Effect of Increases in Peak Flows and Imperviousness on the Morphology of Southern California Streams

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EFFECT OF INCREASES IN PEAK FLOWS AND IMPERVIOUSNESS ON THE MORPHOLOGY OF SOUTHERN CALIFORNIA STREAMS

A report from the Stormwater Monitoring Coalition

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EXECUTIVE SUMMARY

Urbanization in southern California has resulted in direct and indirect effects on natural stream courses that have altered their physical and biological character. Development typically increases impervious surfaces on formerly undeveloped (or less developed) landscapes and reduces the capacity of remaining pervious surfaces to capture and infiltrate rainfall. The result is that as a watershed develops, a larger percentage of rainfall becomes runoff during any given storm. In addition, runoff reaches the stream channel much more efficiently, so that the peak discharge rates for floods are higher for an equivalent rainfall than they were prior to development. This process has been termed *hydromodification*.

Although the effects of increased impervious cover on stream flow have been well documented (Bledsoe, 2001; Booth, 1990; 1991; MacRae, 1992; 1993; 1996), the majority of past studies have focused on perennial streams. Until recently, few comparable studies have evaluated the impacts of urbanization on ephemeral or intermittent streams of arid or semi-arid climates. This had made it difficult to effectively manage stormwater impacts on southern California's natural streams. In response, the Stormwater Monitoring Coalition (SMC) conducted this study to assess the relationship between stream erosion and urbanization. It is anticipated that the results of this study will be useful in developing peak flow criteria for Los Angeles County as well as future stormwater regulations or management strategies.

The goal of this study is to assess relationships between stream channel type and resistance that will allow prediction of channel response under changed conditions associated with increased impervious cover. The specific study objectives are to:

- Establish a stream channel classification system for southern California streams;
- Assess stream channel response to watershed change, and attempt to develop deterministic or predictive relationships between changes in impervious cover and stream channel enlargement; and
- Provide a conceptual model of stream channel behavior that will form the basis for future development of a numeric model.

The intent of this study was to use multiple watersheds (each containing a single site) studied in broad scope rather than a single watershed (with many sites) studied in great detail. Consequently a total of 11 separate sites were selected in 8 distinct watersheds (Table ES-1).

Table ES-1 Study Site List

Site No.	Site Name	CDA (mi^2)	Major Watershed	Type of Site	County
1	Topanga Creek	18.07	Santa Monica Bay	Control Site	Los Angeles
3u	Hasley Canyon	1.55	Santa Clara River	Control Site	Los Angeles
3d	Hasley Canyon	1.66	Santa Clara River	Developed Site	Los Angeles
4u	Plum Canyon	2.23	Santa Clara River	Developed Site	Los Angeles
4d	Plum Canyon	2.40	Santa Clara River	Developed Site	Los Angeles
7u	Borrego Canyon	2.27	San Diego Creek	Developed Site	Orange
7d	Borrego Canyon	3.06	San Diego Creek	Developed Site	Orange
9	Serrano Creek	2.64	San Diego Creek	Developed Site	Orange
10	Santiago Creek	12.36	Santa Ana River	Control Site	Orange
23	Dry Canyon	1.22	Calleguas Creek	Control Site	Ventura
27	Hicks Canyon	1.33	San Diego Creek	Control Site	Orange

CDA = catchment drainage area

The study approach was to evaluate the changes in stream channel configuration over time and compare them to the changes in total basin impervious cover (TIMP) over the same time period. Data collection occurred in two phases. In the first phase background and historic information was gathered on each site and its contributing drainage area. In the second phase detailed field data was collected on the geomorphic condition of each study reach. The combinations of historic and contemporary data were used to develop predictive relationships between changes in impervious cover and channel form.

This study resulted in the following general conclusions regarding the relationship between impervious cover and stream channel form for ephemeral streams in southern California:

1. **Southern California streams exhibit deterministic relationships between bankfull discharge (Q_{bfl}), and measures of channel geometry such as cross section area (A_{bfl}).** Of the field measures calculated, the greatest consistency in relationship to the discharge rate at the bankfull stage, also termed the *Dominant Discharge* (Q_{bfl}), was with the channel cross-sectional area (A_{bfl}). Dominant Discharge exhibited a clear, predictable (or deterministic) relationship with features of channel geometry, such as channel width and cross-section area, i.e. as discharge increases, predictable increases in channel size are observed. An example of this deterministic relationship is shown in Figure ES-1, which indicates that the initial channel response to increases in discharge is to widen; however, with increasing discharge, the rate of channel widening decreases and downcutting is the predominant response.

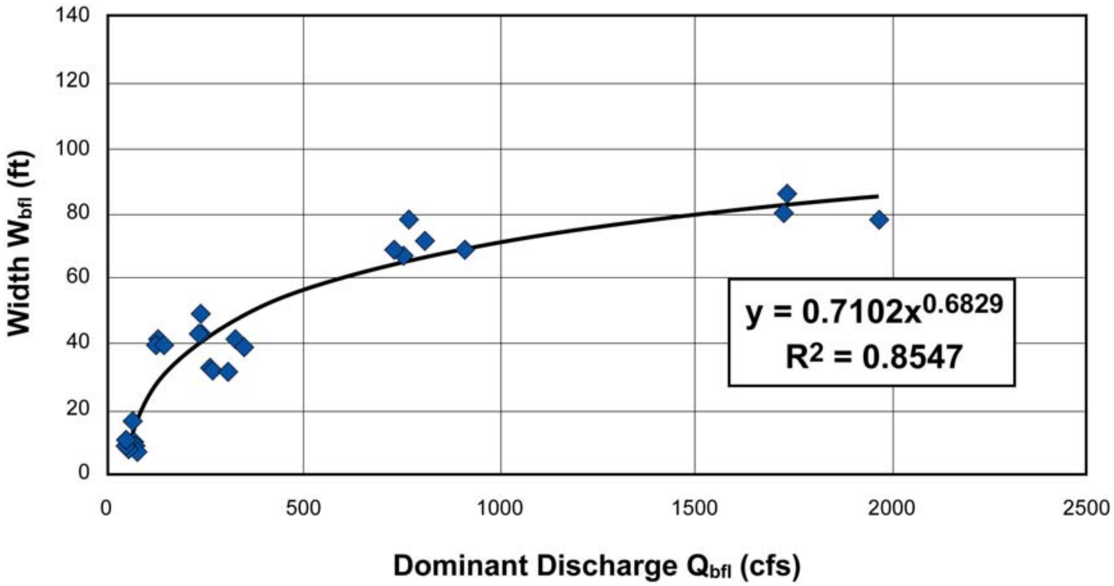

Figure ES-1: Relationship of Dominant Discharge to Channel Width

2. **The ephemeral/intermittent streams in southern California appear to be more sensitive to changes in TIMP than streams in other areas**. Stream channel response can be represented using an *enlargement curve*, which relates the percent of impervious cover (TIMP) to a change in cross-sectional area (Figure ES-2). The data for southern California streams forms a relationship very similar in shape to the enlargement curves developed for other North American streams. However, the curve for southern California streams is above the general curve for streams in other climates. This suggests that a specific enlargement ratio is produced at a lower value of impervious surface area in southern California than in other parts of North America. Specifically, the estimated threshold of response is approximately 2-3% TIMP, as compared to 7-10% for other portions of the U.S. It is important to note that this conclusion applies specifically to streams with a catchment drainage area less than $5mi^2$.

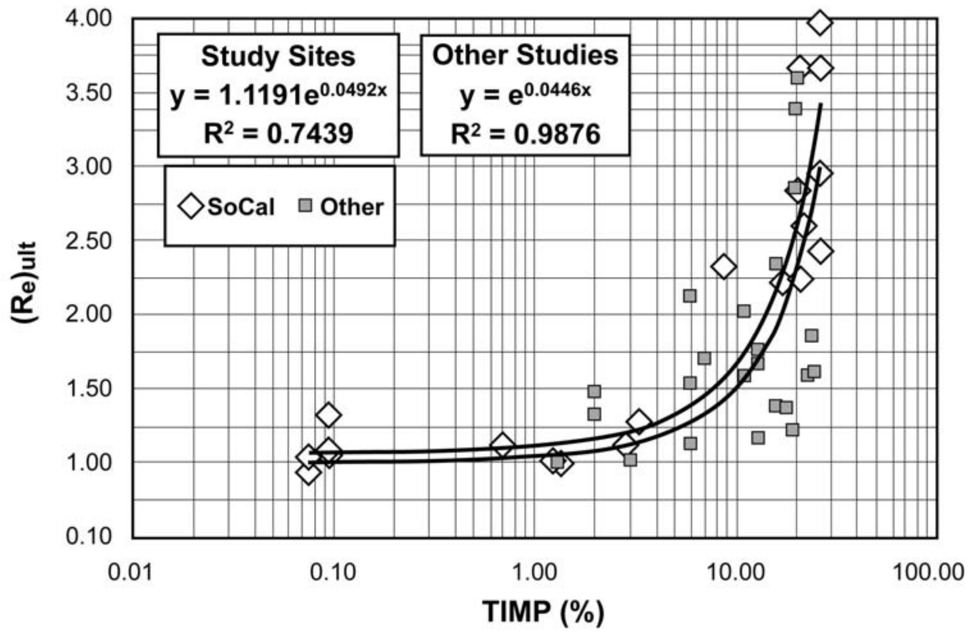

Figure ES-2. Enlargement Curve for Southern California.

Upper curve and data points are for southern California channels in the current study. Lower curve is based on data from other locations in North America.

3. **There is a natural background level of channel degradation that is occurring in all stream channels studied, even in the absence of development within the drainage area.** A minimal rate of change in channel bottom elevation was observed in all sites, regardless of whether the watershed has experienced an increase in impervious cover. Control sites exhibited a state of dynamic equilibrium where downcutting was observed, but channel morphology did not change appreciably over time. In contrast, the developed sites exhibited instability, where one or more measures of channel morphology changed over time. In addition, the rate of change in downcutting was greater in the developed sites than in the control sites. For example, at the Dry Canyon control site downcutting was estimated to be 0.7 ft/yr, while the rate at the developing Plum Canyon site was estimated to be 1.7 ft/yr. These results demonstrate poor channel resistance to increased flow in all stream channels except those subject to bedrock control, such as Topanga Creek.

4. **Streams are sensitive to both peak discharge and duration of discharge.** The ephemeral and intermittent streams investigated in this study appear to be highly sensitive to changes in flow rates associated with increased impervious cover. Additionally, they appear to have a low resistance to erosion, which results in increased susceptibility to channel enlargement in response to increases in the duration of high flows.

The predictive relationships established in this study can be used to evaluate potential effects of proposed development on the stability of natural streams. There are ranges of strategies that can be used to help reduce the potential effects of increased TIMP. However, the selection of a management strategy is dependent upon the extent to which a stream channel has been impacted by development within the watershed, the nature of the stream channel reach under consideration, and the anticipated future watershed conditions (i.e. expected increases in TIMP). Three general strategies should be considered when attempting to manage increases in peak flow:

1. **Limit Impervious Area.** Although the focus of this study was necessarily on TIMP, disconnecting impervious areas from the drainage network and adjacent impervious areas is a key approach to protecting channel stability. Utilizing this strategy can make it practical to keep the effective impervious cover (i.e. the amount hydrologically connected to the stream) equal to or less than the identified threshold of 2-3%.

2. **Control Runoff.** Hydrograph matching is not recommended for a single "design" storm with a specific return period, but rather for a range of return periods from 1 year to 10 years. Accomplishing such hydrograph matching will be challenging, and undoubtedly require a combination of techniques to prevent (retain), as well as to delay or attenuate (detain) runoff and/or stream flow.

3. **Stream Channel Movement.** Allow the greatest freedom possible for "natural stream channel" activity. This includes establishing buffer zones and maintaining setbacks to allow for channel movement and adjustment to changes in energy (associated with runoff). However, where in-stream controls are required consider all potential management options.

It is important to keep in mind that the choice of a management approach or approaches should be dictated by the strategies that are appropriate given the conditions of each stream reach and its contributing watershed. Consequently a suite of management approaches may need to be applied to provide a comprehensive solution to managing potential increases in runoff due to land use change.

Stream channels respond to changes in basin imperviousness in complex ways, and specific responses will vary based on the characteristics of the stream and watershed. An exhaustive analysis of these issues was beyond the scope of this study; nevertheless, the present study represents an important first step in understanding the response of ephemeral streams to increases in impervious cover.

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1.0 INTRODUCTION

The southern California region is expected to experience significant urbanization over the next several decades that has the potential to have significant impact on the many ephemeral or intermittent streams of this arid to semi-arid region. In response to this concern, the 2001 Los Angeles County Municipal Stormwater Permit calls for a study to help develop numeric criteria to prevent or minimize erosion of natural stream channels and banks associated with urbanization.

Working through the Stormwater Monitoring Coalition (SMC), the Southern California Coastal Water Research Project (SCCWRP) has been designated as the facilitator for studies to assess the relationship between stream erosion and urbanization. It is anticipated that the results of this study will be useful in developing peak flow criteria for Los Angeles County as well as future stormwater regulations. Earth Tech, Inc. has been retained to conduct this study to relate measurable urban/suburban development within a watershed to observable changes in stream-channel morphology (including width, depth, cross-sectional area, and plan-form shape) in the southern California region.

1.1 Project Background

The process of urbanization alters many aspects of a landscape and often results in the emplacement of structures and infrastructure. One of the primary changes that has the potential to affect stream courses is alteration of watershed hydrology. Development increases impervious surfaces on formerly undeveloped (or less developed) landscapes and reduces the capacity of remaining pervious surfaces to capture and infiltrate rainfall. The result is that as a watershed develops, a larger percentage of rainfall becomes runoff during any given storm. In addition, runoff reaches the stream channel much more efficiently, so that the peak discharge rates for floods are higher for an equivalent rainfall than they were prior to development. This has been well documented since the early research by Hammer (1972) and Hollis (1975), through the recent efforts of Bledsoe (2001), Booth (1990, 1991), and MacRae (1992, 1993, 1996). Changes in runoff and flow have also been shown to result in impacts on aquatic habitat and species (Benke, et al. 1981, Booth and Jackson 1997, Garie and McIntosh 1986, Jones and Clark 1987, and Pedersen and Perkins 1986).

Although the effects of increased impervious cover on stream flow have been well documented, the majority of past studies have focused on perennial streams. Few comparable studies have evaluated the impacts of urbanization on streams of arid or semi-arid climates where most of the smaller streams are ephemeral or intermittent. Ephemeral streams are defined as those that flow only in direct response to a rainfall event, and (particularly in southern California) are otherwise dry for most of the year. Intermittent streams will have base flow for some of the period between rainfall events, but will also have dry periods throughout the year. Perennial streams will flow throughout the year, having enough base flow to maintain water in the stream channel even during the long months of the dry season.

Two recent projects in California have begun to investigate effects of increased peak flow on arid streams that were either formerly ephemeral (Thompson Creek in Santa Clara County) or presently and historically ephemeral (Arroyo Simi in Ventura County). In each case, reports prepared for these projects summarized the relevant literature and noted the sparseness of work on streams in arid or semi-arid climates. GeoSyntec (2002) provides a substantial review of the literature on this topic, and AQUA TERRA (2004) contributes additional references not covered in the more extensive GeoSyntec (2002) literature review. Of the 123 papers, reports, or books reviewed between these two references, only one citation was noted specifically for considering and evaluating ephemeral streams (Caraco 2000). This emphasizes the lack of reference material available for assessing ephemeral or intermittent streams in dry climates.

There are additional classic (Graf 1987) and recent (Tooth 2000, and Bull and Kirkby 2002) works on stream processes in arid areas not cited by the recent California projects. However, these additional publications do not focus on impacts from increased imperviousness. Therefore, the limited nature of applicable research is particularly problematic for the relatively steep arid and semi-arid streams typically found in southern California, which may have different bed and bank properties than streams in other regions. The lack of research into the impacts of urbanization on ephemeral and intermittent streams also makes it difficult to manage stormwater impacts on natural streams effectively in southern California or other parts of the southwest. Furthermore, the current, rapid pace of urbanization in foothill areas of the study region emphasizes the importance of understanding the relationship between changes in the hydrologic and hydraulic processes of these systems and the resultant change in stability of the streams in arid watersheds. Such an understanding is urgently needed to help managers make informed decisions regarding strategies to protect these streams.

The present study is another step toward understanding the responsiveness of ephemeral stream channels to changes in hydrology (i.e. evaluating their resistance to expected changes in the flow peaks and duration). The approach adopted here differs from the two recent efforts in California to evaluate the impacts of urbanization. AQUA TERRA (2004) used a modeling approach with field verification to evaluate a single watershed using data from six stream channel monitoring points. GeoSyntec (2003), also used multiple stream channel data collection points within a single watershed to evaluate stream channel response to development. The present study evaluated stream channel study sites in multiple, small watersheds from a larger geographic area that includes Los Angeles, Orange and Ventura counties in order to begin developing a regional understanding of the relationship between increased impervious cover and stream channel stability.

1.2 Study Objectives

The primary objective of this study was to find relationships between stream channel type and resistance that would allow prediction of channel response under changed conditions associated with increased impervious cover. Ultimately this effort will contribute to the establishment of stormwater management criteria to help minimize the impacts to stream channels from the conversion of undeveloped (or less developed) areas to residential, commercial, or other intensive land uses.

The study was structured to address specific problems expressed in terms of urbanizing systems (Table 1-1). Although solutions to these problems may not be attainable through this study, they are presented as a desirable outcome of this type of research. More tenable study goals are provided as reasonable expected results of this project. Finally, several viable approaches applied by this project are presented to indicate how the study addressed the stated problems in order to reach the stated study goals.

Table 1-1. Project Structure

Problems	Approaches	Study Goals
1. Understand stream channel response to urbanization in southern California streams. 2. Isolate the effects of urbanization on stream channel response. 3. Identify geomorphic thresholds for southern California streams. 4. Understand the effectiveness of mitigation strategies. 5. Establish a model or procedure to extrapolate relationships based on case studies.	1. Use data obtained from the study sites to establish a stream channel classification system for southern California. 2. Use stream channel type to discriminate among the quantifiable impacts to stream channel morphology. 3. Establish a procedure to assess significance of morphological impacts.	1. Evaluate the impact of urbanization on stream morphology in natural ephemeral stream-channel systems in southern California. 2. Develop cause and effect relations between stream channel morphology change and urbanization. 3. Review potential BMP implementation. 4. Recommend possible applications of this study's findings to other streams and watersheds in southern California.

Since this was an empirical study, it required several stream channel sites that were selected from within a six-county region in southern California. The investigation looked at historical changes in stream channel configuration relative to historical changes in land use. The intent, therefore, was to use multiple watersheds (each containing a single site) studied in broad scope rather than a single watershed (with many sites) studied in great detail. Consequently a total of 11 separate sites were selected in 8 distinct watersheds. The locations of these watersheds are regional, and range from northwestern Los Angeles County through southern Ventura County, and down to central Orange County. The evaluations performed should allow a greater range of site conditions to be evaluated than they would for a single watershed, and ultimately provide results with broader applicability in the southern California region. There is a great need for additional research in this geographic area on the impacts from urbanization, and this need is for both focused (single watershed) and regional (multiple watersheds) investigations. The two recent California studies (AQUA TERRA 2004 and GeoSyntec 2004) were focused studies. The present study is the first regional investigation of ephemeral stream channel response to urbanization.

The objectives of this study, which were needed in establishing the relationship sought by the primary study goal, include the following:

- Create a classification system to generalize responses of different types of stream channels,
- Evaluate stream channel response to watershed change, and
- Attempt to provide a conceptual model of stream channel behavior.

While the results of the current study are only directly applicable to the sites included in this study, the use of a classification system similar to the one proposed here (see Section 3) holds promise for eventually broadening this applicability and allowing extrapolation of results to other similar stream types. Understanding such relationships could be an important part of future watershed and stormwater management by identifying stream channel reaches that are most susceptible to change. Toward this end, Section 4 of this report provides some recommendations for additional research needs to provide a broader scientific basis for the classification of stream channels in all six counties of the study region and their applicability to different development scenarios.

2. DATA COLLECTION METHODS

This study employed a stepwise stream evaluation protocol previously applied at a number of sites throughout North America, and developed partly from research conducted worldwide (Table 2-1). This project evaluated the applicability of this protocol to the semi-arid southern California region. Specifically, the study tested the comparability of relationships derived from southern California streams to data collected in other areas encompassing more diverse hydrologic settings. If the two data sets are comparable, the larger data set can be used to augment the relatively modest data expected from this study; thereby strengthening the reliability of the analysis based on local conditions.

2.1 Evaluation Process

The overall protocol includes eleven steps, but only steps 1 through 5, 7, and 8 have been employed in this study, as this study has been broadly applied to sites in southern California rather than being applied to a single watershed with multiple stream or river channel sites. Each step of the process and a brief summary of its application to this study are provided below. The remaining sections of this report provide background information on the study sites and evaluations performed for the application of this protocol. Detailed field and analytical data are contained in the appendices to this report.

Table 2-1. Eleven-Step Protocol
The Protocol, as applied in this study pertains to the geomorphic component of stream channel investigations.

ID	Name	Question
STEP 1	Study Objectives	What is the nature and degree of the perceived problem?
STEP 2	Past Stream channel	What was the form of the historic stream channel?
STEP 3	Expected Disturbances	What future disturbance is likely to occur?
STEP 4	Present Stream channel	What is the stream channel like today?
STEP 5	Future Stream channel	What will the stream channel look like in the future?
STEP 6	Accept/Reject Future	Is the future stream channel form desirable, acceptable or unacceptable?
STEP 7	Disturbance Control	Can the perturbations be controlled through watershed planning?
STEP 8	Channel Works	Are instream works required, desirable, feasible and practical?
STEP 9	River Management	What is the preferred river corridor management plan?
STEP 10	Engineering Design	What does the detailed design look like?
STEP 11	Implementation	How will the plan be implemented?

Study Objectives. The first step of the protocol is to establish study objectives by defining the problems to be solved, establishing goals for solving these problems, and defining an assessment approach for determining when the goals are reached. For this study, the objectives have been articulated previously in Section 1.2, Study Objectives.

Past Stream Channel. Previously surveyed cross sections were available for each of the study sites, including at least one at every stream channel reach. These cross sections are an important key to evaluating how stream channel morphology differed in the past from its present-day form. The differences in stream channel geometry between past sections and present sections were evaluated for every site. The results of this evaluation are used as a basis for both the stream channel classification system and the stream channel response evaluation discussed in Section 3 of this Technical Report.

Expected Disturbances. This study is focused entirely on expected disturbances related to land use changes within the watersheds of these sites. Therefore, evaluation of expected disturbances is centered on changes in energy and erosion potential at these stream reaches.

Present Stream Channel. The present stream channel configurations are very clearly understood at all of the sites through the diagnostic surveys performed in May 2004. Each stream channel reach had from three to six cross sections surveyed, with characterizations made of the topography and the composition of bed and bank materials. In addition, a longitudinal profile was also surveyed that tied all of the cross sections together spatially and geometrically.

Future Stream Channel. Evaluation of the historical changes in stream channel morphology, combined with the data on bed and bank material composition, and bank cohesion, allowed an assessment of the potential for additional adjustment in stream channel morphology at each of the study reaches.

Accept/Reject Expected Future. If the purpose of this study had been stormwater management for a specific watershed, then the intent of this step would be applicable to the current discussion. However, because this effort is attempting to characterize a broad range of stream channels and assess their thresholds for stream channel change (most specifically enlargement), accepting or rejecting change is not required.

Disturbance Control. This study attempts to provide a generic assessment of the effectiveness of different classes of stormwater management measures, and when they can be appropriate to use in controlling the expected stream channel change resulting from urbanization.

Channel Works (BMPs). This project also considers the need for, and appropriate use of, in-channel management practices and under what conditions they might be appropriate.

2.2 Site Selection

The general goals in site selection were to find stream channels that would be representative of stream channel types across the region. In addition, candidate sites needed to have available historic information on the stream channel and the watershed. Finally, the selected watersheds must have been subject to some degree of development over the period for which information is available.

A detailed discussion of the logic behind the site selection process, and the guidelines applied while selecting the sites used in the study, can be found in the Work Plan prepared for this effort (Earth Tech, 2004). However, a brief summary of each guideline is presented below. A brief description of the sites selected and key background information on each site is presented in Sections 3.

- **Selection Guideline 1. Small Watershed Size.** The target drainage area for selected study sites/reaches was between 1 and 5 square miles, depending upon the degree of impervious cover.

- **Selection Guideline 2. Shear Stress Dominated.** The selected stream channel sites needed to have well-formed morphological characteristics that could be readily distinguished and surveyed using traditional geomorphic and engineering study techniques. Ideally, the stream channel system would be approaching a metastable position and shear stress processes are the dominant channel-forming mechanism.

- **Selection Guideline 3. Natural Channel.** The stream channels were to be primarily undisturbed by direct human activity (as well as could be determined) during the surveyed period. This included such activity as channel straightening, channel enlargement, bank protection or stabilization, upstream or downstream hydraulic control devices, and sediment trapping or containment structures. The length of the undisturbed stream channel needed to be greater than the minimum survey length of 1 to 2 meander wavelengths or the equivalent of 10 to 20 bankfull stream channel widths.

- **Selection Guideline 4. Development.** The watershed areas of the sites had to contain some level of urban (or suburban) development. Preferably at least 5 to 10 percent of the land area within the watershed should be in urban, suburban, commercial, or industrial land use categories.
- **Selection Guideline 5. Historic Cross Sections.** It was absolutely critical that each of the sites has previous stream channel cross-section surveys available for comparison. Ideally, these cross sections would be for one or more time periods prior to, and during the development period. Preferably the surveys would be from a time when a smaller percentage of the watershed was developed than it is currently.
- **Selection Guideline 6. Streamflow Data.** Sites were sought with stream flow data available in or near the study reach. Acceptable data was from actual flow measurements, modeled flow values, estimated peak discharges for specific recurrence intervals, or regional relationships. In the absence of such data, some idea of the number of days in a year that the stream channel contains flowing water was sought.
- **Selection Guideline 7. Aerial Photos.** Although not required, paired, stereographic aerial photographs at a useable scale (e.g., 1:10,000 or better) were sought for one or more historic periods.
- **Selection Guideline 8. Topographic Maps.** A study reach needed maps with a useable scale and contour interval (ideally 1 inch = 50 feet, to 1 inch = 100 feet, and a contour interval of 1 foot).
- **Selection Guideline 9. Geotechnical Data.** The availability of the results of geotechnical investigations that characterized materials similar to the stream channel bank and bed materials for a reach was considered very helpful in the site selection process.

The site selection process was a two-phase effort of (1) identifying potential (or "candidate") sites and (2) picking a subset of these sites for inclusion in the investigation. The process included contacting federal, state, county, and local government agency personnel, faculty members at local universities, and staff at local non-profit organizations to seek recommendations for candidate sites that generally appeared to meet the selection guidelines. The identified candidate sites are shown in Figure 2-1, as well as the final selected sites for the study. Details on the selected sites are given in Section 3.0, including location, topography, local geology, and other salient information.

2.3 Data Collection

Two phases of data collection were conducted for each of the eleven selected study sites. The first phase consisted of collecting background and historic information on each site and its contributing drainage area. The second phase consisted of collecting intensive field data on the geomorphic condition of each study reach. These two phases are described in detail in sections 2.3.1 and 2.3.2 below.

The historic data gathered for this study included the following types:

- Land use maps and/or digital files marking a specific land use coverage at a specific point in time.
- Surveyed cross sections (of distance and elevation) previously measured at each of the study sites.
- Precipitation records for rain gauges close to the watershed areas of the study sites; primarily annual amounts for the period of record.
- Stream flow measurements at local USGS (or other) stream gages; mostly annual peak flows for the period of record.
- Aerial photographs covering a range of times over the watershed area.

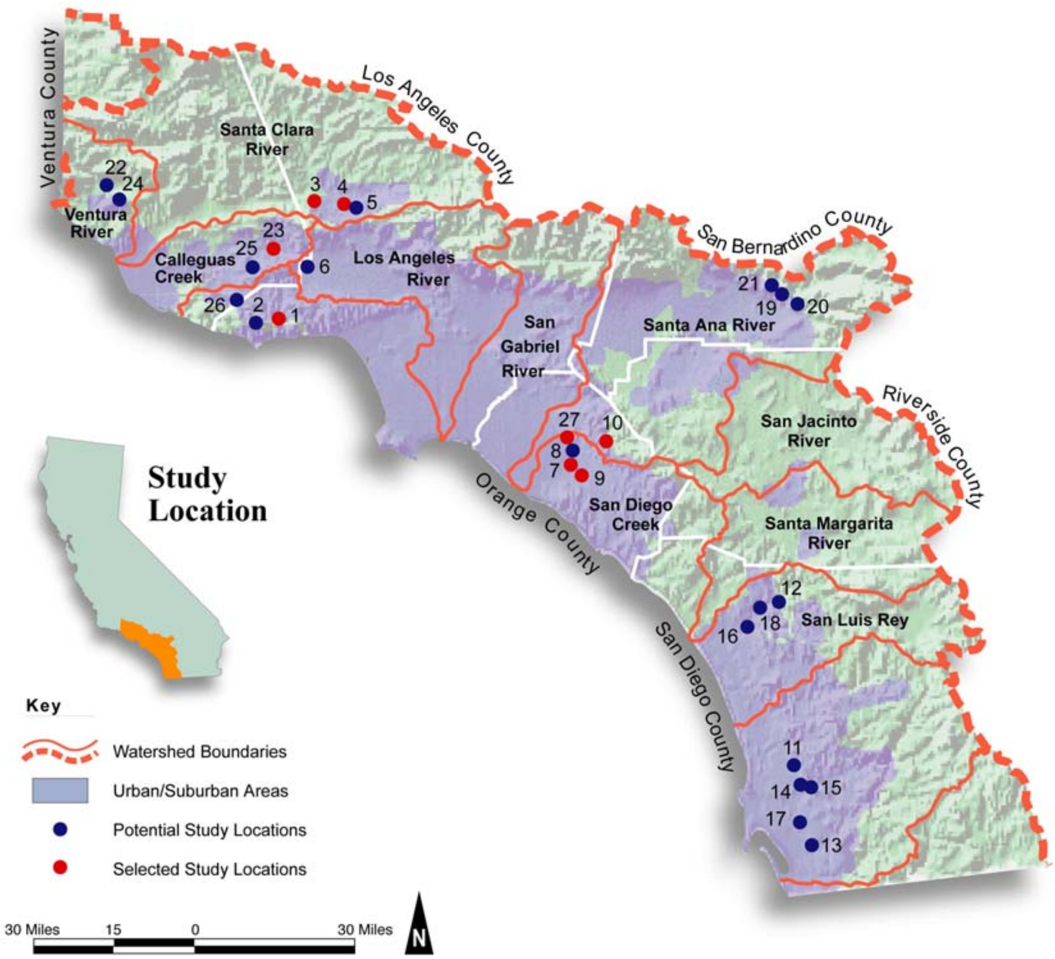


Figure 2-1. Study Sites

Map of study area showing the locations of potential study sites. See Table 1-1 for identification of, and additional information about, the selected study sites.

(Includes all candidates sites.)

- Evaporation (or evapotranspiration) records or approximate amounts for the watershed of the modeled reach.
- Satellite imagery and interpretation for impervious areas in the Hasley Canyon and Plum Canyon watersheds.

The current data was collected during two weeks of field work in May 2004. The specific types of field data collected at each of the stream channel reaches selected for this study include:

- Total-station surveys of the entire study reach that included stream channel cross sections (especially at locations of the previously surveyed cross sections), longitudinal profiles of the stream channel, and other points of interest tied to the geomorphic mapping.
- Geomorphic mapping of the stream channel reach, including up to, and slightly beyond the perceived “bankfull” channel configuration.
- Pebble counts and/or sieve analyses at multiple points across the stream channel to characterize bed materials.
- Sieve analyses and Torvane® shear stress meter readings to characterize bank material sizes and cohesion of both right and left banks.
- Rapid geomorphic assessment of each study reach.

2.3.1 Historic Data

Sources for the historic data are summarized below. These data generally required some amount of processing to make them consistent with the other data sources, and useable with the field-generated data from the current study.

Land Use. Land use data were used as a surrogate for impervious surface area within the watersheds. Land use/impervious cover data came from three primary sources (Table 2-2). The basic land use data came from detailed maps prepared for the Southern California Association of Governments (SCAG) for the years 1990, 1993, and 2001. Older land use data came from aerial photos and interpreted land use maps for the Serrano Creek and Borrego Canyon sites made available by Felicia Federico of UCLA. Data from DigitalGlobe was used to supplement the land use mapping for Hasley and Plum canyons. It consisted of digital orthoimagery collected with the QuickBird® satellite, which was used to supplement the SCAG land use maps. The DigitalGlobe imagery of Hasley Canyon was taken on 23-July-2002, while the imagery for Plum Canyon was taken on 22-March-2003.

Cross Sections. Previously surveyed cross sections came from six primary sources (Table 2-3). Most data were for multiple sections surveyed one or more years apart. The exceptions were Topanga Creek (one section, one survey time), Borrego Canyon (one section for each site, multiple survey times), and Santiago Creek (four sections, one survey time). Monuments used in the original survey, or other recoverable “surrogate” monuments were used to tie the current surveys to their historic cross section counterparts.

Precipitation Records. Rainfall records were sought for each watershed area to provide background information on relative hydrologic conditions for the period of land use change and the related adjustment in stream channel morphology (Table 2-4). Rainfall records were obtained for multiple weather stations near the watershed areas of the sites. The relative locations of the weather stations to the watersheds are shown in Figures 2-2 and 2-3.

Table 2-2. Land Use/Impervious Cover Data

Site		Source	Information
Site 1.	Topanga Creek	SCAG (2004).	Land use mapping with GIS layers for 1990, 1993, and 2001 data.
Site 3.	Hasley Canyon	SCAG (2004), DigitalGlobe (2004).	Land use mapping with GIS layers for 1990, 1993, and 2001 data; satellite imagery for 23-July-2002.
Site 4u.	Plum Canyon (upstream)	SCAG (2004), DigitalGlobe (2004).	Land use mapping with GIS layers for 1990, 1993, and 2001 data; satellite imagery for 22-March-2003.
Site 4d.	Plum Canyon (downstream)	SCAG (2004), DigitalGlobe (2004).	Land use mapping with GIS layers for 1990, 1993, and 2001 data; satellite imagery for 22-March-2003.
Site 7u.	Borrego Canyon (upstream)	SCAG (2004), Aerial Photos.	Land use mapping with GIS layers for 1990, 1993, and 2001 data; aerial photos for 1952, 1967, 1972, 1983
Site 7d.	Borrego Canyon (downstream)	SCAG (2004) Aerial Photos.	Land use mapping with GIS layers for 1990, 1993, and 2001 data; aerial photos for 1952, 1967, 1972, 1983
Site 9.	Serrano Creek	SCAG (2004) Aerial Photos and Interpretation (Federico 2003).	Land use mapping with GIS layers for 1990, 1993, and 2001 data; land use mapping for 1949, 1968, 1978, 1982, and 1997
Site 10.	Santiago Creek	SCAG (2004).	Land use mapping with GIS layers for 1990, 1993, and 2001 data
Site 23.	Dry Canyon	SCAG (2004).	Land use mapping with GIS layers for 1990, 1993, and 2001 data
Site 27.	Hicks Canyon	SCAG (2004).	Land use mapping with GIS layers for 1990, 1993, and 2001 data

Stream Gage Records. Although only two of the sites (Topanga Creek and Santiago Creek) have stream gages near the study reach, we have collected stream flow records from local gages for as many of the reaches as possible (Table 2-5). These gage records have been used to establish flow frequency relationships that are essential for estimating the recurrence interval (RI) of discharge values calculated for the study sites. The process involves prorating the calculated discharge values, by watershed area, to an equivalent discharge at a gage. The gage discharge is then used to estimate a RI with the established flow frequency relationship. Verification of these return period values made with the regional flood frequency relationships developed by the U. S. Geological Survey (Waananen and Crippen 1977).

Table 2-3. Historic Cross Section Data

Site		Source	Information
Site 1.	Topanga Creek	Rosi Dagit, Santa Monica Mountains Resource Conservation District.	Copy of field notes for original survey of cross section TS-1 performed in November 2000 by Orme, et al. (2002).
Site 3.	Hasley Canyon	Matt Yeager, Ph.D. candidate, University of California, Los Angeles.	Electronic file copies of surveys for cross sections HC-1, HC-2, HC-2.5, HC-3, HC-4, and HC-5 taken from October 2001 to April 2003.
Site 4u.	Plum Canyon (upstream)	Matt Yeager, Ph.D. candidate, University of California, Los Angeles.	Electronic file copies of surveys for cross sections PC-2, PC-2.75, PC-3, and PC-4 taken from October 2001 to April 2003.
Site 4d.	Plum Canyon (downstream)	Matt Yeager, Ph.D. candidate, University of California, Los Angeles.	Electronic file copies of surveys for cross sections PC-1, PC-2, and PC-2.5 taken from October 2001 to April 2003.
Site 7u.	Borrego Canyon (upstream)	Professor Stanley Trimble, Department of Geography, University of California, Los Angeles.	Copy of field notes for surveys of cross section (Range) 4A taken in September 1992, April 1993, December 1998, and February 2003.
Site 7d.	Borrego Canyon (downstream)	Professor Stanley Trimble, Department of Geography, University of California, Los Angeles.	Copy of field notes for surveys of cross section (Range) 4D taken in September 1992, April 1993, and February 2003.
Site 9.	Serrano Creek	Felicia Federico, Ph.D. candidate, University of California, Los Angeles.	Copy of field notes for surveys of cross section (Range) C taken in October 1997, and cross sections (Ranges) A2 and A4 taken in September 1991, and May 1993.
Site 10.	Santiago Creek	Jeff Agajanian, U. S. Geological Survey	Copy of field notes for surveys of cross sections XS-1, XS-2, XS-3, and XS-4 taken in April 1995.
Site 23.	Dry Canyon	Darla Wise, Ventura County Watershed Protection District	Electronic file copies of AutoCAD cross sections North, Middle, and South taken in October 2001, January 2002, and March 2003.
Site 27.	Hicks Canyon	Professor Stanley Trimble, Department of Geography, University of California, Los Angeles.	Copy of field notes for surveys of and cross sections (Ranges) A2 and A4 taken in September 1986, April 1992, and April 1993.

Table 2-4. Precipitation Data

Site		Source	Information
Site 1.	Topanga Creek	Los Angeles County Department of Public Works (LA DPW)	LA Co. Stations 6 and 1194
Site 3.	Hasley Canyon	LA DPW	LA Co. Stations 372, 801B, 1012B, 1262, and 1263
Site 4u.	Plum Canyon (upstream)	LA DPW	LA Co. Stations 372, 801B, and 1262
Site 4d.	Plum Canyon (downstream)	LA DPW	LA Co. Stations 372, 801B, and 1262
Site 7u.	Borrego Canyon (upstream)	Orange County Resources and Development Management Department, Watershed and Coastal Resources Division (RDMD); California Irrigation Management Information System (CIMIS)	OC Stations 121, 165, 169, 173, 176 (annual and hourly), and 216; CIMIS Station #75 (hourly)
Site 7d.	Borrego Canyon (downstream)	RDMD and CIMIS.	OC Stations 121, 165, 169, 173, 176 (annual and hourly), and 216; CIMIS Station #75 (annual and hourly)
Site 9.	Serrano Creek	RDMD and CIMIS.	OC Stations 121, 165, 169, 173, 176, and 216
Site 10.	Santiago Creek	RDMD and CIMIS.	OC Stations 121, 165, 169, 173, 176, and 216
Site 23.	Dry Canyon	Ventura County Watershed Protection District (VC WPD)	Ventura Co. Stations 154, 193, and 196
Site 27.	Hicks Canyon	RDMD and CIMIS.	OC Stations 121, 165, 169, 173, 176, and 216

Table 2-5. Stream Gage Records

Agency	Site ID Number	Site Name	Elevation of Gage (ft.)	CDA (mi^2)	Years of Record
LA DPW	F54C-R	Topanga Creek above Mouth of Canyon	265.6	16.0	63
USGS	11104000	Topanga Creek near Topanga Beach, CA	255.0	18.0	49
USGS	11047500	Aliso Creek at El Toro	440.0	7.9	50
USGS	11075800	Santiago Creek at Modjeska	1,210.0	13.0	42
USGS	11096500	Little Tujunga Creek near San Fernando, CA	1,068.4	21.1	46
USGS	11105850	Arroyo Simi near Simi	720.0	70.6	42

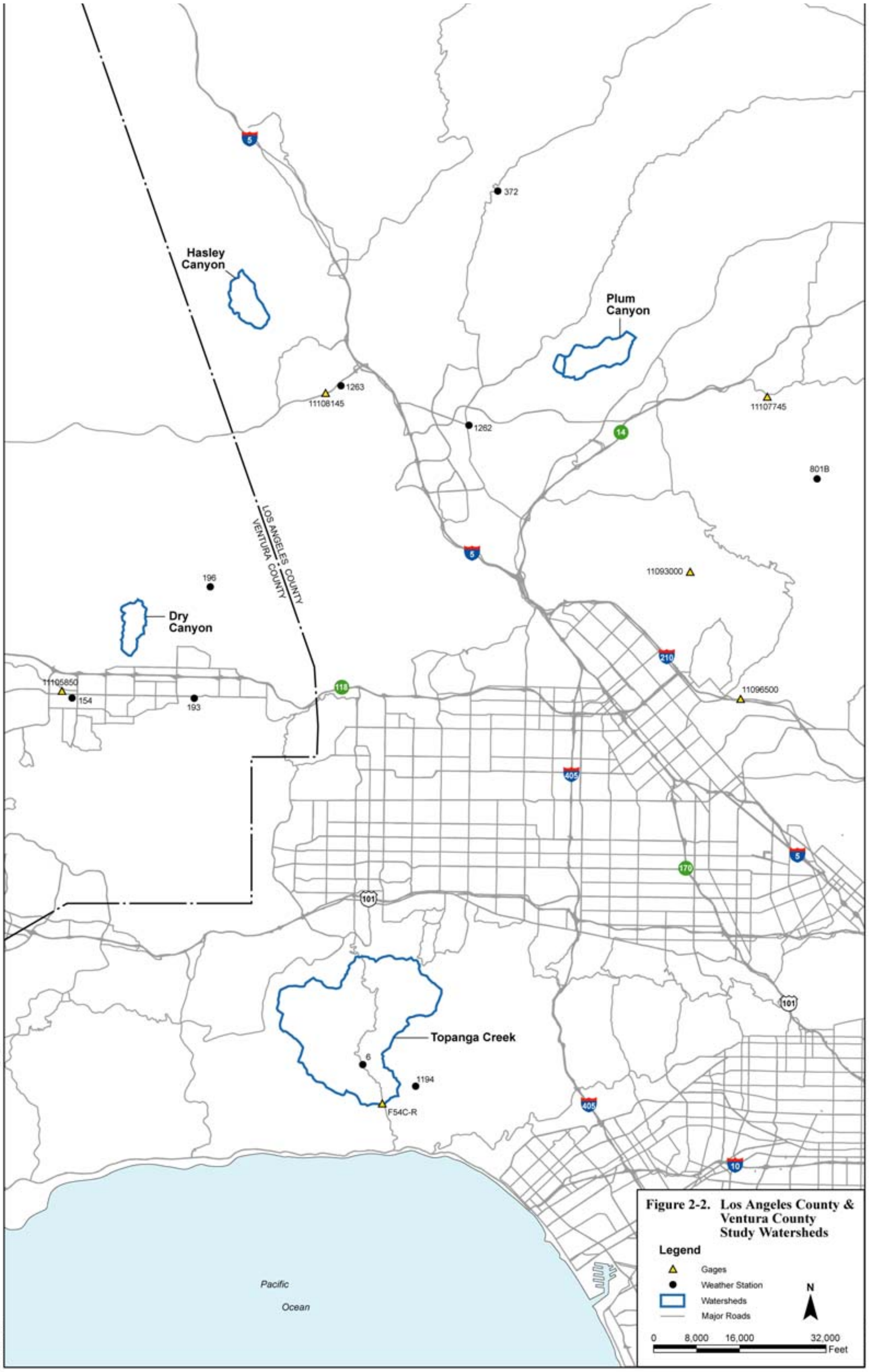


Figure 2-2. Los Angeles County and Ventura County Study Watersheds

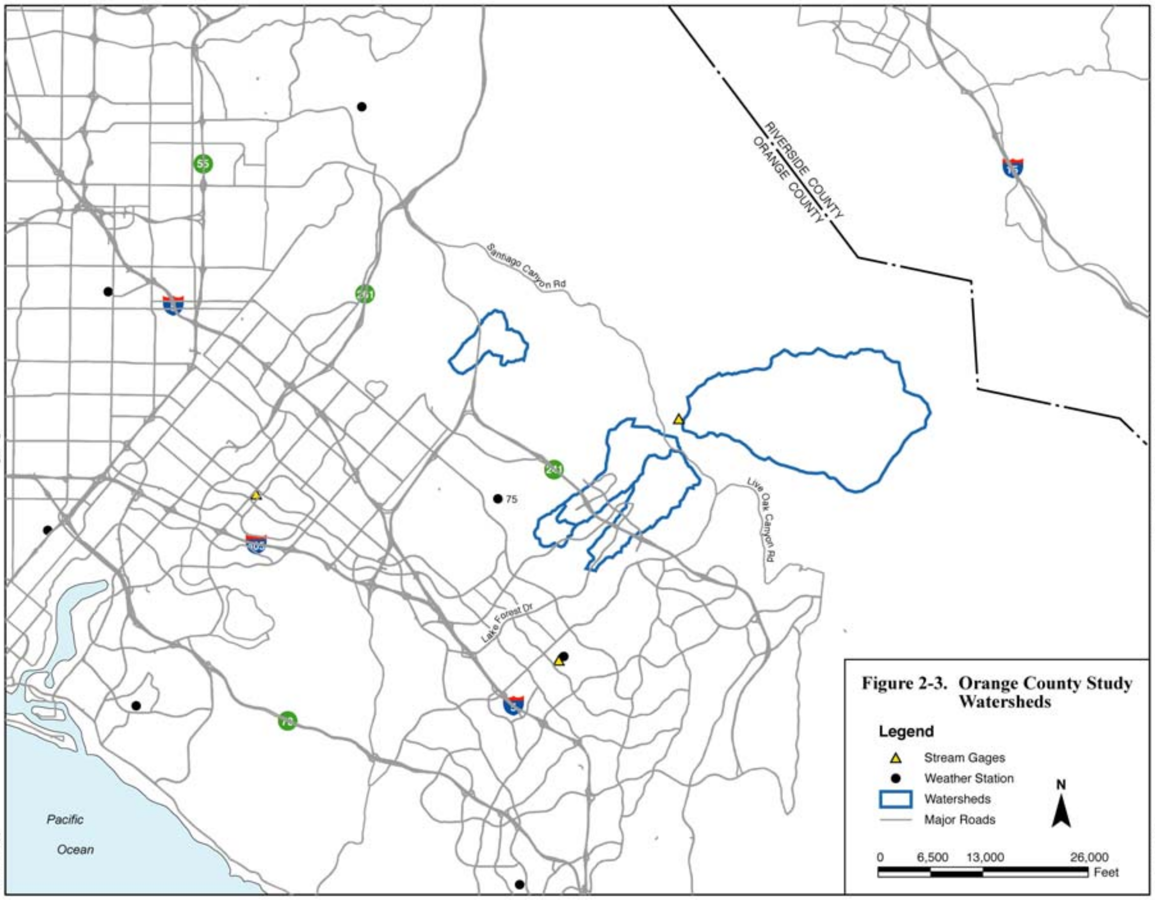


Figure 2-3. Orange County Study Watersheds

2.3.2 Field Data

Current conditions at each study site were evaluated through measurements and observations made during a two-week field program conducted from 3-May-2004 through 13-May-2004. A five- to seven-person field crew collected the data. The field procedures and data collection techniques are briefly described below. Data collected during this field program are provided in Appendix B.

Topographic Surveys. Distance and elevation readings were made using a Leica TPS700 Total Station surveying instrument. This instrument was capable of measuring distance, elevation difference, and declination from the instrument to a survey target, or prism. Readings were taken for specific stream channel features along the reach (thalweg, cut banks, bars chutes, etc.) as well as for the individual cross sections of interest. At least one cross section per site was termed the Master Section, and it coincided with the historic cross section, thus allowing comparison with the historic section(s) for that specific study reach. Generally the Master Section was the middle cross section in a series of three to five sections, and often had more detailed bed sediment data gathered, in addition to being the section used for evaluating historic changes at the site. Spacing of the cross sections were at distances approximately equal to 5 bankfull channel widths apart, for each of the 5 cross sections. Stream channel feature interpretations were also based on the geomorphic mapping prepared for the reach. Cross section surveys provide key data on stream channel morphology and capacity, which can be compared to historic values. Table 2-6 provides the details of which current cross sections match to the historic cross section(s) for each site. Longitudinal profile data, which also were measured during these topographic surveys, are important for deciphering current hydraulic conditions at these reaches, as well as estimating past or future conditions.

Geomorphic Mapping. Detailed mapping of geomorphic features was prepared for the reach at each study site using tape measure readings from a survey centerline that was established for the site during the survey. The centerline tape was turned and extended as needed to complete the full reach. Centerline points were included in the topographic surveys to help align and combine them with the synoptic geomorphic mapping, once both were completed. Specific geomorphic features were mapped that would aid in interpreting the current conditions in the study reach and help define what morphological changes had occurred.

Bed Material. Composition of bed material was characterized through a combination of pebble counts (Wolman 1954) and sieve analyses at a selected number of points across the bed at each surveyed cross section for all study sites.

Bank Material. Composition of the material in the stream channel banks was characterized through a combination of sieve analyses, detailed soil descriptions including standard field assessment of silt and clay fractions.

Rapid Geomorphic Assessment. In addition to the detailed synoptic mapping that was conducted, a quick assessment of the condition of each reach was made with a tool called the rapid geomorphic assessment (RGA; see Section 5.7 for additional details on the RGA).

Table 2-6. Matching Cross Section Surveys

		Historic Cross Section ID[1]					
Site	**Current Section[2]:**	**1**	**2**	**3**	**4**	**5**	**6[3]**
Site 1.	Topanga Creek	--	TS-1	--	ns	ns	ns
Site 3u.	Hasley Canyon (upstream)	--	--	--	HC-2	ns	ns
Site 3d.	Hasley Canyon (downstream)	--	HC-2.5	--	--	ns	ns
Site 4u.	Plum Canyon (upstream)	--	--	--	PC-3	PC-4	ns
Site 4d.	Plum Canyon (downstream)	--	PC-1	--	--	--	ns
Site 7u.	Borrego Canyon (upstream)	--	--	Range 4A	--	--	ns
Site 7d.	Borrego Canyon (downstream)	--	--	Range 4D	--	--	ns
Site 9.	Serrano Creek	--	--	Range D	Range C	Range B2	ns
Site 10.	Santiago Creek	XS-4	XS-3	XS-2	XS-1	--	ns
Site 23.	Dry Canyon	--	South	Middle	North	--	na
Site 27.	Hicks Canyon	--	Range A2	--	Range A4	--	Range A3

(1) Historic sections as identified by the source.

(2) Current section numbering starts at the downstream end of the reach. Unique section identification numbers have been given to each current section for the discussion and data presentation in Appendix C.

(3) Section 6 was surveyed only for Hicks Canyon, and that section was on a tributary, not the main stream channel.

ns Not a surveyed cross section in the current program.

3. STREAM CHANNEL STUDY SITES

The site selection effort covered a six-county region, including Los Angeles, Orange, Riverside, San Bernardino, San Diego, and Ventura counties. There were two general phases in the site selection process. Phase I was a screening process to identify candidate sites that generally appeared to meet the selection guidelines established for the project. Contacts were made either by networking referrals or targeting local agencies in the study region. The final candidate site list included a total of 27 stream channel locations in five of the six counties in the study region. No candidate sites were identified for Riverside County. Locations of all 27 candidate sites are shown in Figure 2-1. Phase II was a closer evaluation of the candidate sites to see how much data was available for each, and how well they met the specific selection guidelines. A total of 8 streams were selected for the study, after it was established that sufficient data was available for each. Two of these streams had multiple sections that proved distinct enough to be treated as separate sites. Therefore, sites 4 and 7 were divided into an upstream (4u and 7u) and a downstream (4d and 7d) site prior to field data collection. The selected sites are identified and key information provided on each in Table 3-1. After field data gathering was completed, it was concluded that Site 3 should also be treated as two separate sites. See the site description for Hasley Canyon in Section 3.1 for a discussion of this adjustment. Therefore, the final list of sites with data used in the evaluation presented in this report, included 11 sites in 8 different watersheds.

Table 3-1. Study Site List

Site No.	Site Name	CDA (mi^2)	Major Watershed	Type of Site	County	Thomas Brother's Map Sheet No.
1	Topanga Creek	18.07	Santa Monica Bay	Control Site	Los Angeles	630
3u	Hasley Canyon	1.55	Santa Clara River	Control Site	Los Angeles	4459
3d	Hasley Canyon	1.66	Santa Clara River	Developed Site	Los Angeles	4459
4u	Plum Canyon	2.23	Santa Clara River	Developed Site	Los Angeles	4461
4d	Plum Canyon	2.40	Santa Clara River	Developed Site	Los Angeles	4461
7u	Borrego Canyon	2.27	San Diego Creek	Developed Site	Orange	861
7d	Borrego Canyon	3.06	San Diego Creek	Developed Site	Orange	861
9	Serrano Creek	2.64	San Diego Creek	Developed Site	Orange	862
10	Santiago Creek	12.36	Santa Ana River	Control Site	Orange	832
23	Dry Canyon	1.22	Calleguas Creek	Control Site	Ventura	478
27	Hicks Canyon	1.33	San Diego Creek	Control Site	Orange	831

CDA = catchment drainage area

3.1 Study Site Streams

The stream channel study sites used in this investigation, with two exceptions, were formed in medium to coarse alluvial materials (sands and gravels). Topanga Creek and Serrano Creek were the exceptions, both being influenced by bedrock. The larger channels formed in alluvial materials have similar wide, shallow shapes (width to depth ratios greater than 20). The smaller watersheds, bedrock channels, and the control sites all have narrower and deeper channels (width to depth ratios smaller than 20).

Topanga Creek. Topanga Creek is located in western Los Angeles County between Highway 101 and the Pacific Ocean. The creek empties directly into Santa Monica Bay between Pacific Palisades and Malibu. The long axis of its watershed is oriented in a north-south direction and much of the watershed is in the Santa Monica Mountains. The watershed has some development in the northernmost part in the Glenview area and also in the central part of the watershed in Fernwood. The study site is located along Highway 27 (Topanga Canyon Boulevard), approximately halfway between Highway 101 and the Pacific Coast Highway. Gage records for this watershed show that it should be considered a perennial stream. Only 6 years in a 68-year record showed a minimum flow of zero.
Topanga Creek has outcrops of resistant volcanic bedrock in or near the channel in the study reach. There are also deposits of very coarse alluvial material, ranging from sand and silt to boulder sizes, in the valley bottom. The alluvium forms a flood plain with an atypical alluvial surface and rugged channel banks.

Hasley Canyon. Hasley Canyon is situated in northwest Los Angeles County west of Interstate 5, north of State Route 126, and between Lake Piru and Castaic Lake. The watershed trends from the northwest to the southeast. Development is occurring in the watershed adjacent to and upstream from the study site. Hasley Canyon is a tributary to Castaic Creek and is situated about 1.4 miles upstream from Castaic Creek's confluence with the Santa Clara River. The stream channel at this site is considered ephemeral, although there is a tributary entering from the west that had a small flow coming from the new large-lot residential development across Hasley Canyon Road. Evaluation of the data for Hasley Canyon demonstrated distinctly different changes at the upstream cross section (#4) compared to the other sections (#1, #2, and #3). It was concluded that a tributary to the main channel joining between section #3 and #4 affected only the lower sections (#1, #2, and #3). Furthermore, the watershed of this tributary includes all of the recently developed land (i.e. all of the increased total impervious surface area (TIMP)). As a result, the Hasley Canyon site has been divided into two sites; an upstream site (section #4) and a downstream site (sections #1, #2, and #3).

The Hasley Canyon channel is formed in a finer grained alluvium in the channel and has a more cohesive channel bank than most of these sites. In addition, there is an obvious enlargement and slight incision of the channel downstream from the tributary channel that drains the adjacent housing development.

Plum Canyon. Plum Canyon is located northeast of Santa Clarita in the Canyon Country of northern Los Angeles County. The watershed is a tributary of Bouquet Canyon, which empties into the Santa Clara River near the town of Saugus. The watershed is a northeast to southwest trending basin that is moderately developed in the lower portion and undergoing development in the upper portions. Two study reaches were used on Plum Canyon as sites, separated by a distance of more than 500 feet. Both sites are considered ephemeral stream channels, and both were dry in May 2004 during field data collection.
Plum Canyon, the stream channels of both the upstream and downstream sites, are formed in coarse materials (sands and gravels) and have wide, shallow channel shapes. These are among the steeper sites, both averaging more than a 2% gradient. Upstream from both sites is a major valley fill that has accounted for most of the new development within the watershed, extending up to the crossing of the Plum Canyon/Whites Canyon Road. In the early to mid 1990s a box culvert (twin 8' x 8' cells approximately 200' long) was installed to carry stream flow from Plum Canyon under the road. An extension of that conveyance (in the form of a single, 10-foot diameter, round concrete pipe) was installed

within the past five years to allow the placement of the valley fill. The outlet of this concrete pipe lies at least 1,500 feet upstream (linear channel distance) from the most upstream channel. This is well beyond the selection guideline of 10-20 bankfull widths (approximately 580 feet to 1,160 feet based on an average bankfull width of 58 feet for the upstream Plum Canyon site).

Borrego Canyon Wash. Borrego Canyon Wash is located in Orange County northeast of Interstate 5 and drains across the new Foothill Transportation Corridor toll road (State Route 241). In its lower reaches (downstream from the study reaches) the wash is confined within a U-shaped concrete channel as it runs adjacent to the former El Toro Marine Corps Air Station. Borrego Canyon Wash empties into Agua Chinon Wash about 1 mile upstream from its confluence with San Diego Creek. The watershed trends from northeast to southwest. A good portion of the watershed from the former Marine Corps base upstream to the toll road is mostly undeveloped. The watershed above the toll road is fairly heavily developed, except in the Whiting Ranch Park, which occupies most of the headwaters area. The two Borrego Canyon Wash study sites are separated by a significant stream channel distance and represent distinct stream channel types. Both sites are considered to be ephemeral stream channels, and both were dry in May 2004 during field data collection.

The Borrego Canyon sites, both upstream and downstream, are formed in alluvial materials consisting of sands and gravels. While both sites have wide, shallow channels, the upstream site has the widest channel of all the study sites, averaging 95 feet.

Serrano Creek. Serrano Creek is located in Orange County. It is similar in size, shape, and alignment to Borrego Canyon Wash and shares a common watershed boundary to along the northwestern side. However, the Serrano Creek watershed is developed to a greater extent than Borrego Canyon wash. Much of the lower portion is occupied by residential development. The middle portion contains primarily commercial type development, although some open space is present. The upper portion has significant areas of residential development, but also contains the Whiting Ranch Wilderness Park. Serrano Creek is a tributary to San Diego Creek with a confluence just east of Interstate 5. The Serrano Creek study site is upstream from Dimension Drive. Although once this site was considered to be an ephemeral stream channel, because of the degree and proximity of development, this site appears to have a small amount of base flow most of the time.

Serrano Creek has a soft sedimentary bedrock that forms the channel bed and most of the channel banks. It is the most deeply entrenched study site, and has the smallest width to depth ratio (averaging less than 4).

Santiago Creek. Santiago Creek is located in Orange County. It is a tributary to the Santa Ana River and drains portions of the southern flank of the Santa Ana Mountains. The watershed is mostly undeveloped except for pockets of houses along Modjeska Canyon Road between Santiago Canyon Road and the Tucker Wildlife Sanctuary. The upper part of the watershed is in the Cleveland National Forest and is undeveloped. This site is considered to be an ephemeral stream channel, and it was dry in May 2004 during field data collection. Santiago Creek serves as a control site.

Santiago Creek is formed in alluvial material that appears to have been modified somewhat by earthmoving equipment to help maintain a flood protection berm adjacent to the channel. This was probably associated with the last major flood event in 1995, and natural hydrologic forces have been at work modifying and maintaining the channel configuration since.

Dry Canyon. Dry Canyon is located in Ventura County on the northern side of Simi Valley, less than a mile north of State Route 118. It is about halfway between the City of Moorpark and the Los Angeles County line. The watershed trends north to south and is a tributary to Arroyo Simi. Flow from Arroyo Simi empties into Arroyo Las Posas, which is a tributary to Calleguas Creek. The watershed is undeveloped except for the Lost Canyon Golf Club. This site is considered to be an ephemeral stream channel, and it was dry in May 2004 during field data collection. Dry Canyon serves as a control site. The Dry Canyon channel is formed in alluvium, though the bed material is primarily sand and the banks are fairly cohesive. This has resulted in a width to depth ratio that is among the smallest of the study sites (averaging less than 6).

Hicks Canyon Wash. Hick's Canyon Wash is located in the foothills of the Santa Ana Mountains in Orange County. It is a tributary to Rattlesnake Wash, which empties into Peters Canyon Wash before it discharges into San Diego Creek. The site reach is north of Portola Parkway, south of the Foothill Transportation Corridor Toll Road, and just east of the Hicks Canyon Haul Road. Most of the watershed is undeveloped. This site is considered to be an ephemeral stream channel, and it was dry in May 2004 during field data collection. Hicks Canyon serves as a control site.

Hicks Canyon appears to be entrenched into a thick (greater than 10 to 20 feet) alluvial sequence. The channel bottom consists of sands with minor amounts of gravel. The banks are made of similar materials that are cohesive. Consequently, the channel has the smallest width to depth ratio of any of the alluvial channels (averaging just over 5).

3.2 Suitability of Selected Sites

One of the great difficulties in this project was locating suitable study sites, due to the specific requirements of the site selection guidelines. Thus it is reasonable to inquire about the satisfaction of selection guidelines by the final sites included in the study. A summary of how well these sites meet the selection guidelines is provided below. There is no specific order of importance of the selection guidelines, however, the first five are all equally important and critical for a successful outcome.

Small Watershed Size. The desired CDA size range for a selected study site was between 1 square mile and 5 square miles. As shown in Table 3-1, all of the study sites fell within this size range, except Topanga Creek and Santiago Creek, both of which are control sites. Thus, all of the watersheds that have experienced some level of development (i.e. the altered sites) are within the desired watershed size range.

Shear Stress Dominated. Streams that have movable beds and erodible banks under the normal range of stream flows (from frequent to infrequent) are considered to be "Shear Stress Dominated." In general this includes channels formed in alluvial materials, but not those formed in bedrock materials. The latter are generally considered to be "bedrock dominated" channels. By this definition, all of the channels included in this study would be considered as shear stress dominated, except Serrano Creek. However, the bedrock in the site reach of Serrano Creek is considered to be soft enough that normal stream flows can erode it.

On the other hand, Topanga Creek, although technically an "alluvial" channel is somewhat limited in its erodibility. The alluvial materials present are dominated by extremely large particle sizes, and are also underlain by resistant bedrock. Therefore, it is very difficult to move these alluvial materials with the frequent (smaller size) flows, and even more difficult to move or erode the bedrock even with rare flood events.

Natural Channel. The stream channel sites used by this study needed to be found in a more or less "natural" state, meaning that they are not controlled by engineering works. By this definition, all of the sites included in this study have natural channels with freedom to deposit or erode bed material or bank material, and alter their geometry by the action of their flows. Many of these channels have "unnatural" stretches either upstream or downstream, and sometimes both. The control sites had very limited amounts of unnatural channel reaches, while the developed watershed sites generally at least had downstream engineering works. One of the control sites, Santiago Creek, had evidence of anthropomorphic manipulation in that a berm had been constructed to limit the flooding extent on the valley bottom for very large flows. However, this berm was well away from the active channel and did not impact the channel configuration of the bankfull (Dominant Discharge) stage. Therefore, the site is considered acceptable as a natural, or self-formed stream channel reach.

Watershed Development. Because this study evaluates the impacts from watershed development on natural stream channels, it was equally necessary to have study sites that included watershed development, except in the control sites. The desired level of development, in terms of impervious area, was a TIMP value of between 5% and 10%. As will be discussed in Section 5, the sites with developed watersheds had TIMP values that ranged from 3.3% to 26.7% (see Table 5-1 in Section 5). In contrast, the control sites had TIMP values that remained very constant throughout the time period that was evaluated, and these ranged from 0.2% to 2.8%. Additional details about the measurement of impervious cover and its change over time in the developed watersheds is provided in Appendix A1.

Historic Cross Sections. Historic cross section surveys provide the means by which channel change can be measured. Therefore, the availability of such surveys for each of the study sites was imperative. The number of historic cross section locations for each site varied, as did the number of times each was surveyed previously, and the total time span covered. Most of the sites had only one previously surveyed cross section (Topanga, Hasley u/s, Hasley d/s, Plum d/s, Borrego u/s, and Borrego d/s). However, all but the Topanga cross section were surveyed more than once. The remaining sites had multiple cross section locations surveyed (Plum u/s: 2, Serrano: 3, Santiago: 4, Dry: 3, and Hick's: 2). Table 2-3 provides background on the match-up between historic sections and sections resurveyed during field data gathering for this project. Appendix Table A4-1 gives details concerning the dates of the previously surveyed cross sections.

Stream Flow Data. Although important, stream flow data was not imperative since engineering practice has provided the means by which flows can be estimated. Certainly actual flow measurements are superior to use than estimated values, but the stream gaging network in southern California is limited. Therefore, a single and distinct stream gage for each of the sites providing accurate and substantive coverage of the stream flow history of each stream was not expected, nor was it realized. Two channels did have stream flow records of significant length at or near the site location, Topanga Creek and Santiago Creek. Other stream gages were located in general proximity to the remaining sites (see Figures 2-2 and 2-3 for the locations). Table 2-4 identifies the stream gage records used in this project, and Appendix A2 provides the annual peak flow record available for each of these gages.

Aerial Photos. Available aerial photos can be used for evaluating land use changes over time, and if they are of a large enough scale, can provide information on channel plan form at specific points in time. Photos obtained for this project were limited in coverage (Table 2-2) and not detailed enough to show channel plan form at any of the study sites.

Topographic Maps. Us of topographic maps for evaluating channel form changes requires that they be at a very detailed scale. The guideline established for this use in the current project was for amps with a scale of least 1 inch equals 100 feet (or better) and a contour interval of 1 foot. No contour maps meeting these guidelines were identified for any of the study sites.

Geotechnical Data. Geotechnical data (descriptions of the soil/sediment materials) were sought to provide historical comparisons with the current data collected at each site of bed and/or bank material. Unfortunately, no geotechnical data was located for any of the study sites.

In summary, the selected study sites meet the critical guidelines established for site selection in this project very well, with one exception. Topanga Creek is limited in that there is only one historic cross section, and it was surveyed relatively coarsely compared to the other historic cross sections surveyed for the other study sites. In addition, the specific location of the historic Topanga Creek section was not reoccupied with a high level of confidence. None-the-less, the data generated for this site is valuable as it provides information for a channel type and watershed size not included in the other sites. This allows better definition of the results as it provides a broader spectrum of plotting positions in many of the deterministic relationships and channel adjustment relationships discussed in later sections of this report. The final sites selected are considered to provide a reasonably robust data set. The main limitations of these data are the relatively short period of time that is covered by the historic period and the similar channel types of all the sites except Topanga Creek and Serrano Creek. However, this is an unavoidable limitation of the study.

4.0 STREAM CHANNEL CLASSIFICATION SYSTEM

Different stream types respond to changes in peak flow in different ways. Therefore, it was necessary to develop a classification system to organize relationships between impervious cover and channel stability and guide management decisions for each stream type. The classification system proposed here focuses on the relevant physical attributes of the system starting with large-scale features (the watershed) and progressing toward detailed consideration of bed and bank properties for specific stream channel reaches.

The framework for the proposed classification system includes three primary factors, or levels that can be used to systematically separate sites into similar management units based on physical characteristics. Each level has a different focus with a specific set of considerations that are described in the subsections below. The levels can be summarized as follows. Details about selecting features of form and process used in classifying streams are provided in Appendix C1.

- **Level 1. Watershed Characteristics.** The first step in classification is to define the nature of the watershed. Watershed characteristics include the physical attributes of the basin including size, shape and topography that may affect runoff patterns in the stream of interest.
- **Level 2. Stream Channel Characteristics.** The next step in classifying stream reaches is to define the stream channel type. Stream channel characteristics involve the stream channel morphology, channel form (shape and slope), energy potential (flows in the stream channel), and degree of alteration
- **Level 3. Stream Channel Resistance.** The third step in classification is an assessment of the expected, or potential, responsiveness of the stream channel system to perturbations in the watershed system by such things as changing land uses. This level focuses on a characterization of the ability of the stream channel to resist erosion based on the inherent mechanical properties of the bed and banks.

4.1 Watershed Characteristics

The first factor for differentiating sites is the size and nature of the watershed, or catchment drainage area (CDA). Zielinski (2002) provides a useful classification of CDA size in urban streams (Table 4-1). An alternate size discriminator could be stream order, though assigning stream order is dependant on the map scale used and the mapping methodology. Because there currently is no consistent regional map that includes all ephemeral and intermittent streams, stream order is not recommended as an alternative for CDA.

The focus of the present study was on smaller drainage areas that generally are more responsive to changes in impervious surface area. Therefore, the proposed classification system focuses on small watershed management units that fall within the size range of the subwatershed- and catchment-size categories of Table 4-1.

While CDA is the most obvious differentiator among watersheds, it is by no means the only characteristic that can be used. Topographic relief, shape, and location within the study region can all affect rainfall-runoff response. However, CDA is likely to have the greatest effect on runoff, so it is the focus of Level 1 of the proposed classification system.

Watershed management units should be delineated in three size ranges, defined by their degree of sensitivity to land use change (Table 4-2). In general, priority should be given to the management of the smallest units first (2.5 square miles or less) as they provide the greatest sensitivity to change and are the most responsive to management actions. Zielinski (2002) offers several other considerations for delineating watershed management unit boundaries.

Table 4-1. Possible Watershed Management Units

Watershed Management Unit	Typical Area of Feature (mi^2)	Relative Influence of Impervious Cover	Sample Management Measure
Catchment	0.05 – 0.5	Very strong	Stormwater management and site design
Subwatershed	0.5 – 30	Strong	Stream classification and management
Watershed	30 – 100	Moderate	Watershed based zoning
Sub-Basin	100 – 1,000	Weak	Basin planning
Basin	1,000 – 10,000	Very Weak	Basin planning

From: Zielinski, 2002.

Table 4-2. Level 1 CDA Categories

Category	Designation	CDA (mi^2)	Explanation
Very sensitive	i	≤ 2.5	Basins of this size show the greatest rates of change in response to urbanization. It is easier for development to impact a larger portion of the CDA.
Mildly sensitive	ii	≤ 10.0	Between 2.5 and 10.0 square miles the rates of change in stream channel morphology in response to changes in impervious area fall significantly.
Least sensitive	iii	≤ 20.0	Basins larger than 10 square miles but less than 20 square miles show some sensitivity to changes in impervious area, but less than the smaller subwatershed areas.

- *Subwatershed size.* In addition to the guidelines in Table 4-2, start delineations downstream from tributary junctions (rather than upstream),
- *Jurisdictional boundaries.* Keep watershed management units entirely within a single jurisdiction(cities, counties, etc.) where possible,
- *Impoundments or stormwater management facilities.* Delineate from the outlet of ponds, lakes, or detention/retention basins,
- *Monitoring stations.* Include existing monitoring stations (stream gages, water quality sample points, etc.) within watershed management unit boundaries where possible,
- *Access points.* Delineate from existing roads or bridges to provide easier access for sample collection or field surveys.

4.2 Stream Channel Characteristics

Level 2 of the classification system focuses on the stability/state of a particular stream reach (Table 4-3). Stream channels are divided into stable or unstable based on the results of the RGA (see Section 5.7). The RGA is a semi-quantitative method for evaluating the stability of a site based on geomorphic indicators observed and recorded in the field. The RGA produces a stability index (SI) that can be used to categorize the geomorphic condition of the stream reach (SI scores range from 0 –1.0). A stability index (SI) score of 0.25 or less indicates that the stream channel is stable, while anything greater that 0.25 indicates that the stream channel is unstable. Alternatively, a qualitative assessment of geomorphic stability can be performed based on observable field evidence of channel instability, such as excessive deposition of sediment, stream channel widening, and/or stream channel scour that is noticeably divergent from upstream and downstream reaches. Unstable stream channels are already reacting to some hydrologic or sediment regime change within the watershed, and therefore have little to no tolerance for additional change to the hydrologic or sediment regime. Unstable stream channels receive no additional classification at this level and are only considered further at the final classification level (Level 3, Stream Channel Responsiveness). Stable stream channels do not show noticeable signs of either aggradation or degradation throughout the reach under consideration. Altered stream channels, i.e. those that have been modified through direct, engineered changes, such as stream channel lining, bed or bank protection, relocation or realignment, stabilization, are not considered further in this classification system, because they fall outside the scope of the present study.

Following the general assessment of stability, stream channels should be further classified according to their morphology (see Table 4-3). The data needed for this classification are the stream channel slope (as measured in the field over a distance of 10 times the stream channel width), and unit discharge (discharge divided by the width of the stream channel). The elevations used to calculate slopes should be a consistent stream channel feature such as the deepest point in the stream channel (thalweg) or the toe of a common bank for the length of the stream channel used. The distance measured for slope calculation should be the curvilinear distance along the flow-line of the stream channel, again using a common feature such as the thalweg (i.e. deepest portion of the channel) or the toe of a bank.

Because discharge data is often not readily available on any given stream, or at any specific point along a stream channel, we recommend using the USGS regional equations (Waananen and Crippen 1977) to calculate the 2-year recurrence interval storm discharge (Q_2), as indicated below. The 2-year equation is selected as the lowest value in recurrence interval for any of the regional equations and the closest to an assumed recurrence for the dominant discharge (1.5 to 2.0 years).

$$\mathbf{Q_2} = 0.14\ \mathbf{CDA}^{0.72}\mathbf{P}^{1.62} \qquad [4.1]$$

Where: **CDA** is catchment drainage area (mi^2)

P is average annual precipitation (in.)

The precipitation value should be selected for a weather monitoring station near the watershed being classified. Selected values of average annual precipitation for stations located in the vicinity of the sites in this investigation are given in Table 4-4. Stream channel widths should be measured in the field at the same time stream channel slopes are measured. Two to four width measurements should be made and averaged to provide the width used to define stream channel morphology with Figure 4-1. The width feature to measure is the top of the “bankfull” channel, which is defined as the top of the “active” channel, which should be discernable (the active channel) by a lack of permanent vegetation and/or the presence of obvious stream channel deposit features such as bar deposits.

Table 4-3. Level 2 Stream Channel Morphology

Condition	Current State	Category	Designation	Indications
Altered	Altered		X	Altered stream channels already have had permanent instream management actions applied; they are no longer considered to be natural
Natural	Unstable		Un	Unstable stream channels show signs of change to the stream channel morphology such as aggradation (excessive sediment deposition), stream channel widening (one or both channel banks have fresh, cut surfaces or undermined bank materials), or channel scour (loose material on the channel bed is scarce and adjacent bank height is significantly different from stable upstream or downstream reaches.
	Stable	Tranquil	St-t	Slope of the stream channel appears to be very shallow; when water is flowing the velocity is relatively slow. Sediment load is very low.
		Anastamosing	St-a	Anastamosing stream channels also have shallow slopes, but slightly steeper than tranquil stream channels. Sediment load is low. Stream channel pattern can be very sinuous, with multiple, inter-twining stream channel threads.
		Meander, Pool-Riffle	St-m	The meandering stream channel is a single conveyance with a slightly to moderately sinuous form that has periodically spaced shallow, rapid flowing water in “riffles” interspersed with deeper “pools.” Depending on sediment type and load riffles can be more transient (fine sediment) or more permanent (coarse sediment) under higher flows. Point bar deposits and cut banks alternate along opposite sides of the stream channel.
		Braided, Cascade-Pool	St-b	The braided stream channel is wide, shallow, and steep with multiple, inter-twining conveyances and an abundant sediment load. Shifting channel positions are common after, or during, periods of channel flow.
		Step-Pool, Canyon	St-s	Cascade-Pool channels are also steep, but have an abundance of very coarse sediment that is beyond the normal capacity of flood flows (except in very rare, high discharge rates). These materials tend to armor the channel and form very persistent, steep-flowing riffle features.

The flow and channel data described above can be used to calculate a unit stream power (2-year peak flow divided by channel width) (Q_2/w). The unit stream power can be plotted against the stream channel gradient for each site (Figure 4-1), This relationship will define the expected form of the stream channel based on measurements of its energy. Deviations from the expected form indicate that the stream reach is in the process of adjusting to a new form. This is discussed in more detail in the next section.

Table 4-4. Selected Annual Precipitation Averages

Station ID	Station Name	Latitude	Longitude	Elevation (feet)	Years of Record	Ave. Annual Precipitation (inches)
LA DPW # 6	Topanga Patrol	34.084167	118.599167	745	77	23.94
LA DPW # 372	San Fran. Pwr Hs	34.533889	118.524167	1,580	63	16.22
LA DPW # 801B	Magic Mountain	34.38833	118.324167	4,720	37	17.53
LA DPW # 1012B	Castaic Junction	34.738333	118.611944	1,005	35	12.40
LA DPW # 1194	Santa Ynez Res.	34.073056	118.566389	735	31	20.25
LA DPW # 1262	Saugus Reclam.	34.413333	118.539722	1,150	19	13.66
LA DPW # 1263	Valencia Reclam.	34.431944	118.620278	1,000	19	12.18
OC RDMD # 121	Santa Ana	33.751111	117.869722	170	96	12.98
OC RDMD # 165	Costa Mesa	33.668611	117.893056	53	48	12.14
OC RDMD # 169	Corona del Mar	33.609722	117.857500	300	44	12.46
OC RDMD # 173	Villa Park Dam	33.814722	117.766667	566	43	15.01
OC RDMD # 176	El Toro	33.627500	117.68333	445	39	14.96
OC RDMD # 216	Laguna Niguel	33.549722	117.70000	200	29	14.58
CIMIS # 75	Irvine	33.688611	117.720556	410	17	14.24
VC WPD # 154	Simi, Co Fire Sta	34.270000	118.781667	760	56	14.85
VC WPD # 193	Santa Susana	34,270833	118.706667	950	47	14.62
VC WPD # 196	Tapo Canyon	34.328333	118.698333	1,525	46	19.20

4.3 Stream Channel Resistance

Level 3 of the classification assesses the ability of the stream channel to tolerate changes in its hydrologic and/or sediment regimes. The hydrologic regime is defined by the quantity and timing of flow, while the sediment regime is defined by the texture (or size distribution) of the sediment load, the quantity of the load, and the timing of its delivery. The quickest and most direct way to evaluate a stream channel's resistance is by plotting its position on the gradient vs. stream power curve (Figure 4-1). If the plotting position of stream power vs. gradient is within the "stable energy" zone for the determined stream channel type, it can be considered as stable. Conversely, if the plotting position is close to the upper limit of the zone, it is an indication of relative instability, because it is approaching, or is within, a transition zone. For example, ω values for Site 23 (Dry Canyon) fall between the 25 and 87 Watts/ft^2 isoclines; therefore this site appears to be a relatively stable braided, cascade-pool system. In contrast, ω values for Site 9 (Serrano Creek) appear to be deviating from the 87 Watts/ft^2 isocline, indicating that the stream channel is shifting to a new morphological form.

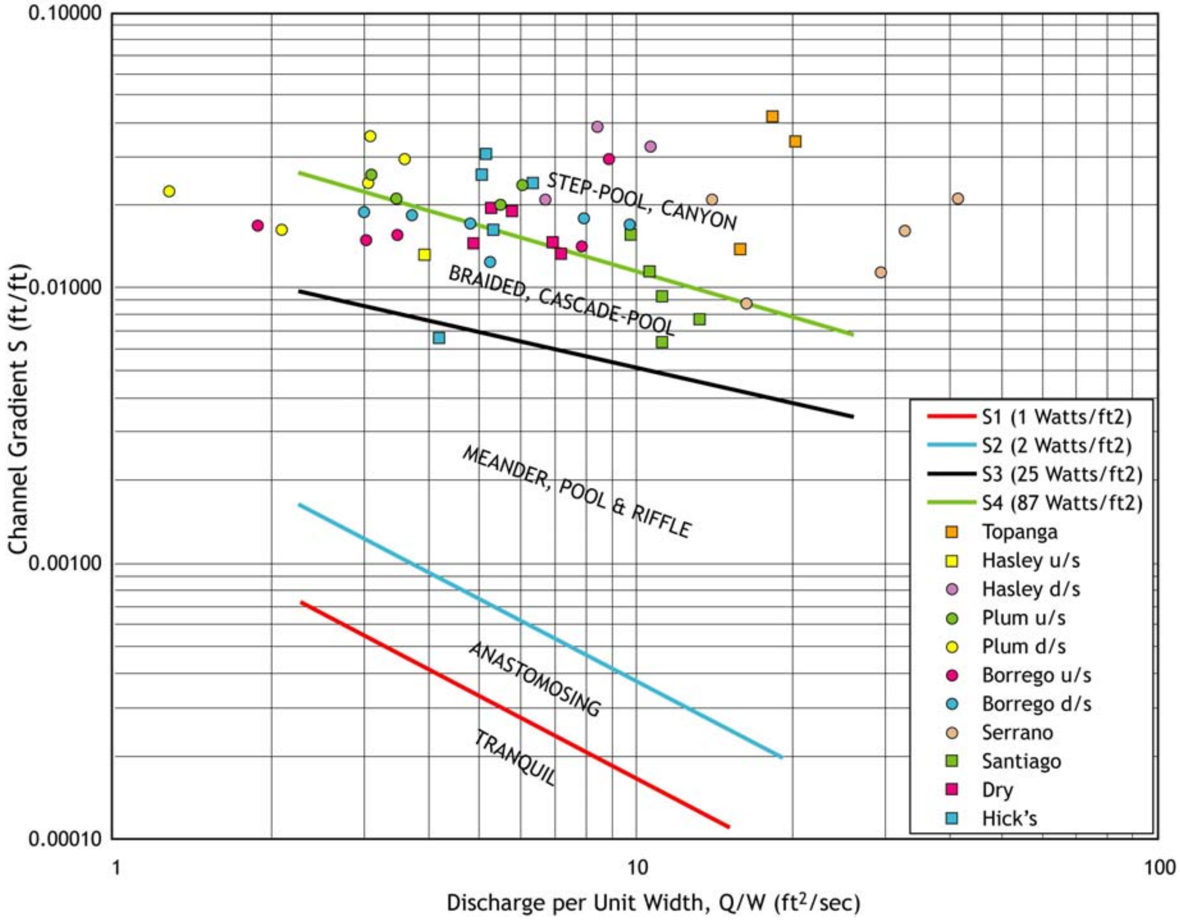


Figure 4-1. Stream Channel Morphology

Stream Power (Discharge/Unit Width) versus Gradient (Longitudinal Slope) for streams within the study area. Energy ranges are defined below:

	Energy Range (Watts/ft^2)	
Classification	*Minimum*	*Maximum*
Step-pool, Canyon	*87.0*	*--*
Braided, Cascade-pool	*25.0*	*87.0*
Meander-pool-riffle	*2.0*	*25.0*
Anastamosing	*1.0*	*2.0*
Non-shear stress dominated	*--*	*1.0*

Additional qualitative classification of channel resistance can be made based on field observations of the relative erodibility of the bed and bank materials (see Table 4-5). For stable stream channels, this evaluation should confirm the plotting position on the stream channel morphology chart (Figure 4-1). In contrast, if the plotting position of a site is within the "meander, pool-riffle" stream channel morphology zone, but the field observations suggest that this site looks more like a "braided, cascade-pool" site, this is an indication that the site is not stable and is about to change stream channel morphology in response to higher energy levels. See Figure 4-2 for an example of this type of assessment.

A more rigorous assessment of the resistance provided by either the bed or the bank is possible using equations for stream power [4.2] and specific stream power [4.3]. First they must be transformed into units of applied shear stress that can be compared to a critical shear stress value for either the bed material or the bank material.

$$\Omega = \rho g Q S \qquad [4.2]$$

where:

Ω = stream power applied to channel perimeter (watts/foot)
ρ = density of channel bed sediment (kilgrams/cubic foot)
g = gravity (feet/second^2)
Q = discharge (cfs) calculated for the channel configuration at which slope, width, and average depth are measured
S = slope of the channel as measured in the field (feet/foot)

Dividing Ω by the stream channel width (W) produces the specific stream power.

$$\omega = \Omega/W = \rho g Q S/W \qquad [4.3]$$

where:

ω = specific stream power (watts/square foot)
W = stream channel width (feet)

Specific stream power can be translated to an applied shear stress, as follows

$$\tau = \rho g d S \qquad [4.4]$$

where:

τ = average shear stress (newtons/square foot)
d = average depth (feet)

Knowing that discharge is a volume per time:

$$Q = AV = WdV \qquad [4.5]$$

where:

A = stream channel cross-sectional area (square feet)

V = average velocity of flow (feet/second)

We can combine equations [4.2], [4.4] and [4.5] to represent stream power in terms of applied shear stress:

$$\Omega = \rho g Q S = \tau V W \qquad [4.6]$$

Finally we can express this in terms of specific stream power:

$$\omega = \tau V \qquad [4.7]$$

Sample Calculation for Channel Form(Hasley Canyon Data)

Step 1 Estimate the drainage area of the watershed to the site and obtain a value of the average annual rainfall for the area.

CDA = 1.66 square miles (from Table 3-1)
P = 12.18 inches (from Table 4-4)

Step 2 Calculate discharge using equation [4.1]

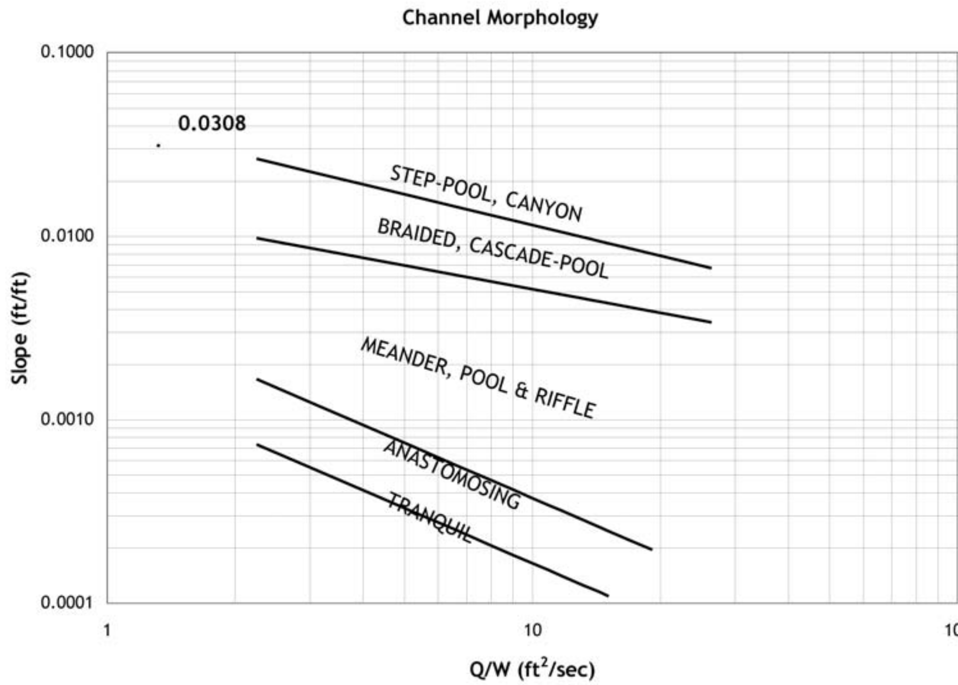
$$Q_2 = 0.14 \times [(1.66)^{0.72} \times (12.18)^{1.62}]$$
$$= 0.14 \times [(1.44) \times (57.38)]$$
$$= 11.57 \text{ cfs}$$

Step 3 Measure bankfull channel width and bankfull channel slope in the field. In this case we are using averages for these values measured from several points in the site reach.

W_{bfl} = 8.71 feet
S_{bfl} = 0.0308 feet/feet

Step 4 Plot these values on the channel morphology classification chart (Figure 3-1).

Q_2/W_{bfl} = 1.33 square feet/second
S_{bfl} = 0.0308 feet/feet



Step 5 Assess channel form as braided based on plotting position. However, field observations suggest the form is actually a step pool form.

Figure 4-2. Example Calculation of Channel Form

Remembering that the length term is a unit value to keep the equation dimensionally correct, it is insignificant in calculations. Therefore, specific stream power can be expressed in terms of calculated shear stress and calculated average velocity. These calculations depend on actual field measurements of the stream channel dimensions and slope, and an estimate of the flow velocity and from there an estimate can be made of the flow rate. In order to apportion the calculated specific stream power to the bed and bank, two “geometric correction” factors are introduced that resolve the specific stream power for these two different parts of the stream channel. They are used in the specific stream power equation [4.7] as follows:

$$\omega = k_b \tau V \qquad [4.8]$$

$$\omega = k_s \tau V \qquad [4.9]$$

where:

k_b = geometric correction factor for the bed (dimensionless)
k_s = geometric correction factor for the bank (dimensionless)

Table 4-5. Level 3 Stream Channel Resistance

Bed Material	**Bank Material** Resistant	Susceptible
Resistant	**Designation**: Bdr / Bkr Generally true for rock channels and rock bed channels with very cohesive to indurated bank materials. These stream channels have the most flexibility for management options as they are best at tolerating changes in hydrologic or sediment regimes	**Designation**: Bdr/ Bks Generally true for rock bed channels with alluvial material in the bank; can also be found in alluvial channels where stream power is not sufficient to carry the current sediment load (braided channel condition).
Susceptible	Designation: Bds / Bkr Unusual for arid streams, though Serrano Creek is an example; there the bed and bank material is a poorly cemented sandstone. Bank material has proven to be more resistant to erosive forces in the stream channel than has the bed material. Channel scour occurs resulting in a deepening of the stream channel. Width to depth ratio of the stream channel should decrease.	**Designation**: Bds / Bks Expect this to occur, if not be common, in ephemeral and intermittent stream channels. Lack of water, or even moisture, in and around the stream channel for much of the year Stream channel scour and widening occurs at the same time. Width to depth ratio should remain relatively constant, but stream channel area (in cross-section) will likely increase.

Using field-measured values to estimate flow (Q), the average velocity can be calculated, the length term is insignificant, and the stream power range has been read from Figure 4-2, so the applied shear stress on the bed can be calculated using equation [4.10] or the bank using equation [4.11].

$$k_b \tau = \omega / V \qquad [4.10]$$

$$k_s \tau = \omega / V \qquad [4.11]$$

In this case it is not necessary to know the value of the correction factors, because the whole term is used to compare to a critical shear stress value (τ_c) determined for either the bed or the banks. Details of the recommended procedure for determining the critical shear stress values are given in Appendix C. A comparison is made between the estimated applied shear stress and the estimated critical shear stress representing the resistance of the bed or bank. Under stable conditions, the following expressions would be true:

$$k_b\tau \leq \tau_{cb} \qquad [4.12]$$

$$k_s\tau \leq \tau_{cs} \qquad [4.13]$$

where:

τ_{cb} = critical shear stress for the bed (newtons/square foot)

τ_{cs} = critical shear stress for the bank (newtons/square foot)

If either expression is untrue, then an unstable condition is present. Depending on which feature is considered stable (or unstable), or if both bed and bank are the same, the classification of stream channel resistance follows from Table 4-6. See Figure 4-3 for an example of this evaluation.

4.4 Classification Summary

This classification is proposed as a starting point for the development of a system that could be applied throughout the southern California region. It does not restrict the classification to ephemeral or intermittent stream channels, but would apply to perennial streams as well. Although the creation of a complete and exhaustive classification system is beyond the scope of this project, a general framework for establishing such a classification system has been presented. This classification system could be used to define characteristics of the watershed-stream channel system that are important in selecting management strategies and approaches, which are discussed in Section 7.2 (Management/Regulatory Approach). A summary of the steps of the proposed stream classification process is provided below. In addition, Table 4-6 provides a summary of the designation of each of the study sites using this classification system.

STEP 1: Locate the CDA within its major watershed.

STEP 2: Identify the CDA category (based on size)

STEP 3: Collect local site information and calculate Q_2 using regional equation [4.1] to estimate stream channel slope and specific stream power

STEP 4: Define stream channel form using calculations from Step 3 and plotting position from Figure 4-1

STEP 5: Estimate stream channel resistance using field evaluations by experienced field personnel, and/or evaluate with measured field data to compare with calculated erosive forces.

Table 4-6. Study Site Classification

Study Site	Watershed Designation[1]	CDA Category[2]	Channel Form[3]	Channel Resistance[4]	Full Designation
1. Topanga Creek	SMB	iii	St-s	Bdr-Bkr	SMB/iii/St-s/Bdr-Bkr
3. Hasley Canyon	SCR	i	Un	Bds-Bks	SCR/i/Un/Bds-Bks
4u. Plum Canyon	SCR	i	Un	Bds-Bks	SCR/i/Un/Bds-Bks
4d. Plum Canyon	SCR	i	Un	Bds-Bks	SCR/i/Un/Bds-Bks
7u. Borrego Cyn.	SDC	ii	Un	Bds-Bks	SDC/ii/Un/Bds-Bks
7d. Borrego Cyn.	SDC	i	Un	Bds-Bks	SDC/i/Un/Bds-Bks
9. Serrano Creek	SDC	ii	Un	Bds-Bks	SDC/ii/Un/Bds-Bks
10. Santiago Ck.	SAR	iii	Un	Bds-Bks	SAR/iii/Un/Bds-Bks
23. Dry Canyon	CGC	i	St-s	Bdr-Bkr	CGC/i/St-s/Bdr-Bkr
27. Hicks Canyon	SDC	i	Un	Bds-Bks	SDC/i/Un/Bds-Bks

EXPLANATIONS

1 Watersheds

CGC Calleguas Creek
SAR Santa Ana River
SCR Santa Clara River
SDC San Diego Creek
SMB Santa Monica Bay

2 CDA Size Ranges (Table 3-3)

i $CDA \leq 2.5$ mi^2
ii $2.5 < CDA \leq 20$ mi^2
iii 20 mi$^2 < CDA$

3 Channel Forms (Table 3-4)

St-b Stable, braided
St-s Stable, step-pool
Un Unstable

4 Channel Resistance (Table 3-6)

Bdr Resistant bed
Bds Susceptible bed
Bkr Resistant bank
Bks Susceptible bank

Disregarding the major watershed location, this classification system could result in one of three size categories, one of seven different channel form types, and one of four distinct channel resistance categories. Therefore, there are potentially 84 distinct classifications (3 x 7 x 4 = 84) of stream channels. The 10 stream channel sites selected for this study represent only 5 distinct channel types in this classification system. Whether or not all 84 stream types are represented in the study region remains to be evaluated.

<u>SAMPLE CALCULATION FOR CHANNEL RESISTANCE</u>
<u>(Hasley Canyon Data)</u>

STEP 1 Establish values for variables of channel characteristics (using field measurements) and properties of water at standard conditions.

W_{bfl}	=	10.6 ft	(from Table 5-6)
S_{bfl}	=	0.0264 ft/ft	(from Table 5-6)
d_{bfl}	=	1.7 ft	(from Table 5-6)
ρ	=	62 lb/ft^3	(density at normal temperatures)
g	=	32 ft/sec^2	(acceleration due to gravity)

STEP 2 Calculate the expected shear stress from the measured channel values using equation [4.4]:

$$\tau = \rho g d_{bfl} S_{bfl} = 62 \times 32 \times 1.7 \times 0.0264 = 89 \text{ newtons/ft}^2$$

STEP 3 Resolve the expected shear stress from Step 2 into an applied shear force on the bed material using the geometric correction factor (k_b), and an applied shear force on the bank material using the geometric correction factor (k_s). The geometric correction factor for the bed shear stress (Lane 1955) is based on the width to depth ratio of the measured channel values established in Step 1 (10.6/1.7 = 6.2). The correction factor for the bank shear stress is also based on channel geometry (Lane 1955).

$$k_b\tau = 0.95 \times 89 = 84.6 \text{ newtons/ft}^2 \quad \text{(Bed material)}$$
$$k_s\tau = 0.75 \times 89 = 66.8 \text{ newtons/ft}^2 \quad \text{(Bank material)}$$

STEP 4 Compare the calculated shear forces on both the bed and bank to resistance values derived with the sediment characteristics measured in the field.

$$84.6 \text{ newtons/ft}^2 \geq 57.2 \text{ newtons/ft}^2 \quad \text{(Bed material)}$$
$$66.8 \text{ newtons/ft}^2 \geq 14.8 \text{ newtons/ft}^2 \quad \text{(Bank material)}$$

STEP 5 Assess channel resistance as Bds-Bks, or a susceptible bed and susceptible banks.

Figure 4-3. Example Calculation of Channel Resistance

5. SUMMARY OF FIELD DATA

For each of the 10 study sites, the following data was collected for both historic and current conditions: 1) characteristics of the catchment draining to the site; 2) rainfall and streamflow; and 3) physical condition of the stream channel.

Land use records and aerial photographs were used to estimate the total impervious surface area (TIMP) values in the study watersheds. Precipitation records were evaluated to gain an understanding of when the wet and dry periods occurred in the regions where the study watersheds are located, and whether or not the rainfall amounts were representative of normal conditions during both the period of land use change and the period of stream channel morphology change. The stream flow records provided data for statistical analyses of peak flow frequency for the different drainage areas and serve as a second piece of evidence to determine the representativeness of the climatic conditions during the period of urbanization. Data on bed and bank material were used to evaluate susceptibility to erosion (critical shear stress) and to help define roughness for hydraulic calculations. The results of these analyses are summarized in the sections below.

5.1 Impervious Surface Area (TIMP)

Data on land uses were either available in ArcGIS format (SCAG data) or were delineated on aerial photographs and imported into AcrGIS. The surface area covered by each land use type was calculated for the watershed (drainage area) of each study site. Each land use type was then assigned a specific percent impervious cover value. Total and percent impervious surface area for each watershed was then calculated based on the extent of land use types within the watershed (Table 5-1). A detailed discussion of the process, the percent impervious cover values used for each land use, and the tabulation of land uses and impervious areas by watershed is provided in Appendix A1.

A word of caution is necessary concerning the use of TIMP to represent the degree of development in a watershed and provide a quantitative value against which to relate observed channel changes. Better relationships would likely result from the use of a different representation of impervious area that accounts for the location of impervious surfaces relative to the stream channel and the connection between impervious surfaces and conveyance routes for surface runoff. Such a measurement is often called CIMP (Connected Impervious Cover) or FRIMP (the FRaction of IMPervious surface that is directly connected to another impervious surface and eventually a storm sewer or to the stream channel). However, FRIMP was not used in this study, for two reasons.

1. It is very difficult to calculate FRIMP because it requires field verification of impervious area connections based on air photo or map interpretation. Not only is it difficult and time-consuming to verify for current conditions, it is nearly impossible to verify estimates for historic conditions. Also, the cost for this level of effort is not reasonable for a regional study of this nature.

2. The bulk of the published literature on the effects of urbanization uses TIMP values, so comparisons of values for southern California would be more appropriate using TIMP values. Nevertheless, it would be useful to revisit the FRIMP values for the study watersheds and compare them to the calculated TIMP values; however, this is beyond the scope of the present study.

Table 5-1. Impervious Area Estimates from Land Use Data

SITE NO.	SITE NAME	PERCENT IMPERVIOUS (TIMP)														
		1949[1]	1952[1]	1967[1]	1968[1]	1972[1]	1978[1]	1982[1]	1983[1]	1990[3]	1993[3]	1997[1]	2001[3]	2002[2]	2003[2]	2004[2]
1	Topanga Creek									2.48%	2.62%		2.82%			
3u	Hasley Canyon (upstream)									1.19%	1.26%		1.34%	1.34%	1.34%	
3d	Hasley Canyon (downstream)									1.19%	1.26%		1.34%	1.34%	3.27%	
4u	Plum Canyon (upstream)									0.15%	0.15%		0.16%		1.73%	16.96%
4d	Plum Canyon (downstream)									0.20%	0.20%		1.64%		1.62%	17.52%
7u	Borrego Canyon (upstream)		1.00%	1.05%		1.03%			1.04%	1.46%	5.80%	13.19%	22.00%			
7d	Borrego Canyon (downstream)		1.23%	1.06%		1.06%			1.08%	1.87%	5.08%	11.47%	21.00%			
9	Serrano Creek	1.08%			1.14%		1.11%	3.74%		5.98%	11.18%	21.75%	26.66%			
10	Santiago Creek									0.23%	0.23%		0.24%			
23	Dry Canyon									0.06%	0.06%		0.70%			
27	Hicks Canyon									0.10%	0.10%		1.24%			

(1) Aerial Photo Interpretation
(2) DigitalGlobe® Satellite Imagery
(3) SCAG Land Use Maps

5.2 Precipitation

Rainfall records were obtained from various sources adjacent to each of the study areas (see Table 2-3). Rainfall data for each of the weather stations listed in Table 2-3, and plots of rainfall amounts over time are provided in Appendix A2. Precipitation data were used to help assess the relative importance of climatic factors on the observed changes in stream channel morphology for the period of land use change covered by this study. Comparisons were made between the rainfall during the post-urbanization period (i.e. the period of interest for this study) and the average annual precipitation to assess the representativeness of the time period being evaluated.(see Tables 5-2, 5-3, and 5-4). Because the empirical investigation methods employed in this study related changes in stream channel form to changes in runoff potential, no direct use of rainfall events, amounts, or intensities was made. The empirical methods attempt to look at cumulative effects rather than specific, event-related results.

Development in the Hasley Canyon and Plum Canyon watersheds has only recently begun; therefore, there is only a short period of record available since urbanization. According to the changes in impervious surface area (see Table 5-1) the limited development in Hasley Canyon began in approximately 2002, while the more extensive development in Plum Canyon began initially in 2002 and continued through 2003. Therefore, the average annual rainfall for the period from 2001 through 2003 was calculated and compared to the average for the period of record for four of the stations near these two watersheds (Table 5-2). For these watersheds, it appears that the rainfall was less than normal during the period of urbanization. Thus, climatic factors probably did not contribute to the impacts on these stream channels.More time has passed since the development in the Borrego Canyon and Serrano Creek watersheds occurred. Using the values of TIMP in Table 5-2 as a guide, the start of development for Serrano Creek was estimated to be around 1980, while in Borrego Canyon it was estimated to be around 1991. Therefore, there are enough records available to consider 3-year, 5-year and 10-year averages for annual precipitation after the start of urbanization (Tables 5-3 and 5-4). Results of these comparisons are much different than for the Los Angeles County streams, and suggest that above-average rainfalls could have played a role in the observed stream channel morphology changes in the Orange County sites. Further discussion concerning the implications of above average rainfall amounts on study results is included in Section 6.2 (Evaluating Changes in Stream Channel Condition).

Table 5-2. Hasley and Plum Canyons Rainfall Comparisons

Comparison of the average precipitation for the period of urbanization to the period of record for the station.

	Station 372[(1)]	Station 801B[(1)]	Station 1262	Station 1263
Ave. Ann. Precip. (inches)	16.22	17.53	13.66	12.18
Length of Record	63	37	19	19
3-Year Period	2001-2003	2001-2003	2001-2003	2001-2003
3-Year Average (inches)	11.64	14.88	13.66	5.86

(1) Only 2 years of record were available for the 2001-2003 period.

5.3 Stream Flow

Stream gage data for peak flows at recording stations at or near study sites were obtained from the USGS web site [http://waterdata.usgs.gov/ca/nwis/nwis] or from Los Angeles County. The data for each gaging station were prepared for plotting flow frequency curves using the Weibull formula (Haan 1977). Values were taken from these curves to prepare regional peak flow curves (CDA vs. peak discharge) for specific, low value recurrence interval events (1.2-year, 2-year, 5 year, and 10-year). Data and curves are provided in Appendix A3.

Table 5-3. Borrego Canyon Wash Rainfall Comparisons

Comparison of the average precipitation for the period of urbanization to the period of record for the station.

	Station 121	Station 165	Station 169	Station 173	Station 167	Station 216
Ave. Ann. Precip. (inches)	12.98	12.14	12.46	15.01	14.96	14.58
Length of Record	96	48	44	43	39	29
3-Year Period	1991-1993	1991-1993	1991-1993	1991-1993	1991-1993	1991-1993
3-Year Average (inches)	17.25	15.03	15.27	20.06	18.97	16.00
5-Year Period	1991-1995	1991-1995	1991-1995	1991-1995	1991-1995	1991-1995
5-Year Average (inches)	17.57	15.00	15.78	19.79	18.89	17.31
10-Year Period	1991-2000	1991-2000	1991-2000	1991-2000	1991-2000	1991-2000
10-Year Average (inches)	16.24	14.36	15.03	18.11	17.84	17.13

Peak flow data were also reviewed as a second approach to consider the impact of climatic factors on the change in stream channel morphology for Borrego Canyon and Serrano Creek. The Santiago Creek gage at Modjeska has a continuous record from 1962 through the present. The entire record of annual peak flows for this gage is presented in Table 5-5. The return periods of the annual peaks from 1980 through 1989 (urbanization period for Serrano Creek) show two flows above an 8-year return period. These flows ranked as the third and fifth largest flows of the 42-year record at this gage. The return periods of the annual peaks from 1991 through 2000 (urbanization period for Borrego Canyon) show two flows above a 10-year return period (ranked as the second and fourth largest flows on record). This concentration of higher than normal flows during these two periods is consistent with the conclusion that climate could have contributed to the morphological changes in the Borrego Canyon and Serrano Creek stream channels.

5.4 Stream Channel Characteristics

Field data gathered in May 2004 consisted of a series of cross sections and a single, longitudinal profile for the entire reach at each site. Measurements of stream channel width, cross-sectional area, average depth, and longitudinal gradient (channel slope) were made for each surveyed cross section (Table 5-6). The common feature used to standardize the measurements among the sites was the bankfull stage (i.e., the elevation/depth of flow that fills the active channel), also referred to in this study as the Dominant Discharge (see Appendix C2 for a discussion of the logic for this determination). In addition, sediments in the stream channel bed and banks were characterized. Hydraulic calculations from the data in Table 5-6 provide an estimate of discharge at the bankfull stage (Q_{bfl}).

Table 5-4. Serrano Creek Rainfall Comparisons

Comparison of the average precipitation for the period of urbanization to the period of record for the station.

	Station 121	Station 165	Station 169	Station 173	Station 167	Station 216
Ave. Ann. Precip. (inches)	12.98	12.14	12.46	15.01	14.96	14.58
Length of Record	96	48	44	43	39	29
3-Year Period	1980-1982	1980-1982	1980-1982	1980-1982	1980-1982	1980-1982
3-Year Average (inches)	16.12	16.30	16.56	17.79	15.85	14.45
5-Year Period	1980-1984	1980-1984	1980-1984	1980-1984	1980-1984	1980-1984
5-Year Average (inches)	15.73	15.38	15.93	18.16	17.11	16.15
10-Year Period	1980-1989	1980-1989	1980-1989	1980-1989	1980-1989	1980-1989
10-Year Average (inches)	16.34	15.90	16.00	18.68	17.56	16.17

Nine of the eleven sites are channels formed in relatively erosive alluvial material. The remaining two sites are bedrock controlled (i.e. outcropping bedrock in the channel and banks within, or very near to, the study reach). Although not caused by geomorphic setting, the most obvious difference in these two sites from other sites is that Topanga Creek (the largest watershed) and Serrano Creek (the most developed watershed) are the only two non-ephemeral stream channels in the study. Both channels had flowing water at the time of the survey in May 2004. However, it was not documented whether flow persisted all year (i.e. whether either stream is perennial). Despite that fact that Topanga and Serrano creeks were both bedrock controlled, differences in the composition of the bedrock influenced their relative resistivity. The Topanga Creek site consists of resistant bedrock that provides the source of coarse sediment in the channel (cobble to boulder size). In contrast, the bedrock in Serrano Creek is a poorly-consolidated sandstone that has proven to have little resistance to erosion.

Differences in channel type help explain some of the variability in channel metrics between the sites. Nevertheless it is useful to consider this data set as a whole and make some general statements about the values obtained for the existing conditions at these sites. Judging by the values in Table 5-6, the calculated discharge rates for the bankfull stage show the greatest consistency among the sites. The standard deviation for the Dominant Discharge (Q_{bfl}) calculated for each site show the lowest values and smallest range of values of any parameter in the table. Figure 5-1 shows the relation between CDA and the Dominant Discharge. The developed sites show higher runoff rates for similar watershed areas. On the other hand, the measured widths and slopes have the highest values and largest range of values. This is logical in that discharge should be the most dependent on watershed size, and therefore vary the least in a short channel reach. The fact that this calculated value is consistent for all of the sites demonstrates that the bankfull stage is a reliable feature to identify in the field and use for comparison purposes. It is also important to point out that the downstream sites at Plum Canyon and Borrego Canyon Wash have smaller values for the Dominant Discharge than the upstream sites. Therefore, it is apparent that in each of these reaches there is loss of flow between the upstream and downstream sites. This can be explained as a loss to infiltration into the porous materials in the channel bottom.

Table 5-5. Stream Gage Record for Santiago Creek at Modjeska

Annual peak flows for the period of record (water years 1962 – 2003)

Rank	Peak Q (cfs)	Peak Date	Return Period (years)	Rank	Peak Q (cfs)	Peak Date	Return Period (years)
11	825.00	16-Mar-03	3.91	20	386.00	20-Jan-82	2.15
42	3.40	21-Dec-01	1.02	17	483.00	29-Jan-81	2.53
34	75.00	25-Feb-01	1.26	5	1,810.00	18-Feb-80	8.60
31	97.00	21-Feb-00	1.39	14	555.00	05-Jan-79	3.07
41	5.60	26-Jan-99	1.05	6	1,550.00	09-Feb-78	7.17
2	6,200.00	23-Feb-98	21.50	39	16.00	07-Jan-77	1.10
24	257.00	26-Jan-97	1.79	18	440.00	01-Mar-76	2.39
33	77.00	21-Feb-96	1.30	28	185.00	08-Mar-75	1.54
4	2,400.00	05-Mar-95	10.75	13	575.00	08-Jan-74	3.31
36	36.00	20-Feb-94	1.19	15	516.00	11-Feb-73	2.87
10	1,370.00	17-Jan-93	4.30	25	241.00	25-Dec-71	1.72
12	807.00	12-Feb-92	3.58	35	56.00	21-Dec-70	1.23
23	274.00	01-Mar-91	1.87	32	90.00	02-Mar-70	1.34
22	287.00	17-Feb-90	1.95	1	6,520.00	25-Feb-69	43.00
30	167.00	25-Dec-88	1.43	26	211.00	08-Mar-68	1.65
27	203.00	17-Jan-88	1.59	8	1,420.00	06-Dec-66	5.38
40	13.00	05-Jan-87	1.08	7	1,500.00	22-Nov-65	6.14
19	396.00	29-Nov-85	2.26	29	175.00	09-Apr-65	1.48
9	1,400.00	19-Dec-84	4.78	38	17.00	02-Apr-64	1.13
16	490.00	24-Nov-83	2.69	37	30.00	10-Feb-63	1.16
3	3,400.00	02-Mar-83	14.33	21	302.00	11-Feb-62	2.05

Given that the variability of channel depth and cross-sectional area are also relatively small, the high variability in the width and slope are quite logical. Since the flow in these sites is conservative (as the data in Table 5-6 suggest) flow is not changing much over time, nor is the depth of flow or channel area. Therefore, adjustment to changes in stream power to maintain channel competency (i.e. its ability to transport sediment load) is accomplished primarily through changes in width and slope of the channels. This is easily accomplished in alluvial channels with the abundance of loose sediment material available to move and be reshaped.

5.5 Dominant Discharge

The concept of using a single, discrete flow to represent the actions of a range of flows that a channel experiences, is very useful. This is the basis for the use of the term *Dominant Discharge*. The actual value of the Dominant Discharge has been defined in various ways, (a) related to channel form (as in meander wavelength), (b) the flow that does the most work, statistically, in carrying sediment, or (c) the flow which fills the channel to capacity (i.e. the "bankfull stage"). Knighton (1984) asserts that there is enough evidence from previous studies to make a compelling case for a convergence of these methods of defining Dominant Discharge.

Table 5-6. Stream Channel Site Data

Average values for measurements and standard deviations taken in May 2004. Actual measurements by cross section are presented in Appendix B1.

Site No.	Name	Value	Q_{bfl} (cfs)	A_{bfl} (ft^2)	W_{bfl} (ft)	d_{bfl} (ft)	S_{bfl} (ft/ft)
1	Topanga	Average	1,427.4	191.1	75.7	6.0	0.0298
		Stnd. Dev.	3.4%	18.0%	9.7%	3.6%	48.3%
3	Hasley	Average	71.0	11.4	10.6	1.7	0.0264
		Stnd. Dev.	7.8%	21.5%	38.1%	12.8%	43.4%
4u	Plum	Average	267.7	49.1	53.7	2.2	0.0216
	Upstream	Stnd. Dev.	11.2%	20.0%	49.2%	23.1%	15.6%
4d	Plum	Average	127.8	32.6	54.8	1.1	0.0257
	Downstream	Stnd. Dev.	7.5%	19.5%	42.7%	22.7%	28.1%
7u	Borrego	Average	343.5	79.0	95.1	1.7	0.0183
	Upstream	Stnd. Dev.	4.2%	32.1%	59.9%	6.5%	34.6%
7d	Borrego	Average	248.1	54.2	54.7	1.9	0.0170
	Downstream	Stnd. Dev.	11.5%	16.7%	34.0%	18.1%	15.5%
9	Serrano	Average	346.1	43.2	17.0	5.2	0.0157
		Stnd. Dev.	3.3%	16.9%	34.7%	22.1%	35.4%
10	Santiago	Average	752.1	136.3	69.9	3.9	0.0101
		Stnd. Dev.	8.9%	16.4%	7.7%	14.6%	35.9%
23	Dry	Average	55.5	11.2	9.6	1.7	0.0163
		Stnd. Dev.	7.6%	9.6%	13.2%	10.6%	17.8%
27	Hicks	Average	48.3	9.1	8.7	1.7	0.0208
		Stnd. Dev.	11.9%	18.0%	13.0%	14.1%	45.9%

The single flow identified as Dominant Discharge is often thought of as a "channel forming" flow that is responsible for the present shape of a natural stream channel. However, the Dominant Discharge is actually just concept, and represents the variability in flows of each watershed. Nevertheless, because of the demonstrated tendency of the Dominant Discharge to be coincident with the current channel form, the bankfull stage can be used to estimate Dominant Discharge. This application is adopted for this study, and the Dominant Discharge is used as a surrogate for the range of geomorphic activities in the channel. Consequently, it provides an effective comparative value among channels.

The obvious concerns with using this feature are how well adjusted it is to the range of flows that are currently representative of watershed activity, and how accurately it can be measured for any given stream channel segment. Both of these sources of error can be significant, but this is an accepted level of uncertainty in geomorphic research when drawing deterministic conclusions about stream channel activity in natural systems. Perhaps the uncertainty is even greater than normal when dealing with bankfull features in semi-arid systems because the channel form can be unduly impacted by the most recent major storm to reach the watershed. Graf (1988) provides a strong argument for the importance of recent flows in dryland watersheds. However, even with the complexities of the relationship between channel form and the range of flows within a watershed (and their timing), this use of the Dominant Discharge concept provided the best opportunity to draw meaningful conclusions about channel behavior in these semi-arid locations.

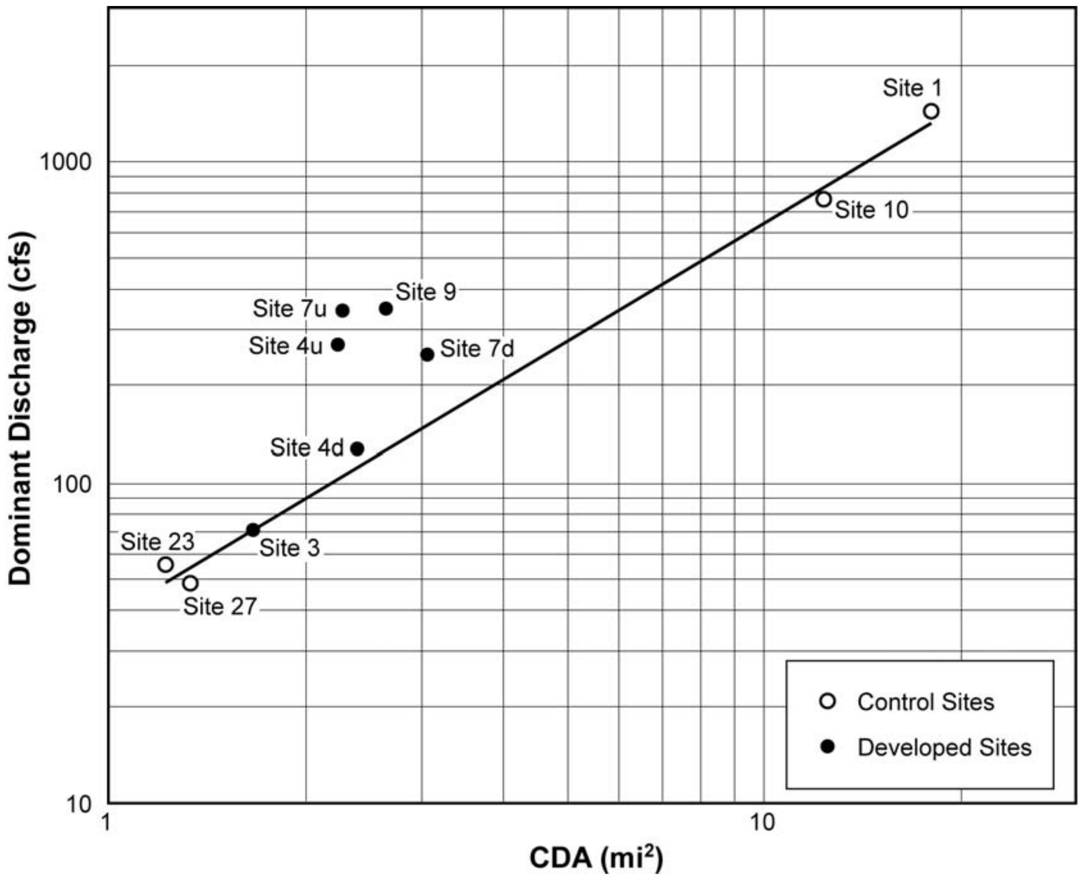


Figure 5-1. Discharge and Drainage Area

The reference line is a best fit for the control sites. Most of the sites with developed watersheds are well above the line, demonstrating greater runoff per unit area than the control sites.

Concerning the specific data for the study sites, the Dominant Discharge calculated for each cross section at every site is based on bio-geomorphic indicators (see Appendix C2). Of interest to this study, as well as urban stormwater managers, is the relative frequency of these discharges. It is well established in the literature that urbanizing watersheds (in the absence of stormwater management measures) have an increase in runoff associated with a storm of a similar frequency. Therefore the return period of the discharge associated with the bankfull stage, the Dominant Discharge, is significant for comparing these sites. Table 5-7 provides two estimates of the value of the return period for the calculated Dominant Discharges for a specific cross section at each of the sites.

Recurrence intervals are estimated with two distinct methods as a means of comparing and validating results. The first method employs the regional equations developed by the U.S. Geological Survey (Waananen and Crippen 1977) to estimate peak discharges for ungaged basins. These equations provide estimates of peak flow for specific recurrence intervals based on watershed size (CDA) and average annual rainfall amounts. Graphs were prepared for each site, plotting recurrence interval vs. discharge, using these equations and specific CDA values and rainfall amounts. The Dominant Discharge calculated for a cross section can then be plotted on the graph to estimated recurrence interval A more detailed description of this process and the results are provided in Appendix C2.

Table 5-7. Recurrence Interval Estimates
Values estimated for current conditions at specified cross sections

Study Site		Section	Date of Survey	Dominant Discharge Q_{bfl} (cfs)	Recurrence Interval	
					USGS Estimate (yrs)	Prorate to Gage (yrs)
1	Topanga Creek	TOP-02	4-May-04	1,381.4	n/a	2.4
3u	Hasley Canyon	HAS-04	9-May-04	64.8	6.2	2.1
3d	Hasley Canyon	HAS-02	9-May-04	77.5	6.6	2.1
4u	Plum Canyon	PLU(u/s)-05	11-May-04	308.2	3.9	5.7
4d	Plum Canyon	PLU(d/s)-02	10-May-04	127.8	7.3	2.5
7u	Borrego Canyon	BOR(u/s)-03	6-May-04	327.7	10.5	6.7
7d	Borrego Canyon	BOR(d/s)-03	7-May-04	292.2	6.6	3.9
9	Serrano Creek	SER-03	7-May-04	353.6	2.8	5.6
10	Santiago Creek	SAN-01	13-May-04	754.4	1.5	4.1
23	Dry Canyon	All stations	11-May-04	55.6	6.4	2.3
27	Hick's Canyon	HIC-04	8-May-04	54.8	6.0	2.2

The second method uses gage records to develop flow frequency curves from which return periods can be read for a corresponding discharge. However, the flow frequency curve is specific for the CDA to the gage. Therefore, the Dominant Discharge calculated for a specific cross section at a study site must be prorated by CDA size to obtain the corresponding flow rate at the gage before its return period can be read from the flow frequency curve.

5.6 Bed and Bank Material

A summary of the particle-size distributions of the channel bed sediment evaluated during field assessment for the current study is given in Table 5-8. The material characterized represents the coarse fraction of bed sediment that is actually or potentially the sediments that result in natural channel armoring. The ϕ_{16}, ϕ_{50}, ϕ_{75}, and ϕ_{84}, values represent the sediment particle size diameter for which 16%, 50%, 75%, and 84% of the cumulative size distribution is smaller. These material size values have been used in the evaluation of channel bed resistance to erosion. In addition to the coarse sediment fraction, the finer sediments were characterized with sieve analyses in the field. The fact that all of these sites had bed sediment ϕ_{50} sizes ranging from sand size (0.01 in. to 0.08 in.) to boulder gravel (greater than 10 in.) indicates that they are poorly to very poorly sorted sediments. The ϕ_{50} size values in Table 5-8 classify most of the "armor fraction" of these sediments in the cobble gravel size range (2.5 in. to 10 in., Compton 1962). The only real distinction among these sites based on sediment size is the order of magnitude difference of the Topanga sediment from the other sites.

A Torvane® shear meter was used to measure the cohesion of the bank materials. The size distributions of bank materials as a description of cohesion (using units of applied shear force) are ultimately used in evaluating the susceptibility of the bed and bank materials to erosion based on the estimated applied shear forces of the Dominant Discharge. Results of the analysis of sediment data, including the size-fraction distribution, are provided in Appendix B2.

Table 5-8. Summary of Particle Size Data

Values presented in this table are from pebble counts, using the Wolman (1954) method, of the coarsest materials in the channel bed at each cross section.

Watershed	Cross-Section ID	Equivalent Diameter For Selected Particle Size Fractions			
		ϕ_{16} (in)	ϕ_{50} (in)	ϕ_{75} (in)	ϕ_{84} (in)
Topanga Canyon	TOP-01		29.95		44.98
	TOP-02		35.65		44.96
	TOP-03		17.49		22.13
Hasley Canyon Upstream	HAS-04	2.05	3.46	4.72	5.00
Hasley Canyon Downstream	HAS-01	2.95	5.04	5.71	5.94
	HAS-02	2.05	2.83	3.19	3.27
	HAS-03	2.13	2.91	3.15	3.23
Plum Canyon Upstream	PLU-01u/s	2.01	3.11	3.62	3.78
	PLU-02u/s	3.43	5.87	7.60	8.15
	PLU-03u/s	1.97	3.07	3.66	4.02
	PLU-04u/s	2.99	5.39	7.20	7.72
	PLU-05u/s	2.60	3.94	4.76	4.96
Plum Canyon Downstream	PLU-01d/s	4.09	8.15	9.13	9.21
	PLU-02d/s	2.40	3.15	3.35	3.43
	PLU-03d/s	2.17	3.35	3.82	4.06
	PLU-04d/s	1.93	3.62	5.67	5.79
Borrego Canyon Wash Upstream	BOR-01u/s	3.74	6.93	8.43	8.98
	BOR -02u/s	3.15	4.69	5.55	5.83
	BOR -03u/s	3.19	3.82	4.37	4.49
	BOR -04u/s	3.74	5.20	5.79	6.02
	BOR -05u/s	3.19	5.20	6.57	7.52
Borrego Canyon Wash Downstream	BOR-01d/s	2.56	3.43	3.98	4.25
	BOR -02d/s	4.80	8.11	9.53	9.92
	BOR -03d/s	2.60	4.41	5.35	5.63
	BOR -04d/s	2.32	4.13	5.59	5.91
	BOR -05d/s	3.94	7.09	7.48	7.56
Serrano Creek	SER-01	3.19	4.21	5.16	5.35
	SER-02	3.94	6.89	7.52	7.60
	SER-03	2.64	4.17	5.67	5.91
Santiago Canyon	SAN-01	1.81	3.35	4.17	4.41
	SAN-02	2.28	5.83	6.81	7.05
	SAN-03	7.13	8.90	9.37	9.84
	SAN-04	2.68	5.08	5.35	5.43
	SAN-05	2.36	3.74	4.72	5.24
Dry Creek	DRY-01	2.76	4.76	6.38	6.50
	DRY-02	3.39	5.59	6.06	6.22
	DRY-03	1.93	3.11	3.43	3.58
	DRY-04	2.44	3.39	3.98	4.45
Hick's Canyon Wash	HIC-01	4.06	7.64	8.98	9.41
	HIC-02	2.48	3.58	5.12	5.43
	HIC-03	0.87	1.22	1.30	1.46
	HIC-04	0.87	1.10	1.26	1.34
	HIC-05	1.97	3.70	4.13	4.13

5.7 Rapid Geomorphic Assessment

Channel stability at each site was evaluated using a Rapid Geomorphic Assessment (RGA). The RGA is a semi-quantitative method for evaluating the stability of a site based on geomorphic indicators observed and recorded in the field. The RGA produces a stability index (SI) that can be used to categorize the geomorphic condition of the stream reach. The calculated stability index values suggest that all of the study sites are either already unstable or are in transition to being unstable (Table 5-9). The two control sites, Hicks and Dry canyons, had the lowest SI scores while more developed watersheds, such as Plum and Serrano canyons had appreciably higher SI values. Nevertheless, the "undisturbed" watersheds still exhibited moderate channel instability. These results suggest that all channels are continually undergoing adjustment and that there is some level of naturally occurring background hydromodification within southern California watersheds, even in the absence of development.

Table 5-9. Rapid Geomorphic Assessment

Results of evaluation process designed to assess the stability of a stream site

	Site	Stream Type	AI	DI	WI	PI	M	SI	Stability Class
1	Topanga Canyon	AL(Ar)	0.33	0.40	1.00	-	3	0.43	A
3	Hasley Canyon	AL	-	0.89	0.83	0.43	4	0.54	A
4u	Plum Canyon u/s	AL	0.80	0.80	0.71	1.00	4	0.83	A
4d	Plum Canyon d/s	AL	0.83	0.60	0.71	1.00	4	0.79	A
7u	Borrego Creek u/s	AL	0.83	0.40	0.80	0.86	4	0.72	A
7d	Borrego Creek d/s	AL	0.83	0.83	0.71	0.67	4	0.76	A
9	Serrano Creek	RC	-	1.00	0.83	0.43	3	0.75	A
10	Santiago Creek	AL	0.60	0.80	0.60	0.57	4	0.64	A
23	Dry Creek	AL	-	0.57	0.83	0.43	4	0.46	A
27	Hick's Canyon	AL	-	0.71	0.75	0.14	4	0.40	T

Explanation:

AI Evidence of aggradation
DI Evidence of degradation
WI Evidence of widening
PI Evidence of plan form adjustment
SI Stability Index (see interpretation of SI value below)

SI Value	Interpretation	Comment
$0 \le SI \le 0.25$	S - Stable	The morphologic features do not show evidence of progressive alteration and type and variance in the dimensions of morphologic features is within acceptable levels.
$0.25 < SI \le 0.4$	T - Transitional	The type and variance of observed morphologic features indicates that the stream channel is in or about to begin the initial stages of adjustment.
$0.4 < S \le 1.0$	A - In Adjustment	The type of morphologic features suggests that the channel system has been de-stabilized and is in the middle of adjusting to new conditions.

5.8 Data Summary

The data collected for this study, both historical and field data, have been summarized and described in this section. More detailed presentations of this data are provided in Appendix A (land use, precipitation, stream flow, and historic surveys) and Appendix B (survey comparisons and channel materials). A basic assessment of the data including some general implications about the channel and watershed systems that they describe has also been provided. These serve more to describe the study sites and provide background and general findings based on the data collected.

6. CHANNEL RESPONSE

Results of the analysis of stream channel response to changes in watershed TIMP are presented in this section, followed by a discussion of the implications of these results for management purposes in Section 7. Analysis of channel response was based on an evaluation of the discernable changes in channel form and how they relate to measurable changes in watershed imperviousness (TIMP). Various channel metrics (measurements of channel form) are evaluated to establish these relationships. Summarized below are the results of channel-specific data evaluation and the connections between changes in channel morphology and the changes in watershed development (i.e. imperviousness). More detailed discussion and data on these evaluations are provided in Appendix C.

6.1 Stream Channel Morphology

Stream channel morphology was evaluated based on channel width (W_{bfl}), average channel depth (d_{bfl}), and cross sectional area (A_{bfl}, or the combination of width times average depth), and flow velocity (V_{bfl}). Width and cross sectional area are measured directly from the plotted cross sections derived through current and historic field surveys. Average depth was calculated from the measured data ($d_{bfl} = A_{bfl} / W_{bfl}$). Flow velocity was also calculated using channel slope (S_{bfl}) and estimates of roughness derived from sediment data collected during field surveys. These features were measured at the stage (water surface elevation) of the Dominant Discharge, also referred to as the "bankfull" stage (hence the various subscripts of "bfl"). Details of the selection of Dominant Discharge for use among the channels is given in Appendix C2.

The channel features for a specific stream type were plotted against the estimated Dominant Discharge ($Q_{bfl} = A_{bfl} * V_{bfl}$) to look for a correlation values that would indicate deterministic behavior. The following three relationships were established:

1. There is a logarithmic relationship between dominant discharge (Q_{bfl}) and channel width (W_{bfl}; Figure 6-1). The data used in this plot excluded the braided channel types (Sites 4d and 7d) and the canyon channel type (Site 9).
2. Dominant discharge (Q_{bfl}) is realated to cross sectional area (A_{bfl}) by a power function (Figure 6-2). The data set for this assessment included all of the sections for all of the study sites.
3. There is an inverse logarithmic relationship between the width to depth ratio (W_{bfl} / d_{bfl}) and the ratio of excess shear stress for the bed materials to the excess shear stress for the bank materials (Figure 6-3). The latter ratio expressed on the x-axis is a measure of the inherent ability of the channel bed and bank materials to resist the erosive forces associated with flowing water. The term "excess" in this case is the difference between actual calculated shear stress on the bed or bank and the critical shear stress required to move (or erode) particles. The full expression is provided in Appendix C3, along with an expanded discussion of the evaluation process. The correlation of these values is considerably lower than it is for the channel geometry components ($R^2 = 0.67$), but is surprisingly good considering the range of activities represented by this measure of channel shape.

The relationships between channel features and the Dominant Discharge (Figures 6-1 and 6-2) demonstrate a predictable or deterministic behavior in the channel geometry at these sites. As discharge increases, there is an expected increase in channel size. Comparing Figures 6-1 and 6-2 show that the initial channel response to increases in discharge is to widen; however, with increasing discharge, increased depth (i.e. downcutting) is the predominant response. The relationship of channel shape to excess shear stress (Figure 6-3) also establishes a good basis for the predictable nature channel form. The shear stress relationship also suggests threshold behavior for the widening or deepening of the stream channel. After a minimal level or bed and bank resistivity has been exceeded, the width-to-depth quickly declines (i.e. channel incision). All of these relationships provide useful techniques to fill data gaps in time series assessments of channel changes.

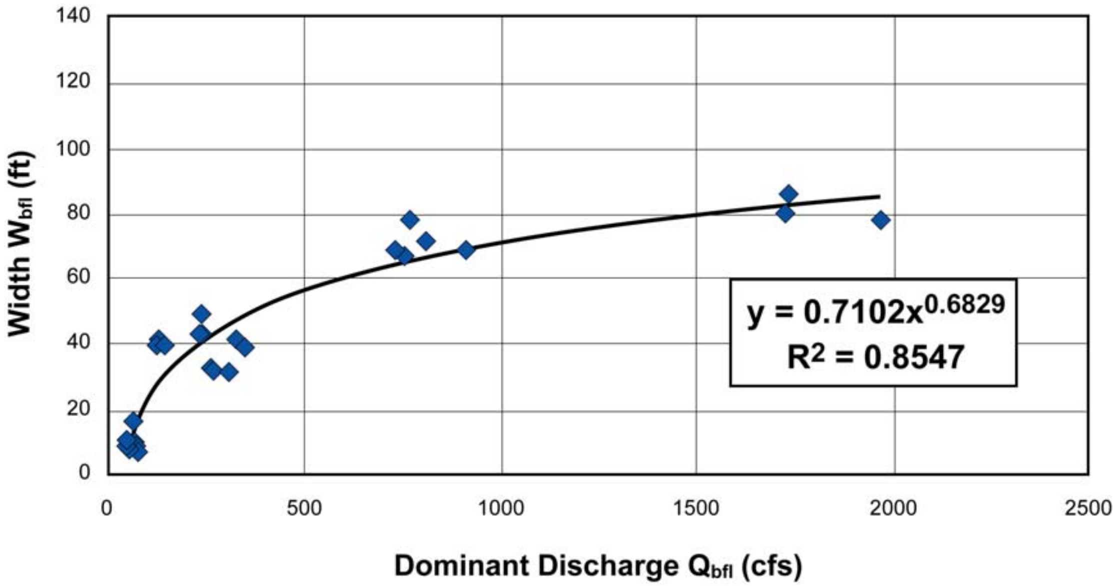


Figure 6-1. Channel Width and Dominant Discharge

6.2 Evaluating Changes in Stream Channel Condition

Natural stream channels exhibit changes over time in their geometry (width, depth, and slope) due to changes in environmental conditions. Various conceptual models exist that can be used to explain the state of a stream channel relative to an equilibrium condition, including steady state, dynamic equilibrium, and metastable equilibrium. The literature on this subject is quite large and the application of terminology has been somewhat inconsistent. Therefore, the terms and concepts discussed here in relation to conceptual models of channel adjustment are defined below.

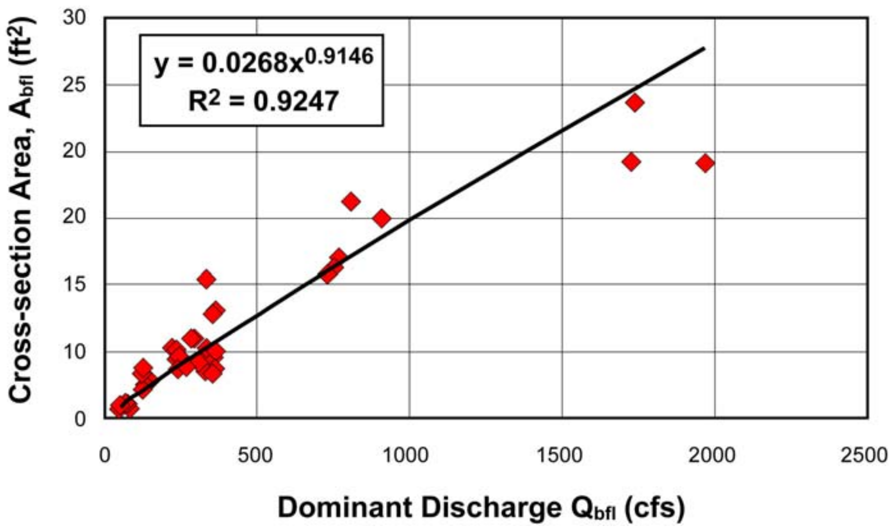


Figure 6-2. Cross Section and Discharge

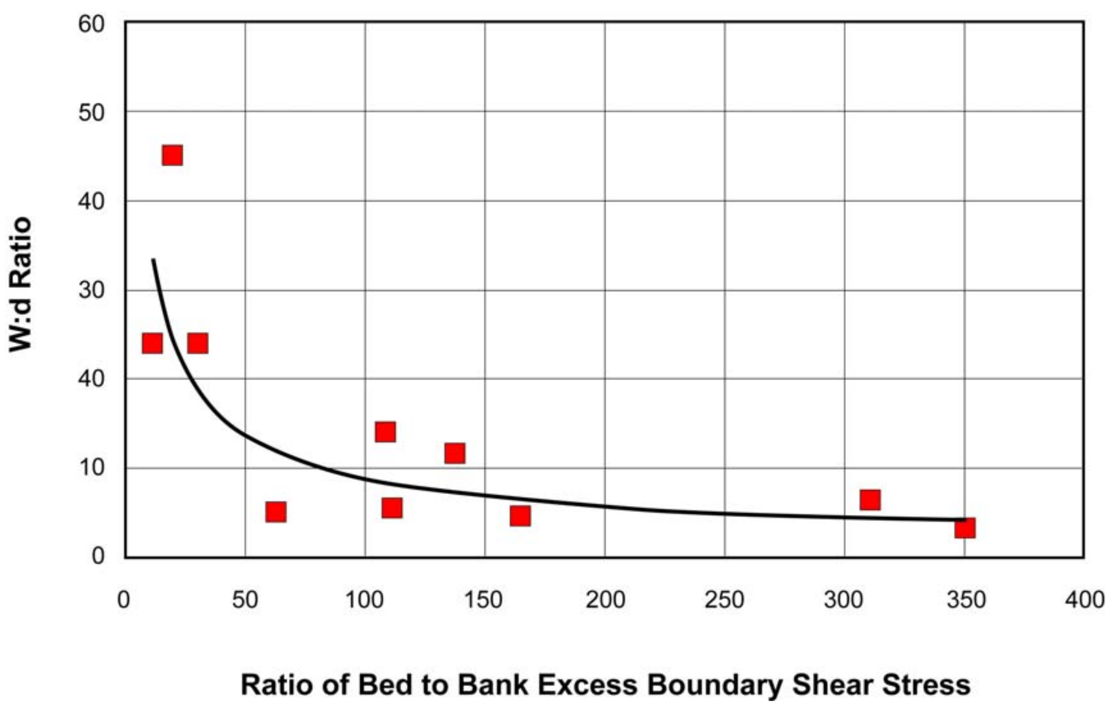


Figure 6-3. Channel Shape and Resistance

Width to depth ratio as a function of the product of specific stream power and the ratio of bed to bank excess boundary shear stress

- **Steady State.** Channel form components, including the width, depth, and slope, vary over time, but always within a definable range about a mean value that does not change over the period of time under consideration. Such a system is usually identified only for short time periods.

- **Dynamic Equilibrium.** Channel form components vary about a mean value that slowly changes over time. This type of condition usually can be identified for longer time periods than the Steady State condition.
- **Metastable Equilibrium.** Channel components also vary about a slowly changing mean value. However, this mean value can suffer rapid and dramatic change if a threshold is passed. Thus, the Metastable Equilibrium state is multiple periods of dynamic equilibrium separated by significant adjustment.
- **Statistical Stationarity.** Demonstration of a steady state condition through the application of statistical evaluation of one or more components of channel form.

In the present study the length of time represented by the data set is relatively short, which makes evaluating the system equilibrium a challenge. In addition, because this investigation is looking at artificially induced change in the equilibrium of these systems, it is important to be able to distinguish between internal (or natural) system change, and external (or artificial) change. The attempt to sort out the equilibrium status of these systems included the use of "control" sites where little to no development has occurred over the period of historic measurement of channel form.

Two of the control sites were Dry Canyon (Ventura County) and Hicks Canyon (Orange County). Each of these sites had multiple measurements at the same channel cross section over time periods of 3 years and 18 years respectively. Although both of these sites demonstrated periodic, or cyclical behavior in the adjustment of some channel geometry components (including W_{bfl} and A_{bfl}), they also exhibited an abrupt change in the thalweg elevation that to-date does not appear to be reversing. Neither change appears to have resulted from excessive storm events or other external causes. Therefore, it appears that the studied channel systems in southern California are not in a steady state condition, and the statistical stationarity of this system (at least in terms of the thalweg elevation) cannot be demonstrated. In other words, even in the absence of external forces, there is a natural rate of change of stream channel depth over time (see also Appendix C3, Section C3.4).

Both the control and the developed sites experienced channel degradation (i.e. negative change in the thalweg elevation) over the period studied. The average degradation rate over the longer period of records was 0.12 ft./yr. for the control sites and 0.31 ft./yr. for the developed sites. It appears that one of the effects of increased TIMP is an increase in the *rate* of channel degradation.

In addition, the precipitation averages during the periods of change for the stream channel sites adjacent to these control sites differed in each area (see Section 5.2). The Ventura County and LA County data suggest that changes occurring at Hasley Canyon and Plum Canyon occurred during a period of lower than average precipitation. The data for Orange County suggests the opposite situation, with higher than average precipitation amounts occurring during the periods of channel change. However, the actual impact of these higher than normal rainfall amounts and stream flows (see Section 5.3) on the Orange County sites, does not appear to alter the conclusion that changes in TIMP were the primary cause of channel change, and not higher than normal rainfall. The most important argument for this assertion is that the channel conditions at nearby Hick's Canyon remained stable during this same period, even though it was experiencing a decrease in thalweg elevation. Thus the same rainfall conditions that were causing significant channel erosion at Borrego Canyon Wash and Serrano Creek, were not significantly altering the channel conditions at Hick's Canyon other than the thalweg elevation.

The fact that deterministic relationships have been demonstrated for a number of channel geometry components and for channel boundary resistance (as described earlier in Section 5), argues for these systems being at least in a dynamic equilibrium. Since statistical stationarity cannot be demonstrated, dynamic equilibrium is still possible and steady state is not likely. Furthermore, because the developed watersheds are undergoing imposed changes, and the stream channels are responding to this perturbation, significant adjustments are occurring in the general mean values of the system in its state of dynamic equilibrium. This suggests further refinement of the model to one of dynamic metastable equilibrium. More detailed discussion of this topic is provided in Appendix C3.

6.3 Stream Channel Response

Evaluation of channel enlargement requires multiple data points over a time sequence that includes the predevelopment condition (as the baseline or beginning point in time), the current condition (as the end-point), and one or more "historical" data points. The historical data points represent conditions that occurred along the time sequence between the baseline and the end point. In many cases the current conditions do not represent the ultimate end of the adjustment response (the ultimate end point). Therefore, the ultimate condition must be estimated, if possible, using specific and consistent techniques. A full description of the channel enlargement evaluation process is provided in Appendix C4. A brief summary of the procedure follows:

1. Collect available data and decide whether the data coverage is adequate.
2. Establish the baseline time marker (the actual date, or a time of t_0) and channel baseline condition (A_{pre}) for each site.
3. Evaluate all historical points between the baseline time marker (t_0) and the present time (t_{ext}) to understand their condition. Decide whether a single response or multiple responses are occurring at each site.
4. Predict the ultimate condition of the channel at each site upon completion of the adjustment (assuming the existing condition is not the ultimate condition). Appendix C4 provides a discussion of the techniques for completing Steps 3 and 4 if the data set is incomplete.
5. Use the data output from Steps 2, 3, and 4 to construct the *relaxation curve* for each site.
6. Since all of the sites have varying amounts of change in their watershed with regard to TIMP, and this causes varying amounts of channel adjustment, an enlargement curve (defined below) is developed to understand and compare data. To do create the enlargement curve we must assume or predict values of the time it will take to reach the ultimate condition, and the value of that ultimate condition (A_{ult}), for each adjusting site.

Two important aspects of channel change are compared over time, (a) the change in thalweg elevation and (b) the change in channel cross section area for the bankfull stage. The availability of all of this data for historic and/or baseline conditions is not always ideal, so adjustments must be made to complete the evaluation. However, all of the data mentioned above, except the channel slope, can be calculated from surveyed cross sections.

Comparison of the cross-section area of the channel at the bankfull or Dominant Discharge stage (Q_{bfl}) at different points in time produces a ratio of channel cross section area (A_{bfl}) from a later period to the earliest, or baseline period. This comparison is termed the enlargement ratio (R_e), and takes the form of Equation [6.1].

$$(R_e)_{his} = A_{his} / A_{pre} \qquad [6.1]$$

where:

A_{his} = Cross section area of the bankfull channel at an historical point in time (square feet).

A_{pre} = Cross section area of the bankfull channel for the baseline condition (square feet).

Similar comparisons are made for the existing condition (A_{ext}) and the projected, ultimate condition (A_{ult}). The ultimate condition requires an estimation of channel metrics at the end of the adjustment period. None of these sites has reached its ultimate condition in response to the development that has occurred, as this can take several decades (see Appendix C4). Therefore, the ultimate channel condition, and the time it will take to achieve it, must be estimated. The amount of time required for the full adjustment to be completed is called the *relaxation period*. The plot of the adjustment process over time is called the *relaxation curve*. Data from the current study are plotted in Figure 6-4 along with a reference relaxation curve developed using data from urban stream channels on Austin, Texas, which have similar geomorphic and hydraulic conditions, but somewhat different precipitation patterns.

The data plotted on Figure 6-4 are the results of the current investigation with the curve developed for the Austin data. It appears that the changes occurring at the current study sites are still within the initial stages of adjustment, and thus too close to the increase in TIMP to effectively predict the complete adjustment process. Therefore, it is still premature to prepare a relaxation curve developed only with the southern California data from the study sites. In addition, some of the study site data, particularly for the Plum Canyon and Borrego Canyon Wash sites, are not typical of the enlargement data in general.

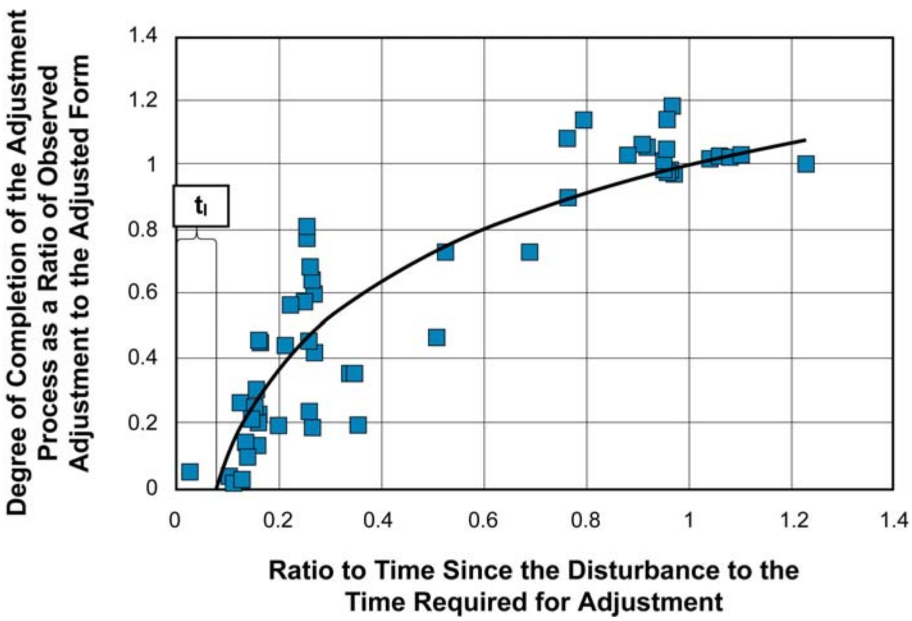


Figure 6-4. Relaxation Curve and Study Data.
Curve developed for urban channels in the Austin, Texas area formed in alluvium. Data points shown are for the study sites in southern California.

The Plum Canyon (LA County) and Borrego Canyon Wash (Orange County) sites are similar to each other and dissimilar to the other sites. Each of these stream channels had two sites, an upstream and a downstream site. On each stream the downstream site has a smaller channel and smaller Dominant Discharge than the upstream site, indicating a loss of flow downstream (i.e. a losing stream). In both cases the upstream sites showed a significant increase in channel size in response to the increase in TIMP, followed by a decrease in channel area. At Site 4u (Plum upstream) the channel cross section area initially increased more than 100% [$(R_e)_{his}$ = 2.22] and then decreased to a size only 43% greater than the baseline condition [$(R_e)_{ext}$ = 1.43] as recorded in the current survey data. At Site 7u (Borrego upstream) the enlargement ratio initially went to 1.37, declined to 1.25, increased to 1.47 and then decreased to 1.06 in the current survey. In neither case did the enlargement ratio continue to increase, albeit at a declining rate of increase, toward an expected ultimate value (as the curve in Figure 6-4 shows). In contrast, the other sites with developed watersheds (Sites 3u, 3d, 4d, 7d and 9) did show consistent increases in enlargement ratios.

A possible explanation for the changes observed at the upstream Borrego Canyon and Plum Canyon sites is suggested in a conceptual model proposed by Andrews (1979). His model identifies three phases of channel adjustment.

- The **First Phase** of Andrews' Three-Phase response model predicts straightening of the channel thalweg and destruction of the bed forms leading to homogenization of the bed materials and fluvial features in the longitudinal sense. This increases the slope and decreases channel resistance thereby effectively increasing the energy available in the watercourse to perform work.
- In the **Second Phase** of the adjustment process, Andrews' model predicts one of three responses: downcutting, widening or both downcutting and widening. The actual response will depend on the absolute resistance of the boundary materials as well as the relative resistance of the bed and bank materials at the least resistant bank toe stratigraphic unit (MacRae, 1992). The net effect of channel widening would only be temporary, however, as eventually the channel becomes too wide to support continued growth.
- The **Third Phase** would result in a new channel forming (incising) into the newly formed, extra-wide channel. Channel change from this point would then follow the more common response to increased flow and reduced sediment load with the typical enlargement of the channel to a new equilibrium position.

The current observations at the upstream Borrego Canyon and Plum Canyon sites are likely at the transition between the second and third phases of Andrew's 3-Phase model; the channel has constricted after initially enlarging significantly. The bank materials in the upstream Borrego and Plum reaches are highly erodable (mostly unconsolidated sands) while the bed may have been armored with cobbles prior to urbanization. Consequently, the resistance of the bank materials is very low relative to the bed materials as is the absolute resistance of the bank materials to the applied stress. Consequently, while there may have been some downcutting it is likely that the initial response was widening. Furthermore, overbank flows would have easily reworked the loose sands in the overbank area creating chutes and scouring out the wide swath of channel that was observed at the upstream sites.

Although the data from the current study are not adequate by themselves to develop a specific relaxation curve for southern California streams, they were used in conjunction with the established curve (in Figure 6-4) to develop an enlargement curve (Figure 6-5). The data for southern California streams forms a relationship very similar in shape to the enlargement curves developed for the larger database of North American streams. However, the database for southern California streams plots above the general line for the other data, suggesting that a specific enlargement ratio is produced at a lower value of impervious surface area in southern California than in other parts of North America. It is important to emphasize that the data for southern California streams are from systems in the initial stages of adjustment, and therefore are less reliable than they would be if the data were from a more advanced stage of adjustment.

Nevertheless, there are some important conclusions that can be drawn from the data of the current study.

- The channel systems studied here are very sensitive to external changes in the impervious areas within their watersheds. Increases on the order of 2% to 3% in TIMP have initiated increases in channel cross sectional area. The threshold of response for channel enlargement in southern California appears to be substantially lower than in other parts of North America.

- On the short time frame considered in this investigation (10 to 20 years) these systems are considered to be in a state of dynamic equilibrium. The control sites exhibit signs of active downcutting (thalweg elevation decreases) over time while maintaining stable channel morphology. This indicates that all channels are undergoing change; however, the rate of change may be different between streams that are subject to increases in peak flow and those that are not. Longer time series of analysis is necessary to more clearly define these relationships.

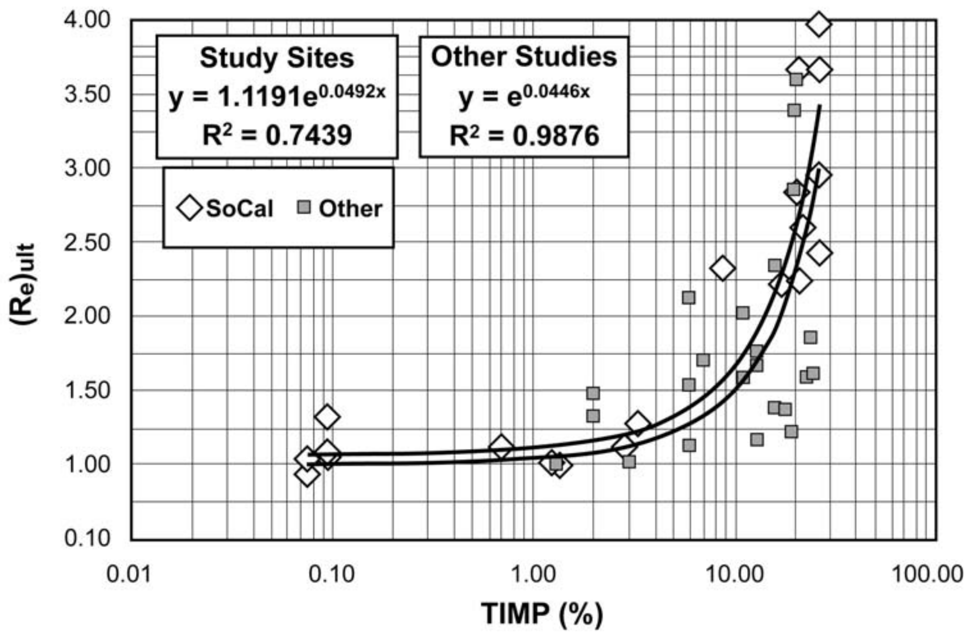


Figure 6-5. Enlargement Curve for Southern California.
Upper curve and data points are for southern California channels in the current study. Lower curve is based on data from other locations in North America.

- Because the measurement error is of the same order of magnitude as the sensitivity values, these systems should be considered to have zero tolerance for increases to TIMP values, and be managed accordingly. This includes adopting one or more of the following management strategies:

  1. Zero tolerance for runoff increases (if not actually reducing runoff to below pre-development levels); or
  2. Employ active management of stream channels to maintain or stabilize the stream channel condition and habitat; or
  3. Establish a “no build” or “no disturb” riparian corridor to accommodate the expected channel adjustment response to the expected change in watershed imperviousness.

7. CONCLUSIONS AND RECOMMENDATIONS

The affects of urbanization on stream channels have been well studied in perennial systems in the humid regions of the U.S. The results of these studies are widely accepted, and demonstrate that increases of urban (or developed) areas within a watershed lead to increases in stream channel size (depth and/or width) and a decline in the diversity of aquatic species and the quality of aquatic habitat. The present investigation attempted to expand this understanding into ephemeral and intermittent stream channels in semi-arid climates. However, because many of the smaller stream channels in arid to semi-arid areas are ephemeral and intermittent, the present study focused solely on changes in stream channel morphology and did not address impacts to aquatic habitat.

The primary concerns about the affects of urbanization on natural stream channels in southern California, from a regulatory/management perspective, can be summarized as follows

a) How do semi-arid stream channels differ from humid area stream channels in their response to increases in impervious area?
b) How can effective controls be selected for minimizing the impacts from increases in impervious area?
c) Which situations and what conditions are appropriate for use of the identified controls?

The following subsections provide answers to these questions to the extent that the data generated by, and analyzed under, this investigation will allow.

7.1 Conclusions

The focus of this study was to relate changes in watershed development to observed changes in the morphology of the stream channel draining the watershed. The study sites selected were intentionally small (i.e. all less than 20 mi^2 and most less than 5 mi^2) since stream channels draining smaller watershed areas are most sensitive to changes in impervious cover. Ephemeral stream channels can be found in all climates, the main difference between regions is the size at which the contributing watershed area becomes large enough to support perennial stream flow. This size is dependent on a number of variables, but climate is a significant variable. In general, stream channels in arid areas remain ephemeral with larger catchment drainage areas than stream channels in more humid regions. This difference contributes to their increased sensitivity to changes in TIMP.

Based on the results of the present investigation, several principles of urbanizing ephemeral stream channels are suggested. The first principle concerns watershed area.

Principle 1. CDA Size Focus. The drainage area contributing runoff to a stream channel is a key characteristic for determining stream channel size. Ephemeral/intermittent stream channels are no different than perennial streams in this regard.

- Hydromodification from changes in impervious area are most recognizable in watersheds smaller than about 20 square miles.
- Watersheds in the present study with CDA < 15 $mi.^2$ are ephemeral, with one exception (Serrano Creek appears to have a nuisance base flow from surrounding residential areas).
- Management of impervious area and connected impervious area is most critical in the smallest watershed management units (CDA ≤ 2.5 square miles).

The results of this investigation suggest that the threshold for TIMP (total impervious area) at which changes in stream channel morphology would be expected is lower in the semi-arid sites that are typical of southern California than for comparably-sized sites on perennial streams in more humid areas. Based on the current data set the apparent threshold in the value of TIMP for initiating stream channel morphology change is between 2% and 3%. Similar threshold values for perennial streams generally are closer to 7% for the northeastern U. S. (Schueler 1998) and 10% for the northwestern U. S. (Booth 1997).

The sites in this investigation that experienced changes in their morphology all had relatively low resistance to bed and bank erosion. This leads to the second principle of urbanizing (and arid) ephemeral streams:

Principle 2. TIMP Sensitivity Ephemeral stream channels are also affected by change in total watershed imperviousness (TIMP). The ephemeral/intermittent stream channels of the arid to semi-arid study region in southern California appear to be more sensitive to such changes than are perennial streams in the literature.

- The threshold of ephemeral stream channels for exhibiting changes to stream channel morphology due to change in TIMP value, is between 2% and 3% change in the total impervious area for the watershed.
- The threshold of response will vary based on stream type. For example, ephemeral stream channels that are configured like Topanga Creek with highly resistant bed and bank materials are likely to have a higher TIMP threshold for stream channel change.

The form of a stream channel is a composite response (by its ability to resist erosion) to the cumulative applied forces of stream flow. The forces imposed on the stream channel result from its hydrologic and sediment regimes, the size and timing of flows and the stream channel form, particularly the slope of the stream channel, or energy grade. The resistance of the stream channel to the imposed erosive forces is dependent on the competence and cohesion of the materials forming the stream channel bed and banks. This relates both to characteristics of the stream channel form as well as the resistance of its bed and bank materials.

The stream channels studied in this project included control sites, where little or no watershed development had occurred, and developed (i.e. adjusting) sites, where changes in TIMP had occurred over a period of time. Some minimal rate of change in channel depth and area was observed in all sites (control and adjusting); however, the rate of change was greater in the developed sites than in the control sites. The control sites exhibited a state of dynamic equilibrium because downcutting was observed, but channel morphology did not change appreciably over time. The adjusting sites exhibited instability, as some significant change had occurred in one or more measure of channel morphology. These results demonstrate poor channel resistance to increased flow in all the adjusting channels except Topanga Creek. However, because this is a relatively small data set, generalizations made from the current data will have to be confirmed with a more extensive inventory of stream channel form, stream channel slope, and bed and bank material resistance for both ephemeral streams and perennial streams in the study area.

A key component of stream bank resistance, especially in smaller streams, is the vegetation present and the impact it has in providing resistance to erosion through root binding or energy dissipation. While the study sites had vegetation present to varying degrees, it did not appear to be a significant component of the stream channel stability, particularly at those sites experiencing changes in stream channel morphology. This probably has as much to do with climate, because the dry conditions in ephemeral stream channels in southern California persist for large blocks of time through the year, favoring a limited vegetative cover for banks, and hence less cohesive stream channel banks.

This leads to the third principle of urbanizing ephemeral streams:

Principle 3. Stream Channel Resiliency is Low. The small sample of ephemeral stream channels taken in this investigation whose morphology is changing, had relatively low resistance to erosion. However, further investigation is needed to verify and quantify any differences in stream channel resistance between ephemeral and perennial streams in southern California. The role of vegetation in stream channel resistance also needs to be better defined.

- It is suspected that ephemeral stream channels have a narrower range in resistance and resiliency than perennial streams, and that this is on the lower end of the resistance scale, however there is no conclusive proof of this in the results of the current investigation.
- The low impact of vegetation on stream channel resiliency appears to be a significant difference between ephemeral and perennial streams.

The management of increased stormwater runoff due to development must be concerned not only with the total volume of runoff but also with the flow peaks for individual flood events (both of which increase with increasing TIMP). If the results of the current study are representative of ephemeral stream channels in southern California, then it appears concern for both volume control and peak control should be exercised for control of hydromodification. Because these stream channels appear to be more sensitive to changes in TIMP (Principle 2) it follows that they would be very sensitive to increases in flow rates. Additionally, they appear to have a low resiliency, or resistance to erosion (Principle 3), so it would also follow that these stream channels are more susceptible to channel enlargement. Change in the flow rate would imply not only the peak flow rate but also the duration of time that erosive flows occur. Therefore, it would appear that maintaining the current regime (i.e. hydrograph matching) would be necessary to avoid stream channel enlargement.

This leads to the fourth principal of urbanizing ephemeral streams:

Principle 4. Management Considerations. As an extension of Principles 2 and 3, ephemeral stream channels are expected to be sensitive to both the larger flow peaks resulting from volume control, and the extended duration of erosive flows under peak control.

- In the absence of channel stabilization or other in-stream controls, retention methods are likely to be more effective than detention methods.

Management options and strategies to address these concerns are discussed further in Section 4.2 to explore the alternatives available to watershed managers.

Previous stormwater management investigations were primarily concerned with perennial stream channels. This investigation has looked at a small number of sites on ephemeral/intermittent stream channels in a very large region with significant diversity. In spite of a considerable effort to locate study sites with the broadest representation possible, the sites selected provide only a limited representation of that diversity. Still, these sites have provided some very useful results in characterizing ephemeral stream channels. Differences clearly exist between the ephemeral/intermittent stream channels of this study and the perennial stream channels in the literature in sensitivity to increases in TIMP and stream channel resiliency. Some of these differences have been better clarified by this study, while others have been identified for further investigation.

This investigation and its results should provide both the regulatory community and management personnel with insights into ephemeral/intermittent stream channel behavior and management options that were previously not available or elucidated.

7.2 Management/Regulatory Approach

Management of stormwater ultimately begins with a vision of how the drainage network and stream channel system should look and function. This will determine the opportunities and constraints possible for stormwater management. The vision must be realistic and flexible, and is not likely to be the same for all watersheds. The focus of this investigation has been on physical properties of the "natural" stream channel, its response to changes in watershed development, and management implications.

7.2.1 Management Objective

Once the vision has been established, stormwater management starts with the establishment of global goals and objectives for the watershed. From these goals and objectives will follow the specific objectives for local stream channel reaches and smaller subwatershed areas. If preservation (or re-establishment) of natural stream channel appearance and function is one of these specific, local objectives, the results of this study provide a modest start toward establishing some of the criteria needed to meet this objective. The classification system provided in Section 4 forms the basis for making informed decisions regarding the type and focus of stormwater management and stream channel maintenance applications. By focusing on maintaining a viable, "natural" stream channel (at least in form and function), management approaches include some form of runoff control (to lessen possible increases in the volume of water in the stream channel) and/or stream channel protection (to prevent stream channel erosion due to increased forces on the bed and bank materials). The relative effectiveness of these two types of management is represented in Figure 7-1.

7.2.2 General Approaches

Three general approaches for accomplishing the specified stormwater management objectives are described below. They involve a trade-off between runoff control, and stream channel protection.

Natural Channel Design (NCD). This management approach is concerned primarily with preserving the native (and stable) condition of the stream channel reach under consideration. Because the emphasis is on preserving existing functions, this approach precludes in-channel activities that are not created using materials that are not native to that location and emphasizes surface runoff controls as the primary management tool. Allowable development within the contributing watershed can only be tolerated to the threshold level before surface runoff control must be implemented. The threshold for a watershed will depend on the type of stream channel and the nature of the stream channel slope, soil characteristics and bedrock in the watershed. For example, a stream channel with highly resistant bed and banks (like Site 1, Topanga Creek) will be able to accommodate a significantly higher level of change without a meaningful adjustment in stream channel morphology. Other stream channels (like the remaining study sites) can only tolerate a change in TIMP of between 2% and 3% above the "natural" condition of the pre-disturbed watershed. Therefore, zoning and building density restrictions to encourage low-impact, or "smart" development will be very important with this approach, as well as runoff controls.

Geomorphologically-Referenced River Engineering (GRRE). The goal of this management approach is to preserve the appearance of natural stream channel function to the greatest extent possible while limiting instability in stream channel morphology. Geomorphic principals are used to design a stable stream channel given the expected hydrologic and sediment regimes (which will be different than the pre-disturbed state). The stream channel is re-shaped to this design using a minimum of hard, engineered structural elements within the stream channel so that the natural appearance is preserved while the new stream channel form can remain stable. However, both surface runoff and in-channel controls are required to maintain the hydrologic and sediment regimes for which the new stream channel is designed. Allowable development that can be tolerated under this approach has fewer restrictions than the NCD approach in that the new stream channel is designed to accommodate flows that are larger than the flows that shaped the stream channel under the natural conditions of the watershed prior to development. None-the-less, surface runoff controls eventually become just as critical to the stability of the new stream channel design, as it maintains semi-autonomous behavior. In-stream controls are employed to the extent they are needed, and are not necessarily created with native materials.

Traditional River Engineering (TRE). The goal of this management approach, also referred to as "hard-lining," is to create the most efficient conveyance system possible for stormwater, and provide the greatest degree of protection for the bed and banks of the stream channel that provides stormwater conveyance. The stream channel system is engineered to accommodate flows up to the design storm level, whatever that may be, and is protected by hard-lining the bed and banks. Surface runoff controls are much less important under this approach than they are under the NCD or GRRE approaches.

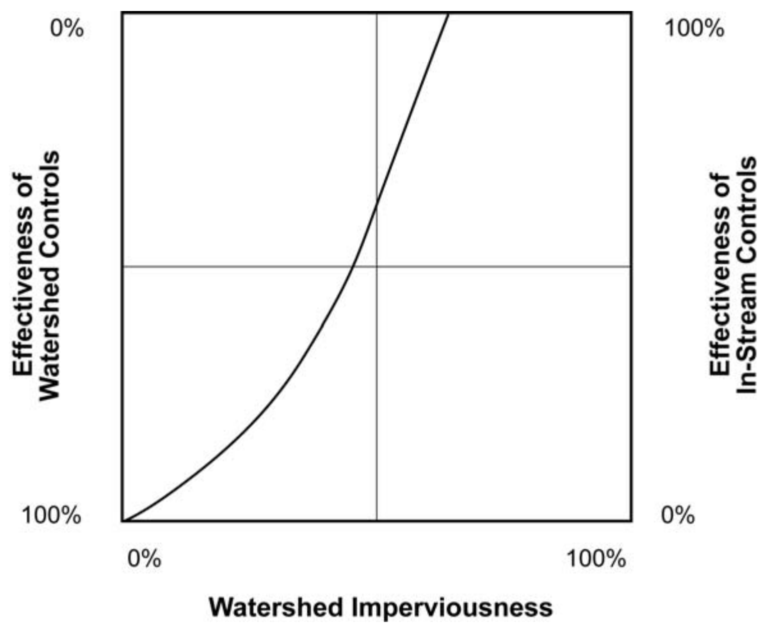


Figure 7-1. Effectiveness of Stormwater Management Control Strategies

Management approaches are selected so that they match the general goals and objectives for the watershed, as well as the specific objectives established for the stream channel reach in question. Because this investigation is concerned primarily with natural stream channel form and function, it focuses only on stormwater quantity and sediment load as it relates to stream channel activity, and is not directly concerned with water quality. There are a variety of best management practices (BMPs) available for controlling stormwater quantity, and a number of sources for obtaining information about these practices (EPA 1999, 2002, Mays 2001, WEF 1992). Controlling runoff can be organized into three general areas of control (source control, conveyance system control, and centralized control). Specific practices that illustrate these areas are listed in Table 7-1a. In-stream management practices also fall into multiple areas (grade control, sediment regime control, and bank stabilization). Some specific practices are listed in Table 7-1b. These tables list representative stormwater management options, but are not intended to be exhaustive lists.

7.2.3 Management Strategies

A general framework for assessing stormwater management strategies is presented in Table 7-2, which describes the applicability of four management strategies. The strategies are based on the current amount of development (i.e. TIMP) in a watershed and the expected stream channel stability. Functional relationships between these strategies, the management approaches discussed previously in this section, and the stream channel type classification system presented in Section 4 of this Technical Report are explored further in the discussions of these strategies presented below.

Preservation. The strategy for watersheds that have relatively little development and therefore a low percentage of impervious area is to take advantage of the opportunity to maintain or preserve a stable stream channel system. The recommended management for these watersheds is to first to consider NCD, as this is likely to be one of those rare occasions where NCD can be effective. The stream channel in its existing form is considered desirable and worth retaining. The stream channel is also considered to be a metastable system where change in stream channel form under natural conditions is considered acceptable over the planning horizon of 100 years. Management efforts are based almost entirely on surface runoff control with limited in-stream actions.

Table 7-1a. Stormwater Management Practices

Focus	Objective	
	Retention	Detention
Source Control	• Dry well • French drain • Cistern • Rain barrel • Bioretention	• Detached downspouts • Vegetated areas
Conveyance System Control	4. Porous pavement 5. Channel diversions	6. Rural drainage profile 7. Grassed swales 8. Stream Corridor Buffer zones 9. In-line detention 10. Reconnecting channel to the floodplain
Centralized Control	• Infiltration basin • Retention basin	• Constructed wetlands • Detention basin

Table 7-1b. In-Stream Management Practices

Focus	Practices	
	Soft Engineering	Hard Engineering
Grade Control	• Riffle • Boulder clusters	• Drop structures • Channel lining
Sediment Regime Control	• Pool • Sediment introduction	11. In-line detention 12. In-line sediment trap
Bank Stabilization	• Grading and vegetation of stream banks • Vegetated gabions	• Riprap • Rock gabions • Pavers • Channel lining

Restoration. Watersheds with greater amounts of impervious area require management focused on bringing an unstable stream channel system back into a stable situation. Part of the management effort, ultimately, is to decide on an acceptable level of development for the watershed. Although the stream channel is destabilized, it can be restored to pre-disturbance form through control of the sediment-flow regime and in-stream works strategically located for grade control. Once provided with the right balance of control, the stream channel is able to restore itself through its own means. Erosion control is still primarily managed with surface runoff controls, although the emphasis on in-stream measures has increased to include localized sites and unstable and incised stream channel reaches.

Rehabilitation. Watersheds with significant impervious areas that are still manageable in total amount can have seriously degraded stream channels that are highly unstable and require significant effort to bring the stream channel back into a new, and stable, condition. The stream channel cannot be restored to its pre-disturbance form due to irrevocable changes to its form. However, the stream channel can be modified through a combination of surface runoff and in-stream works in accordance with the vision for the stream channel-valley system. Erosion control is based on matching the morphology of the stream channel with the new sediment-flow regime established for the stream channel based on implementation of a preferred SWM Alternative. SWM measures a required for new development and retrofit of existing developments. The emphasis on in-stream measures has increased to include localized sites and all unstable stream channel reaches.

Table 7-2. Stormwater Management Strategies

Strategy Name	Applicability	Description
Preservation	Stable Channel TIMP ≤ 6%	Stream channel is expected to be stable; Effort will be to keep it stable.
Restoration	Unstable Channel 6% < TIMP ≤ 10%	Stream channel is likely to be experiencing some instability (increase in capacity, change in hydraulic geometry values, etc.); effort will be correct changing inputs and nudge stream channel back to normal conditions
Rehabilitation	10% < TIMP ≤ 20%	Stream channel probably has experienced irreparable changes (not able to restore "normal" conditions); effort will be to create a new (and maintainable) "natural" stream channel configuration.
Stabilization	20% < TIMP	Stream channel has become extremely unstable and is on the verge (or in the middle) of significant morphological changes; effort will be to stabilize conditions with any means necessary and prevent excessive change.

Stabilization. The worst case is in a watershed with levels of impervious area that are so high the focus of stream channel management must be on stabilizing a situation that will only get worse if nothing is done to address the stream channel erosion. The stream channel has become entrenched and the valley is confined by development, floodplain fill, and/or infrastructure encroachment. Instability is systemic to the majority of the main stream channel and erosion threatens property and infrastructure. Further adjustment of the stream channel is anticipated and will exacerbate the problem. Surface runoff controls for new developments and retrofit options for existing developments can achieve significant reductions in erosion potential. However, surface runoff management is not sufficient to stabilize the stream channel that is undergoing valley formation and susceptible to catastrophic failure during rare flood flow events. In-stream works are required to reconnect the stream channel to its floodplain, arrest the down-cutting process and stabilize the stream channel. Due to encroachment of development into the floodplain and infrastructure located within the valley, lateral migration of the stream channel may not be desirable. In this case GRRE at TRE approaches may be required, and these approaches may have no alternative except to hard-line the stream channel. In this situation surface runoff controls become redundant from an erosion control perspective. However, surface runoff control measures may be necessary for water quality or flood hazard issues. Surface runoff controls may also be required to meet the long-term vision for the watershed as the urban landscape reshapes itself through in filling and redevelopment.

7.2.4 Implementation of Management Strategies

Selection of a management strategy is dependent upon the extent to which a stream channel has been impacted by development within the watershed. The first step in implementing a management plan requires local communities to inventory and characterize each channel segment. This may result in a single stream having one or more stream segments with each of the four management goals. Therefore, land use controls and in-stream practices would vary based upon the established strategy for that particular stream segment. Table 7-3 summarizes the criteria and methods that could be used by communities to manage their stream networks.

Table 7-4 summarizes the various management approaches discussed earlier and shows linkages with implementation strategies that are appropriate for a given channel type and degree of TIMP. This table is based on practical, nationwide experience in stormwater management implementation that has been tailored for consideration in the southern California setting. In addition to this table, there are a three general strategies which should be considered when attempting to manage increases in peak flow:

1. **Limit Impervious Area.** Although the focus of this study was necessarily on TIMP, disconnecting impervious areas from the drainage network and adjacent impervious areas is a key approach to protecting channel stability. Utilizing this strategy can make it practical to keep the effective impervious cover (i.e. the amount hydrologically connected to the stream) equal to or less than the identified threshold of 2-3%.
2. **Control Runoff.** Hydrograph matching is not recommended for a single "design" storm with a specific return period, but rather for a range of return periods from 1 year to 10 years. Accomplishing such hydrograph matching will be challenging, and undoubtedly require a combination of techniques to prevent (retain), as well as to delay or attenuate (detain) runoff and/or stream flow.
3. **Stream Channel Movement.** Allow the greatest freedom possible for "natural stream channel" activity. This includes establishing buffer zones and maintaining setbacks to allow for channel movement and adjustment to changes in energy (associated with runoff). However, where in-stream controls are required consider all potential management options.

It is important to keep in mind that the choice of a management approach or approaches should be dictated by the strategies that are appropriate given the conditions of each stream reach and its contributing watershed. Consequently a suite of management approaches may need to be applied to provide a comprehensive solution to managing increases in peak runoff.

7.3 Applicability

Impacts to stream channels resulting from changes within the contributing watershed area, such as development and increased impervious area, are generally viewed as negative. Although no positive impacts were identified at any of the study sites, positive results are possible. The best example of this would be a stream reach that has an excess sediment load prior to development (i.e. an aggrading reach). Increased runoff and stream flow resulting from development could increase the carrying capacity of the stream enough to accommodate the excessive sediment load, thus producing a stable reach.

In order to relate the measurable changes in stream channels to changes in development, a measurable variable for development must be identified. The most commonly used value to represent development changes has been the areal extent of impervious area. This can be measured, laboriously, from maps and aerial photographs, or it can be estimated from existing land use maps with accepted conversion values. The latter method provides an estimate of the total impervious area (TIMP) in a watershed. A more accurate assessment of the actual impacts from development would come from the use of "connected impervious" area, or "CIMP" (also termed FRIMP). However, CIMP cannot be estimated as easily or effectively from land use data as can TIMP. CIMP must be carefully measured or delineated using detailed aerial photographs and (if available) detailed maps such as development plot plans or municipal parcel maps combined with extensive ground-truth checks. This is possible, though difficult, for current conditions, but it becomes much more difficult (if not virtually impossible) for historical conditions where ground-truthing is not possible. The degree of difficulty in calculating CIMP values and the scarcity of CIMP values in previous studies led to the decision to use TIMP values in the current investigation rather than CIMP values.

Table 7-3. Implementation of Recommendations

Management Goal	Management Strategy	Role of Local Government	Funding	Implementation Approach
NCD – Preservation Stable Channel 0% ≤ TIMP ≤ 6%	Minimize Impervious Area Maximize Infiltration Preserve Environmentally Sensitive Areas	Land use planning Zoning restrictions Develop design standards for “smart growth”	Private developers	Inventory stream characteristics Complete assessments of individual watersheds Complete land use planning Preserve environmentally sensitive areas Establish stream channel/valley buffer zone Develop "smart growth" design standards that • Maintain "natural" shear stresses and hydroperiod of watershed. • Post-development runoff volumes to closely equal pre-development runoff volumes • Post-development peak rate of runoff < pre-development peak rate of runoff Implement riparian vegetation planting/ management program Monitor field conditions
NCD – Restoration Unstable channel 6% ≤ TIMP ≤ 10%	Minimize addition of new Impervious Area Maximize infiltration Preserve strategic environmentally sensitive Areas Restore “natural” hydroperiod Restore natural characteristics of stream channels	Land use planning Zoning restrictions Develop design standards for “smart growth” Restore natural characteristics of stream channels	Private developers Public capital improvements	Inventory stream characteristics Complete watershed assessments Complete land use planning Preserve environmentally sensitive areas Establish stream channel/valley buffer zones Develop "smart growth" design standards • Maintain "natural" shear stresses and hydroperiod of watershed. • Post-development runoff volumes to closely equal pre-development runoff volumes • Require post-development peak rate of runoff to be less than pre-development peak rate of runoff Implement riparian vegetation planting/ management program Develop design criteria to retrofit existing development to mitigate increases in runoff volume and peak discharge rates Plan, design and implement projects to retrofit existing development. Limit in-stream works (localized erosion problems) Monitor field conditions

Table 7-3 (continued)

Management Goal	Management Strategy	Role of Local Government	Funding	Implementation Approach
GRRE – Rehabilitation Unstable channel 10% ≤ TIMP ≤ 20%	Preserve existing hydroperiod Stablize stream channels	Development of design standards for runoff peak and volume controls Stablize stream channels	Private developers Public capital improvements	Inventory stream characteristics Develop design criteria for a new development to maintain existing runoff volume and peak discharge rates • Post-development peak rate of runoff = or < pre-development peak rate of runoff Plan, design and implement BMPs to retrofit existing development. Preserve vegetative cover of stream channel and buffer strips along stream channel Substantial In-stream works to stabilize stream channel • Establish grade controls • Use bioengineering techniques to stabilize stream channels
TRE – Stablization Unstable channel 20% ≤ TIMP	Stablize stream channels	Stablize stream channels	Public Capital Improvements	Inventory stream characteristics Maximize storage of stormwater runoff to reduce in-stream peak discharges Channel hardening & grade controls • Maximize use bioengineering techniques to stabilize stream channels • Maximize use of "natural" materials to harden Stream channels • Preserve vegetative buffer strips along stream channel Flow Diversions

In addition to concern over physical changes to stream channels (hydromodification) that result from increased impervious areas, impacts to habitat can also be significant. Natural stream channels offer some of the best opportunities in the southern California region for threatened and endangered bird species to avoid the pressures of development. Stable riparian zones can also support native plant species effectively. Such habitat is predicated on conditions remaining stable within the stream channel. Adjustment of plant and animal species to unstable conditions within the stream channel would require a separate, study. A study of this type should focus on the expected adjustments to various types of stream channel changes (widening, deepening, loss of soil, etc.) by a variety of biotic communities. The current study had to necessarily focus on understanding the physical system while attempting to understand the relationships of change within it.

Although stream flow records were available for only 2 of the 10 study sites, all of the stream gage records obtained were used primarily for establishing generic flow frequency relationships and return periods. This can be effectively accomplished (and was in this study) using nearby gage data. Therefore, the lack of specific gage data for each site is more a concern for convenience rather than reliability of results. Also, measuring stream flows for specific storms before and after development and relating that to changes in impervious area would be very helpful data for this investigation. However, in watershed studies as in much of scientific endeavor, there is always a gap between the ideal data set and the actual data set. The relation that was possible to measure compared stream channel changes (that resulted from changes in discharge) directly to the changes in impervious area. This did not provide the ideal comparison (impervious area to stream flow, stream flow to stream channel change) but it does provide a quantifiable relationship between stream channel change and impervious area change.

7.4 Study Limitations

The charge of this study, the defined objectives, and the adopted approaches were all very ambitious. However, the need for data on these types of systems in this environmental setting is great, and aim was therefore to maximize results for the available resources. Thus, the results should be recognized as preliminary.

This study attempted to define several complex relationships involving stream channel response to watershed change using a modest data set that covers a relatively short period of time. Because there are many variables that affect the complex relationships between TIMP, runoff, and geomorphic response in stream channels, the study design attempted to limit the potential influences of certain variables to better evaluate the response of others. However, in reality it is difficult to achieve the desired control of variables that is required for definitive results in a study of this type. Consequently, it is important to be aware of the following points while assessing the results of this study.

- The data gathering and assessment requirements of this project included three major efforts that each could have been addressed as stand-alone investigations. Stream channel classification, evaluation of Dominant Discharge, and assessment of form and process of streams located in urbanizing watersheds of a semi-arid region could each have been a significant investigative effort on their own. Therefore, the analytical effort was great relative to the data set generated.
- The scale of the study region is very large compared to the actual area included in the study. The size of the study region, excluding the interior drainage areas, is nearly 6,300 square miles. The total watershed area covered by the sites used in this study is less than 33 square miles.
- The nature and response of watersheds in drylands is generally different than watersheds in humid areas. Dryland streams have fewer stream flow events and the importance of the flows from the last storm event is greater (Graf 1988). Knowing the magnitude of the latest flood event is important for interpreting the channel features measured after that event. However, in all cases, the field measurements of channel features did not follow a wet season with significant storm events, and thus are considered representative of the lower range of more normal events in these systems.
- Although a sizeable effort went into gathering data for this study, a relatively small data set was generated and used to evaluate channel response. Therefore, compelling as the results of this study may be, they must be considered preliminary.

7.5 Additional Research Needs

There is a large body of research into the effects of urbanization on increases in peak flow from regions of the county with wetter climates. However, this information is nearly absent for semi-arid regions, like southern California. This investigation is one of the first to assess the response of ephemeral/intermittent stream channels in an arid region with changing hydrology due to urbanization of the watershed. This is a common condition throughout the six counties of the study area that grew at a rate of more than 12% between the last two censuses. Communities are increasingly concerned about the damage to the environment and to property but are uncertain as to how to make sound management decisions to control the situation. This investigation has identified a number of principles that appear to characterize the relationship between urbanization and the stability, or lack of stability, of ephemeral/intermittent stream channels. However, the investigation included a very limited number of streams. Therefore, it is recommended that future investigations be conducted to confirm and expand the understating of the unique processes involved.

(A) Survey stream channels in the study area with reconnaissance or remote sensing techniques to identify and classify the critical "natural" stream channel reaches that still remain in this region, and help focus management efforts and prioritize future research.

(B) Measure stream channel form, stream channel slope, and bed and bank material resistance for both ephemeral streams and perennial streams in the study area that fall into the category of critical "natural" stream channel reaches. This could include streams and rivers in the study region with watersheds greater than the size limits recommended for the classification system here.

(C) Study USGS and county stream gage data that span the period of urbanization in various locations throughout the study region to establish quantitative values for increased flows. Tie back to percent change in impervious area for this time period. Quantitatively assess whether relationships exist that could predict "effective rainfall" levels (the minimum precipitation needed to produce an "effective" flow in the stream channel) based on watershed size and TIMP

(D) Investigate in greater detail the measurement or estimation of impervious area through various methods and establish a correlation between them. This will create a common set of assessment values that would allow the use of older photographs and newer digital imagery remote sensing techniques to overlap TIMP calculations for longer time periods.

(E) Identify more candidate sites for future studies. Establish a permanent set of sites that will be less likely to be affected by future development or stream channel "improvements." Use the long-term monitoring of these sites to quantify natural rates of change over various climatic cycles.

(F) Develop and test conceptual and/or predictive models for use in evaluating management strategies and specific management options in different watersheds and stream channel types.

(G) Broaden understanding of ephemeral stream channels in the six county region with additional characterization and study; perhaps extending into the truly arid (interior drainage) parts of this region.

(H) Resurvey the study sites within the current water year to capture the impacts on these stream channels from an excessively wet rainfall season.

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