to address the impacts of hydromodification on the beneficial uses of streams;

b) Characterize stream segments currently having erosion problems,

c) Develop, test, and apply an assessment method to evaluate possible future erosion problems,

d) Develop design criteria, control measures, and guidance on management strategies,

e) Involve the public, stakeholders, and other interested parties to ensure acceptability of the HMP,

f) Manage the impacts of hydromodification on streams through the implementation of the HMP,

g) Monitor the effectiveness of the control measures and management strategies, and amend the HMP as needed.

Hydrologic Processes (Chapter 3)

Urbanization causes increases in the drainage density and degree of networking (rain gutters, curbs/gutters, drainage pipes), and increases in the percent imperviousness and connectivity of impervious areas. Urbanization also may result in soil compaction, removal of native vegetation, and reductions in the width of the riparian corridors. Increases in impervious surface increases peak flows, especially in the more frequent events, increases runoff volume, increases the duration of smaller flow events, and increases the frequency and duration of sediment transporting flow events. Seasonal flow regimes may also change with urbanization. Dry season baseflows can decrease where the loss of infiltration is significant. In turn, reduced baseflows may limit riparian vegetation. Summertime baseflows can increase in areas where excess irrigation is significant compared to normal dry season flows and alter wetland and riparian hydro-periods.

Geomorphic Processes (Chapter 4)

Fluvial geomorphology deals with forms and characteristics of stream channels and the processes that create them. Over time and before human disturbances, channel planform, slope, and cross sectional dimensions evolved to balance stream flow energy and the need to transport sediment load. A natural stream channel is “stable” when its cross section, plan form, and profile features are in dynamic equilibrium such that the stream neither aggrades, degrades, or changes in geometry or meander pattern during the present climatic regime.

Increases in impervious surfaces and the associated changes in runoff have the potential to destabilize streams. The degree of change is highly variable and depends on the characteristics of the watershed and on the development style. Effects include increasing the frequency and duration of geomorphically significant flows and increasing the amount of "*work done*" on the stream bed and banks. These in turn can lead to increases in stream depth, or incision, and erosion of stream banks in some segments; increased sediment transport, and deposition in downstream segments closer to the Bay.

Riparian Ecology (Chapter 5)

Habitat and its associated plant and animal types are strongly correlated to the available water supply, its frequency of inundation, and watershed disturbance patterns. The frequency and duration of inundation on floodplain surfaces and side channels create hydro-periods that establish different ecological communities and add to the diversity of the riverine corridor. Flooding creates habitat that varies in its productivity and structural complexity depending on the timing and duration of inundation, type of substrate, vegetation, and upstream erosional processes. Riparian vegetation along abandoned channels and emergent wetlands creates off stream habitat and provides increased physical structure to habitats including refuges, spawning/nesting and rearing habitat, and food resources.

Assessment Methods (Chapter 6)

Chapter 6 of the literature review summarizes several assessment tools that can be combined to formulate an assessment method. These tools include classification, empirical methods, mapping and modeling. An assessment method must incorporate factors that describe the characteristics of watersheds, stream types, development style, and existing riparian conditions. Watershed and stream channel characterization is the first step towards any assessment addressing the physical and ecological conditions of a watershed and stream network. The watershed scale characterization helps focus attention on the processes impacted by development and the actual causes of the observed impacts rather than focusing in on the symptoms, such as bank failures.

Historical information can be used to help explain the observed physical and ecological processes and existing stream channel conditions. The historical analysis can provide insight into likely response to hydromodification and can be used to verify assumptions on the expected channel response.

The current direction of research is to utilize simplified methods, or indices that can be used to distinguish between eroding or non-eroding, or stable and unstable channel conditions. Indices, such as ratios of stream power, are attractive because they are simple to use and inexpensive to apply. Indices of stability, energy, or erodibility must be referenced to the erodibility of the most sensitive boundary condition.

Management Strategies (Chapter 7)

Management strategies often integrate a series of progressive control measures including land use planning, distributed on-site control measures, regional facilities, and stream restoration.

Elements of such a strategy are as follows:

a) Preserve the natural hydrologic conditions and protect sensitive hydrologic features, sediment source characteristics and sensitive habitats. Avoid, to the extent possible, the need to mitigate for hydromodification.

b) Minimize the effects of development through strategic design (e.g., reduce connected impervious surfaces) and through the implementation of environmentally sensitive on-site distributed BMP’s (e.g., wetlands, swales, infiltration gardens, etc.)

c) Manage the stream corridor itself by implementing in-stream controls, such as grade controls, biotechnical bank stabilization controls, and restoration. Provide allowances for the modified stream flow characteristics and enhance the beneficial uses of streams.

d) In some cases, a regional stormwater management system may be cost effective. These strategies could include regional floodplain management, secondary collection and drainage systems, and large-scale detention and infiltration basins.

Available Local Data (Chapter 8)

Chapter 8 of the literature review summarizes the *Available Local Data* that could be useful in addressing hydromodification, implementing an assessment method, and identifying solutions.

Conclusion

The literature review covered many aspects of hydromodification in response to the RWQCB requirements to address the impacts from new and redevelopment projects on the beneficial uses of streams in the Santa Clara Basin. Important elements of hydrologic and geomorphic processes have been described and discussed in terms of changes caused by urbanization. Assessment tools and management strategies have also been discussed and summarized. Information from the literature review was used in creating the overall approach to developing the HMP.

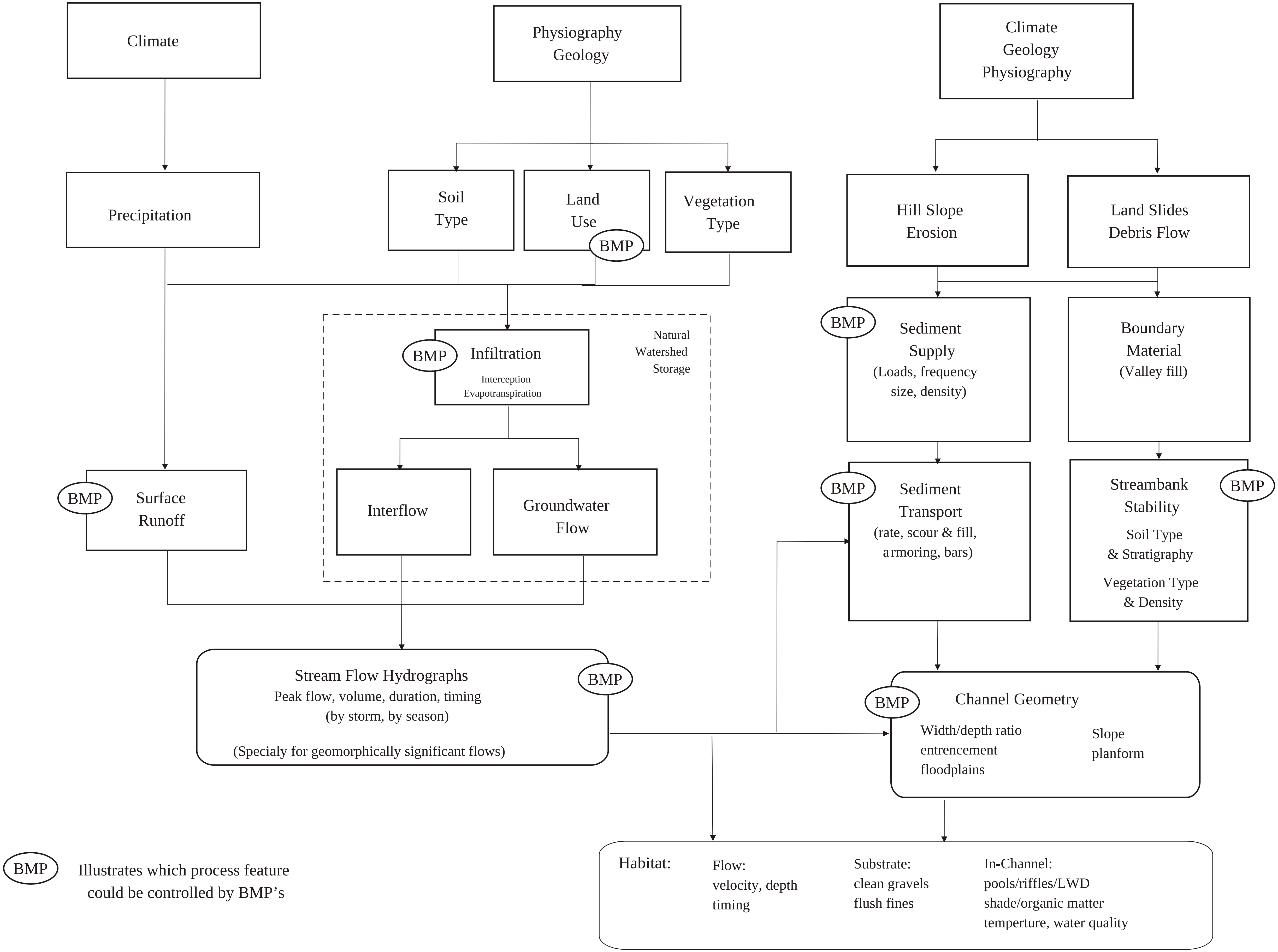

Figure E1. CONCEPTUAL MODEL ILLUSTRATING THE LINKAGES BETWEEN THE HYDROLOGIC AND GEOMORPHIC PROCESSES TO BE ADDRESSED IN HYDROMODIFICATION

Source: GeoSyntec Consultants, Walnut Creek

Santa Clara Valley
Urban Runoff Pollution Prevention Program

Hydromodification Management Plan
Literature Review

by

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1 Background

1.1 Problem Statement

Urbanization is defined as the transformation of land into residential, commercial, and industrial properties, and associated drainages, roads, sewers and other community planned infrastructure. Urbanization modifies natural watershed and stream processes by altering the terrain, modifying the vegetation and soil characteristics, introducing pavement and buildings, and installing drainage and flood control infrastructure, and altering the condition of stream channels through straightening, deepening, smoothing, and sometimes armoring. These changes affect rainfall interception, infiltration, runoff and stream flows (i.e., modifies the hydrologic characteristics), and affects sediment supply and transport of sediment in the stream system. As the total area of impervious surfaces increases, infiltration of rainfall decreases, forcing more water to run off the surface as overland flow. This increases the volume of storm runoff and concentrates it into shorter time periods, so that the frequency and duration of intense, fast flows are increased. Ultimately, these increases intensify sediment transport, causing changes sediment transport characteristics and the hydraulic geometry (width, depth, slope) of channels. The larger peak flows and volumes and the intensified erosion of streams impair the beneficial uses of the stream channels. These types of changes have been documented in the Bay Area on Wildcat Creek, San Antonio Creek, Novato Creek, San Pedro Creek, and others (SFEI, 2001b, 2000, 1998, 2001a).

The RWQCB, San Francisco Bay Region, under the National Pollutant Discharge Elimination System (NPDES) is requiring stormwater programs to develop and implement management measures and prepare a Hydromodification Management Plan (HMP). Hydromodification is defined as the change in runoff characteristics from a watershed caused by changes in land use conditions. The HMP must describe how dischargers plan to manage changes in urban runoff from specifically new and significant redevelopment projects and protect the beneficial uses of streams. One of the requirements in the new permit is to prepare and submit a review of the literature to help educate those responsible for preparing and implementing this plan, and to help identify assessment methods to predict channel instability due to hydromodification.

A *Conceptual Model* of the hydrologic and geomorphic processes relevant to hydromodification is presented in Figure 1. The process begins with the regional factors of climate, geology, and physiography, which in turn affect the amount of runoff and sediment sources discharged to stream channels. Land use, soil and vegetation characteristics affects the proportion of rainfall that infiltrates the ground or runs of the surface. The nature of the local climate, geology, and physiography also affect the frequency and type of sediment supplied to the stream system. The imposed changes in the stream flow and sediment load characteristics ultimately change the physical and ecological characteristics of stream channels. This document provides a summary of these processes to help develop an understanding of how these features are impacted and how they might be controlled.

There are many types of impacts to streams from development depending on historical landscape practices and natural events. Observed impacts in the Bay Area include streambed incision, bank failures, siltation, temperature increases and water quality degradation, and loss of habitat features like suitable substrate, pools, tree cover, and overhanging banks. In semi-arid areas where ephemeral streams are common, summer base flows may actually increase from irrigation and other outdoor uses of water changing the natural hydo-periods and eventually plant and animal communities. This literature is focused on the impacts to the physical changes of stream channels due to changes in the runoff patterns from urbanization. Although no less important, the following impacts are not covered in this literature review. These include concrete linings, culverts and outfalls, bridge constrictions, riprap and other erosion control, floodplain development, water diversions, aggregate extraction, agriculture and seismic activity.

1.2 Regulatory Framework

The California Regional Water Quality Control Board (RWQCB) is the regulatory agency that issues NPDES permits to municipal agencies for stormwater discharges to San Francisco Bay. Beginning in 2000, in response to direction from the State Water Resources Control Board and changes to NPDES permits in Southern California, the RWQCB began to reissue or amend existing permits to include stricter requirements for control of stormwater from new development and redevelopment projects. The first Bay Area permit to include the new requirements was Order 01-119 (October 2001), which amended Provision C.3. of the Santa Clara Valley Urban Runoff Pollution Prevention Program's reissued NPDES permit (Order 01-024, February 2001).

Provision C.3. contains requirements to address impacts of new and redevelopment projects on beneficial uses of streams resulting from both pollutants in stormwater runoff and erosion caused by changes in the amount and timing of stormwater runoff. Under Provision C.3.f. – *Limitation on Increase of Peak Stormwater Runoff Discharge Rates*, new and redevelopment projects above certain impervious surface thresholds must include measures to address changes in runoff due to increases in impervious surfaces created by the project and to control runoff in a manner to protect streambeds and banks from erosion. The permit provision specifically requires the development of a HMP which would prioritize stream segments, establish in-stream and runoff criteria, and provide guidance on management measures, which could include a combination of on-site, in-stream, and regional control strategies. The Regional Board has prescribed the following:

a) "Post-project runoff shall not exceed estimated pre-project rates and/or durations, where the increased stormwater discharge rates and/or durations will result in increased potential for erosion or other adverse impacts to beneficial uses, attributable to changes in the amount and timing of runoff (Provision C.3.f.i).

A number of municipalities in other states (i.e., Maryland, Florida, and Washington) are presently implementing measures similar to these requirements. These states have been active in developing standards, procedures and management strategies to control stormwater runoff. In California, Ventura County, Orange County, Los Angeles County, the City of Long Beach, and the City and County of San Diego are in various stages of drafting and implementing stormwater permit provisions similar in scope to the revised Provision C.3.

1.3 Santa Clara Valley Urban Runoff Pollution Prevent Program

The Santa Clara Valley Urban Runoff Pollution Prevention Program (SCVURPPP) is an association of 15 agencies in Santa Clara Valley – 13 cities, Santa Clara County, and the Santa Clara Valley Water District (SCVWD) – that share a common NPDES permit to discharge stormwater runoff to South San Francisco Bay. The SCVURPPP incorporates regulatory, monitoring and outreach measures aimed at reducing pollution in urban runoff to the "maximum extent practicable" to improve the water quality of South San Francisco Bay and the streams of Santa Clara Valley. The Program began in 1990 with the signing of a Memorandum of Agreement among the "Co-permittees'', and in February, 2001, the Program received its third 5-year NPDES permit. Provision C.3. of this permit was amended in October, 2001, by the RWQCB to include expanded requirements for controlling pollutants from new and redevelopment activities. The Program operates according to an Urban Runoff Management Plan (URMP), which consists of an area-wide plan and individual Co-permittee plans describing what the 15 Co-permittees will do, collectively and individually, to reduce urban runoff pollution. The URMP contains performance standards for each Program element, including Development Planning Procedures and Construction Inspection. Performance standards represent the level of implementation that Co-permittees need to achieve to control urban runoff pollutants to the "maximum extent practicable" (the mandate of the NPDES permit). Co-permittee URMPs describe their local work plans, legal authority, best management practices, and standard operating procedures to achieve the performance standards.

Under the current Development Planning Procedures Performance Standard, the Co-permittees have been requiring site design measures and post-construction control measures for projects that have "significant stormwater pollution potential" (i.e., projects that will have significant impacts on stormwater quality, as determined through an environmental review process). For the most part, control measures implemented to date have focused more on removal of stormwater pollutants than on control of increased peak flows and volumes of runoff from developed sites. Provision C.3. requires the Program to develop an enhanced performance standard that includes: 1) specific size thresholds for defining projects that are subject to the new regulations (based on the amount of impervious surface); 2) specific numeric flow- and volume-based criteria for design of stormwater control measures; and 3) criteria and guidance for control of runoff peak flow and volume based on the results of the HMP.

1.4 Need for literature review

This literature review is prepared to satisfy the requirement of the HMP and deliver a review of the literature by September 2002. One of the first steps in this process is the development of a literature review that summarizes the various aspects of the effects of urbanization on hydrology and geomorphology, available assessment tools that can be used to address the problem, and management strategies that agencies can use to implement the HMP.

In addition to meeting the permit requirement, the literature review has the following purposes:

a) To provide the technical basis for the selection and application of methods for assessing the hydrologic and geomorphic impacts of urbanization, and for developing design criteria and implementation plan.

b) To educate those who will be approving the HMP (e.g., Management Committee, RWQCB) or will have to live with the plan (development community).

The literature review is focused on the hydrologic and geomorphic impacts from hydromodification. This document does not address many other potential impacts to stream channels caused by urbanization, for instance scour at outfalls or bridge abutments. The literature review summarizes the hydrologic and geomorphic processes that function to define the physical characteristics of channels and their riparian corridors. Although water quality and riparian ecology are critical to the health of the riparian corridor, this report focuses primarily on the physical characteristic of stream systems.

The physical and ecological characteristics of the riparian corridor are created and maintained by a spatially and temporally dynamic system of stream and watershed processes. The state of the riparian corridor is a result of the time-integrated effects of climate, physiography, and land use. It is therefore imperative to understand the key processes that are altered and how such alterations ultimately affect the observable stream and riparian attributes. Watersheds, valleys and streams must be characterized to understand the cause of degradation rather than just the symptoms. If this is accomplished, we will be able to identify channels that are most sensitive to changes in hydrology, sediment supply, or riparian vegetation. Subsequently, we will then be able to provide guidance on the most probable geomorphic stream responses, and adequately select management strategies that will protect beneficial uses.

Decades of research have revealed that urbanization frequently results in severe stream degradation, but the complexity and variability of stream responses make it difficult to predict channel instability and make informed decisions regarding management strategies (Bledsoe, 2001). This literature review summarizes the important hydrologic and geomorphic processes involved in channel stability and describes expected responses to hydromodification. The literature review also summarizes the various assessment tools that researchers have developed and used to address hydromodification and the potential management strategies agencies can use to manage future development.

2 Goals and Objectives

2.1 Goals

The primary goal of the HMP requirement is to protect and restore the physical, chemical, and biological functions of stream systems in urban areas, subject to considerations of benefits and costs. Benefit-cost considerations suggest two secondary goals based on stream conditions. A top priority is protection of existing healthy stream systems with a goal that urbanization will not result in a net loss of ecological functionality. For impaired systems, the goal is to achieve the maximum attainable practical restoration of functions. In this regard, the emphasis of the HMP is on understanding and managing the cumulative effects of urbanization on hydrology, water quality, and geomorphology on a watershed scale, rather than on prescribing controls for each development without a basis for evaluating the potential benefits.

These goals are similar to goals already developed by agencies and municipalities in the Santa Clara Valley. For example, the Santa Clara Valley Water District's 15 year Clean Safe Creeks & Natural Flood Protection Plan "reflects a comprehensive stream stewardship program that seeks to better preserve natural systems. Progressive methods make it possible to protect valley residents, while at the same time improving water quality, maintaining and restoring riparian corridors for wildlife habitat and creating trails and parks for recreational enjoyment." The City of San Jose has developed a Riparian Corridor Policy, the purpose of which is to "promote the preservation of riparian corridors." The Policy establishes riparian corridor development guidelines that include riparian setback requirements for various land uses. The goals for the HMP are also consistent with the Regional Board's Stream Protection Policy, and the Regional Board Staff's recommendations for incorporating stream protection goals into the Basin Plan.

2.2 Objectives

In order to meet the above goal and the RWQCB requirements (Section 1.2), the following objectives have been defined:

a) Develop a watershed-based HMP for approval by the RWQCB to address the impacts of hydromodification on the beneficial uses of streams;

b) Develop, test, and apply an assessment method to evaluate potential hydrograph change and impacts to stream channels from proposed projects, and identify where such changes can cause increased erosion of creek beds and banks, silt pollutant generation, or other impacts to beneficial uses;

c) Develop design criteria, control measures, and guidance on management strategies to address hydromodification and identified impacts;

d) Manage the impacts of hydromodification on streams through the implementation of the HMP,

e) Monitor the effectiveness of the control measures and management strategies, and amend the HMP as needed.

2.3 Criteria for Selecting Articles

Based upon review of the HMP permit requirements and understanding of the goals and objectives, the following criteria were used in selecting articles for review:

a) Peer reviewed journal articles
b) Local and regional sources,
c) semi-arid climates,
d) physical processes that influence stream channel characteristics,
e) effects of urbanization on channel stability,
f) thresholds of channel stability,
g) assessment methods,
h) guidance (by others) on integrated watershed management,
i) alternative on-site and in-stream control measures, and
j) habitat quality.

The above criteria were identified at the beginning of the literature review to focus attention on the most important issues for the South San Francisco Bay Area. However, during the collection and review of the articles, it became clear that not all the criteria could be satisfied to the same level of detail. For example, many articles are published on hydrologic and geomorphic processes affecting stream channels, many articles on the effects of urbanization on stream channels and changes in runoff characteristics. There are few articles on threshold criteria and on assessment methods directed at hydromodification. There are few articles addressing control measures or approaches to minimizing the affects of hydromodification.

Given the constraints on the number of articles addressing some of these criteria, it became clear that some of these criteria would be hard to meet. Few peer-reviewed studies have addressed hydromodification in specifically in semi-arid climates. Most of the research has been conducted in the Pacific Northwest, Ontario Canada, and the northeast. Thus the majority of this literature review is based on work conducted in different climatic and physiographic regions of the country than that found in the Bay Area, and therefore this work will need to be adapted to local conditions. We supplemented peer-reviewed literature with reports on local project conducted by professionals in the Bay Area.

Articles were identified through Internet and library searches, professional journals, books, conference proceedings, and the author’s personal files and from the references in published articles. Table 1 lists the articles found during the search and its associated information. The Project Team also had personal knowledge of sources of local information relevant to this topic that wouldn’t normally show up in a library search. The University of California library system was used to search for relevant articles. Internet and library searches involved key words based on the criteria listed above.

Potential articles were reviewed to see how relevant they were to the topic of interest and which of the criteria were satisfied. Each article was entered into a database (Table 1) that identified reference information and the criteria that are satisfied. Articles believed to be the most relevant were reviewed in detail first. Over time, the potential list of literature grew to about 80, of which about 50 were ultimately used in this literature review.

3 Hydrologic Processes

Hydrology plays a critical role in influencing the physical characteristics and ecological health of stream corridors. The characteristics of weather, water flow, and sediment flow define both the stream's geomorphic processes and ecological functions. Rainfall and ultimately runoff control the transport of sediment and the characteristics of channel forms from headwater streams to ocean discharges. Chapter 3 briefly describes the more important processes of the hydrologic cycle of primary interest to the development of a HMP.

3.1 Climate

One of the important aspects of hydrology is the seasonal distribution of rainfall. The patterns of rainfall in a particular watershed are dictated by the region and local topography. Is the rainfall distributed over several months in small increments or does it fall in cloudburst of short duration? The Santa Clara Basin has a Mediterranean climate, characterized by extended periods of precipitation during the winter months with little rainfall from spring to fall. The wet season generally extends from November through April, with little rainfall in the months between May through October. Portion of the Santa Cruz Mountains receives 40 to 60 inches of rainfall each year, while the central portion of the valley receives 13 to 14 inches per year. Within the last 100 years of record, rainfall in the central part of the valley has ranged from 6 inches to over 30 inches. Periods of extended droughts are not uncommon in California and in the Santa Clara Valley. Short-term droughts of 5 to 7 years have occurred several times in the last 100 years (Balance Hydrologics 1999).

Leopold et al. (1964) discuss how climate affects weathering of the earth's surface and the erosion process. Intense rainfall has more erosive energy and its runoff can transport greater quantities of sediment than light but constant rainfall. Intense rainfall can also trigger numerous shallow landslides and debris flows when soils are already saturated. High amounts of seasonal rainfall in the Bay Area have been known to trigger numerous earth flows in terrain dominated by clay-rich stratigraphy. The characteristics of climate influence the nature of watershed processes, stream characteristics, and riparian communities that proliferate in these regions. The natural episodic nature of floods, fires, droughts create natural perturbations that temporarily disrupt stream conditions and functions. In California, indigenous plant and animal communities are adapted and are actually rejuvenated by these disrupting events (Hecht 1994). These natural events and the changes in stream channels created by them can influence the interpretation of observed bank erosion and modeling results.

3.2 Hydrologic Cycle

Figure 2 illustrates the typical hydrologic cycle in which water is transported in its various forms from rainfall, to runoff, to evaporation. A complete description of the hydrologic cycle can be found in most college textbooks (e.g., Linsley, 1982; Mosley and McKerchar, 1993). This discussion concentrates on those parts of the hydrologic cycle most important to hydromodification and defining stream channel conditions.

Under certain weather conditions, water vapor condenses into water droplets that fall to the earth's surface as rain. Part of the rainfall is intercepted by vegetation (interception) and the rest falls to the ground. Of the fraction that falls to the ground, a percentage infiltrates into the ground and a percentage runs off as overland flow. Of that portion that infiltrates into the ground, some will remain near the surface (interflow) and some will percolate to deep groundwater aquifers. Both shallow and deep subsurface flow feed springs, streams and rivers and help sustain year round baseflow.

There are three flow pathways that runoff can take to reach streams, rivers, lakes and oceans – overland flow, interflow, and groundwater flow. The fraction of total volume and how fast this volume is conveyed to streams depends largely on topography, soils, and geological characteristics of the watershed. The rate at which rainfall moves through the watershed as overland flow or as subsurface flow influences the dynamics and character of the riparian corridor. The amount of water that is temporarily held within the watershed can be thought of as temporary storage. Soil has the capacity to store water and slowly release it to streams and rivers, thus providing summertime baseflows in perennial streams.

Stream flow and groundwater flow are interconnected along stream channels. When adjacent groundwater elevations are higher than the water surface in stream channels, groundwater discharges to the stream and maintain baseflows (gaining stream). When groundwater elevations are less than the water surface elevation in the stream, surface water infiltrates into the ground (loosing stream). Whether streams are loosing or gaining streams is highly variable in both space and time. The portion of rainfall that is intercepted, held in the soil by capillary forces, or used by vegetation is evaporated and/or transpired back to the atmosphere.

Infiltration and Soil Water Storage

Infiltration is the rate at which rainfall passes through the soil surface into the pores and interstices between soil particles. Infiltration rates can be influenced by the amount of antecedent rainfall and resulting amount of water stored in the soil matrix (soil moisture). Initially the rate of infiltration is high, but as the volume of water in the soil increases from infiltration, the rate at which additional rainfall infiltrates the ground surface is reduced to the rate at which water can percolate to deeper zones. Percolation is the penetration of water through the soil matrix down to the groundwater table. Percolation is typically slower than infiltration, at least initially. When the soil is saturated, the rate of infiltration is about equal to percolation. The total storage available in the soil column is equal to the porosity of the topsoil (typically around 43 percent for sand and clay to 47 percent for loams). The field capacity of the soil column (typically around 5 percent for sand to 38 percent for clay) is that percentage of the total water storage that is available to evapotranspiration. The difference between total storage and the field capacity is that portion of soil water that can drain to stream channels.

Flow Pathways

Depending on soil types, topography and drainage density a certain percentage of rainfall infiltrates into the ground and becomes interflow or groundwater flow (Figure 2). Interflow is shallow subsurface flow that migrates down topographic gradients through soil pores and fissures eventually to a water body such as a stream or river. Groundwater flow is deeper than interflow and also migrates down hydraulic gradients. The rate at which rainfall reaches streams and rivers through these two subsurface pathways is much slower than the rate at which water reaches streams and rivers by overland flow. Overland flow reaches stream channels on the order of minutes to hours. Interflow is much slower than surface runoff. Interflow can reach streams in hours or days after the storm. Subsurface flow is dependent on the hydraulic conductivity of the soil matrix and the hydraulic gradient, which can supply water to springs and streams for months and years after the rainy season (Knighton, 1998).

In locations where soils are highly permeable and slopes are shallow, a significant portion of rainfall accumulates and infiltrates into the ground resulting in decreased stream flows. In contrast, where the soils have low permeability and slopes are steep, a large fraction of rainfall runs overland and quickly becomes stream flow. The rate that rainfall is transported to streams and rivers can vary considerably between these two extremes even within the same watershed. Stream characteristics typically reflect the natural properties of its watershed. Urban planning can take advantage of this knowledge when laying out development to avoid and maintain high infiltration zones.

The dominant runoff process in semi-arid climates is Hortonian overland flow. Overland flow is commonly referred to as "Hortonian" or "Saturated" overland flow. Hortonian overland flow is said to begin when rainfall intensity is greater than the infiltration capacity of the soil. Infiltration depends on soil type, moisture content, organic matter, vegetation cover, and season. In simple terms, infiltration is usually greatest in the beginning of the winter season or at the beginning of storms when the soil is the driest. Saturated overland flow occurs when the soil becomes saturated rather than having its infiltration capacity exceeded. Long periods of light rain can saturate soils (Knighton 1998). Saturated soil conditions frequently occur at the base of slopes and in surface depressions where flow converges. Saturated conditions also occur where surface soils are thin and underlain by impervious strata – such as duripan. As a result, the antecedent moisture condition of the watershed is important in determining runoff characteristics. A storm of a given size in early winter can produce much less runoff than the same size storm in late winter. Runoff therefore can be highly variable both spatially and temporally. Hydrologic modeling and the assessment of urban development should also account for this spatial and temporal variation.

Drainage Density

Overland flow starts out as sheet flow, but quickly becomes concentrated in rills, gullies and channels. The nature of this network of channels is described in geomorphic textbooks. Of interest to this work is the measure of total channel length per unit watershed area - or "*drainage density*". Drainage density is governed by the erodibility of the surface soils, slope, and high rates of runoff. Urbanization can increase drainage density through the creation of road shoulders, gutters, ditches and canals. Increases in drainage density also make it easier for overland flow to reach stream channels in a short period of time.

Channel incision in lowland stream reaches has lead to increase channel development in headwater segments and an increase in sediment supply to streams. Channel development refers to headword expansion of first order streams. Watershed assessments in the Bay Area have documented increases in sediment supply as a partial result of increases in drainage density. These include Wildcat Creek, San Antonio Creek, Novato Creek, San Pedro Creek (SFEI, 2001b, 2000, 1998, 2001a). Changes in drainage density have been documented as far back as the 1800's in the Bay Area when grazing and agricultural were the predominant land uses. Some regions, such as the Lake Tahoe Basin, mange land development through measures of drainage density.

3.3 Change in the Hydrologic Cycle

Urbanization has a major effect on the hydrologic cycle. When large areas are rendered impervious, the area of infiltration is reduced, surface storage and interception may also be reduced, and overland flow takes place readily on smooth impervious surfaces (Hollis, 1975). Urbanization converts open land into impervious areas for residential, commercial and industrial uses through paving, roofs, soil compaction, and loss of vegetation. Booth et al. (1997) uses the increase in percent connected imperviousness as the basis to predict the likelihood of channel destabilization.

Urbanization, or more specifically the increase in impervious surfaces and connectedness of drainage channels, has a significant effect on flow pathways and the timing of runoff and watershed storage. Urbanization changes the natural relative proportions of overland flow, interflow, and groundwater flow to stream channels (Booth et al. 1997). As a result, the natural storage of water in the watershed is reduced and the relationship between groundwater and stream flow are changed. Hence, more erosive energy is available to perform work on the streambed and banks. When there is a long-term change in the volume of water supplied, the channel adjusts its hydraulic geometry. Until the channel planform, slope, and cross sectional dimensions have all adjusted to a new equilibrium, the channel is said to be unstable.

Streams can change from mostly perennial streams to ones with flashier discharges and reduced intermittent to nonexistent baseflows. Streams can change from gaining streams to loosing streams, and sometime surface flows are known to disappear altogether. These types of changes have been documented in the Bay Area on Wildcat Creek, San Antonio Creek, Novato Creek, and San Pedro Creek (SFEI, 2001b, 2000, 1998, 2001a).

In climates where the ecology is adapted to a seasonal cycle of water supply, urbanization can increase summertime water availability due to runoff from excess irrigation, car washing, and system leaks and changes the ecology to one suited to a continuous water supply. The County of Sacramento has measured summertime urban slobber and estimates that about 0.86 cfs of summertime runoff occurs per square mile of urban development (Eva Butler & Associates 2002). In Los Angeles, drainage channels have been measured with 20 cfs of flow in the summertime where historically these channels were dry.

3.4 The Stream Flow Hydrograph

It is well established that stream flow characteristics (magnitude, frequency, duration, rate of change and timing) are the major driving forces that control the physical and ecological conditions of a riparian corridor. As water flows downstream, it imposes shear and drag forces on the boundary material due to its weight and velocity that scours, erodes and otherwise shapes the channel boundary, which in turn shapes the environment and ecological processes that exist within the corridor.

The stream flow hydrograph represents the change in flow magnitude over time (Figure 3). The hydrograph is characterized by its peak, duration (time period of flow event), and a total volume measured as the integrated area under the curve. From baseflow, there is a rising limb as flow rate increases, a peak flow rate, and a gradual falling limb as flows recede back towards baseflows. Peak flow generally occurs when 100 percent of a sub-basin is contributing runoff to the point of interest.

Current management practices generally focus on flood control and thus peak flow and volume control. Current issues of stream channel stability must also address duration and frequency of occurrence of a range of flow events, especially sediment-transporting events. This is discussed in more detail in Chapter 4.

3.5 Change In Runoff Hydrograph

Urbanization increases peak flows and runoff volume, and decreases lag time and event duration (Booth et al. 1997; Urbonas et al., 1995; Booth, 1990; Hollis, 1975; Hammer 1972). Small storms typically generate a small amount of runoff. Under developed conditions, runoff tends to be flashier with a quicker rise and fall of the hydrograph, greater peak flow and volume, and shorter duration and times of concentration. Small storms now generate a significant amount of runoff compared to undeveloped conditions.

Hollis (1975) concluded that the effects of urbanization are greatest for the more frequent storm events and diminishes as the flood size and recurrence interval increases (includes two studies in California: Sacramento Creek and Colma Creek). The small frequent floods are affected more dramatically, while the large episodic floods are not significantly affected. Figure 4 presents a generalization of the results reported by Hollis. This Figure shows the percentage increase in runoff from urbanization from pre-developed conditions for a range of flow magnitudes under two impervious surface percentages. The relative increase in runoff is most dramatic for flows with a frequency of 1 to 2-years and smaller, where flows increased as much as 20 times.

According to Hammer (1972) and Hollis (1975), at 10, 15 and 30 percent impervious development, peak flows with a recurrence intervals of 2 years increased by factors of 2, 3 and 5, respectively. Urbonas et al. (1995) reported increases in peak flows from 58 times, to 3 times, to 1.8 times, for the 2-year, 5-year and 100-year storms, respectively. Considering the discussion on geomorphically significant flows in Chapter 4, these changes have a significant impact on stream geomorphology. Booth (1990) used a continuous simulation model to assess the effects of urbanization on runoff and found that urbanization increases peak flows and runoff volumes of all storm events. Urbonas et al. (1995) reported increases in runoff volume of 38, 3, and 1.8 for the 2-year, 5-year and 100-year storms, respectively. Booth (1990) also reported significant increases in the total hours a stream was at a specified flow rate (flow duration). For example, at 20 percent imperviousness, flow duration at the 2-year recurrence level increased by a factor of 30 to 100 times. In other words, the total number of hours that the stream flows at the 2-year level increased 30 times.

Drainage networks increase the drainage density of a watershed and reduce the lag time necessary for runoff to reach the creek. For example, rain gutters, streets and storm drains provide a direct connection between impervious surfaces and the stream channel. The result is that a large portion of rainfall is translated into runoff, which occurs more rapidly. Increases in roof drains, gutters, ditches, sewers, storm drain networks, accelerate the conveyance of the runoff to stream channels.

The frequency of sediment transporting flows and channel disturbing flows dramatically increases by a factor of 10 or more (Booth, 1991; Booth et al. 1997). Using a two-dimensional modeling approach, Bledsoe et al. (2001) found that at 18 percent imperviousness, the frequency of significant scouring events increases by 5 fold. They also found that connected impervious areas clearly increased runoff magnitude more than disconnected impervious areas, especially with high conveyance and connectivity; the frequency or duration of sediment transporting events also increased significantly. Changes in runoff patterns are more dramatic in more permeable watersheds, and exhibit a more abrupt erosive response to urbanization because there is a larger change between the pre-developed pervious conditions and the urbanized impervious condition.

3.6 Summary of Impacts on Hydrology

Although there is a wide range in the degree of change, there are some general conclusions that can be drawn on the effects of urbanization on hydrology. These are that urbanization:

a) Development has varying degrees of influence on stream flow changes depending on the natural watershed and development characteristics. Urbanization changes watershed storage and pathways of runoff, reducing lag times.

b) The relative proportion of subsurface to surface flow shifts to primarily surface runoff and the natural storage of the watershed is reduced.

c) Increases peak flows by factors of 2 to 60, especially in the more frequent events.

d) Increases runoff volume by factors of 2 to 40.

e) The long-term duration of flows increase, especially for the smaller frequent storms. Increases duration of smaller flow events by factors of 30 to 100.

f) Sediment transporting flows increase by factors of 5 to 10 for the studies reviewed. This would be dependent on stream type and the size of bed material.

g) Reduced base flow can cause a reduction in riparian vegetation. Loss of riparian vegetation can be a destabilizing factor of channel stability.

h) The frequency of occurrence of runoff events increase, especially for the smaller frequent storms.

i) Seasonal flow volume shifts. Dry season baseflows can decrease where the loss of infiltration is significant. Reduced baseflows may cause a reduction in riparian vegetation.

j) Summertime baseflows can increase in areas where urban dry season flow is significant compared to normal dry season flows.

k) Alter wetland and riparian hydro-periods.

4 Geomorphic Processes

Geomorphology deals with the forms and characteristics of the earth’s surface and the processes that create the observed forms and characteristics. Weathering, erosion and transport are the fundamental geomorphic processes that supply much of the sediment load to stream channels. Figure 5 conceptually illustrates the geomorphic processes of erosion, transport and deposition. Leopold et al. (1964) wrote, “*Streams are the gutters downs which flow the ruins of its continents. Silt, sand, gravel, and solutes carried by the stream are the ruins produced largely by weathering.*” Landslides, debris flows and hill slope erosion periodically supply eroded material to the valley floor and stream channels. This material is transported downstream, broken down into smaller sized rock, sorted, deposited, scoured, and continually reworked. Fluvial geomorphology deals with forms and characteristics of a stream channel and the processes that create them. The processes of runoff and sediment transport interact with the material making up the channel boundary, creating features such as terraces, floodplains, channel planform and geometry, and instream channel features, such as pools, riffles, bars, and secondary channels.

Over time and before human disturbances, channels evolved to the conditions that balanced the need to transport the available water and sediment load with channel planform, slope, and cross sectional dimensions. As vegetation co-evolved with the channel, it too influenced channel stability. As sediment is carried downstream to the lowlands it is deposited in deltas, on floodplains, terraces, and alluvial fans. It supplies sand to coastal beaches and fine sediments to tidal marshes, mudflats, and estuaries. The process can be very complex because of local variability and the episodic nature of storms and landslide events.

4.1 The Drainage Basin

The drainage basin may be defined as the area that is bound by topographic highs, such as mountain ridges, collects rainfall and contributes runoff to a particular set of channels. Given a point in a stream channel, a drainage area can be defined as the area upstream that collects rainfall and contributes runoff to that specific point. Considering the erosional processes, the sediment eroded from the hill slopes within the drainage basin might be collected and stored in the valley floor. Fluvial processes can then rework sediments and further transport materials downstream forming attributes such as bars, fans, floodplains, and terraces.

A network of stream and river channels form in the drainage basin, which consists of several different stream types depending on the channel’s location along the longitudinal profile, gradient, sediment load characteristics, and discharge. Montgomery and Buffington (1993) describe the variability in natural watersheds, the variability in stream channel characteristics within watersheds, and the variable response a stream channel make take depending on local conditions and its location within the network of stream channels. Sediment supply and size, stream discharge and slope vary within the stream network and a stream’s response to in these variables will also vary. Understanding these relationships will help predict a channel's response to hydromodification and identify management strategies.

Although we speak of specific channel types and divide the longitudinal profile into zones, stream morphology and habitat is truly a continuum of form and structure. The physical processes that create the observable channel character do not distinguish between arbitrary boundaries. Water and sediment are transported in a continuum along the channel bottom. Stream geometry, planform and profile adjust to distribute the loss of flow energy uniformly along the channel alignment. Species of plant and animal spread out along the riparian corridor unaffected by the definition of transport zone. The discharge of concentrated urban runoff or the removal of large quantities of sediment can affect the channel for great distances both upstream and downstream from the point of activity. Thus an assessment method should consider the complete longitudinal distance.

4.2 Lane's Principle and Dynamic Equilibrium

Stream channel size and form are established through a balance between the imposed flow energy and the ability of the channel margin to resist erosion, as well as supply and transport the available sediment load from its watershed through the stream system. The most frequently referenced relationship on channel equilibrium is Lane's Principle (1955), which states that the product of sediment load and grain size is proportional to the discharge and channel slope, thus:

$$Q_s \cdot D_{50} \propto Q_w \cdot S$$

Where Q_S is sediment load; D_{50} is the 50^{th} percentile of the grain size distribution; Q_w is the stream discharge; and S is the channel slope. Assume for example, that the sediment load characteristics remain constant and discharge is increased due to urbanization, than Lane's Principle says that a concomitant decrease in slope is required to maintain equilibrium or there will be an increase in sediment size or volume to establish a new equilibrium (Figure 6). If sediment load is trapped behind a dam or basin and all else being equal, then according to Lane's Principle a decrease in slope is required to reestablish equilibrium. In the field, a decrease in channel slope will be observed as channel incision.

A natural stream channel is often defined as "stable" when its cross section, plan form, and profile features are maintained over time such that the stream neither aggrades, degrades, or changes in dimension or meander pattern during the present climatic regime. When a stream channel migrates laterally by eroding into its outer bank and depositing sediment on its inner bank, while maintaining its general shape, channel stability is maintained even though the channel is active. The channel is neither aggrading nor degrading its bed and it is maintaining its floodplain. Under these conditions, the river is said to be in "*dynamic equilibrium*". Channel instability occurs when scouring leads to degradation or when excessive deposition leads to aggradation. Both aggradation and degradation are often accompanied by bank failures, a change in channel dimension, meander pattern, and slope, and the floodplain can often be abandoned. Prediction of channel instability should include locating zones of degradation and aggradation; bank failures, incision, armoring, excessive cut bank formation on meander bends, change in slope and loss of floodplain.

Aggradation / Degradation

Sediment load and grain size are important factors in the dynamic equilibrium concept. Changes in sediment load can lead to channel changes and instability. Increased sediment load (Q_S) results in increased slope assuming all else remains the same. Sediment settles out on the bed until a new slope and shear stress are capable of transporting the new load. In urban areas where sediment load is reduced (due to imperviousness, landscaping, dams, aggregate extraction, etc.) the slope is often reduced (channel incision) and the bed coarsened if gravelly until a new balance is achieved. With all else being equal, a channel with gravel will have a steeper slope than one with sand because greater shear stress is require to initiate motion.

As alluvial channels migrate laterally, part of the sediment load is interchanged with bank materials. If the channel is entrenched, then interchange may be minimal and both banks may be dominated by erosion. Sediment load can accumulate within a reach and be augmented by erosion within another part of the same reach. Sediment continuity studies are often conducted to predict the scour effects from development projects. Channel instability can also result from sedimentation, as it forms local deposits (in-channel bars) and force flows into adjacent banks, thus accelerating erosion and widening the channel. Increased discharges (Q_w) tend to increase sediment transport potential, channel cross sectional area, accelerate meander migration, and eventual lengthening of meanders, and changes in the longitudinal profile. In particular, increase discharges tend to flatten stream slopes by incision in upper reaches (headcut migrates upstream) and deposition in lower reaches. Incision tends to be more severe in streams dominated by fine and readily erodible bed materials (e.g., sand), and less severe in coarse bedded rivers.

Changes in channel characteristics can be quite complex and evolve over time – from catastrophic events that take days to incremental changes that take years to several decades. For example, a channel may fill initially due to large sediment inputs, but ultimately scour back to its original grade (Figure 6). Bank failures caused by channel incision may temporarily increase sediment load, thus temporarily preventing incision in downstream reaches. Downstream channels that were initially incised may be refilled with sediment from upstream erosion (i.e., aggradation). This would be considered a reach that is alternately filling and scouring. If the floodplain is not abandoned the channel would be considered stable. In local streams, such as Wildcat Creek, alternating incision and erosion has been documented by SFEI (2001b).

Head cuts or abrupt steps in channel gradient are over steepened slopes initiated by a change in base level or an increase in runoff. Changes in base level can be caused by excavation of the channel bed from gravel mining, and excessive incision below culvert outfalls. Head cuts typically migrate upstream due to over steepened slope; increased velocity causing increased shear stress, and increased localized sediment transport.

Entrenchment

Entrenchment can be an important element in understanding and characterizing streams in the Bay Area. Entrenchment describes the relationship between the stream channel and its valley features. Entrenchment defines whether a stream is deeply incised into the valley floor or contained by adjacent landforms. Adjacent landforms control the flood prone width adjacent to the stream channel, which may consists of well-developed floodplain, a restricting terrace, or narrow valley walls. The more the stream flow is confined, the more flow energy is available to scour and erode the channel bed. Levee and embankments artificially confine flood flows and increase channel erosion.

Valley types in the Bay Area can be confined in the uplands whose valley floor generally consists of bedrock, landslide and earth flow material (SFEI, 1998, 2000, 2001a, 2001b). Upland streams have higher energy streams and fewer deposits of sediment in the bed itself. At the point where upland stream segments discharge to valleys with shallower slopes, the transported material settles out and forms alluvial fans. The alluvial fan generally consists of unconsolidated heterogeneous material washed down from the upland valleys. The banks of a stream channel cut into an alluvial fan are often easily erodible and have poor riparian vegetation conditions. As the stream proceeds downstream the valley becomes wide and gently sloping lowlands generally consisting of fine-grained alluvium (sands and gravel) reworked over time and deposited in layers making up wide floodplains. Downstream further and as the stream discharges to the Bay the stream becomes marsh and wetlands consisting of fine silts and clays.

4.3 Modification in Sediment Load Characteristics

In addition to water supply, sediment supply influences riverine geomorphology and ecological conditions. A range of sediment supply conditions can exist, ranging from sediment-starved to sediment-overwhelmed that influence morphological characteristics of the channel, its habitat and its stability. A sediment-starved stream will have a tendency to become unstable by incising its bed, leading to bank failures, or its bed could become armored. A sediment-overwhelmed stream will have a tendency to increase shear stress on the banks from flows being diverted around deposits. The sediment load, its particle size range, input timing and mechanisms, and longitudinal distribution contribute to the development of geomorphic surfaces and instream deposits that form the foundation for riparian and aquatic habitat.

Local studies by SFEI have documented sediment supply sources and impacted geomorphic processes to varying degrees on Wildcat Creek, San Antonio Creek, Novato Creek, and San Pedro Creek (SFEI, 2001b, 2000, 1998, 2001a). Sediment sources from streambed and bank erosion, landslides, earth flows, and headword expansion of tributaries were measured or estimated. Historical assessments were completed and evaluated to determine the cause of erosion and its influence on fluvial geomorphic processes over time. Detailed field measurements of the changes in bed elevation and channel cross sections, comparisons between historical data and current conditions were used to study the changes in sediment transport processes and compared to watershed development. This assessment process leads to explaining how has the sediment transport process change and what are the likely causes of the observed changes.

The episodic nature of storms (including El Nino), fire and earth flows are believed to be dominant controlling factors in defining the characteristics of many stream channels in the Bay Area including Santa Clara Valley (Hecht 1994). Sudden influx of sediment to the stream channels can occur from landslides following wildfires or from channel banks following severe drought with over stressed vegetation. These episodic and natural occurring events temporarily establish a new set of stream conditions and vegetation patterns that gradually returns to similar hydraulic geometry over time. Multiple events can often occur in short periods of time, for example during an extremely wet winter season. The sediment carried downstream could initially fill pools and overbank areas, followed by gradual scouring and depletion of the in-stream stored sediment. In stable systems, most of the sediment load passes through the stream corridor over a period of 2 to 5 years following the event. For the largest events of significant change, streams may take decades to reach a new stable equilibrium. The extent and frequency of occurrence can vary along the stream profile and locations where the stream slope decreases rapidly tend to be most affected by deposition and scour from the pulse of sediment (Hecht 1994, Reeves et al. 1995).

Urbanization can cause spatially variable increases or decreases in sediment supply to stream channels. During urbanization with construction and disruption of the land surface, sediment loads can increase but for a fairly short time. However, urbanization has often involved putting entire channels, tributaries or stream reaches into storm drains or box culverts, These underground systems are usually connected to impervious surfaces above ground that might supply negligible amounts of sediment, causing the downstream channel to become sediment starved and potentially destabilized. If erosion control measures are in place during the construction period, the increased sediment load might consist mostly of fine material that is unsuitable for aquatic habitat. Suitable habitat generally consists of clean coarse sand and gravel such that water can migrate into the substrate and supply oxygen to macroinvertebrates and other organisms that live in the bed material. Fine sediment originating from urbanization can smother suitable bed material by filling in the small interstices between larger particles and negatively impacting aquatic habitat. Years after initial development, once the land surface is covered with pavement and other impervious surfaces, the sediment supply is reduced significantly as runoff is increased. Runoff is collected on impervious pavement and routed through pipes and concrete channels reducing the chance of picking up and transporting sediment.

Although we don’t want to ignore these important spatial and temporal factors, incorporating these conditions into an assessment method for hydromodification can make the method overly complex, at least for this first stage of developing the HMP. Some of this variability can be maintained by incorporating long-term records of rainfall in the assessment method.

4.4 Modification Of Geomorphically Significant Flows

Researchers have shown that there is a specific range of flows that are important in defining channel form and controlling the rate at which sediment is transported through the stream system. Leopold et al. (1964) suggested that geomorphically significant flows range from a lower limit of competence where bed material begins to move in quantity to an upper limit established where flood flows are no longer contained in the channel. The frequency and duration of geomorphically significant flows are the primary factors that control channel stability, or instability, and should be considered in an assessment method.

Leopold et al. (1964) realized that from the standpoint of "*work done*" in erosion and transport of sediment load carried by rivers, a large percentage of the total sediment transported is performed by relatively frequent events of moderate magnitude. Figure 7 illustrates Leopold's effective work concept. Curve a presents the frequency of occurrence (number of hours or days with flow of a specific magnitude) of the range of flows in a watershed with the smaller flows occurring more frequently than the infrequent large flood events. Curve b presents the sediment discharge as a function of stream discharge. Clearly the larger flows move more sediment during an individual event when compared to single events of smaller flows. However, when the frequency of sediment moving events is considered, Leopold found that the frequent but competent flow events move the most sediment over time and maintain the channel dimensions. Curve c shows the product of sediment discharge and frequency. The concomitant discharge corresponding to the peak sediment load corresponds to the channel forming discharge with a recurrence interval around 1.6 years. In natural stream systems, the channel forming discharge is within 80 to 100 percent of bankfull. Bankfull discharge has traditionally been defined as the flow that just fills the main channel to a point where water begins to spill out onto its floodplain. Traditional flood control practitioners still frequently use this definition. Dunne and Leopold (1978) provided a definition that has become widely accepted among geomorphologists:

> *"Bankfull stage corresponds to the discharge at which channel maintenance is most effective, that is, the discharge at which moving sediment, forming or removing bars, forming or changing bends and meanders, and generally doing work that results in the average morphological characteristics of channels."*

They indicate that the recurrence interval (RI) for bankfull flows is 1.3 to 1.7 years on average. Using this definition, bankfull does not necessarily mean top-of-bank. In a stable system the floodplain, which can range from a broad flat expanse across a valley floor to a slight nick point or inner bench on an entrenched channel, equals the elevation of bankfull. Incised channels can have bankfull (channel forming) elevations lower than top-of-bank, or may not exhibit bankfull indicating features at all if recently unstable.

Carling (1987) measured sediment load (bed material ranged from 110 mm to 135 mm) under a range of flows from baseflows to flood flows and defined three regimes: winnowing, maintenance, and adjustment. Figure 8 provides an illustration of these three flow regimes in relationship to stream bank. Carling found that the dominant process for flows up to 60 percent of bankfull was *winnowing* of fine material and that bulk gravels were essentially undisturbed. Within this range of flows, very little of the smallest sized bed material was mobilized. As flows increase above 60 percent of bankfull, there is rapid increase in the gravels mobilized over the first flow regime. Carling referred to this as a "threshold" for channel *maintenance*. For flows greater than 60 percent and up to bankfull, transport of the available sediment load is most effective at sustaining the channel form. Within this range, gravels up to the 84th percentile are mobilized in quantity. The largest coarse gravel is not yet mobilized. The third flow regime *adjustment* all bed material sizes are mobilized with the full bed width active

Urbanization significantly alters the frequency of occurrence and duration of runoff events especially for smaller more frequent storms (Figure 8). This modification in hydrology significantly alters the characteristics of geomorphically significant flows, including flows defined as the channel forming discharge (MacRae, 1992). MacRae (1992) and MacRae et al. (1993) investigated the role of moderate flow events on bank structure and channel response to increases in flow in the mid-bankfull flow range. Using frequency analysis, MacRae showed that with urbanization there is a significant increase in the frequency of flows in the mid-bankfull to bankfull flow. He suggested that the greatest increase in potential scour following urbanization is likely a result of increases in this flow range. Bledsoe and Watson (2001) reported that the frequency of significant scouring events increased by factors of 2.5 to 5 for two watersheds with 18 percent impervious cover. This research indicates that the assessment method should include an analysis of the changes in the frequency and duration of geomorphically significant flows and that control measures could have the most effectiveness by focusing in on this range of flows.

4.5 Adjustments in Channel Geometry

The *dynamic equilibrium* concept implies that the channel attributes; width, depth, slope and planform, can be expressed as functions of discharge and sediment load characteristics. Stream discharge and sediment load act on the boundary materials to create the cross-section dimensions, profile and planform. A change in discharge or sediment load initiates a series of adjustments in the channel attributes, resulting in direct changes in the characteristics of the river.

Urbanization of a watershed causes long-term changes in stream morphology and channel enlargement is the most common response to urbanization and an increase in watershed runoff (Booth, 1990). Morisawa et al. (1979) observed channel cross-section enlargement when 20 to 25 percent of the watershed reached 5 percent impervious cover. Channel cross sectional area increased 5 to 7 times the undeveloped condition at full development. MacRae (1996) reported that the width of channels increased from 1.63 times to 3.8 times. MacRae also stated that channel width was closely associated with the strength of the least resistant bank stratigraphic layer.

An increase in the channel forming discharge leads to an increase in both the width and depth of the channel to accommodate the additional flow. Increases in peak flows and flow durations either cause quasi-equilibrium expansion where the channel cross section increases to accommodate the increased flows, or catastrophic failure involving channel incision and bank collapse. Quasi-equilibrium expansion is the gradual increase in cross sectional area to accommodate the new higher flow regime. This type of change often goes unnoticed, yet is still considered an unstable channel. In contrast, rapid incision and bank failures frequently create a proportionately larger channel whose capacity has little resemblance to the existing flow regime (Booth, 1990).

4.6 Impacts On Stream Bank Stability

The erodibility of stream banks is still one of the most difficult aspects in assessing stream channel destabilization. Bank erosion can be caused by undercutting, abrasion during flow, slumping from positive ground water pressures during waning flood flows, water forced into bank from obstructions such as boulders or large woody debris, and collapse of bank vegetation by wind throw, disease, fire, or floating large woody debris during high flows. The ability of a stream bank to resist erosion is dependent on many factors: soil materials, stratigraphy, vegetation density, root strength and apparent cohesion, the amount of clay or cementing of the matrix particles, bank height and slope. Stream channels bounded by clays, compacted silts and loess are often more resistant to erosion and respond more slowly to hydrologic changes than channels bound by loosely consolidated sands and gravels. The vegetation adds apparent cohesion through the binding effects of roots. Knighton (1998) reported that root density of about 18 percent increased resistance to erosion by more than 100 times.

Watershed and stream channel soils are highly diverse and are linked to large-scale geologic features. The material making up the channel boundary has significant influence on the resulting geometry of the stream channel. Boundary material influences both the erodibility and vegetation assemblages that in-turn provide resistance to bank erosion. Stream banks that are more resistant to erosion tend to have smaller width to depth ratios and will respond slower to perturbations. Stream channels that are less resistant tend to have larger width to depth ratios and are likely to respond much more quickly by experiencing severe or pervasive bank retreat. In Sacramento County a single stream can flow through several soil types and will have varying channel conditions. Streams that flow through relatively permeable soils tend to be dominated by trees and woody plants whose roots help create more erosion resistant banks. In this situation, stream channels tend to evolve into entrenched channel cross sections. Streams that flow through impermeable soils tend to be dominated by herbaceous vegetation that cannot provide the same level of erosion resistance. The result is wider-shallower channels (Zentner & Zentner, 1999).

The ability to develop quantitative measures of the potential to erode stream banks is difficult at best. Most research to date has focused on empirical evidence of bank failures in relationship to various degrees of development. For example, Booth et al. (1997) reported finding a good correlation between channel stability and increases in urbanization. Streams display the onset of degradation at a consistent level of development. Figure 8 is reproduced from Booth’s paper, which shows the ratio of undeveloped flows to urbanized flows plotted against the percent imperviousness of the contributing watershed. Instability is clearly observed when the effective impervious area increases to 10 percent or more. Even lower percent imperviousness causes significant degradation is sensitive watersheds and a reduced level of function throughout the system as a whole (Booth et al., 1997). Booth (1990, 1991) and Schueler (1994) have reported channel instabilities and abrupt declines in aquatic ecosystem health at 10 to 20 percent imperviousness. Ten to 20 percent imperviousness seems to be a consistent level of development upon which the onset of channel adjustment is apparent. The percent of impervious surfaces is surprising low suggesting that the fluvial geomorphic balance is highly sensitive to changes in the controlling variables.

Andrews (1982) found that bank stability in East Fork River in Wyoming appears to be controlled by the process of scour and fill. In order for the banks to be maintained at a constant width over time, the rate of bank erosion must be balanced by the rate of deposition. The accumulation and depletion of sand sized bed material is concentrated in the near-bank region of a cross section and thus significantly influenced bank stability and retreat. Forty to 70 percent of the change in sediment stored in a cross-section occurs in 1/3 of the channel width near the banks. Andrews (1982) described how the process of high flows and sediment transport deposit layers of sediment creating a stratified structure to stream banks. The lower "*basal*" layer is often made up of loosely consolidated coarse sands and gravel, grading upwards to fine sand and silt, overlain by organic matter and vegetation (Figure 9). The basal layer is easily eroded when the shear stress exceeds the thresholds for transport. When scour occurs, the basal bank material is eroded and banks become undercut and unstable. The overhanging bank eventually sloughs off into the channel. Conversely, when sediment accumulates, it accumulates along the toe of the bank protecting the basal layer. Andrews' work suggested that the "*critical threshold*" for bank stability is dependent on the ability of the basal layer (or least resistant layer) to resist erosion.

4.7 Vegetation Effects on Channel Characteristics and Stability

Vegetation both influences channel processes and is influenced by these same processes. Stream channel destabilization is often attributed to a loss of woody vegetation, especially if the pre-urban balance was established with vegetation present. Dense vegetation adds roughness and slows flow velocity, reduces shear stresses on stream banks and adds soil cohesion through root structure. Large woody debris (LWD) also adds roughness and slows flow velocity, and has the added benefit of creating habitat. Removal of LWD as a management practice is known to contribute to bank erosion.

A study completed by the Missouri Department of Conservation and the Soil Conservation Service (1993) reported that dense woody vegetation along the Missouri River prevented banks from failing during floods of 1993 (Wallace 1994). Root strength of vegetation increases bank stability by holding sediment in place. The influence of vegetation on bank stability is greatest in low-gradient, unconfined reaches where a loss of vegetation can lead to bank failures and dramatic channel widening. The removal of vegetation for flood control or other purposes can lead to stream bank erosion.

Channel geometry may be sensitive to the types of riparian vegetation. For example, characteristics of its rooting structure can have different effects upon resistant to bank erosion, such as lateral spreading roots of alders as opposed to taproots of willows.

Different species have varying degrees of tolerance to disturbance such as bays versus oaks, where bays may fall into the channel but may still proliferate, but oaks will likely die. Different species also have different tolerances to having sediment deposited around them or to having their trunks inundated for longer periods of time, such as the difference between willows and alders. Some species can tolerate extended periods of drought or reductions in water table especially those with deep taproots.

4.8 Summary of Impacts on Fluvial Geomorphology and Stream Stability

This section focused on the effects of urbanization on the geomorphic characteristics of stream and rivers. Researchers have documented various types of observed channel response to urbanization and changing hydrology, these include:

a) Modification of geomorphically significant flows (e.g., sub-bankfull flows, channel forming discharge). Geomorphically significant flows range from about mid-bankfull flows to bankfull or just over bankfull flows.

b) Hydromodification can reduce the recurrence interval for channel forming discharges, increase the frequency and duration of geomorphically significant flows and increase the amount of "*work done*" on the stream boundary.

c) Modification of the sediment load and its characteristics. Urbanization can both increase and decrease sediment loads to stream channels depending on the nature of development.

d) Adjustment of channel dimensions to accommodate new stream flows (expansion, incision and/or aggradation depending upon position in watershed, sediment supply, slope, etc.)

e) Adjustment in channel slope to accommodate new sediment loads and stream competence. Adjustments occur both downstream (aggradation, degradation) and upstream through headcutting from the point of discharge.

f) Adjustments of channel planform, sinuosity, meander belt etc.

g) The ability of a stream bank to resist erosion is dependent on many factors: soil materials, stratigraphy, vegetation density, root strength and apparent cohesion, the degree of clay or cementing of the matrix particles, bank height and slope.

h) Adjustment in species and diversity of riparian vegetation. Vegetation both influences channel processes and is influenced by these same processes.

i) Degradation in habitat quality and complexity, habitat and species diversity, and species abundance.

j) Increases in impervious surfaces and the associated changes in runoff clearly have the potential to destabilize streams. The degree of change is variable and depends on the characteristics of the watershed and on the development style

k) Pulses of sediment originating from landslides and earth flows periodically disrupt current channel forms, which over time evolve back to similar conditions before the disruption.

l) Different stream types can respond in different ways to the same change in the controlling variables. For example, the most likely response to an increase in flow in an armored bed with easily erodible bank is widening. Whereas, the response in sand bedded streams with resistant banks is likely incision followed by bank collapse.

5 Riparian Ecology

Understanding the relationship between riparian ecology and the hydrologic and geomorphic processes is critical to developing adequate management strategies. Habitat and its associated plant and animal communities are strongly correlated to the available water supply, its frequency of inundation, and watershed disturbance patterns among other things. The frequency and duration of inundation on low-lying floodplain surfaces and side channels create hydro-periods that establish different ecological communities and add to the diversity of the riverine corridor. Various plant communities have different moisture tolerances and consequently colonize different landforms.

The river, adjacent riparian forests and wetlands are the major habitat types of the floodplain ecosystems. Riparian forests are immediately adjacent to the rivers, while wetlands occur in low-lying areas - primarily backwater areas extending laterally from the main channels. Under natural conditions, moderate to high flows mobilized gravel beds, initiated channel migration, inundated floodplains, maintained aerated riffles, deep pools, and bed material quality for native fishes and invertebrates, and maintain complex channel and floodplain habitat. Floodplain scour and deposition lead to a complex mosaic of habitat types along stream channels that in turn support a rich array of biological communities. Flooding creates habitat that varies in its productivity and structural complexity depending on the timing and duration of inundation, type of substrate, vegetation, and upstream erosional processes. Native aquatic and riparian species evolved under a flow regime and sediment loads with seasonal and year-to-year variability. Riparian vegetation along abandoned channels and emergent wetlands creates off stream habitat and provides increased physical structure to habitats including refuges, spawning/nesting and rearing habitat, and food resources. Many fish species wait until the first sign that the annual spring flood has begun to start breeding. Many insect larvae wait for flooding to begin to lay eggs, hatch, or metamorphose. Flooding results in increased fertility for the river, as nutrients are washed out of soil and organic matter is added to the flow stream. Flood flows can distribute seeds and provide maintenance flows for establishment.

Aquatic species require certain environmental conditions during their life cycle for breading, rearing, hiding and migrating. These conditions include for example, depth and velocity of flow, temperature and oxygen levels of the flowing water. Hydromodification can erode the streambed eliminate suitable substrate for fish and macroinvertibrates. Siltation from eroding stream banks can smother suitable substrate, reduce the oxygen supplied to the interstices of gravel beds, and fill pools that fish and other aquatic species depend on. Failed stream banks also eliminate overhanging banks that provide shade and hiding places from predators. Urban runoff and a loss of riparian vegetation increase the temperature of the water from optimum conditions required by indigenous aquatic species. In semi-arid areas where ephemeral streams are common, hydromodification can increase summer baseflows from irrigation and other outdoor uses of water changing the natural hydo-periods and eventually plant and animal communities.

6 Characteristics of Urbanization That Have The Greatest Impacts On Stream Channel Physical Characteristics

Hammer (1972) evaluated several types of development and conditions on stream channel enlargement using data from 78 watersheds in the Philadelphia region of Pennsylvania. Fifty watersheds had large scale residential, commercial and industrial land uses. Twenty-eight watersheds were considered rural. Hammer evaluated 17 categories of urbanization: three land use groups, three age of development groups, existence of streets and sewers, four nonimpervious land uses, land slope and length of flow path, slope and length of channel to watershed outlet, and extent of channel alterations. The most significant factor affecting channel enlargement is medium to high-density development; including row houses, commercial areas, airport runways, shopping centers and parking lots. The second most significant factor is sewered streets followed by row houses fronting on sewered streets. Houses with rain gutters directly connected to sewered streets are as significant as high-density development. Areas of development less than 4 years old showed minor channel changes, while areas greater than 4 years old showed noticeable increases in channel dimensions. The impact of impervious development increases with increasing land slope and channel slope and decreases with distance of the development from the channel (Hammer, 1972). Whipple et al. (1981) reported that densely developed areas correlated with greater stream erosion and wide stream buffers (≥50 feet) of natural vegetation are correlated with less erosion.

Doyle et al. (2000), Bledsoe (2001), and Bledsoe and Watson (2001) evaluated relationships between channel stability and different characteristics of urbanization. Doyle et al. found that there was a significant difference in channel stability between low-density development and medium/high density development. Bledsoe wrote, "*not all impervious surfaces are created equal*". Various watershed and development conditions control the magnitude of change and its impact on the riparian corridor. Connected impervious surfaces, especially those areas with high conveyance and drainage connectivity, clearly and significantly altered stream flow characteristics and impacted stream channel stability (Bledsoe et al 2001).

The following urbanization factors have been found to effect stream channel stability more significantly than other parameters investigated.

a) Increased drainage density and connectedness from rain gutters, curb & gutters, sewers, channels.

b) Increased imperviousness areas and connectivity of impervious surfaces.

c) Location of development relative to stream channels, existence of buffer strips.

d) Natural watershed soil characteristics (high infiltration areas vs. low infiltration areas) and the extent these areas were developed.

e) Decreased interception and evapotranspiration by removal of vegetation.

7 Assessment Tools

One of the objectives of this literature review is to describe potential assessment tools that can be used to evaluate hydromodification from proposed projects and predict where such changes can cause increased potential for erosion of creek beds and banks. An assessment method is defined as a combination of tools used together to study the problem at hand. According to Bledsoe and Watson (2001), an assessment method must incorporate factors that describe the characteristics of watersheds, stream types, development style, and exiting riparian conditions. They recommend that a combination of stream classification, energy based indices, predictive scientific assessment, and risk-based models be used as the foundation for good decision-making. Booth (1990), Stein and Ambrose (2001) recommend GIS mapping and spatial analysis of watershed and stream features. SFEI (1998, 2000, 2001a, 2001b) has developed and tested a watershed assessment approach that combines historical analysis and detailed field measurement to predict the health of watersheds, including channel stability. The Oregon Watershed Assessment Manual is focused on fish habitat, but has many elements that could be adapted for HMP. It is designed to help determine how well a watershed is working in terms of ecological health defined by indicators of fish habitat and water quality. The overall goal of this manual is to help watershed managers determine where there is a need to restore natural processes or features. Montgomery and MacDonald (2002) propose a diagnostic approach for assessing channel condition, identifying sensitive stream segments, and predicting channel response. Bledsoe (2001) has developed a risk-based approach incorporating the probability that a stream channel will be unstable to assist regulators and managers in implementing control measures. Recently, the Journal of the American Water Resources Association (April 2002) published a series of papers addressing “Integrated Decision-Making for Watershed Management: Processes and Tools”. The main theme of this series is to describe methods and tools that can be used to make informed decisions regarding the protection of watershed resources, including the socioeconomic impacts of these decisions. The direction of the current state-of-thinking in this series is to integrate and link physically, ecologically and economically based models into a single framework to analyze environmental impacts stemming from alternative watershed management strategies (Diplas, 2002). The sections that follow describe some of these assessment tools that could be developed into an assessment method for the Santa Clara Basin.

7.1 Stream Classification

It is clear that the first task of any watershed and stream network assessment must be to define and understand the physical and ecological processes of the stream system of interest. Several classification systems have been developed and are being used today: Montgomery and Buffington (1993), Rosgen (1996), Schumm (1963) and Pfankuch (1975). The Montgomery and Buffington system and the Rosgen system are discussed below.

Montgomery and Buffington (1993) recommend that stream channels be classified according to their processes-based characteristics to identify which channels are more sensitive to changes in the controlling variables, to provide guidance on the probable response of these streams, and to adequately select management strategies that will protect these stream segments. The classification system employs a wide range in scales that reflects different levels of resolution, including 1) geomorphic province, 2) watershed, 3) valley, 4) reach, and 5) in channel scales. Montgomery and Buffington (1993) recommend that classification be completed down to the reach scale to assess impacts from urbanization. The in channel scale includes pools, riffles, glides, runs, rapids, etc. as individual units. This scale is typical of biological assessments.

Geomorphic Province. The geomorphic province is an area with similar climate and physiography that have established similar landforms and erosional processes. The geomorphic province consists of watersheds and ultimately defines the sediment source characteristics and the boundary material through which streams flow.

Watershed Scale. The watershed is an area that is bound by topographic highs and contains the discharge and sediment transport processes that define stream channel characteristics. Watersheds can be sub-divided into zones with similar geologic and climate conditions (e.g., streams originating from the Santa Cruz Mountain Range versus streams originating from the Diablo Mountain Range).

Valley Scale. The valley scale includes descriptors of valley fill material, sediment supply, and transport capacities. Montgomery et al. classify valley segments into the dominant fluvial geomorphic process; i.e., erosional zones vs. transport zones vs. depositional zones. This level of classification can provide insight into the linkage between upstream modification in discharge or sediment supply and observed downstream impacts.

Reach Scale. The reach scale is defined as a segment of channel with similar channel characteristics. Montgomery and Buffington (1993) define six channel types for reach scale analysis: cascade, step-pool, plane bed, pool-riffle, dune-ripple, and braided channel forms. A complete description of these channel types can be found in Montgomery and Buffington (1993). Stream channels have varying characteristics within reaches. Each of the stream types has varying degrees of sediment supply, transport capacity, and sensitivity to changes in discharge and sediment load. Furthermore, each stream type can respond differently to changes in discharge and sediment load. Seven possible changes can occur depending on type; these include changes in width, depth, slope, sinuosity, bed surface grain size, roughness and scour. The sensitivity and response of stream channels will vary among channel types, its position within the watershed and its disturbance history.

Montgomery and Buffington (1993) recommend the following application of their classification system:

a) Identify zones of potential source material, transport, and deposition. The most reliable method is to use field observation and mapping, although it is the most time consuming and expensive. Soil maps and slope measurements from topographic maps can be used if cost is an issue, although it is less accurate.

b) Evaluate past channel changes and their response using historical information, such as aerial photographs, maps, and surveys. Historical information can be valuable in explaining watershed processes, existing channel conditions and determining channel response to future changes.

c) A comparison to adjacent undisturbed channels can be done if historical data does not exist. Relationships between channel dimensions (width, depth) and discharge can be used to evaluate changes in the disturbed stream.

d) All comparisons should be made on the basis of stream type. Stream type is the foundation of their assessment method.

D. L. Rosgen (1985, 1994) developed an alternative stream classification system. Rosgen's classification system has four levels of resolution: 1) geomorphic characterization; 2) morphological description; 3) stream "state" or condition; and 4) verification. The system mainly employs morphological field measurements, which in effect reflect integrative effects of various factors. The classification is based on well-defined, quantitative criteria parameters. The system is said to be applicable to a wide range of streams without modification, including both perennial and ephemeral streams. The system was originally developed using hundreds of stream data sets (1985) and was later tested against 450 additional streams and refined (1994). Distribution of characteristic values was evaluated and the "most frequently observed" values were identified and used to establish his numerical criteria between stream types. US Department of Agriculture (USDA) in a variety of its projects has adopted this classification system.

Geomorphic Characterization (Level 1). The purpose of this level is to provide a broad characterization that integrates landform, valley and channel morphology. This level incorporates the influences of climate and depositional history. Parameters used in this level include entrenchment ratio, slope, cross section morphology (e.g., width/depth ratio), and plan view morphology (e.g., sinuosity). Streams are to be classified into one of seven major, plus two supplementary, stream types.

Morphological Description (Level 2). At this level, the major stream types are further refined into six minor types, based on dominant channel materials and finer slope ranges. The stream types are given numbers related to median particle size of the channel material. This produces 41 major stream types. The parameters used in this level include entrenchment, width/depth ratio, sinuosity, slope, and channel material.

Stream "State" or Condition (Level 3). Level 3 characterizations relates to the channels stability, response potential and functions. The streams are assigned with sub-types, based on the following characteristics (Rosgen, 1985): riparian vegetation, organic debris and/or channel blockages, stream size (width), flow regime, sediment supply, depositional features, and meander patterns. Furthermore, such characteristics as confinement features, stream bank erodibility, channel stability, and fish habitat indices, can also improve the classification of this level.

Verification (Level 4). The classification of this level involves direct measurements and observation of streams such as sediment transport, bank erosion rates, aggradation/degradation, hydraulic geometry, biological data, etc., to provide site-specific data and support more comprehensive and detailed evaluation.

Rosgen (1994) recommends the application of his classification system as follows:

a) To simplify and facilitate the communication regarding the evolution of streams; that is, in lieu of describing changes in individual variables in details, the evolution can be summarized by shifts in the streams' type.

b) To help establish guidelines for appropriate construction of in-stream structures so that they not only meet their objectives, but help maintain the stability and function of the streams.

c) To systematize and improve the estimation of various design parameters for engineering work, such as Manning's n values and constants used in hydraulic-geometry relations.

d) To provide good background knowledge on natural tendencies of streams, which is critical for any restoration projects.

e) To support management decision making through ability to predict streams' behavior and responses, based on the stream types.

7.2 Discharge Thresholds for Channel Stability

Booth (1993) evaluated several other studies that have measured the sediment transport and the concomitant discharge in natural systems {i.e., Pickup and Warner, 1976; Andrews, 1984; Leopold, 1988; Carling, 1988, and Sidle, 1988}. Booth (1993) concluded that the threshold of bedload transport is around 50 percent of the 2-year flow. Reported threshold values ranged from 40 to 60 percent of effective discharge, which varied from more than once per year to once in 2-years. Effective discharge is defined as the flow that moves the greatest quantity of sediment over the long-time (Leopold et al., 1964). Effective discharge is often equal to bankfull discharge, but not always (Pickup and Warner, 1976).

Booth (1993) compared flow frequency data generated for King County, Washington, and found that the 1-year discharge ranged from 25 to 50 percent of the 2-year flow. However, this option became problematic when defining the 1-year flow using the annual series or partial duration series. The 1-year partial duration event is approximately equal to the 1.6-year event on the annual series. Although no single threshold can work on all stream types, a threshold of ½ of the 2-year discharge has promise at least for gravel bedded rivers in King County (Booth & Jackson, 1997). However, in Ontario Canada, attempts to control the 1-year or 2-year discharge with no consideration for the duration of flows have resulted in equally degraded streams as implementing no BMP at all (MacRae, 1996).

Duration thresholds attempt to maintain pre-development durations of all sediment transporting flows. However, without maintaining infiltration in the watershed the total volume of runoff increases and so the durations of some flow magnitude(s) must increase.

Attempting to reduce and control stream flows to levels below the threshold of motion for bed material will result in its own set of problems – mainly aggradation. The balanced state between sediment load characteristics, discharge and slope must be maintained to prevent channel destabilization. Furthermore, the basin size to control flows below the threshold of motion would have to be about 20 percent of the drainage area, which of course would be prohibitively expensive.

7.3 Permissible Velocity Threshold

One of the earliest methods for evaluating bank erosion was developed in the late 1920's. Fortier and Scobey developed permissible velocities and critical shear stress values for a range of cohesive and non-cohesive soil types (ASCE 1992). This method was originally developed for agricultural engineers designing irrigation canals, such that the earthen erodible boundary would be stable while water flowed through these canals. According to the ASCE manual, the primary factors affecting erosion and scour include soil type and composition, velocity, depth, steep slopes, boundary roughness and abrupt changes in channel configuration. Table 2 lists the recommended values for selected soil types.

Table 2. Maximum Permissible Velocities Recommended in ASCE Manual

Material Type	Velocity (fps)	Shear Stress (lb/ft2)
Fine sand	1.50	0.027
Sand loam, noncolloidal	1.75	0.037
Silt loam, noncolloidal	2.00	0.048
Alluvial silts, noncolloidal	2.00	0.048
Firm loam	2.50	0.075
Stiff clay, very colloidal	3.50	0.26
Alluvial silts, colloidal	3.75	0.26
Shales and hardpans	6.00	0.67
Fine gravel	2.50	0.075
Graded loam to cobbles, noncolloidal	3.75	0.38
Graded silts to cobble, colloidal	4.00	0.43
Coarse gravel, noncolloidal	4.00	0.30
Cobbles and shingles	5.00	0.91

Most of our hydraulic formulations assume that the channels are sufficiently wide that the effects of sidewalls are negligible. However, when dealing with channel bank erosion, we are specifically interested in the erosive conditions near the channel sides. Features like vegetation add roughness elements that affect the flow conditions near the bank. Generally, the maximum applied shear stress occurs on the channel bottom, while the applied shear stress on the channel sides, with channel widths greater than 3 times its depth, is about 76 percent of the maximum value. The ASCE Manual shows an example of the relationships of shear stress as a function of the closeness to the channel sidewalls.

7.4 Bed Mobility Indices

Several authors who have evaluated indices of channel stability have used some form of the critical shear stress on bed material to assess potential destabilization.

One of the earliest and most common relationships of sediment transport "*thresholds*" is Shields diagram of incipient motion. The derivation of incipient motion was based on a balance between the forces acting on a submerged particle on a streambed. These include the drag force defined by the shear stress imposed by the flowing water and the resistance force defined by the weight of the particle. A critical shear stress can be defined such that the drag force just balances the resistant force. Shields defined and plotted a dimensionless shear stress (τ^*) as the ratio of drag force to gravitational force.

$$\tau^* = \frac{\tau_b}{(\rho_s - \rho)\cdot gD} \qquad \tau_b = \rho ghS$$

$$\tau^* = \frac{hS}{1.65D}$$

Where τ_b is the bed shear stress, ρ_s is the density of sediment, ρ is the density of water, g is the gravitational constant, D is the grain size, h is depth, and S is the channel slope. Shields measured this parameter τ^* for a range of particle sizes under a range of flows to develop the diagram. Shields diagram plots τ^* against the flow characteristics expressed as the particle Reynolds number. As the flow becomes fully turbulent, which is the case for most natural creeks and rivers, τ^* becomes approximately constant for hydraulically rough surfaces. This constant is shown as 0.06 on the Shields diagram, but is often taken as 0.045, or even 0.03, if absolutely no movement is required. Using data from the Rocky Mountain region of Colorado, Andrews (1984) measured values of the dimensionless shear stress for flows at bankfull ($\tau^* = 0.046$ for bed material ranging in size from 23 mm to 120 mm). He also noted that it is very rare for τ^* to be greater than two to three times the threshold for motion and that stable channels cannot be maintained when τ^* exceeds 0.080. This approach could be implemented in Santa Clara County if bed loads were measured during field studies.

Shields diagram was derived using uniform grain sizes, but is often used for mixed-grained beds with the D50 representing the mixture. In reality however, there is no single τ^* to move any particular grain size, but it depends on its surrounding conditions. The theory of equal mobility states that all particles in a mixed bed tend to move about the same time. Smaller particles tend to be hidden in between larger particles and thus are sheltered from the flowing water. Larger particles are more exposed to the actions of shear and thus are more easily moved. Andrews, E. D. (1983) developed the following relationship for the critical shear stress (τ_i^*) of particle **"i"** in a distribution of particle sizes:

$$\tau_i^* = \tau_{D_{50}}^* \cdot \left(\frac{D_i}{D_{50}}\right)^{\beta}$$

Where the exponent β is taken to be somewhere between –0.8 to –0.9, reflecting some ability of the flow to selectively transport finer grained particles. Andrews estimated his exponent to be –0.872. True equal mobility requires β of –1.0. Flood flows tend toward equal mobility, whereas low flows tend towards selective transport, leading to armoring.

Bledsoe and Watson (2001a) developed a mobility index using 270 streams from throughout the world and a regression analysis with 80 percent accuracy in separating stable meandering streams from braiding or incising streams. They conclude that the best indicators of stability involve a ratio of the erosive forces (or some measure of excess power) to the resisting forces. These ratios outperform absolute measures of flow energy. Bledsoe and Watson (2001a) suggests the following index:

$$S\sqrt{\frac{Q_w}{D_{50}}}$$

Where Q_w is stream flow. Note that their index is a form of the Shield's parameter (although not unitless), where depth and slope are replaced with discharge. The above indices however are based on the mobility of bed material and do not apply to situations where the erosion of stream banks is the dominant failure mechanism or when vegetation density is important. Bledsoe and Watson (2001a) qualified their results by suggesting that flow energy be referenced to a more detailed description of the limiting factors controlling the boundary's resistance to erosion.

7.5 Erosion Indices for Channel Stability

Booth (1990) investigated the effects of urbanization on stream channels in Washington State. Booth's analysis suggests that unit stream power (Sp) may be reasonable measures to distinguish between eroding and non-eroding channels and computed a threshold value of 80 watts/m^2 for stream power for streams in his area.

$$Sp = \frac{\rho g Q_w S}{w}$$

Where w is the width of the stream channel. Eroding and non-eroding stream channels were determined by field inspection of channel banks. Booth defined eroding channels as having cut banks more than 1 year old and higher than the commonly observed 10 to 30 centimeter banks.

Rhoads (1995) also supports use of the stream power to assess channel instabilities. Stream power is a measure of the "*rate of doing work*" in overcoming resistance and also in moving sediment down gradient and eroding stream banks. Using published literature, Rhoads described how changes in discharge, sediment transport, and channel stability could be explained using stream power. Variations in stream power measures include total, reach averaged, cross-section averaged, and stream power per unit width.

Some measure of the stream resistance to erosion must be included in the parameterization. The D50 is the most common parameter used as an indicator of the stream boundary conditions. MacRae (1993, 1996) found that threshold criteria must include a measure of erodibility of the most sensitive boundary material (basal layer) and that criterion based on flow alone is not adequate.

MacRae (1993, 1996) recommends that the erosion potential about the channel boundaries should remain the same under both developed and undeveloped conditions over the range of expected flows. A discharge control strategy that maintains the same sediment transport characteristics provides the closest reproduction of post-development conditions. MacRae referred to this method as "*Distributed Runoff Control*", which has been adopted by the Ontario Ministry of the Environment and Energy (1994). To this end, MacRae developed a "*time integrated*" erosion based index (E_s):

$$E_s = \frac{\sum \left(q_{s\,out} - q_{s\,in}\right)_{post} \cdot \Delta t}{\sum \left(q_{s\,out} - q_{s\,in}\right)_{pre} \cdot \Delta t} \qquad\qquad q_s = a \cdot \left(\tau_b - \tau^*\right)^b$$

Where ($q_{s\,out} - q_{s\,in}$) represents the change in sediment storage within a stream reach, for the pre-developed and post developed conditions, respectively, and "a" and "b" represent empirically based coefficients. In MacRae's method the critical shear stress in the sediment transport function is based on the erosion resistance of the bed as well as each stratigraphy layer in the stream banks.

7.6 GIS Mapping and Spatial Analysis

GIS mapping is becoming a widely used and powerful tool for evaluating watershed scale issues and management decisions. In this case, GIS can be used to overlay the watershed and stream characterization spatial data on existing and future development plans to identify sensitive stream segments at risk of being impacted by urbanization. Booth (1990) suggests that flow, topography, geology and channel roughness can be used to identify sensitive stream segments susceptible to erosion. Simple map overlays of geology, channel slopes, topography, channel roughness, and flow looking for critical areas can provide a simple tool to identify areas susceptible to erosion and sensitive stream segments.

Stein and Ambrose (2001) investigated cumulative impacts of urbanization on riparian ecosystems using GIS and spatial analysis on a watershed scale for the Santa Margarita Watershed, near Temecula, California. They investigated changes in land use and riparian ecosystem quality over time using aerial photography and Army Corps of Engineers 404 permit records. They used a Rapid Impact Assessment Method to *qualitatively* assess habitat quality using six criteria and spatially analyzed how these quality indicators changed over time and space. Their analysis consists of a measure of the concentration of impacted sites and a measure of the degree of autocorrelation between sites. Stein and Ambrose found that the current piecemeal approach to development and 404 permits has lead to the overall degradation of the entire stream system. The incremental cumulative impacts of the many small projects disrupted watershed scale processes and resulted in fragmented habitat, loss of floodplain, loss of migration corridors, and overall channel degradation. These in turn affect habitat, plant and animal species diversity, abundance, and health. To provide better management of cumulative impacts and protection of aquatic resources, Stein and Ambrose recommend a watershed level approach that incorporates past and proposed actions and develops an understanding of the watershed scale processes.

They are also developing an Army Corps of Engineers, Special Area Management Plan (SAMP) designed to assess cumulative impacts on a watershed scale. They begin by characterizing the watershed, its physical and ecological processes. They perform a historical analysis; map geology, soils, slopes, and land use; model hydrology; investigate sediment processes, source and transport; and investigate groundwater – surface water interactions. They then identify opportunities and constraints and formulate approaches to future development to minimize impacts to ecological resources. Their alternative management practices are presented in the following section of Management Strategies.

7.7 Watershed Science Approach

The San Francisco Estuary Institute (SFEI) has developed and tested a *Watershed Science Approach* on several stream systems in the Bay Area (SFEI, 1998, 2000, 2001a, 2001b). Their approach focuses on identifying the historical changes in land use and changing hydrology since European development, and on the changes in sediment supply sources and resulting channel geomorphic features. The approach incorporates the use of a decision tree analysis and has a unique way of mapping channel conditions – streamline graphs for both the right and left banks, as well as channel thalweg. Although the methodology was developed around detailed field data collection, a simpler modified approach has been used when budgets and schedule were limiting.

The approach includes detailed field measurements of the voids left behind from past erosion and of the channel geometry, planform and longitudinal profile of the stream system. Information on natural and man-caused erosion problems is also identified. Variables in the assessment include quantities of sediment stored in the system; rate of erosion; sediment supply from streambeds, banks, landslides, earth flows, and headword expansion of tributaries; channel cross sectional geometry, planform, and profile changes over time; bed material grain size distributions; measurements of pool and large woody debris numbers and frequency. And like many others, this method includes mapping geology, soils, slopes, and land use; and investigate impacts from lowering groundwater tables.

7.8 Oregon Watershed Assessment Manual

The Oregon Watershed Assessment is designed to help determine how well a watershed is working in terms of ecological health, defined by indicators of fish habitat and water quality. Although this manual focuses on fish habitat, many of the components and activities are relevant to HMP issues. This manual describes a methodology that could be used as a model to help develop the HMP assessment method.

The assessment manual describes steps for identifying issues, examining the history of the watershed, describing its features, and evaluating various resources within the watershed. The overall goal of this manual is to help watershed managers determine where there is a need to restore natural processes or features related to fish habitat and water quality. Specific goals include the following:

a) Identify features and processes important to fish habitat and water quality.

b) Determine how natural processes are influencing fish habitat and water quality.

c) Understand how human activities affect fish habitat and water quality.

d) Evaluate cumulative effects of land management practices over time.

It is designed to work on any landscape in Oregon, from the coastal rain forests to the inland deserts, with its own characteristic geology, climate, physiography and natural disturbance regimes (storms, fires, landslides). The assessment begins with the large-scale watershed characteristics and processes, and then incorporates reach scale information by stratifying streams into a hierarchy of *Channel Habitat Types*, on the basis of channel slope and valley width (i.e., gradient and confinement). Fifteen channel habitat types are considered at a scale that is small enough to predict patterns in channel characteristics, yet large enough to be identified from topographic maps and limited filed work. The development of their classification system was based on adapting several existing systems to cover the variability of Oregon streams. This stratification is intended to help identify which stream segments have a high potential for fish production and which are the most sensitive to disturbances. This information, along with current fish production data, leads to identifying the following:

a) Areas with the highest potential for improvements.

b) Highest priority areas for restoration.

c) The types of improvement actions that will be most effective.

The watershed assessment methodology consists of four main components:

1) *Start-Up and Identification of Issues*.

2) *Watershed Descriptions*, incorporating the Historical Assessment and Channel Habitat Type Classification.

3) *Watershed Characterization*, incorporating hydrology, sediment sources, channel modification, water quality, riparian habitat types, and fish and fish habitat types.
4) *Watershed Assessment*, incorporating an evaluation of the Conditions and development of a Monitoring Plan.

7.9 Diagnostic Assessment

Montgomery and MacDonald (2002) propose a diagnostic approach for assessing channel condition, identifying sensitive stream segments, predicting channel response, and developing monitoring plans to assess impacts. A diagnostic approach is recognized in the medical field as an appropriate method to assess complex systems. Their example approach is essentially a matrix method, or consumers report method, with symbols representing measures of sensitivity, response, or other criteria (Figure 9). The highly variable nature of stream channels requires that the assessment method consider the location within the stream network, regional and local geomorphic characteristics, channel type, spatial and temporal variability of sediment transport and flow, riparian vegetation, disturbance history and persistence of the imposed changes. The diagnostic approach includes an evaluation of the geomorphic characteristics that are sensitive to changes in transport capacity, sediment load, type and density of vegetation, availability and abundance of obstructions (LWD).

The first step in the diagnostic approach is to define and characterize the stream system of interest, including a historical analysis of past influences. The second step is to perform field observations to evaluate various indicators of channel conditions. Potential indicators includes channel slope, confinement, entrenchment, riparian vegetation, overbank deposits, channel pattern, bank conditions, gravel bars, pool characteristics, and bed material. The energy-based indices could be computed and incorporated into this approach. A matrix showing how each stream segment performs according to a set of selected criteria is created and explained.

The diagnostic approach has several advantages over other more rigid methods, such as Pfankuch (1975). Some of these advantages include, 1) attempts to understand the cause of degradation rather than characterize the symptom, 2) provides insight into channel processes and watershed conditions, 3) more comprehensive, 4) if documented well, should be both clear and defensible, 5) should eliminate the desire to treat the symptom rather than the causes of channel degradation. There are also some disadvantages, which includes, 1) potential for bias on interpretation, 2) misrepresentation of the certainty of the assessment, 3) increased data requirements, 4) requires trained personnel beyond that of a workshop and short course, and 5) increased costs.

7.10 Risk-Based Assessment

Bledsoe and Watson (2001b) presented an interesting approach using a probability modeling method to predict channel patterns and instability. According to Bledsoe and Watson this method addresses the uncertainty in using the indices discussed previously and provides a means of judging the sensitivity of stream channels to changes in the controlling variables. Because the characteristics of stream channels are highly variable and impacted by random events, a statistical approach allows one to integrate the entire seasonal and year-to-year distribution of rainfall as well as the antecedent conditions. A probabilistic methodology may provide a more useful tool for management, planning, and policy making.

Their approach involves logistical regression equations that relate continuous parameters like flow energy, slope and bed material to single qualitative dependent variables, such as stable or unstable. The intent is to develop a probabilistic approach to predict the occurrence of stable meandering channels versus braiding and incised channels as a function of simple measurable hydraulic and sediment variables. This method was developed using various descriptive data for 270 streams, of both sand and gravel, from around the world. They looked at 74 different regression models. The best results were obtained using bed slope in conjunction with annual flood discharge or in some cases bankfull discharge. Results also varied by stream type. However, models of this type do not provide any information on the cause of channel changes or why the change occurred. This method incorporates their mobility index describe above, which was used as a first cut at testing this approach, but recommend that the method be developed with a better description of the channel boundary, flow regime, soils and wood influences, floodplain connectivity, and development style. Risk-based models that include these parameters need to be developed for local conditions based on local data.

7.11 Computer Modeling

The JAWRA (2002) published a series of papers addressing “Integrated Decision-Making for Watershed Management: Processes and Tools”. The main theme of this series describes methods and tools that can be used to make management decisions regarding the protection of watershed resources, including the socioeconomic impacts of these decisions. The direction of the current state-of-thinking is to integrate and link physically, ecologically and economically based models into a single framework to analyze environmental impacts stemming from alternative watershed management strategies (Diplas, 2002). For example, Newbold (2002) presents an optimization scheme to select management sites to improve habitat and water quality. This approach has been used as an alternative to GIS mapping. Weinberg and Randall (2002) present an integrated approach using hydrodynamic, water quality, fish population, water allocation, and economic models for the Central Valley, California. Their focus is to assess water management alternatives on the environment and agricultural economies for balancing water allocation and proving sustainable development. Gassman (2002) uses an integrated modeling approach to assess environmental impacts, economics, and alternative management decisions on livestock production.

The Maryland Department of the Environment (MDE, 2000) completed an evaluation of stream response to traditional stormwater management practices; all involving some form of detention basin design. This approach is being followed by Ventura County to assess channel stability along Calleguas Creek as a pilot test of the method (personal communication with Jayme Laber, 2002). MDE used the hydrologic modeling software HSPF to simulate runoff and discharge from detention ponds under four different sizing criteria, existing, 2-year peak flow design, extended detention, and distributed runoff control proposed by MacRae (1994). They investigated channel stability using a critical shear stress ratio, where the bed shear stress was predicted using modeling results and critical shear was based on bed material samples. When the shear stress ratio is less than 1 the channel bed material is stationary. The channel was considered stable when the applied bed shear stress is less than 1.2 times the critical value (i.e., shear stress ratio of 1.2) and unstable when the applied bed shear was 2.5 times or greater than the critical value. These ratios were determined for Maryland streams. Using these threshold ratios, the stream discharge that produces these critical shear stress values was computed and compared against the discharge from each of the pond volumes investigated and the risk of channel instability predicted. These ratios appear similar to the conditions reported by Carling (1987) where the critical value was 60 percent of bankfull and significant adjustment in channel geometry was highly probably at 130 percent of bankfull (or 2.2 times the critical value). The MDE approach does not address increases in the duration of mid-bankfull flows or the actual long-term sediment transport loads.

7.12 Summary of Assessment Methods

Watershed and stream channel characterization is the first step towards any assessment addressing the physical and ecological conditions of a watershed and stream network {Bledsoe & Watson (2001a), Montgomery and Buffington (1993), Stein and Ambrose (2001), Rosgen (1996), Montgomery and MacDonald (2002)}. The watershed scale characterization helps focus attention on the processes impacted by development and the actual causes of the observed impacts rather then focusing in on the symptoms, such as bank failures. The characterization may take different forms depending on the focus of the assessment. Streams can then be classified according to their sensitivity to hydromodification, potential to be eroded, or risk of being impacted by future development.

The SFEI supports a watershed assessment approach that combines historical analysis with detailed field measurements to estimate the various sources of sediment supply, how its changed over time due to changing land uses, and how its changed stream channel morphology and ultimately habitat conditions. Historical information is used to help explain the observed physical and ecological processes and existing stream channel conditions. How has the flow and sediment transport processes, and stream channel geometry been altered in the past? Are the observed stream bank failures a result of past agricultural practices or recent hydromodification? What is the observed stream response to increases in stormwater discharge? The historical analysis can provide insight into likely response to hydromodification and can be used to verify our assumptions on the expected channel response.

In order to identify sensitive stream channels at risk of being impacted by urbanization, characterization of the development patterns, existing, past, and future is required. Conditions must be compared to the stream characterization data. Simple map overlays of sensitive stream segments with development patterns can provide a simple tool to identify stream segments at risk. A well-designed GIS based system can be developed to identify upstream urbanization at any point in the watershed.

The direction of current research is to developed simplified methods, or indices that can be used to distinguish between eroding or non-eroding, or stable and unstable channel conditions (Booth, 1990; Bledsoe, 2001; and MacRae, 1996). Indices, such as ratios of stream power, are attractive because they are simple to use and inexpensive to apply. However, as with any simplified scheme, the level of physical representation of true conditions is significantly reduced. Bledsoe (2001) recommends that we avoid single parameter methods. Indexes of stability, energy, or erodibility must be referenced to the erodibility of the most sensitive boundary condition (e.g., basal layer). The time-integrated erosion index proposed by MacRae (1993) combined with continuous records of discharge and sediment yield analysis provides the most physically based approach to address the impacts from hydromodification (Bledsoe 2001).

The risk-based modeling approach presented by Bledsoe and Watson (2001b) has potential to be developed for the Santa Clara Valley. Although its description is based on their energy index, it can be modified to include other relevant parameters measured locally. Similar risk assessment methods have been used in the hazardous waste management industry. Methods that include the limiting stream bank material is not yet developed. The attractiveness of this method is its use as a management, planning, and policy-making tool. For example, it is unlikely or perhaps impossible that a method can be developed that explicitly determines that a stream channel will be stable or unstable given a certain set of circumstances with 100 percent accuracy. Thus a probabilistic approach would allow managers to define a level of risk, which they are willing to accept.

Reach specific and site-specific thresholds based on hydraulic and sediment transport modeling are more scientifically defensible but will be more expensive than using indices (Booth, 1990). The current state-of-thinking published in the JAWRA (April 2002) suggests that physically, ecologically and economically based models could be linked into a single method to assess impacts on stream channels from urbanization as well as alternative management strategies (Diplas, 2002). The Maryland Department of the Environment and Ventura County are developing fairly extensive hydrologic and sediment transport modeling. Most all the research on the effects of urbanization and development of the tools described above used some form of continuous hydrologic modeling.

Bledsoe et al. (2001) developed some guidance on assessment methods and suggested the following steps:

a) Identify channels that are the most sensitive to changes in stream power,

b) Understand the context of stream bank erodibility and limiting conditions

c) Calibrate models and stability criteria regionally

d) Include key parameters, such as the flow regime, existing conditions and characteristics of channel banks, the degree of entrenchment, influences of geology and woody debris, floodplain connectivity, and development style.

8 Management Strategies

Effective enforcement of regulatory mandates to protect the beneficial uses of stream channel and aquatic habitat presumes an ability to reliably evaluate the past and present land use decisions on stream channel conditions and functions, and to predict future impacts for development. Effective methods to assess and monitor channel conditions are needed to evaluate the success of current efforts and restore degraded streams.

8.1 Maryland's Low-Impact Development Strategies

Prince George's County (PGC) and the Maryland Department of Environmental Resources (MDE) have developed a low-impact development (LID) strategy to address runoff associated with new development. As discussed in Chapter 3, development can significantly alter the hydrologic processes by reducing or eliminating infiltration and modifying the natural runoff hydrographs. Their manual describes the methods, strategies, and controls used to create a "hydrologically functional landscape" that mimics the natural hydrologic regime to the extent practical. The primary emphasis of LID is to maintain or recreate the natural hydrologic regime as much as possible.

The main themes of the LID strategy are to establish a "*Hydrologically Functional Landscape*" using a "*Distributed Control*" approach along with a set of "*Integrated Management Practices*". Their *Hydrologically Functional Landscape* approach requires development to mimic the natural hydrologic cycle to the extent possible using distributed management practices. They recommend characterizing the watershed and identifying important hydrologic features that must be maintained, such as highly permeable soils, riparian areas, wetlands, etc. The *Distributed Control* approach refers to retaining and infiltrating as much of the excess runoff volume as possible in discrete units throughout the development so that control is not concentrated in single large facilities. The intent is to manage excess runoff at the source rather then at the end-of-pipe. *Integrated Management Practices* are a set of control measures that when implemented will help maintain the pre-development hydrograph. These include for example, rain gardens, dry wells, infiltration trenches, swales and buffer strips.

The preservation of the pre-development hydrology is investigated using runoff volume, peak flow, and water quality. LID attempts to minimize increases in volume, maintain pre-development peaks and time-of-concentration, and provides for water quality treatment. Preservation of frequency/duration is assumed if the development can match the specified pre-developed design storm hydrograph. For protection of stream channels, the design storm is based on the 1-year or 2-year frequency storms. As discussed in Chapter 4, control of the 1- or 2-year storm because it is defined as the flow that controls the shape of the stream channel is not adequate.

The first step in this strategy is design features that minimize the changes in the pre-development hydrograph by reducing impervious surfaces, disconnecting impervious areas, disconnecting roof drains, as well as many others. Once all the strategies for minimizing the increase in runoff are used, then management practices that retain the excess runoff volume are employed (e.g., rain gardens, infiltration, vegetation filters). These should be distributed units throughout the development. In some cases where site design and retention are not enough, detention is then employed, where some of the excess runoff is held in storage and later released at a slower rate.

One of the issues using this method is the design storm approach. The design storm approach is traditionally a flood control design approach that is typically found to be inadequate for environmental and water quality needs. The design storm approach requires assumptions on soil type, antecedent conditions, storm type and duration. This method typically over predicts runoff from open space and stream flow statistics rarely match storm event statistics. Studies have been done showing the difference between single event design storm methods to continuous simulation methods and design storm methods often over predict pre-development runoff and if post-development was designed to over predicted pre-development flows, then the resulting changes could still impact stream channels (Strecker, 2001).

8.2 The Pennsylvania Handbook of Site Planning and Best Management Practices

The Pennsylvania Handbook of Best Management Practices (PHBMP 2000) provides site planning and best management practices (BMP) selection guidelines for erosion control, stormwater runoff, water quality, watershed management, and habitat protection. The PHBMP summarizes the state-of-the-art in site planning and BMP alternatives in a comprehensive watershed management program for the Northwestern United States.

The central premise of Pennsylvania watershed management program is that effective site layouts and designs can minimize the need for conventional structures for storm drainage and BMP's, thereby reducing the costs of development. Strategic site planning also provides community benefits by incorporating natural features that maintain the sensitive habitats, natural hydrologic functions and enhancing aesthetics and recreational value. Among the many aspects of a comprehensive watershed management program are provisions applicable to protecting sensitive and natural habitats. These include:

a) Identify and map sensitive areas, soil type and conditions, and natural drainage features early in the planning process,

b) Develop a plan to preserve, protect, or enhance sensitive areas and the natural hydrologic and filtering functions,

c) Preserve protective buffers adjacent to water bodies,

Among the sensitive hydrologic and habitat areas to be protected include stream corridors, wetlands, steep slopes and highly erodible soils.

Preserve the Natural Hydrologic Conditions. The first strategy in the PHBMP is to minimize the changes in post-development hydrology and maintain, to the extent practical, the natural infiltration process. Preserving areas for infiltration provides stable baseflows, groundwater recharge, reduced flood flows, reduced pollutant loads, and reduced costs for conveyance and storage. The PHBMP recommends the following control measures:

a) Reducing and disconnecting impervious surfaces is considered to be the single most important management practice to minimize changes in hydrology.

b) Preserving natural drainage features, such as swales, channels,

c) Preserve natural depressional storage areas, such as wetlands, ponds, and pools.

Minimize the Effects of Development. The second level of management is protecting sensitive areas through site and land use planning. The PHBMP recommends the following control measures:

a) Provide setbacks and buffers between development and sensitive areas,

b) Cluster development in the least sensitive areas,

c) Provide conservation easements and tax incentives to preserve sensitive areas,

d) Minimize the amount of grading and topographic changes.

Selection and Use of BMP's. The intent of the PHBMP is to preserve sensitive natural features and to develop stormwater systems that mimic the natural hydrologic cycle as much as possible. BMP's such as swales, bioretention (rain gardens), permeable pavement, dry wells, and vegetated roof covers. Natural features with important hydrologic functions include streams, lakes, wetlands, and areas of native vegetation, high quality habitats, and natural depressions. By taking advantage of these natural features, the scale and complexity of BMP's can be reduced. The choice of BMP;s should be done on a watershed scale, where the assessments identify sensitive areas as describe above and BMP's selected to supplement land use measures. The approach for BMP's includes

a) Breaking up impervious surfaces and drain to open areas,

b) Apply BMP's near the source of runoff and try to emulate the natural hydrologic processes,

c) Identify impervious surfaces that has the potential to degrade water quality and evaluate the need for treatment,

d) Satisfy infiltration and groundwater recharge near the source impervious surfaces to emulate the natural hydrologic processes,

e) Satisfy the hydrologic control measures.

Regional Stormwater Management. In some instances the watershed planning studies can be used to develop regional stormwater management projects that help achieve the goals of the program. Riparian corridor management is an effective BMP for controlling flooding on a regional scale. Regional facilities are not recommended for infiltration and groundwater recharge objectives. These methods are best utilized as smaller dispersed units spread through out the development (PHBMP 2000).

8.3 Melbourne Urban Stormwater Management Strategies

The Melbourne Water Company, Victoria, in cooperation with the Environmental Protection Authority (EPA) and local governments formed the Stormwater Committee and developed the Best Practice Environmental Management Guidelines for urban stormwater to protect environmental values and beneficial uses of receiving waters. These guidelines provide information on performance objectives, a range of potential BMP's, BMP selection, public awareness, and management plans. Although no real BMP's are provided to address hydromodification, the Committee recognizes that urbanization changes both the quantity and quality of runoff, causing channel degradation, reduced groundwater inflows to streams, increases in urban slobber during summer, and channel erosion.

One of the strategies implemented is the formation of Catchment Management Authorities (CMA), which is equivalent to a watershed management agency. The CMA combines the role of previous agencies, such as the Land Protection Board, River Management Authority, Sustainable Redevelopment Committees, and water quality groups. The goal of the CMA is to ensure sustainable use of natural resources, protection of land and water resources, and conservation of natural and cultural heritage.

The foundation of their environmental protection program is *State Environmental Protection Policies* that stipulate environmental quality objectives and identify beneficial uses of *Waters of Victoria*. Their program consists of an integrated approach towards managing urban runoff peak flow and volumes, water quality and habitats necessary to support a healthy aquatic community. Flood protection and public safety remain a fundamental aspect of planning and design, but at the same time, BMP's designed for water quality and habitat purposes can benefit flood management (e.g., maintaining natural floodplain functions).

Three principles form the framework to achieve their management objectives:

- First, *AVOID* stormwater impacts and preserve existing natural channels, wetlands and riparian vegetation through source controls. These measures can include such things as land use planning, education, regulation and practices to limit changes in quantity and quality before it enters the storm drain system.
- Second, *MINIMIZE* impacts to natural waterways by using structural controls to reduce or delay runoff, intercept or remove pollutants after entering the storm drain system.
- As a last resort, *MANAGE* the receiving water body itself by using bed and bank stability techniques, treatment measures, and clean-up programs.

Strategic land use planning in a water sensitive manner is proposed by minimizing the extent of impervious surfaces and mitigating changes in the natural hydrograph through on-site reuse and storage. Integrating flow paths and storage features into the landscape and development is a key technique in water sensitive urban design and maintaining the natural hydrograph. Stormwater is treated as a *resource* rather than a *burden*. The size and costs of the traditional storm drainage system can be reduced. Establishing a multi-purpose corridor integrating stormwater management with habitat protection and recreation is an important design element. Benefits of this approach include protection of sensitive habitats and wildlife, filtration of stormwater through vegetation, provides a public amenity and recreational opportunities (e.g., trails, parks) and flood protection by maintaining natural floodplain functions.

Land use planning begins by strategic *Site Planning* that includes a site analysis, land capability assessment, and finally layout of the development. The purpose of the site analysis is to identify the natural features of the landscape that need to be considered during planning and design. Natural features include such things as topography, drainage patterns, soils, geology, sensitive areas and natural wetlands, riparian corridors, vegetation and wildlife corridors. Developers are required to demonstrate that the proposed development will not affect downstream resources and any proposed control measures will sufficiently mitigate potential stormwater impacts. A land capability assessment determines the scale and arrangement of development that protects the resources identified through the site analysis. Once the site analysis and land capability assessment are complete the areas of developable land can be identified. Land use plans can then be developed that are consistent with the principles of environmental protection and water sensitive design. Land use plans identify how and where development can occur within the site to produce the least impact on the ecosystem.

Source controls are typical of water quality controls used in the Santa Clara Valley Urban Runoff Pollution Prevention Program and include such things as materials management, construction site BMP’s, education programs, maintenance activities, and monitoring. Structural controls are also typical and consist of screening type devises, settling basins, infiltration, swales and wetland type basins.

Of most interest are their *flow management* alternatives. These include filter strips, swales, distributed sub-basin storages, hybrid channels, and detention and infiltration basins. The most unique alternatives include minimizing directly connected impervious areas, on-site reuse of stormwater, small-distributed storage throughout development, and multipurpose recreation-storage facilities.

8.4 Santa Margarita Watershed SAMP

As describe above, Stein and Ambrose (2001) investigated cumulative impacts of urbanization on riparian ecosystems for the Santa Margarita Watershed, near Temecula, California. They describe the use of the Army Corps of Engineers Special Area Management Plan (SAMP) for Orange County, California that includes a discussion of management strategies. Their proposed strategies include the following:

a) Development will be concentrated in areas with naturally impervious soils,

b) Avoid areas that disrupt key sediment sources and maintain the natural episodic nature of sediment loads, as well as aggradation/degradation processes,

c) Avoid areas with high erodibility,

d) Note timing of peak flows of tributaries and main stem of the river and avoid development that concentrates peak flows in downstream reaches, maintain pre-development time-of-concentration,

e) Restrict or eliminate development on floodplains. Use floodplains for flood control; riparian habitat, recreation and water quality.

f) Avoid development in sensitive habitat areas and maintain connectivity between habitats, maintain buffer zones between development and riparian corridors.

g) Maintain the natural hydrologic processes as much as possible, primarily maintaining infiltration of rainfall,

h) Reduce the percentage of impervious surfaces and the connectivity between impervious surfaces, eliminate connecting roof rain gutters to streets, reduce the degree of storm drain connectivity to the extent possible.

8.5 Integrated solution strategies

The above example management approaches are essentially integrated strategies in that they implement a series of progressive control measures: land use planning, distributed on-site control measures, followed by regional solution and stream restoration.

The progressive integrated strategy can be summarized as follows:

a) Preserve the natural hydrologic conditions and protect sensitive hydrologic features, sediment source and sensitive habitats. Avoid, to the extent possible, the need to mitigate for hydromodification.

b) Minimize the effects of development through conscientious design (e.g., reduce connected impervious surfaces) and through the implementation of environmentally sensitive on-site distributed BMP's (e.g., wetlands, swales, infiltration gardens, etc.)

c) Manage the stream corridor itself by implementing in-stream controls, such as grade controls, biotechnical bank stabilization controls, and restoration. Provide allowances for the modified stream flow characteristics and enhance the beneficial uses of streams.

d) In some cases, a regional stormwater management system may be cost effective. These strategies could include regional floodplain management, secondary collection and drainage systems, and large-scale detention and infiltration basins.

8.6 On-site solutions

This section briefly summarizes potential on-site solutions that could be incorporated into the HMP and regional solutions. The main theme of these alternatives is to maintain the natural functions of the hydrologic and geomorphic processes as much as possible, minimize the magnitude of change caused by development, and then integrate stormwater control measures into the development to mitigate expected impacts.

a) Preserve the natural proportion of rainfall infiltration and surface runoff to create a hydrologically functional landscape within development that mimics the natural hydrologic regime to the extent practical.

b) Protect sensitive hydrologic features, sediment source and sensitive habitats. Avoid, to the extent possible, the need to mitigate for hydromodification. Provide setbacks and buffers between development and sensitive areas.

c) Preserve areas of naturally high infiltration to maintain, to the extent practical, stable baseflows and groundwater recharge. Which in turn can reduce flood flows, reduced pollutant loads, and reduced costs for conveyance and storage.

d) Reduce and disconnect impervious surfaces, such as roof drains, gutters, parking lots and streets. Allow surface runoff from impervious surfaces to drain to pervious areas, natural and artificial hydrologic features, such as swales and wetlands.

e) Cluster development in the least sensitive areas, such as low infiltration areas, low sediment supply zones, and away from natural hydrologic features such as natural swales, wetlands, and riparian corridors.

e) Minimize the amount of grading and topographic changes. Use sediment control measures, such as settling basin and traps, hydroseeding, mulching, terracing, etc.

f) Integrate water quality and flow controls into the landscape. BMP’s can include filter strips, swales, constructed wetlands, dry wells, infiltration trenches, and permeable pavement.

g) Develop integrated flood control, water quality, hydromodification, and habitat features in multi-purpose facilities.

h) Incorporate larger scale detention and infiltration basins when necessary and into public open spaces and parks. Incorporate multi-purpose facilities, such as parks and detention basins where practical.

i) The most unique alternatives include on-site reuse of stormwater, small-distributed storage throughout development, hybrid channels, bioretention (e.g., rain gardens), multipurpose recreation-storage facilities, and vegetated roof covers.

j) Consider stormwater as a *resource* rather than a *burden*.

8.7 In-stream solutions

This section briefly summarizes potential in-stream solutions that could be incorporated into the HMP and regional solutions. The main theme of these alternatives is to protect the natural functions of the riparian corridors, and if necessary, modify stream channels so that they convey the new urban stream flow hydrology.

a) Manage and protect natural riparian corridors for flood control on a regional scale. Restrict or eliminate development on floodplains. Use floodplains for flood storage; riparian habitat, recreation and water quality.

b) Implement bed and bank stability techniques, treatment measures, and clean-up programs. Common biotechnical erosion control measures include pole cuttings, brush mattresses, fascines, deflectors, crib walls, in-stream woody material, rock grade control structures, root wads, etc.

c) Provide for the new hydrologic regime by modifying the stream channel so that the channel can accept the new flows without erosion and bank failures, and damage to habitat. Stream channels respond and can be modified in several different ways: widening, deepening, changing slope, roughening channel surface, and changing sinuosity.

d) Create hybrid channels that include flood control, hydromodification and water quality objectives that support habitat for riparian communities.

e) Maintain physical and hydrologic connectivity between stream channels and floodplains, and between upstream habitat patches and downstream habitat patches.

f) Maintain a diversity of habitats, plant communities and physical structure within channels and floodplains, and between riparian and upland habitats.

g) Maintain flow energy dissipation along the stream channel by installing, or leaving in place, features that add roughness. If the stream can't eat the energy, the energy will eat the stream.

9 Available local data

SCVWD Fisheries and Aquatic Habitat Collaborative Effort

The Fisheries and Aquatic Habitat Collaborative Effort (FAHCE), is a multi-agency endeavor convened by the SCVWD and the Department of Fish and Game to develop an interim fisheries and aquatic habitat management plan. FAHCE participants include the SCVWD, the Department of Fish and Game, the U.S. Fish and Wildlife Service, the National Marine Fisheries Service, the Natural Heritage Institute, the Guadalupe-Coyote Resource Conservation District and the City of San Jose. The goals for FAHCE include: 1) identify the contribution of SCVWD facilities and operations to existing fishery habitat conditions within the context of the variety of factors impacting salmon and steelhead populations; and 2) identify reasonable flow and non-flow measures that will improve habitat conditions for such fish populations within the context of competing water and land use demands. The study objectives were to identify and evaluate alternative management actions based in part on the above studies and on the following:

- Improve habitat conditions to maintain fish populations in good condition;
- Protect, maintain, and improve habitat conditions for species listed under the State and Federal Endangered Species Acts or identified as California Species of Special Concern; and
- Improve the availability and suitability of stream corridor and channel habitat for a diversity of species of fish and wildlife.

The FAHCE project quantified the following factors: 1) diversity, abundance, and condition of existing salmon and steelhead resources; 2) habitat quantity and quality that may limit these target fish populations; 3) types and locations of non-flow measures that could change existing conditions; and 4) alternative flow regimes that could change the conditions that limit the target fish populations.

The FAHCE study area included Coyote Creek (below reservoir), Upper Penitencia Creek, Stevens Creek below reservoir, and Guadalupe River and its major tributaries (Los Gatos, Guadalupe Creek, Alamitos, and Arroyo Calero Creeks). Analysis of the results from the study have not been released due to ongoing litigation, with the exception of the salmonid habitat survey database, which was used in the Potentially Sediment Impaired Creek Report to prioritize reaches that may be impaired by sediment. The location and description of potential anadromous fish barriers and the results from temperature modeling analyses were made available to Program staff in 2002. Program staff understands that additional information is forthcoming and will be valuable in conducting a limiting factors analysis in Stevens, Coyote and Guadalupe River watersheds.

SCVURPPP Coyote Watershed Pilot Assessment

The SCVURPPP's Pilot Watershed Assessment of Coyote Creek is utilizing mostly existing data, but some new data, to characterize and assess the physical and biological condition of the watershed. The assessment includes: 1) the development of a stream classification to characterize stream functions and geomorphic processes, 2) evaluation of stream functions (e.g., maintenance of aquatic habitat and hydrological regime and channel dynamics) and how future and potential management actions will affect these functions, 3) identification of information gaps and research opportunities, and 4) prioritization of management actions that will improve the physical and biological functions in the watershed. The assessment focused on the mainstem Coyote (downstream of reservoir) and Upper Penitencia Creek. Evaluating sediment impacts to fish habitat and aquatic health of streams is one component of the assessment. The Pilot Coyote Watershed Assessment Report is scheduled for release in September 2002.

Santa Clara Basin Watershed Management Initiative (WMI) Pilot Watershed Assessment

The WMI is completing pilot watershed assessments of Upper Penitencia Creek, Guadalupe River and San Francisquito Creek. The assessment framework was developed to provide a procedure for using environmental indicators, based on existing data to conduct a watershed assessment. Threshold values were identified for quantifiable parameters and were used when possible to evaluate the ability of a waterbody to support a primary use/interest. The stakeholder group identified five primary beneficial uses/interests as the basis of the assessment. Logic diagrams were developed to systematically determine the level of support of a primary use/interest through a "weight of evidence" approach. Creeks within each of the watersheds were classified into stream segments and each segment was assessed to determine support, non-support or unknown due to insufficient data.

The results of the assessment included an identification of limiting factors, which focused on physical, chemical and biological conditions in the stream and the riparian corridor that caused non support or partial support of primary uses. The limiting factors consist of the indicators that did not meet the threshold criteria specified in the assessment framework. It is the Program staff's understanding that specific limiting factors within each stream segment and the suspected cause, when identifiable, will be described in the WMI Watershed Assessment Report (WAR), scheduled to be released in Fall 2002. The WMI limiting factors analysis will be useful to the SCVURPPP watershed assessment approach identified in this Workplan.

Surface Water Ambient Monitoring Program/Regional Monitoring and Assessment Strategy (SWAMP/RMAS)

The goal of the SWAMP/RMAS program is to monitor and assess all waterbodies of the San Francisco Bay Region in order to identify reference sites and waterbodies or sites that are impaired, based on data and information that provide a weight-of-evidence assessment of water quality. Objectives of the program include: (1) assessing the physical, chemical, and biological condition of waterbodies in the region in order to determine if waterbodies are impaired and beneficial uses are being protected; (2)

measuring environmental indicators of stressors (e.g., pollutants or other water quality parameters), laboratory exposure/effects measurements (e.g., toxicity tests), and ecological response (e.g., benthic macroinvertebrate community analyses) from the same location and/or season; (3) generating data and information during different seasonal conditions; (4) generating data and information that is somewhat evenly distributed across a waterbody to provide a screening level of assessment; (5) determining if impacts are associated with specific stressors or land uses; and (6) evaluating monitoring tools in the watershed in order to develop a program that uses the best environmental indicators to achieve the purposes of the program.

Six San Francisco Bay watersheds were monitored in FY 00-01 (none were located in Santa Clara Basin). An additional five watersheds were monitored in FY 01-02, including two in the Santa Clara Basin (Stevens and Permanente Creeks). Some of the data collected in Stevens Creek (e.g., bioassessment, physical habitat assessment, suspended sediment concentrations) will be useful to assess the health of the aquatic biota and condition of the physical habitat for salmonid fish.

SCVURPPP Multiyear Monitoring Plan

A Multi-Year Receiving Waters Monitoring Plan was submitted to the Regional Board as part of the SCVURPPP FY 02-03 Draft Workplan in fulfillment of SCVURPPP NPDES Permit Provision C.7 and specifically Provision 7b of SCVURPPP's NPDES Permit Order adopted February 21, 2001 by the Regional Board. The Plan identifies monitoring activities in Santa Clara Basin Watersheds over an eight-year period and contains the following information: watershed location (prioritized based on WMI and SCVURPPP assessment priorities), data type (chemical, biological, physical, and trash), number and frequency of sampling events, FYs (8 years starting with FY02-03 through FY09-10), rationale, and lead agency. The information on data type utilizes a tiered monitoring approach discussed by the RWQCB staff in its RMAS memo (February 8, 2001 Draft Monitoring Design in Regional Board-lead Pilot Watersheds, Spring 2001) that includes the following monitoring categories: screening level, detailed investigation, and status and trends. Implementation of detailed investigations will be determined from the results of screening level monitoring, as well as from the data gaps identified in the watershed assessments and other studies described above.

The Multi-Year Monitoring Plan identified special sediment-related studies to be implemented in Stevens, Coyote and Upper Penitencia Creek Watersheds in coordination with the focused studies developed in accordance with this Workplan. The Plan addresses data gaps, such as aquatic habitat survey data in Saratoga and Permanente Creek, which were identified in the Potentially Sediment Impaired Creek Report. The Plan also includes monitoring activities that will be identified in the Hydromodification Management Plan (HMP), which is being developed to satisfy Provision C.3 of the SCVURPPP NPDES permit. Monitoring efforts for the HMP will include identifying baseline conditions of stream channels, as well as evaluating the effectiveness of control measures that are implemented to reduce the hydrologic effects of land development on stream stability and geomorphology. These activities will be clearly identified each year as part of SCVURPPP's Annual Monitoring Plan.

SCVWD Flood Protection Projects

The SCVWD is currently involved in several projects to increase channel capacities to allow for a 100-year flow event. These projects typically require baseline data collection to identify existing channel and flow conditions. These data include geological characterization, sediment loading and transport capacities, flow frequency and flood hydrographs, and surface water profiles, and floodplain access. This information can be used to assess potential impacts of sediment to aquatic habitat. The District is currently involved in several flood protection projects in the streams that were identified in SCVURPPP sediment report as high and medium priority for future watershed assessments. These watersheds include Coyote Creek mainstem, Upper Penitencia Creek and Guadalupe River. The Guadalupe River flood control projects are near the construction phase and provide existing data useful for a watershed analysis. The other projects are still in the planning stages and have less data available; however, they may provide opportunities to collect valuable data using available resources.

SCVWD Stream Maintenance Program (SMP)

The SMP describes routine stream and channel maintenance on facilities of the Santa Clara Valley Water District (District) throughout Santa Clara County. These activities include sediment removal projects, vegetation management and bank protection. Location and volume of sediment removal in streams within District jurisdiction were used in the SCVURPPP sediment report as a factor to prioritize stream reaches that may be impaired by sediment. Additional analyses on sediment size and accumulation rate at these sites can be useful in future sediment analyses. In addition, bank protection projects provide information indicating where instream sources of sediment may occur.

Alum Rock Park Riparian Management Plan

Alum Rock Park Riparian Management Plan (published report and data; City of San Jose) field measurements within Alum Rock Park, City of San Jose channel cross sections, longitudinal profiles, bank stability evaluation.

SCVWD GIS System

The following GIS layers are a subset of the total maintained by the SCVWD. These are thought to be the most relevant to the development of the HMP.

Description of GIS Layers	
Partial Index to USGS Quad Sheets	Historical Flooding - 1978 to 1997
Coyote Creek Riparian Station Creek Alignment Vegetation	Historical Flooding - Points
City of San Jose Creek Vegetation Buffer	Flooding in San Mateo County
Santa Clara County Creek Vegetation Buffer	Artesian Wells in Santa Clara County since 1994
Barriers to Fish Passage	Depth to First Groundwater
Saratoga Creek Bank Characteristics	Elevation of Groundwater
Saratoga Creek Habitat Characteristics	General Geology of the Santa Clara Basin
Saratoga Creek Pollution Impacts	Groundwater - Sub-Basins

Saratoga Creek Outfalls	Groundwater - Basins
Saratoga Creek Survey Points	Groundwater - Flow Direction
California Aqueduct	Groundwater - Hydrographic Units
SCVWD Canals	Groundwater Recharge Facilities
EIR Creeks 500 ft Buffer	Portrayal of Land Subsidence - 1934 to 1967
SCVWD 500 Scale Creeks	Storm Drain network in Santa Clara County
Label Points for SCVWD 500 Scale Creeks	USGS 7.5 Minute Quad Grid for Santa Clara County
EIR Creeks Land-use Buffer	Map Index for 1939 Aerial Photography
Santa Clara County Dams	Important Farmland 2000 (Farmland Mapping and Monitoring Program)
EIR Routine Maintenance Creeks	SCVWD Land Use - 1999
Barclay Mapworks Hydrology Layer	Llagas Watershed Land Use
Lakes and Reservoirs not found in Reservoirs shapefile	Land Use (ABAG)
Pajaro River Watershed Creeks	Open Space Locations (GreenInfo Network)
Santa Clara County Reservoirs	City of San Jose General Plan -2020
San Benito County Creeks (from TIGER 2000)	Important Farmland 1998
San Benito County Waterbodies (from TIGER 2000)	Open Space Areas (GreenInfo Network)
San Francisquito Watershed Creeks	Hydrographic Unit Delineations
2001 Stream Maintenance Program Canals with Route Measures	SCVWD Rainfall Stations
2001 Stream Maintenance Program Sediment Removal Work Areas	Average Rainfall for Santa Clara County
2001 Stream Maintenance Program Work Areas	Santa Clara Basin Geology
Historic Stream Monitoring Stations	Serpentine Soils in Santa Clara County
Stream Monitoring Stations	Soil Infiltration Rates in Santa Clara County
Generalized extents of Tidal Influence	Soil Types in Santa Clara County
Historic and current USGS streamflow monitoring stations	Groundwater Recharge Basins in Santa Clara County
USGS 100K scale creeks	Santa Clara Valley Floor
Location and Height of Bank Erosion - Guadalupe Creek Mitigation Project	Santa Clara County General Plan
Channel Segment Classification - Guadalupe Creek Mitigation Project	Reservoir Watersheds
Geomorphic Surfaces - Guadalupe Creek Mitigation Project	Santa Clara Basin WMI Watershed Delineation
Instream Woody Material - Guadalupe Creek Mitigation Project	SCVWD Minor Watersheds
Location and Depth of Undercut Banks - Guadalupe Creek Mitigation Project	SCVWD Major Watersheds
Soil Classification - Guadalupe Creek Mitigation Project	
Understory and Midstory Vegetation Classification - Guadalupe Creek Mitigation Project	

10 Glossary of Terms

To be completed at a later date.

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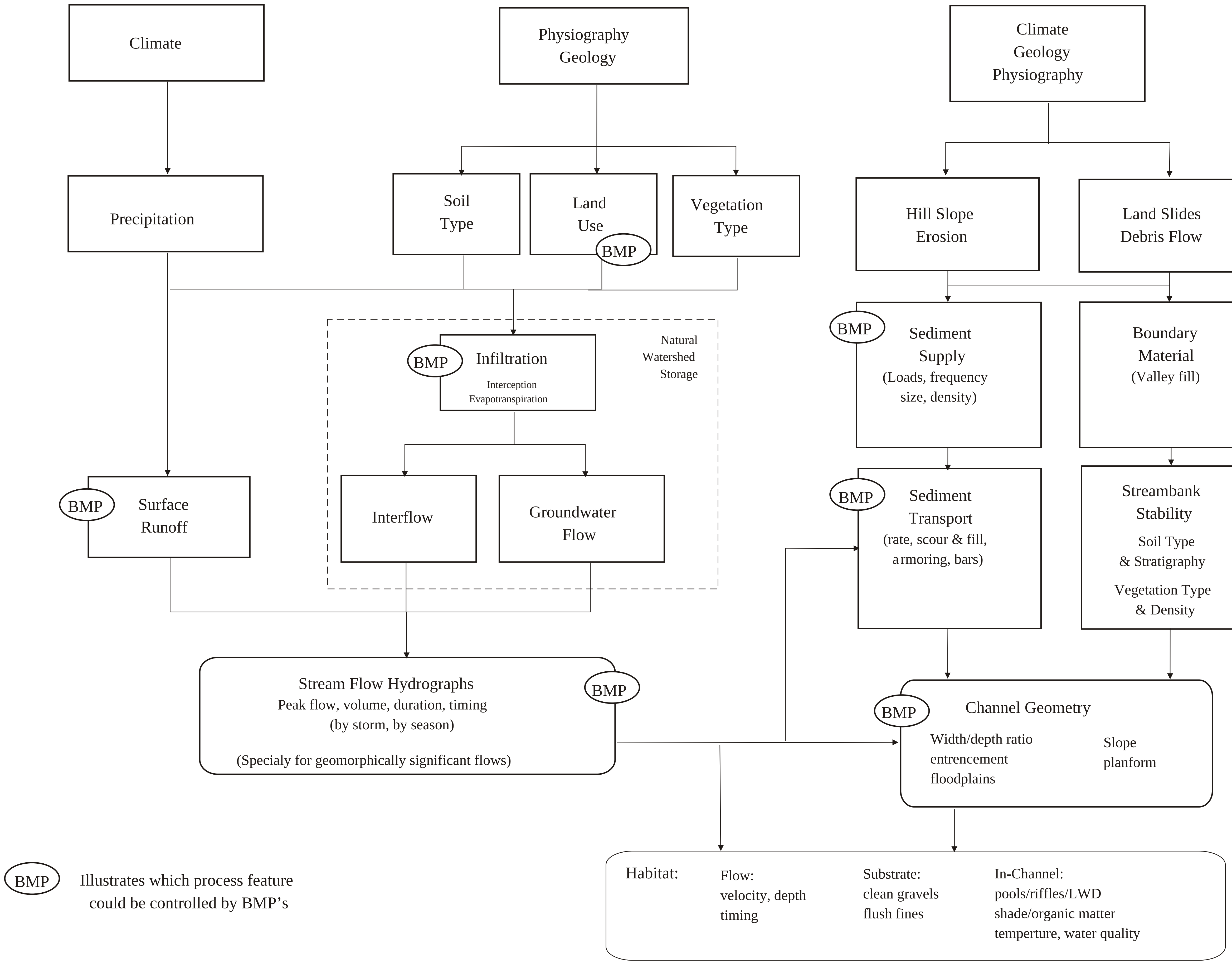


Figure 1. CONCEPTUAL MODEL ILLUSTRATING THE LINKAGES BETWEEN THE HYDROLOGIC AND GEOMORPHIC PROCESSES TO BE ADDRESSED IN HYDROMODIFICATION

Source: GeoSyntec Consultants, Walnut Creek

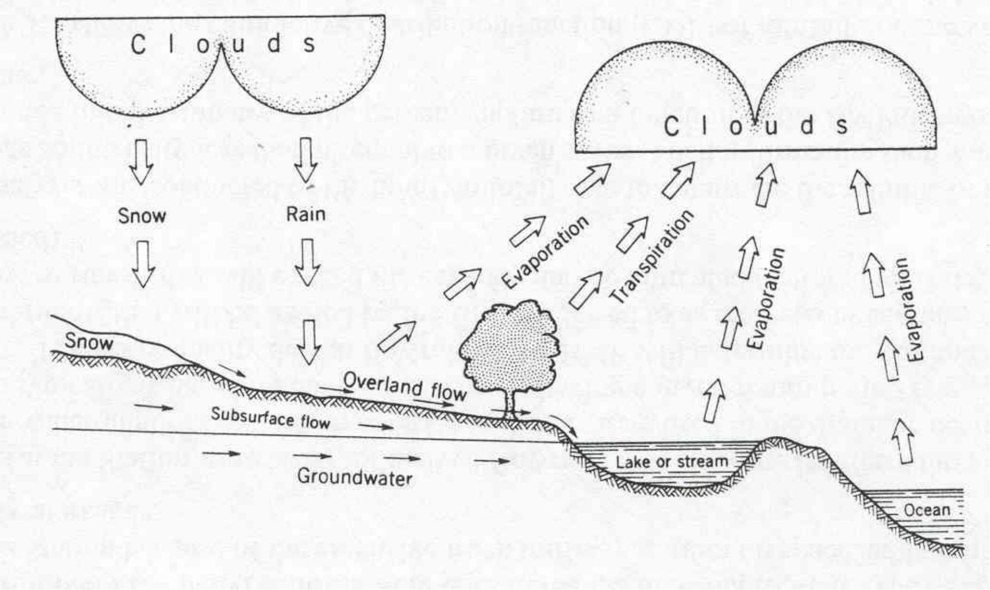


Figure 2. Schematic diagram of the hydrologic cycle

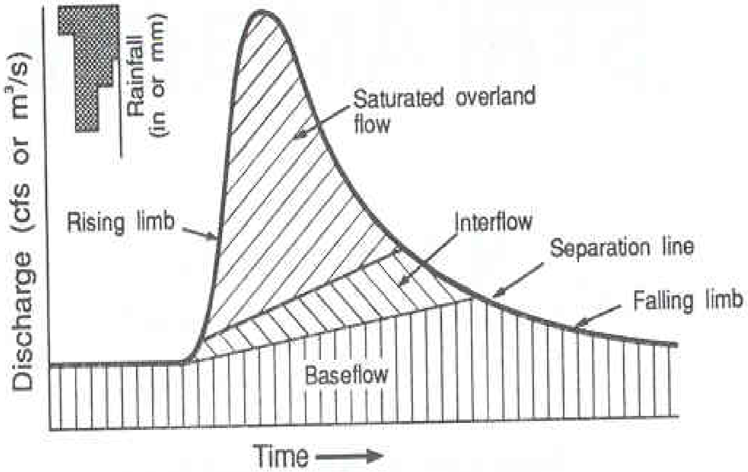


Figure 3. A hydrograph with separation of sources of stream flow

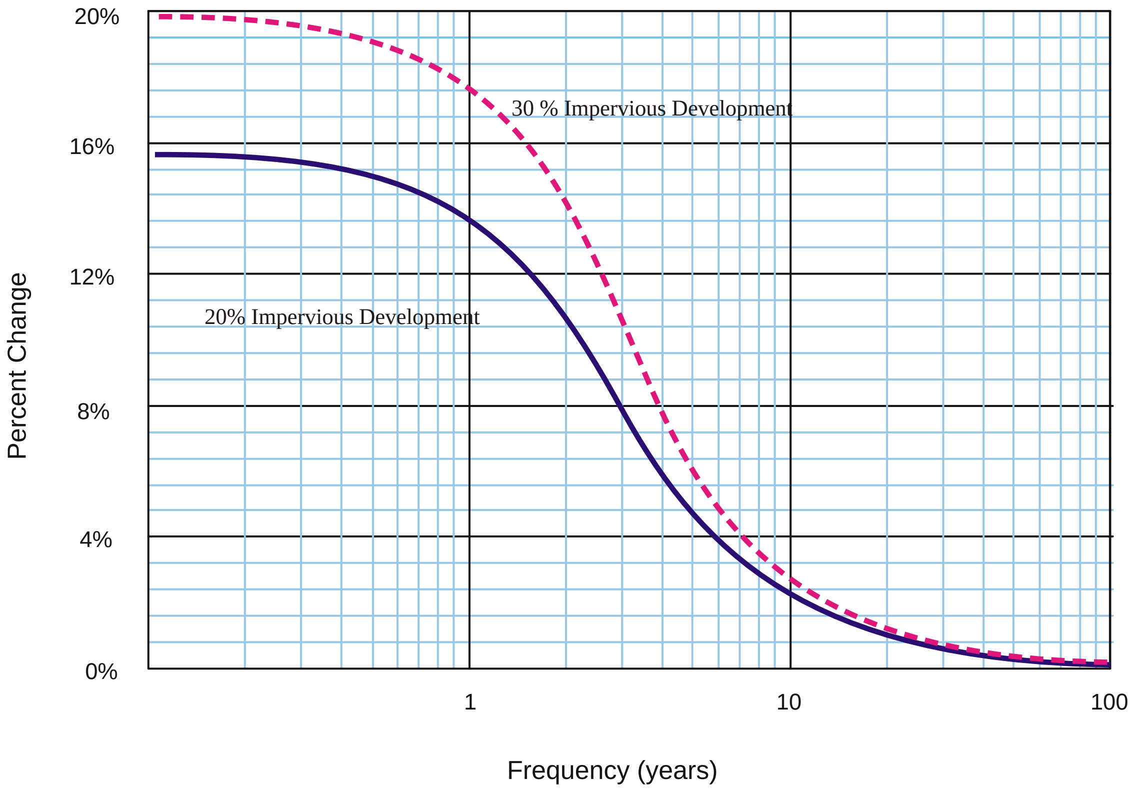


Figure 4. Generalized Results Reported by Hollis (1975) on the Percent Change in Runoff

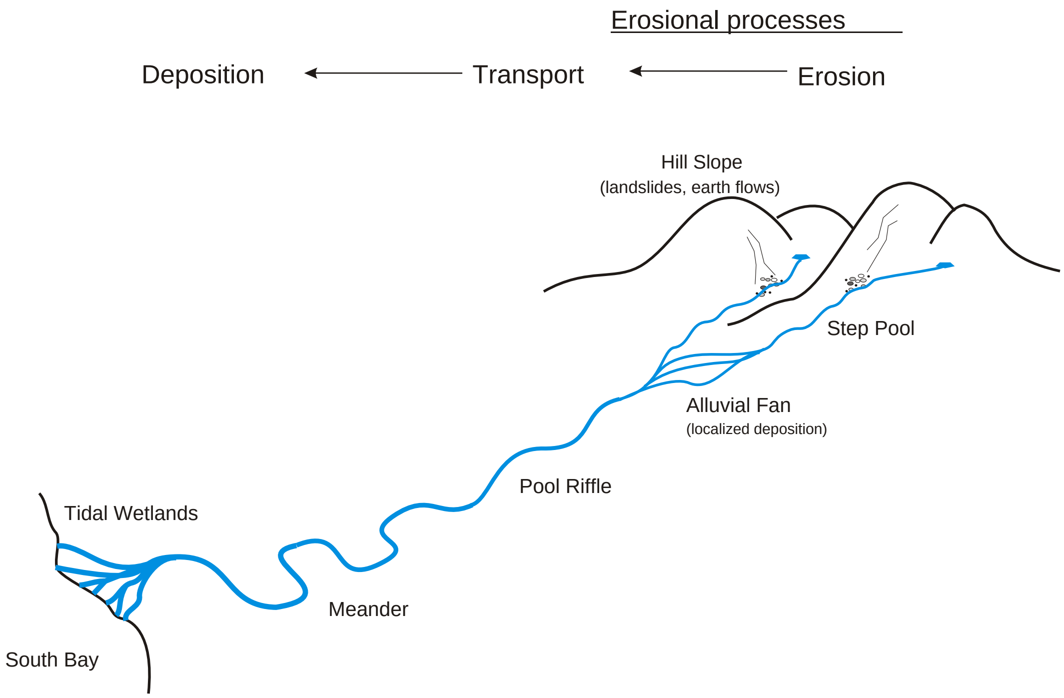


Figure 5. Illustration of Fluvial Geomorphic Processes and Sediment Transport

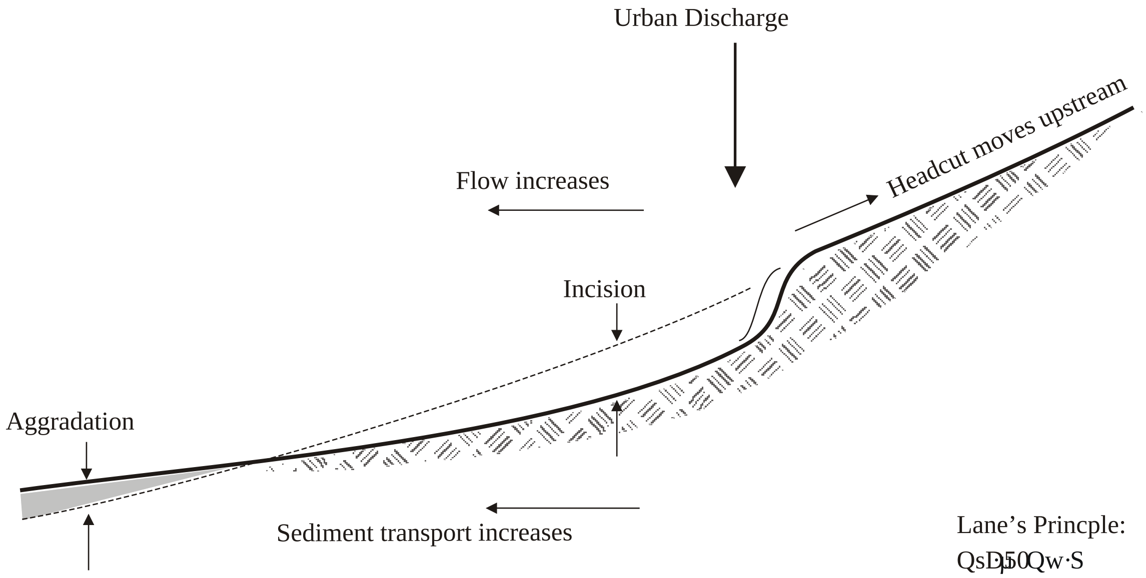


Figure 6. Example Changes in Longitudinal Profile (Slope) as a Result of Urban Discharges

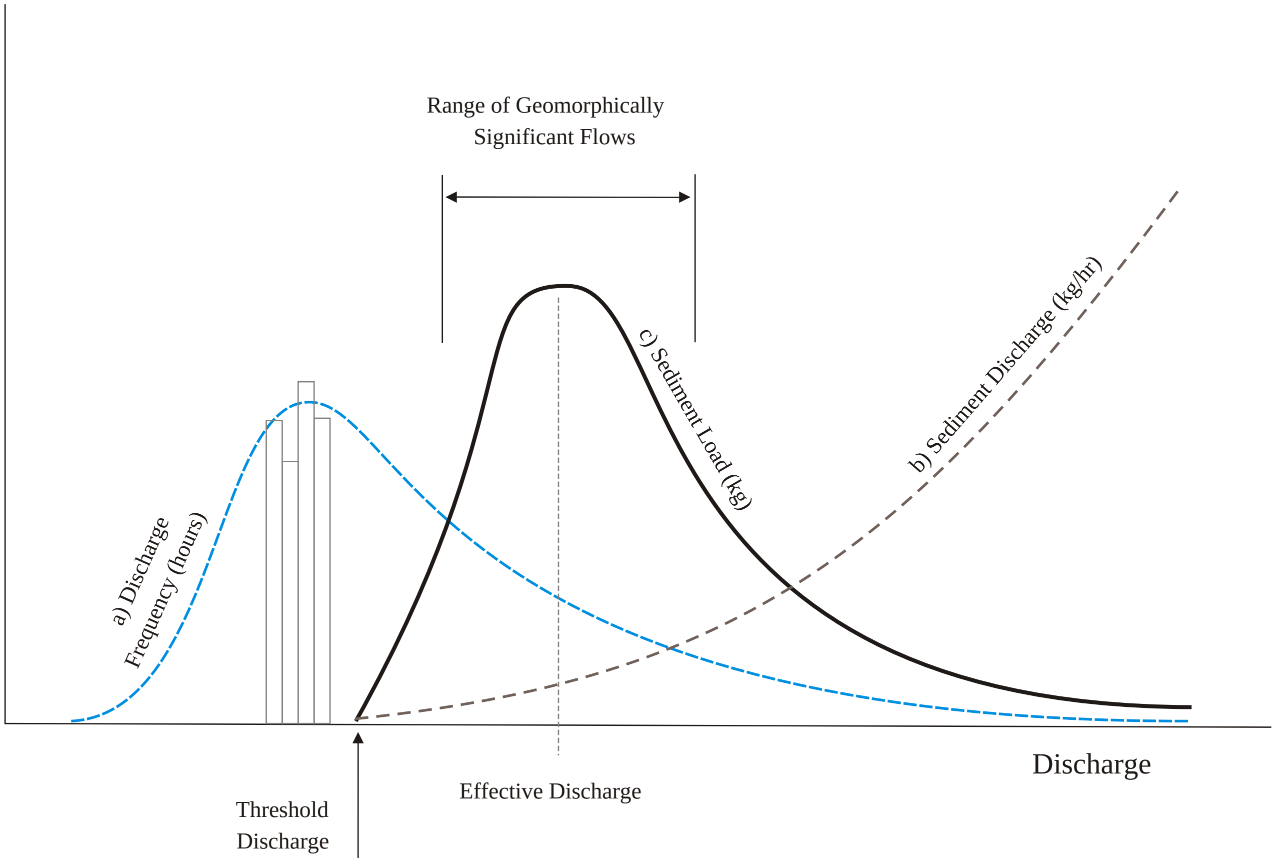
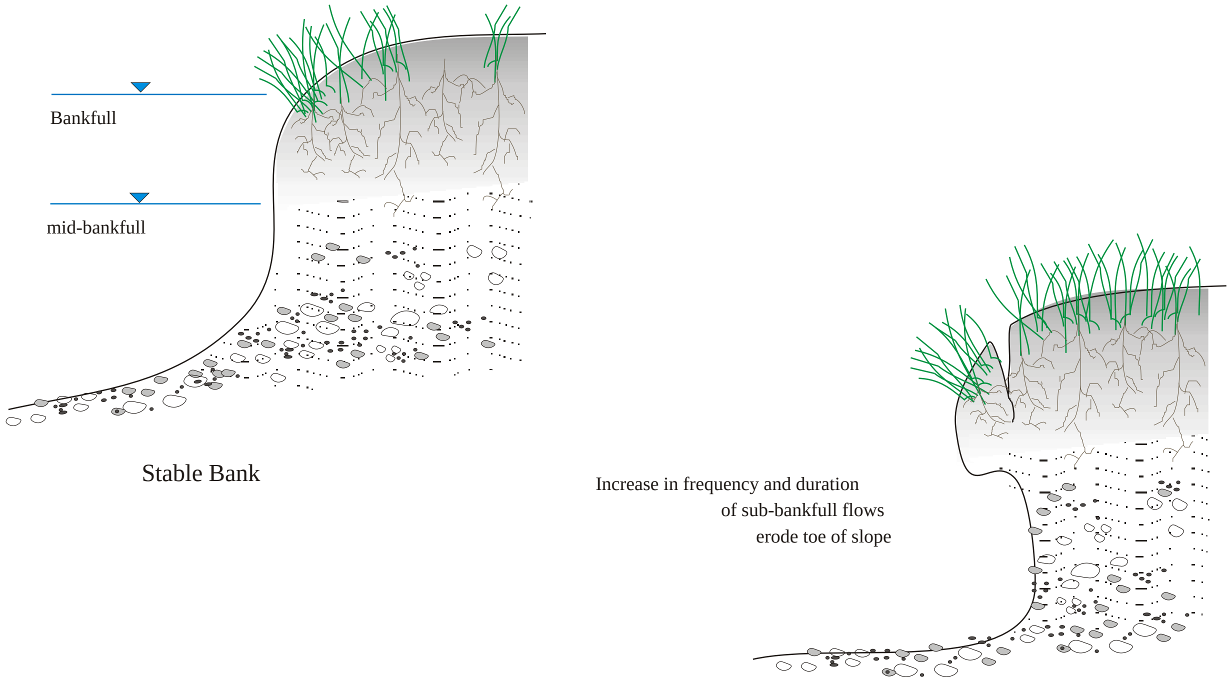


Figure 7. Leopold's (1964) Effective Work Curve Model



Stable Bank

Increase in frequency and duration
of sub-bankfull flows
erode toe of slope

Unstable Bank

Figure 8. Relationship of Channel Bank Erosion to Geomorphically Significant Flows

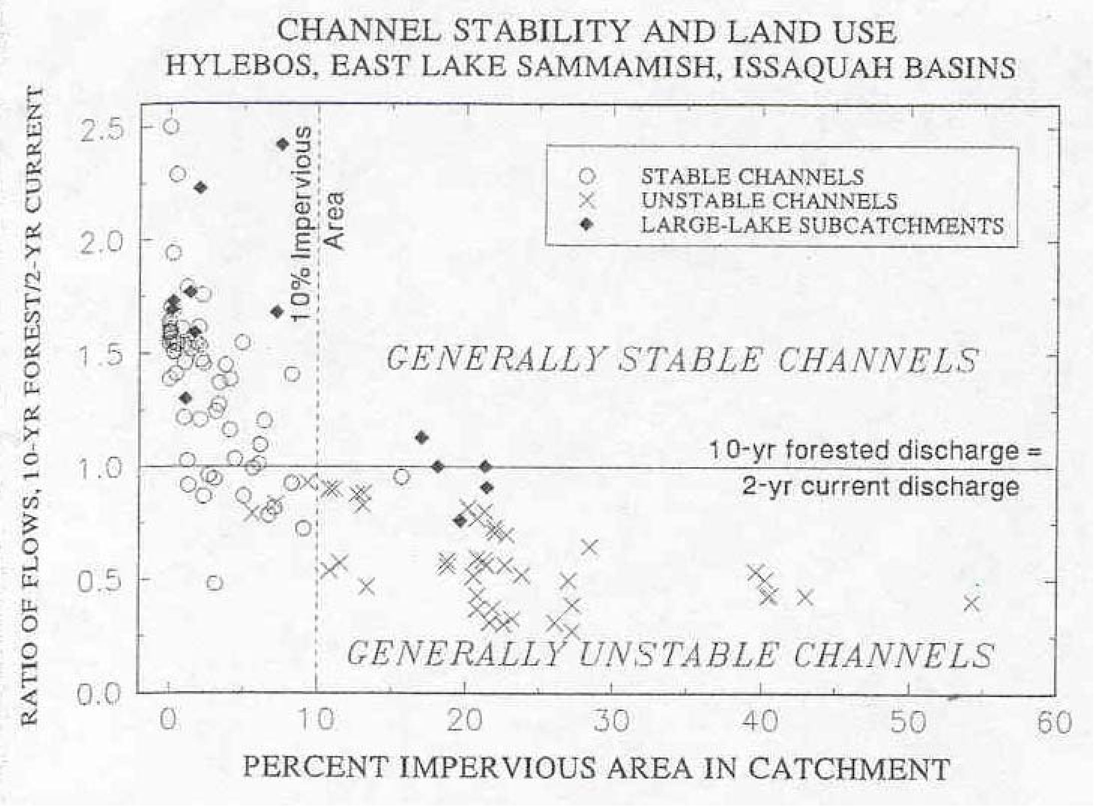


Figure 9. Example Results Reported by Booth and Jackson (1997)

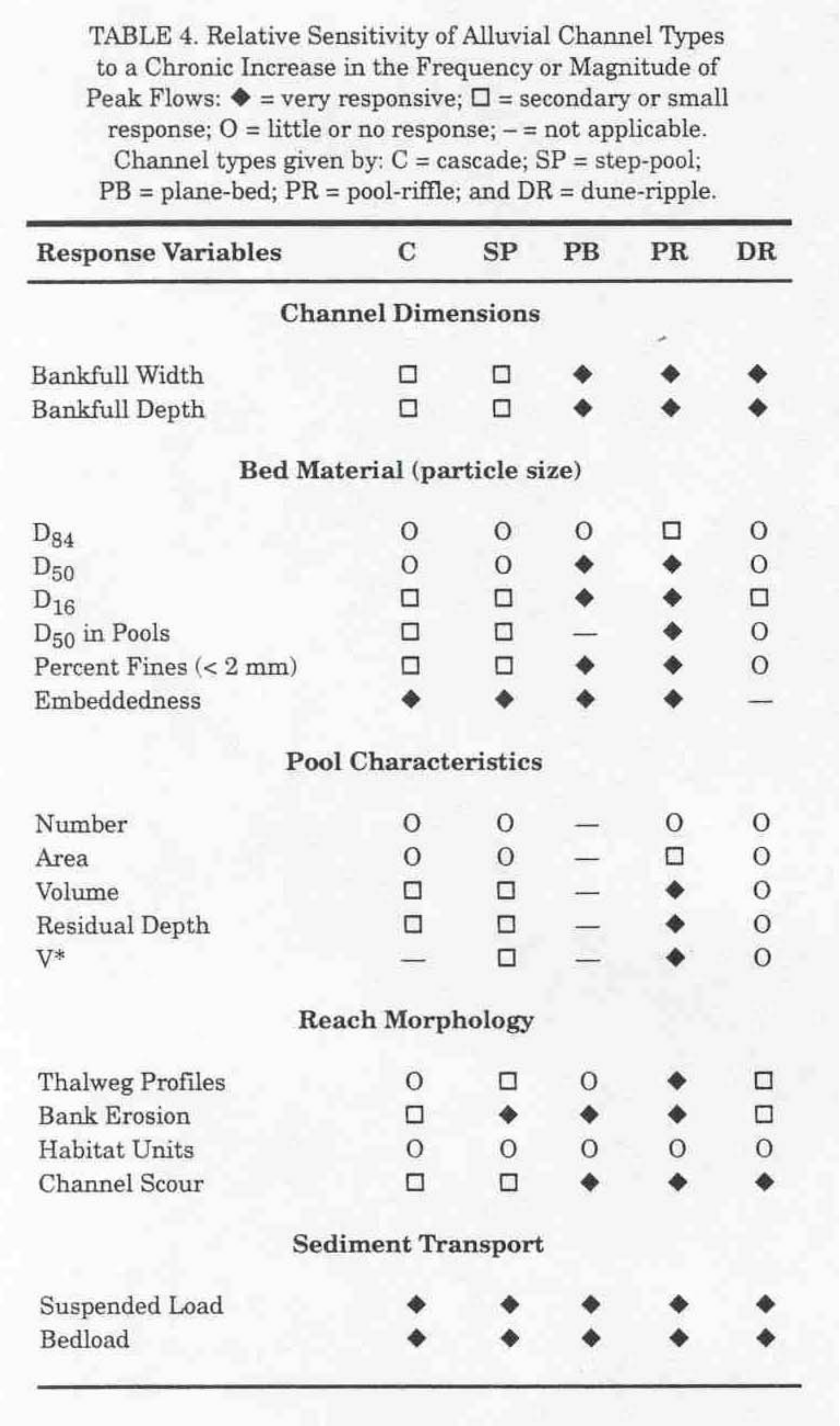


TABLE 4. Relative Sensitivity of Alluvial Channel Types to a Chronic Increase in the Frequency or Magnitude of Peak Flows: ◆ = very responsive; ☐ = secondary or small response; O = little or no response; – = not applicable. Channel types given by: C = cascade; SP = step-pool; PB = plane-bed; PR = pool-riffle; and DR = dune-ripple.

Response Variables	C	SP	PB	PR	DR
Channel Dimensions					
Bankfull Width	☐	☐	◆	◆	◆
Bankfull Depth	☐	☐	◆	◆	◆
Bed Material (particle size)					
D_{84}	O	O	O	☐	O
D_{50}	O	O	◆	◆	O
D_{16}	☐	☐	◆	◆	☐
D_{50} in Pools	☐	☐	—	◆	O
Percent Fines (< 2 mm)	☐	☐	◆	◆	O
Embeddedness	◆	◆	◆	◆	—
Pool Characteristics					
Number	O	O	—	O	O
Area	O	O	—	☐	O
Volume	☐	☐	—	◆	O
Residual Depth	☐	☐	—	◆	O
V*	—	☐	—	◆	O
Reach Morphology					
Thalweg Profiles	O	☐	O	◆	☐
Bank Erosion	☐	◆	◆	◆	☐
Habitat Units	O	O	O	O	O
Channel Scour	☐	☐	◆	◆	◆
Sediment Transport					
Suspended Load	◆	◆	◆	◆	◆
Bedload	◆	◆	◆	◆	◆

Figure 10. Example Results Using Diagnostic Assessment Method, Montgomery and MacDonald (2002)

Table 1. List of Articles Obtained and Reviewed for Inclusion in the Literature Review

ID No.	Author	Year	Title	Publication	Vol. No.	Effect of Urban.	Chan. Stability	Assess. Method	Thres holds	Mngt Strategy	Solu-tion	WQ Habitat	Local region	Semi-arid
1	Allen, Peter M. and Rebecca Narramore	1985	Bedrock Controls on Stream Channel Enlargement with Urbanization, North Central Texas	Water Resources Bulletin	21 (6)	X	X							
2	Andrews, E. D.	1984	Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado	Geological Society of America	95		X	X						X
3	Andrews, E. D.	1982	Bank Stability and Channel Width Adjustment, East Fork River, Wyoming	Water Resources Research	18 (4)		X	X						X
4	Ashworth, Phillip J. and Robert Ferguson	1989	Size-selective entrainment of bed load in gravel bed streams	Water Resources Research	25 (4)		X	X						
5	Barker, B.L., Nelson, R.D., Wignosta, M.S.	1991	Performance of Detention Ponds Designed According to Current Standards	Puget Sound Research 91. Puget Sound Water Quality Authority. Duxbury, Alyn C., Chair. University of Washington		X								
6	Bledsoe, Brain P.	1999	Specific stream power as an indicator of channel pattern, stability, and response to urbanization	Thesis		X	X	X						
7	Bledsoe, Brain P.	2001	Relationships of Stream Responses to Hydrologic Changes	Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation, Proceedings of an Engineering Foundation Conference, August 19-24, 2001, Snowmass Village, CO		X	X	X			X			
8	Bledsoe, Brian P. and Chester C. Watson	2000	Observed Thresholds of Stream Ecosystem Degradation in Urbanizing Areas: A Process-based Geomorphic Explanation.	Watershed management & operations management 2000: science and engineering technology for the new millennium. Flug, Marshall, Frevert, Donald K., Watkins, David W.		X		X	X					
9	Bledsoe, Brian P. and Chester C. Watson	2001	Effects of Urbanization on Channel Instability	Journal of the American Water Resources Association	37 (2)	X	X							
10	Bledsoe, Brian P. and Chester C. Watson	2001	Logistic Analysis of Channel Pattern Thresholds: Meandering, Braiding, and Incising	Geomorphology	38			X	X					
11	Booth, D.B. and Jackson C.R.	1997	Urbanization of Aquatic Systems: Degradation Thresholds, Stormwater Detection, and the Limits of Mitigation	Journal of the American Water Resources Association	33 (5)	X			X		X			
12	Booth, D.B., Montgomery, D.R., Bethel, J.	1996	Large Woody Debris in Urban Streams of the Pacific Northwest	Effects of Watershed Development and Management on Aquatic Ecosystems, Proceedings of an Engineering Foundation Conference, Snowbird, Utah, ASCE, Aug. 4-9, 1996		X								

Table 1. List of Articles Obtained and Reviewed for Inclusion in the Literature Review

13	Booth, Derek, B.	1990	Stream-channel incision following drainage-basin urbanization	Water Resources Bulletin	26	X	X	X	X		X			
14	Booth, Derek, B.	1991	Urbanization and the natural drainage system--imipacts, solutions, and prognoses.	Northwest Environmental Journal	7	X					X			
15	Booth, Derek, B.	1993	Rationale for a "Threshold of Concern" in Stormwater Release Rates	AWWA (?)	?				X					
16	Brown, K. B.		Housing Density and Urban Land Use as Indicators of Stream Quality	Watershed Protection Techniques http://www.stormwatercenter.net/Library/Practice_Articles.htm	2 (4)									
17	Buffington, John M and David R Montomery	1997	A Systematic Analysis of Eight Decades of Inciptient Motion Studies, with Special Reference to Gravel Bedded Rivers	Water Resources Research	33 (8)		X		X					
18	Cain, JR.	1997	Hydrologic and geomorphic changes to the San Joaquin River between Friant Dam and Gravely Ford and implications for restoration of Chinook salmon (Oncorhynchus tshawytscha).	MLA thesis, University of California, Berkeley, CA.								X	X	X
19	Carling, Paul	1988	The concept of dominant discharge applied to two gravel-bed streams in relation to channel stability thresholds	Earth Surface Processes and Landforms	13		X		X					
20	Carling, Paul	1984	Deposition of Fine and Coarse Sand in an Open-Work Gravel Bed	Canadian journal of fisheries and aquatic sciences	41		X							
21	CH2 M Hill	1998	Pennsylvania Handbook of Best Management Practices for Developing Areas	BOOK										
22	Coats, R.	1986	Cumulative watershed effects: a historical perspective	Proceedings of the California Watershed Management Conference										
23	Cobb, T.A.	1986	Analyzing Cumulative Effects in Watersheds: a Legal View	Proceedings of the California Watershed Management Conference										
24	Corish, Kathleen	1995		Clearing and grading strategies for urban watersheds										
25	Diplas, P.	2002	Integrated Decision Making for Watershed Management: Introduction.	Jour. of the American Water Resources Association	38 (2)			X		X				
26	Doppelt, B., Scurlock, C., Frissell, C., Karrk J.	1993		Entering the Watershed: A New Approach to Save America's River Ecosystems										

Table 1. List of Articles Obtained and Reviewed for Inclusion in the Literature Review

27	Doyle, Martin W., Jonathan M. Harbor, Cecil F. Rich, Anne Spacie	2000	Examining the Effects of Urbanization on Streams Using Indicators of Geomorphic Stability	Physical Geography	21 (2)	X	X							
28	Ellis, Brian, Brian Shutes and Michael Revitt	1995	Ecotoxicological approaches and criteria for the assessment of urban runoff impacts on receiving waters	Stormwater runoff and receiving systems: impact, monitoring, and assessment. Herricks, E.E. (ed).		X						X		
29	Environmental Protection Agency, Office of Water	1997	Urbanization and Streams: Studies of Hydrologic Impacts	EPA: 841-R-97-009		X	X							
30	Eva Butler & Associates	2002	East Franklin Drainage Corridor Alternative Design Project, Hydrology, Geomorphology, and Vegetation Planning	Report to Sacramento County Department of Public Works				X		X	X	X	X	X
31	Frissell, C.A., Liss, W.J., Warren, W.J.	1986	A hierarchical framework for stream classification: Viewing streams in a watershed context	Environmental Management	10			X						
32	Fullmer, D.G.	1994	Sustainability and Ecosystem Management: an analysis of the concept	Ecosystem Management Guidebook, Draft Region 5. USDA Forest Service, Pacific SW Region	2									
33	Gassman P., E. Osei, A. Saleh, and L. Hauck		Application of an Environmental and Economic Modeling System for Watershed Assessments.	Jour. of the American Water Resources Association	38 (2)			X		X				
34	Graf, W.L.	1975	The Impact of Suburbanization on Fluvial Geomorphology	Water Resources Research	11 (14)	X	X							
35	Grant, G.	1987	Assessing Effects of Peak Flow Increases on Stream Channels: a Rational Approach	Proceedings of the California Watershed Management Conference										
36	Hammer, Thomas R.	1972	Stream and channel enlargement due to urbanization	Water Resources Research	8	X	X							
37	Hartly, David, C. Rhett Jackson, and G. Lucchetti	2001	Stream Health After Urbanization by J.K. Finkenbine, J.W. Atwater and D.S. Mavinic	Journal of the American Water Resources Association	37 (3)	X								
38	Harvey, Michael M. and Chester C. Watson	1986	Fluvial Processes and Morphological Thresholds in Incised Channel Restoration	Water Resources Bulletin	22 (3)		X		X					
39	Hecht, Barry	1994	South of the Spotted Owl: Restoration Strategies for Episodic Channels and Riparian Corridors in Central California.											
40	Hollis, G.E.	1975	The Effect of Urbanization on Floods of Different Recurrence Intervals	Water Resources Research	11 (3)	X								
41	Horner, R. R.	1994		Fundamentals of urban runoff management: technical and institutional issues										
42	Horner, R.R., Booth, D.B., Azous, A.A., May, C.W.	1996	Watershed Determinants of Ecosystem Functioning	Effects of Watershed Development and Management on Aquatic Ecosystems Aug. 4-9, 1997				X						

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43	James, L.A.	1991	Incision and Morphologic Evolution of an Alluvial Channel Recovering from Hydraulic Mining Sediment	Geological Society of America Bulletin	103									
44	Jobson, Harvey E. and William P. Carey	1989	Interaction of Fine Sediment with Alluvial Streambeds.	Water Resources Research	25		X							
45	Juracek, Kyle E.	2000	Channel Stability Downstream from a Dam Assessed Using Aerial Photographs and Strea-Gage Information	Journal of the American Water Resources Association	36 (3)		X	X						
46	Karr, J.R.	1996	Rivers as Sentinals: Using the Biology of Rivers to guide Landscape Management.	River ecology and management : lessons from the Pacific coastal ecoregion. Naiman, R.J., Bilby, R.E. (ed). 1998.				X	X					
47	Klein, Richard, D.	1979	Urbanization and Stream Quality Impairment	Water Resources Bulletin	15	X						X		
48	Knighton, David.	1998	Fluvial Forms & Processes, A New Perspective	BOOK			X							
49	Komar, Paul D.	1987	Selective grain entrainment by a current from a bed of mixed sizes: a reanalysis	Journal of Sedimentary Petrology	57		X							
50	Kondolf, G. Mathias	1993	Geomorphic and Environmental Effects of Instream Gravel Mining	Landscape and Urban Planning	28							X	X	X
51	Kondolf, G. Mathias	1996	The flushing flow problem: defining and evaluating objectives	Water Resources Research	32 (8)							X	X	X
52	Kondolf, G.M.	1995	Geomorphological Stream Channel Classification in Aquatic Habitat Restoration: Uses and Limitations	Aquatic Conservation	5									X
53	Kondolf, G.M.	2001	Planning Approaches to Mitigating Adverse Human Impacts on Land-inland-water Ecotones	Ecohydrology and Hydrology	1									X
54	Kondolf, G.M., Smeltzer, M.W., Railsback, S.	2001	Design and Performance of a Channel Reconstruction Project in a Costal California Gravel-bed Stream	Environmental Management	28 (6)									X
55	Leopold, L.B.	1973	River Channel Change with Time- an Example	Geological Society of America Bulletin	84	X	X							
56	Leopold, L.B.													
57	Leopold, L.B., Wolman, M.G. and Miller, J.P.	1964	Fluvial Processes in Geomorphology	BOOK			X							
58	MacRae, C.R.	1993	An Alternate Design Approach for the control of Instream Erosion Potential in Urbanizing Watersheds	Proceedings of the Sixth International Conference on Urban Storm Drainage, Sept 12-17, 1993. Torno, Harry C.	2	X					X			
59	MacRae, C.R.	1992	The Role of Moderate Flow Events and Bank Structure in the Determination of Chanel Response to Urbanization	Resolving conflicts and uncertainty in water management: Proceedings of the 45th Annual Conference of the Canadian Water Resources Association. Shrubsole, Dan, ed. 1992		X	X	X	X					

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60	MacRae, C.R.	1996	Experience from Morphological Research on Canadian Streams: Is Control of the Two-Year Frequency Runoff Event the Best Basis for Stream Channel Protection	Effects of Watershed Development and Management on Aquatic Ecosystems, ASCE Engineering Foundation Conference, Snowbird, Utah		X	X	X	X					
61	Maryland Department of the Environment	2000	Stream Response to Stormwater Management Best Management Practices in Maryland	BOOK			X	X	X	X				
62	Melbourne Water Corporation, Environmental Protection Authority	1999	Urban Stormwater Best Practice Environmental Management Guidelines	BOOK										
63	Menning, K.M., Erman, D.C., Johnson, K.N., Sessions, J.	1996	Modeling Aquatic and Riparian Systems, Assessing Cumulative Watershed Effects, and Limiting Watershed Disturbance	Sierra Nevada Ecosystems Project: Final Report to Congress, Addendum. http://ceres.ca.gov/snep/pubs										
64	Mongomery, D.R., Buffington, J.M.	1993	Channel classification, prediction of channel response, and assessment of channel condition.	BOOK										
65	Montgomery, David and Lee MacDonald	2002	Diagnostic Approach to Stream Channel Assessment and Monitoring	Journal of the American Water Resources Association	38 (1)									
66	Mount, J.F.	1995	California rivers and streams : the conflict between fluvial process and land use	BOOK										
67	Newbold, S.	2002	Integrated Modeling for Watershed Management: Multiple Objective and Spatial Effect	Jour. of the American Water Resources Association	38 (2)			X		X				
68	Pasternak, Gregory	1994		Foundations of Urban River Management (Guadalupe River)										
69	Pickup, G., Warner, R.F.	1976	Effects of hydrologic regime on magnitude and frequency of dominant discharge	Journal of Hydrology	29	X								X
70	Pitt, Robert	1995	Biological effects of urban runoff discharges	Stormwater runoff and receiving systems: impact, monitoring, and assessment. Herricks, E.E. (ed).		X						X		
71	Reeves, G.H., L.E. Benda, K.M. Burnett, P.A. Bisson, and J.R. Sedell	1995	A Disturbance-Based Ecosystem Approach to Maintaining and Restoring Freshwater Habitat of Evolutionarily Significant Units of Anadromous Salmonids in the Pacific Northwest	American Fisheries Society Symposium, vol. 17, pg 334-349	17							X		
72	Rhoads, B.L.	1995	Stream Power: A Unifying Theme for Urban Fluvial Geomorphology.	Stormwater runoff and receiving systems: impact, monitoring, and assessment. Herricks, E.E. (ed).				X	X					
73	Roni, Philip; T.B. Beechie, R.E. Bilby; F.E. Leonetti; M.M. Pollock; and G.R. Pess	2002	A Review of Stream Restoration Techniques and a Hierarachical Strategy for Prioitizing Restoration in Pacific Northwest Watersheds	North American Journal of Fisheries Management	22			X			X			
74	Roper, Bret B., Jeffery J. Dose, and Jack E. Williams	1997	Stream Restoration: Is Fisheries Biology Enough?	Fisheries	22 (5)			X						

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75	San Francisco Estuary Institute	1998	Sediment Sources and Fluvial Geomorphic Processes of Lower Novato Creek Watershed	Report to Sacramento County Department of Public Works		X	X	X					X	X
76	San Francisco Estuary Institute	2000	Application of the SFEI Watershed Assessment Science Approach to San Antonio Creek.			X	X	X					X	X
77	San Francisco Estuary Institute	2001a	San Pedro Creek Geomorphic Analysis.			X	X	X					X	X
78	San Francisco Estuary Institute	2001b	Wildcat Creek Watershed, A Scientific Study of the Physical Processes and Land Use Effects.			X	X	X					X	X
79	San Joaquin River Riparian Habitat Restoration Program (SJRRHRP)	1998	Historical Riparian Habitat Conditions of the San Joaquin River	Report to the SJRRHRP								X	X	X
80	Schueler, Thomas R.	1995	The Importance of Imperviousness.	Watershed Protection Techniques	1 (3)	X								
81	Schueler, Thomas R.	1995	Green Parking Lots	Site Planning for Urban Stream Protection http://www.cwp.org/SPSP/TOC.htm										
82	Schueler, Thomas R.	1996	Crafting Better Urban Watershed Protection Plans	Watershed Protection Techniques	2(2)									
83	Schueler, Thomas R. and John Galli	1995	The environmental impacts of stormwater ponds	Stormwater runoff and receiving systems: impact, monitoring, and assessment. Herricks, E.E. (ed).		X						X		
84	Sidle, R. C.	1988	Bed load transport regime of a small forest stream	Water Resources Research	24		X							
85	Simmons, Dale and Reynolds, Richard, J.	1982	Effects of Urbanization on Base Flow of Selected South-Shore Streams, Long Island, New York	Water Resources Bulletin	18 (5)	X								
86	Stien, Eric and Richard Ambrose	2001	Landscape Scale Analysis and Management of Cummulative Impacts to Riparian Ecosystems: Past, Present and Future	Journal of the American Water Resources Association	37 (6)	X		X						X
87	Strecker, Eric	2001	Low-Impact Development. Is It Really Low or Just Lower?	Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation, Proceedings of an Engineering Foundation Conference, August 19-24, 2001, Snowmass Village, CO						X				
88	Urbonas, Ben and Barabara Benik	1995	Stream stability under a changing environment	Stormwater runoff and receiving systems: impact, monitoring, and assessment. Herricks, E.E. (ed).		X	X							X
89	Urbonas, Ben and Glidden, M.W.	1983	Potential Effectiveness of Detention Ponds	Southwest Storm Drainage Symposium, Texas A&M		X								X
90	USEPA	1999		Preliminary data summary of urban stormwater best management practices. EPA-821-R-99-012										

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91	WA State Dept. of Ecology	2000	Vols. I & III	Stormwater Management Manual for Western Washington. Pub # 99-11. http://www.ecy.wa.gov/programs/wq/stormwater	1 (3)									
92	Waananen, Arvi O.	1977	Flood-prone areas and land-use planning : selected examples from the San Francisco Bay region, California	Geological Survey professional paper ; 942										X
93	Watson, Chester; David Biedenharn; and Brian Bledsoe	2002	Use of Incised Channel Evolution Models in Understanding Rehabilitation Alternatives	Journal of the American Water Resources Association	38 (1)		X				X			
94	Weaver, L. Alan, and Greg C. Garman	1994	Urbanization of a Watershed and Historical Changes in a Stream Fish Assemblage	Transactions of the American Fisheries Society	123	X								
95	Weinberg M., C Lawrence, J. Anderson, J. Randall, L. Botsford, C. Loeb, C. Tadokoro, G. Orlob, and P. Sabatier.	2002	Biological and Economical Implications of Sacranemto Watershed Management Options.	Jour. of the American Water Resources Association	38(2)			X		X				
96	Whipple, William Jr., James M. DiLouie, Theodore Pytler Jr.	1981	Erosion Potential of Streams in Urbanzing Areas	Water Resources Bulletin	17	X	X							
97	Wilcock, P.R., Kondolf, G.M., Matthews, W.V., Barta, A.F.	1996	Specification of Sediment Maintenance Flows for a Large Gravel-bed River	Water Resources Research	32 (9)									X
98	Wilcock, Peter R. and John B. Southard	1988	Experimental study of incipient motion in mixed-size sediment	Water Resources Research	24		X							
99	Williams, Garnet P.	1978	Bank-Full Discharge of Rivers	Water Resources Research	14		X							
100	Williams, James	1995	Channel and habitat change downstream of urbanization	Stormwater runoff and receiving systems: impact, monitoring, and assessment. Herricks, E.E. (ed).		X								
101	Zentner and Zentner	1991	A Draft Guidebook for Assessing the Functions of Second Order Streams in the Central Valley of California.	BOOK								X	X	X