# TECHNICAL MEMORANDUM

# Causes of Degradation and Aggradation in the Santa Ana Region

**Prepared by:**

**RBF Consulting**
**14725 Alton Parkway**
**Irvine, California 92618**

**January 18, 2017**

# TABLE OF CONTENTS



## APPENDICES

## FIGURES

# 1 INTRODUCTION

The 2010 Santa Ana Region (SAR) MS4 Permit requires the Permittees to identify potential causes of stream degradation and aggradation. This technical memorandum is part of the larger study for the Permittees to develop the SAR Hydromodification Management Plan.

## 1.1 Watershed Background

### Santa Ana River Watershed

The Santa Ana River Watershed is located in southern California, south and east of the city of Los Angeles. The Santa Ana River Watershed includes much of Orange County, the northwestern corner of Riverside County, the southwestern corner of San Bernardino County, and a small portion of Los Angeles County. The Santa Ana River Watershed is bound on the south by the Santa Margarita Watershed, on the east by the Whitewater Watershed and on the northwest by the San Gabriel River Watershed. The area of the Santa Ana River Watershed is approximately 2,650 square miles.

### Santa Ana Region

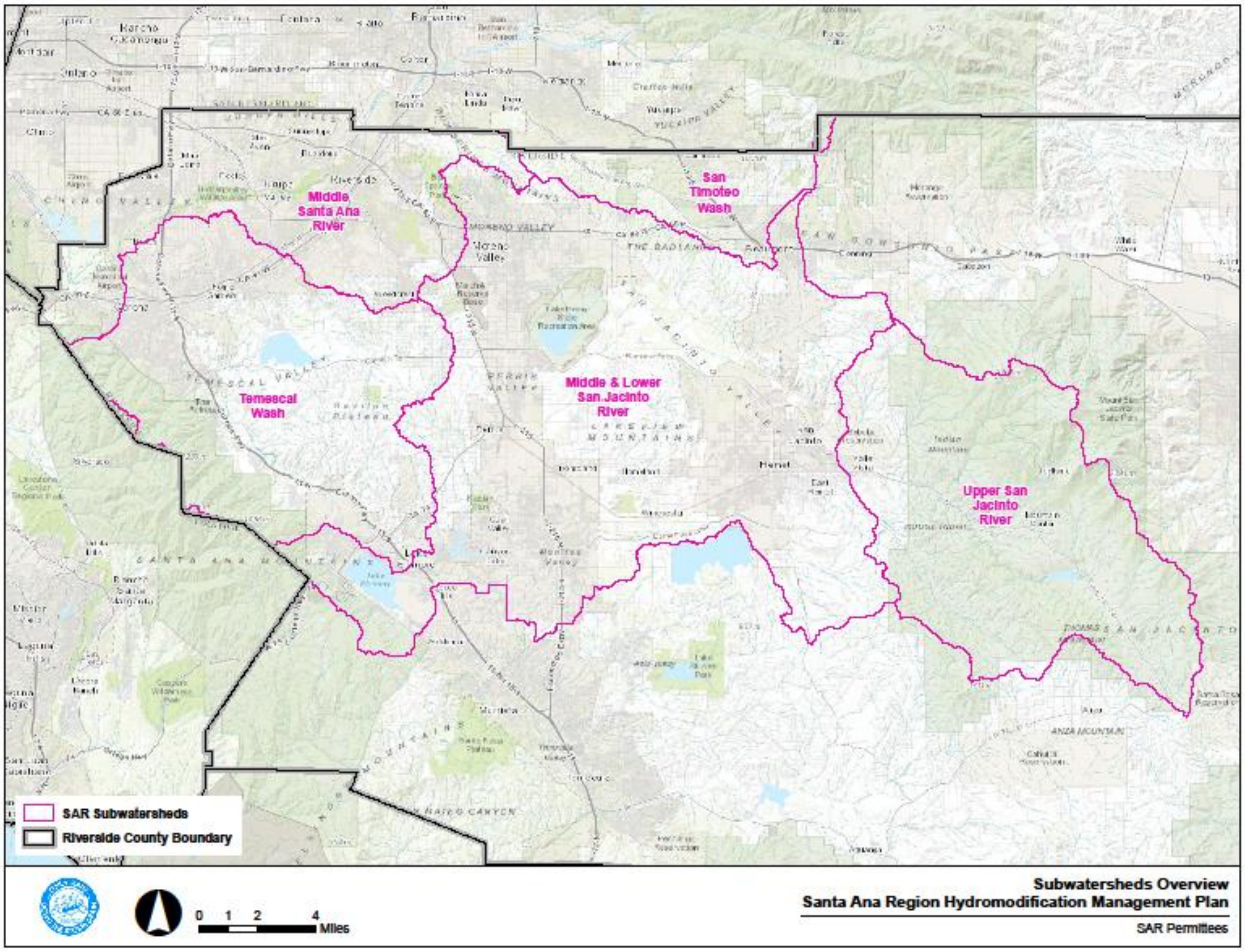
The SAR is that portion of the Santa Ana River Watershed within Riverside County and is the area addressed by this technical memorandum. The SAR extends approximately 63 miles from east to west, and more than 29 miles from north to south. The SAR lies between the Santa Ana Mountains and the San Bernardino Mountains; the topography of the SAR varies highly with altitudes ranging from 415 feet to 8,200 feet. The San Jacinto River is a tributary of the Santa Ana River. Runoff from the 768-square mile San Jacinto River Watershed is regulated by Railroad Canyon Dam and natural storage in Lake Elsinore. Only as a result of rare high intensity storm events that result in overflow from Lake Elsinore will water flow into the Santa Ana River.

The surface drainage system from the remainder of the SAR, which includes the cities of Jurupa Valley, Eastvale, and Riverside, drain through local systems to Reach 3 of the Santa Ana River.

## 1.2 Purpose

The purpose of this technical memorandum is to identify potential causes of stream degradation and aggradation in all major subwatersheds of the SAR, including Upper San Jacinto River, Middle and Lower San Jacinto River (see map on next page), Temescal Wash, and San Timoteo Creek. The Middle Santa Ana River (MSAR) Subwatershed is not investigated in this report. The MSAR has been identified as an adequate sump in Section 3.2. of Appendix A based on drainage, tributary area, and floodplain characteristics of the river. Figure 1 identifies the geographic layout of the four subwatersheds of study.

**Figure 1: Location Map**



# 2 METHODOLOGY

The causes of channel degradation and aggradation were determined using two methods: examination of historical and current aerial photographs, and a Geographic Information System (GIS)-based desktop study. The following sub-sections summarize each method.

## 2.1 Aerial Photographs

Current aerial photographs were provided by Microsoft Bing. These aerials were examined to get a general idea of the existing condition of the subwatersheds. Specifically, the aerials were used to locate drainage basins, areas of significant degradation, aggradation and regions of dense urban development.

Historical aerials were obtained from the USGS Earth Explorer online database, available for download at http://earthexplorer.usgs.gov/. The aerial photographs were selected based on the engineer's best professional judgment to exhibit the channel conditions that are representative of the evolution of the subwatershed and, if any, examine the timing and the extent of degradation and aggradation of selected channels. Based on availability, aerial photographs ranged from 1948 to 2013. Historical aerials used for the study have been included as Attachment B of this Technical Memorandum.

## 2.2 GIS-based Desktop Study

A GIS-based methodology for identifying potential causes of degradation and aggradation was developed by the Southern California Coastal Water Research Project (SCCWRP) entitled "Hydromodification Screening Tools: GIS-Based Catchment Analyses of Potential Changes in Runoff and Sediment Discharge" dated March 2010 (Technical Report 605 - Appendix B).

According to this report, many of the same physical properties that determine the hydrologic response of a subwatershed also determine the magnitude of sediment production from those same areas. It also states that three factors were found to exert the greatest influence on the variability of sediment production rates:

1. Geology Types;
2. Land Cover; and
3. Hillslope Gradient

The SCCWRP report used the three factors to create Geomorphic Landscape Units (GLUs), which are similar to Hydrologic Response Units (HRUs). HRUs and GLUs are the grouping of like subwatershed qualities (e.g., sedimentary-developed-10% to 20% slope) and are used to reduce model complexity and data requirements. Comparing existing GLUs versus those of "prior to identified degradation and aggradation" conditions provides evidence for the causes of degradation and aggradation.

For this study a strict GLU analysis was not used. The three factors were kept separate to simplify the analysis and provide an overview of how the subwatersheds are structured.

### 2.2.1 Geology Types

The geology types used for this study were obtained from the California Geological Survey and State Mining & Geology Board (http://www.conservation.ca.gov/cgs/Pages/Index.aspx). Each subwatershed was divided into its respective geology types, with special consideration to areas of Sedimentary Rocks – Alluvium, especially in the downstream reaches of the subwatershed.

According to *Geomorphology: A Systematic Analysis of Late Cenzoic Landforms* by Arthur L. Bloom, alluvium is considered to be continually progressing toward the sea. Additionally, the mean grain size of bedload alluvium decreases in a downstream direction due to the loss of competence, i.e., the measure of a stream's ability to transport a certain maximum grain size of sediment. Because the velocity of flow tends to decrease in the lower reaches of a subwatershed, the energy available for transporting bedload alluvium decreases. The channelization of these natural channels may have increased the competence of the channels, notably in the lower reaches, resulting in an increased potential for the degradation of the lower reaches.

### 2.2.2 Land Cover

The land cover types were obtained from the National Oceanic and Atmospheric Administration (NOAA) Ocean Service, Coastal Services Center (http://csc.noaa.gov/digitalcoast/dataregistry/#/). Each subwatershed was broken up into five land cover types:

1. Agricultural/Grass
2. Developed
3. Forest
4. Scrub/Shrub
5. Other (water, bare rock, etc.)

The most important land cover type to consider is "developed". In the absence of hydrologic controls, as a subwatershed undergoes urban development, the potential for runoff may increase, and the potential sediment supply may decrease, possibly creating an imbalance within the subwatershed.

### 2.2.3 Hillslope Gradient

The hillslope gradients were based on a U.S. Geological Survey (USGS) 10 meter Digital Elevation Model (DEM) from http://seamless.usgs.gov/website/seamless/viewer.htm. The subwatershed was broken up into a 10 meter by 10 meter grid, where the grids were divided into three hillslope gradients:

1. 0 to 10%
2. 10 to 20%
3. Steeper than 20%

Regions of steeper slopes generally have a higher potential for erosion, degradation and aggradation.

# 3 SUBWATERSHEDS

This section describes the four subwatersheds examined as part of this study and explains the results of the aerial photograph review and GIS-based desktop study.

## 3.1 Upper San Jacinto Subwatershed

The Upper San Jacinto Subwatershed is located on the northeast portion of the SAR. The headwaters of the San Jacinto River originate in the San Jacinto Mountains of San Bernardino County. The downstream point of the Upper San Jacinto Subwatershed is at the confluence of Bautista Creek, Poppet Creek, and the San Jacinto River in the city of San Jacinto. The subwatershed drainage area to this confluence encompasses 246 square miles. The upper portion of the San Jacinto River flows through the San Bernardino National Forest and unincorporated land of Riverside County. The upper portion of the San Jacinto River is about 23 miles long and ranges from the outlet of Lake Hemet and the confluence herein specified.

Lake Hemet is the major water storage facility within this subwatershed. The dam was established in 1895 downstream of the Garner Valley Basin and operates on the principles of water supply. In addition to decreasing the downstream flow rate, the dam acts as a major debris basin.

### 3.1.1 <u>Study Reach</u>

The reach of the Upper San Jacinto River Channel that is under investigation extends for 1.7 miles from Blackburn Street to Grant Street in Valle Vista, an unincorporated community of Riverside County. No improvements within the floodplain have been made; the study reach is a natural braided channel with some vegetation observed along the long flow branch.

### 3.1.2 <u>Historical Aerial Photographs</u>

From the historical aerial photographs (Appendix A), it can be seen that this stretch of the channel has not been modified since 1972. In addition, limited development has occurred within the observed floodplain between 1972 and 2013. Agricultural activities take place south of Highway 74.

### 3.1.3 <u>GIS-based Desktop Study</u>

The following subsections summarize the results of the GIS-based desktop study for the Upper San Jacinto Subwatershed.

#### *3.1.3.1 Geology Type*

The Upper San Jacinto Subwatershed is dominated by plutonic and metavolcanic rocks (72.4%) in the upper reaches. Lower reaches, as well as the Lake Hemet plateau, are for the most part made of sedimentary rock, including alluvium, gneiss, argillite, and sandstone. Sedimentary rocks have the highest relative potential for erosion. The presence of Lake Hemet contributes to the capture of coarse grained sediments detached from reaches upstream of the Lake; the clear reservoir outflow increases the potential for erosion along the lower reaches.

#### *3.1.3.2 Land Use*

The Upper San Jacinto Subwatershed is for the most part undeveloped. Valle Vista, along with pockets of development in the upper reaches of the subwatershed, account for .82% of the entire drainage area located within Riverside County. Undeveloped areas include forest (39.2%), scrub/shrub (62.7%), grassland (6.8%), and agriculture (5.2%). The low levels of development have contributed to the maintenance of the natural hydrologic response of the subwatershed. The dynamics of the dam operations may have altered this balance for the San Jacinto River, thus impacting the frequency and intensity of flows observed in the downstream channel. Tributaries of the San Jacinto River are not impacted by development.

#### *3.1.3.3 Hillslope Gradient*

With the exception of the mouth of the Upper San Jacinto River and the Lake Hemet plateau, the majority of the upper reaches have a high potential for erosion as they exhibit gradient greater than 11%. While the majority of the developed land is located in the lower sediment production areas, the construction of Lake Hemet may have altered part of the transport of coarse grained sediments that originate from the high yield areas.

**Figure 2: Upper San Jacinto Subwatershed Land Cover Types**

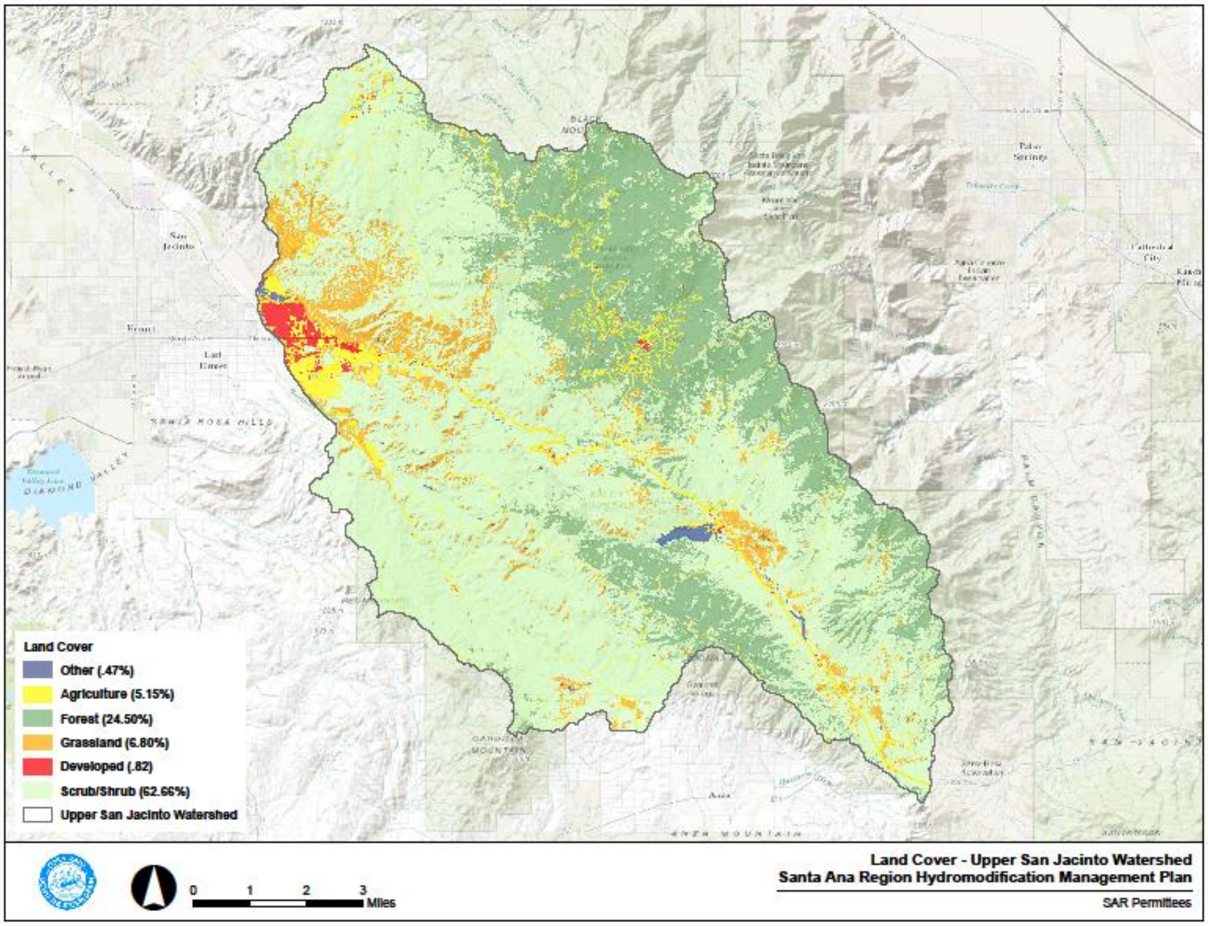


**Figure 3: Upper San Jacinto Subwatershed Geology Types**

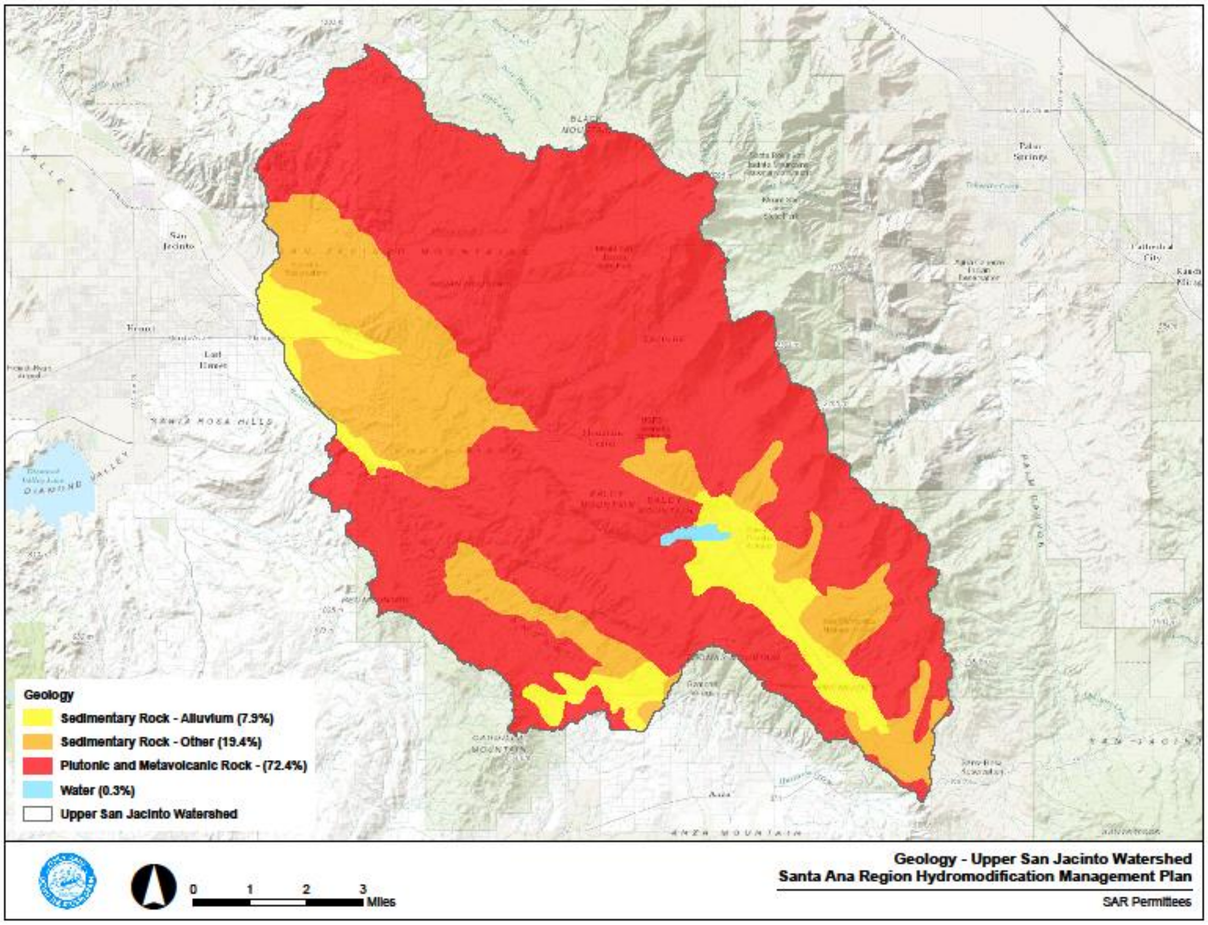
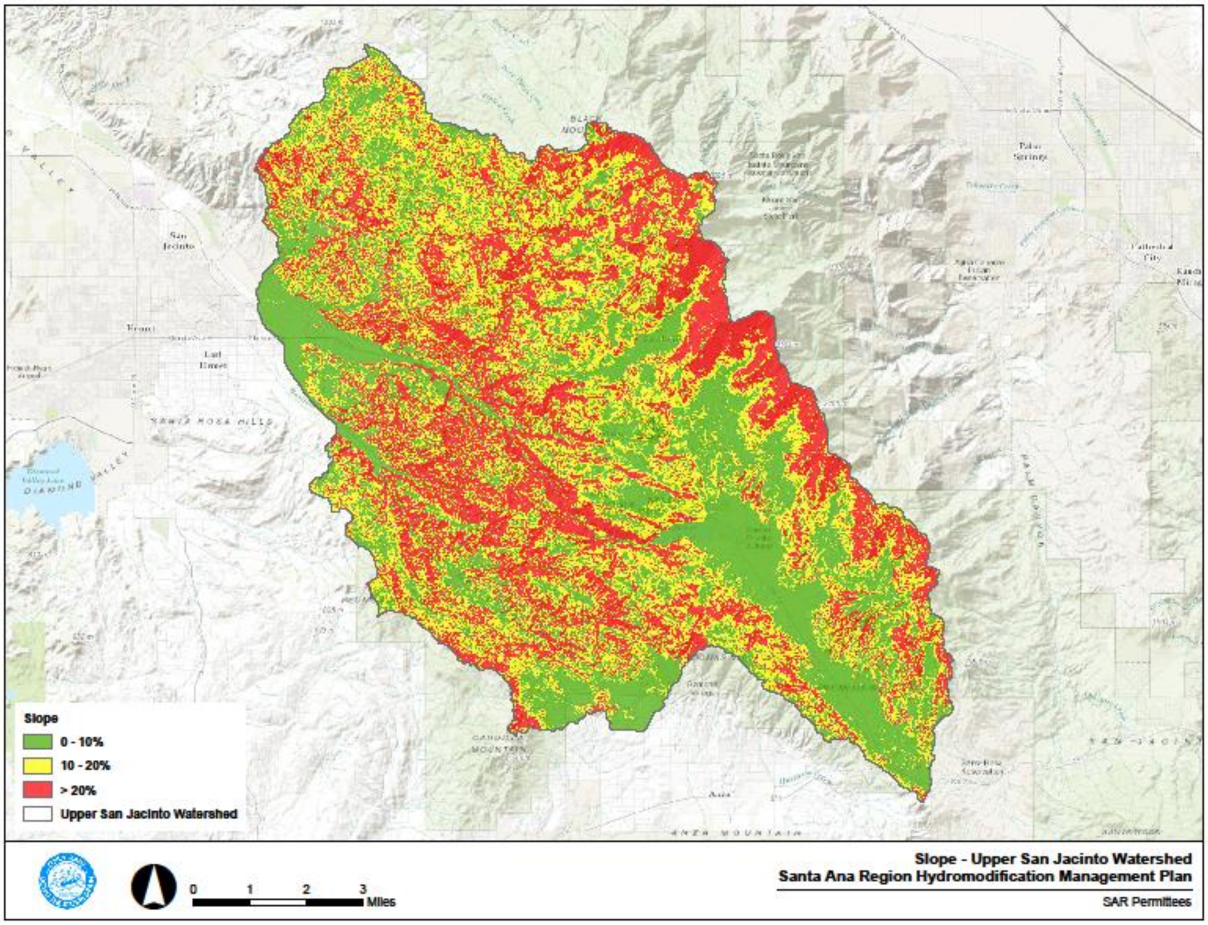


**Figure 4: Upper San Jacinto Subwatershed Hillslope Gradients**



#### 3.1.4 Conclusion

Urban development within the Upper San Jacinto Subwatershed is limited (.82%) and has occurred at the mouth of the San Jacinto River, within Valle Vista, an unincorporated community of Riverside County. The majority of the upper, steeper reaches have remained in a natural condition. Generally, this would be beneficial because the steep slopes and undeveloped land would still produce significant sediment to replenish the downstream channel. The presence of Lake Hemet in the Subwatershed has partially reduced the supply of coarse grained sediment from transport to the downstream channel reaches.

Compared to "prior development" conditions, land uses have remained the same. Future urban development, if any in the upper reaches, may alter the Subwatershed dynamics and ultimately result in changes in the channel stability.

### 3.2 Middle and Lower San Jacinto Subwatershed

The Middle and Lower San Jacinto Subwatershed is located within the central part of the SAR. The downstream point of the Lower San Jacinto Subwatershed is the outlet of Lake Elsinore. The drainage area of the Middle and Lower San Jacinto Subwatershed encompasses 510 square miles. The combined middle and lower sections of the San Jacinto River are 35 miles long. Major tributaries to the subwatershed include Potrero Creek, Perris Valley Channel, and Salt Creek Channel. The San Jacinto River flows through the cities of San Jacinto, Perris, Menifee, Canyon Lake, and Lake Elsinore.

The San Jacinto River drains to Canyon Lake and Lake Elsinore. The Railroad Canyon Dam was built in 1928, creating the 11,600 acre-feet Canyon Lake. The Elsinore Valley Municipal Water District operates the lake based on water supply considerations and maintains a minimum lake elevation of 1,372 feet for the benefits of residents of the Lake Elsinore/Canyon Lake area. In addition, the Canyon Lake Property Owners Association leases surface rights for water recreation and regulates residential development around the edge of the lake.

Lake Elsinore is a 90,000 acre-feet natural lake located downstream of Canyon Lake. A spillway set at a relative elevation of 42 feet runoff exceeding this elevation discharges into Temescal Wash. Canyon Lake and Lake Elsinore contribute to the decrease in downstream flow rates, and represent a physical barrier to the transport of coarse grained sediments.

#### 3.2.1 Study Reach

The study reach of the San Jacinto River starts approximately at Interstate 215 and extends for 3.1 miles to Ethanac Road within the city of Perris. Because of limited definition, available aerial photographs for the entire reach are as old as 39 years (oldest is circa 1975). Older aerials exist but their definition does not allow the engineer to distinguish the path of the San Jacinto River. In 1975, the San Jacinto River had already been channelized. Bed and banks of the channel are made of soft earthen material. Stabilization efforts have been implemented to the reach: banks are protected and consistent vegetation exists. Degradation and aggradation may still occur if hydrologic and sediment regimes are modified.

Aerial photographs indicate that there has been significant urbanization of the Subwatershed within the 1972-2013 period. The trend may be a contributing factor to the degradation and aggradation of the morphology of the channel.

### 3.2.2 Historical Aerial Photographs

From the historical aerial photographs (Appendix A), it can be seen that this stretch of the channel has been channelized. The engineer may also observe that stabilization work has occurred on the bed and banks of the channel. This may be related to the constant base flow received from public owned treatment works (POTWs), as well as the important urban development that has occurred over the 1972-2013 period. During this time the Subwatershed transitioned from being predominantly agricultural to predominately urban development.

### 3.2.3 GIS-based Desktop Study

The following subsections summarize the results of the GIS-based desktop study for the Middle and Lower San Jacinto River Subwatershed.

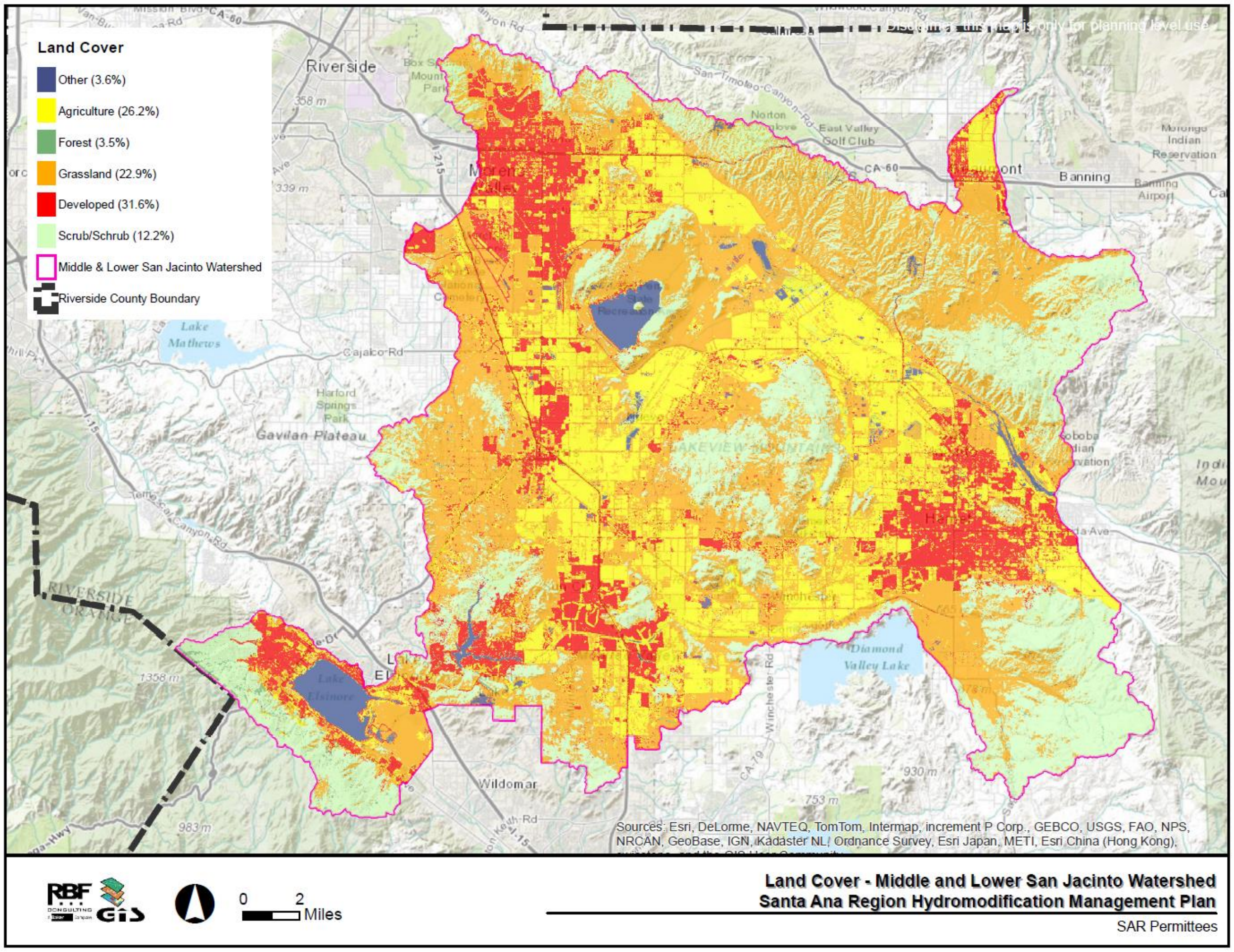
#### *3.2.3.1 Geology Type*

The setting of the Middle and Lower San Jacinto River Subwatershed consists of the lowlands of the overall Subwatershed, thus the geologic soils present within the valley are primarily sedimentary rocks (67.6%). Sedimentary rocks notably account for 50.7% of alluvium and have the highest relative potential for erosion. Plutonic and metavolcanic rocks account for 32.4% of soil types within the Subwatershed, notably on the Santa Rosa Hills and the Lakeview Mountains that are in proximity to the San Jacinto River. Because the debris basins capture the majority of coarse grained sediment from these mountainous areas, the clear reservoir outflows increase the potential for erosion along the lower reaches and the San Jacinto River.

#### *3.2.3.2 Land Use*

Major areas of urban development (31.6% of the Subwatershed) are concentrated within Moreno Valley, the Hemet area down gradient from the Santa Rosa Hills, Menifee and Canyon Lake, as well as the northwest side of Lake Elsinore. Agriculture and grassland remain a dominant activity within the lowlands of the Subwatershed, combining for more than 49.1%. The development of several communities has resulted in a significant change in the subwatershed's imperviousness and associated increase in the frequency and flow experienced in the channel. Aerial photographs confirmed that several segments of the channel have been channelized to convey runoff from the observed urban development.

**Figure 5: Lower and Middle San Jacinto Subwatershed Land Cover Types**



# Figure 6: Lower and Middle San Jacinto Subwatershed Geology Types

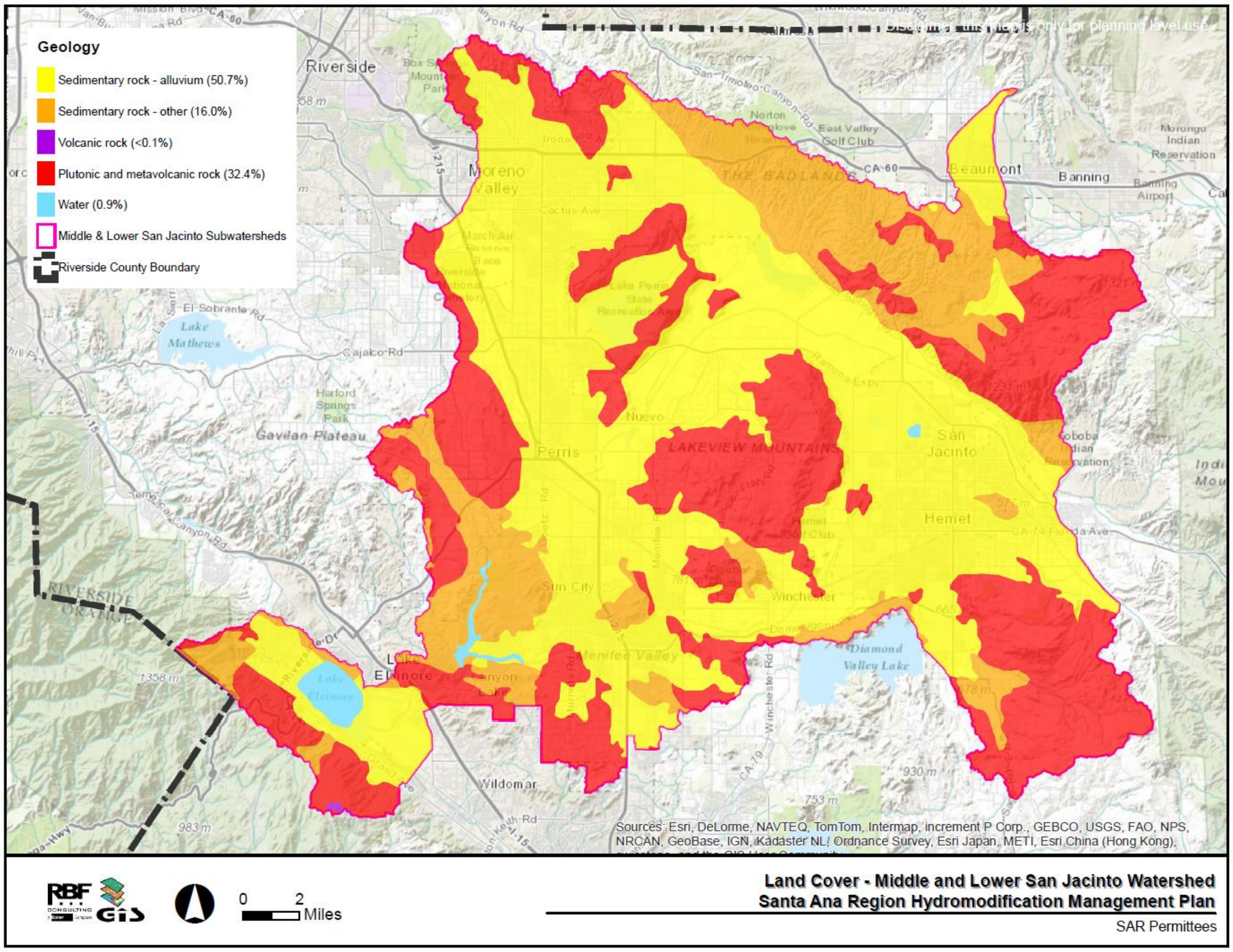
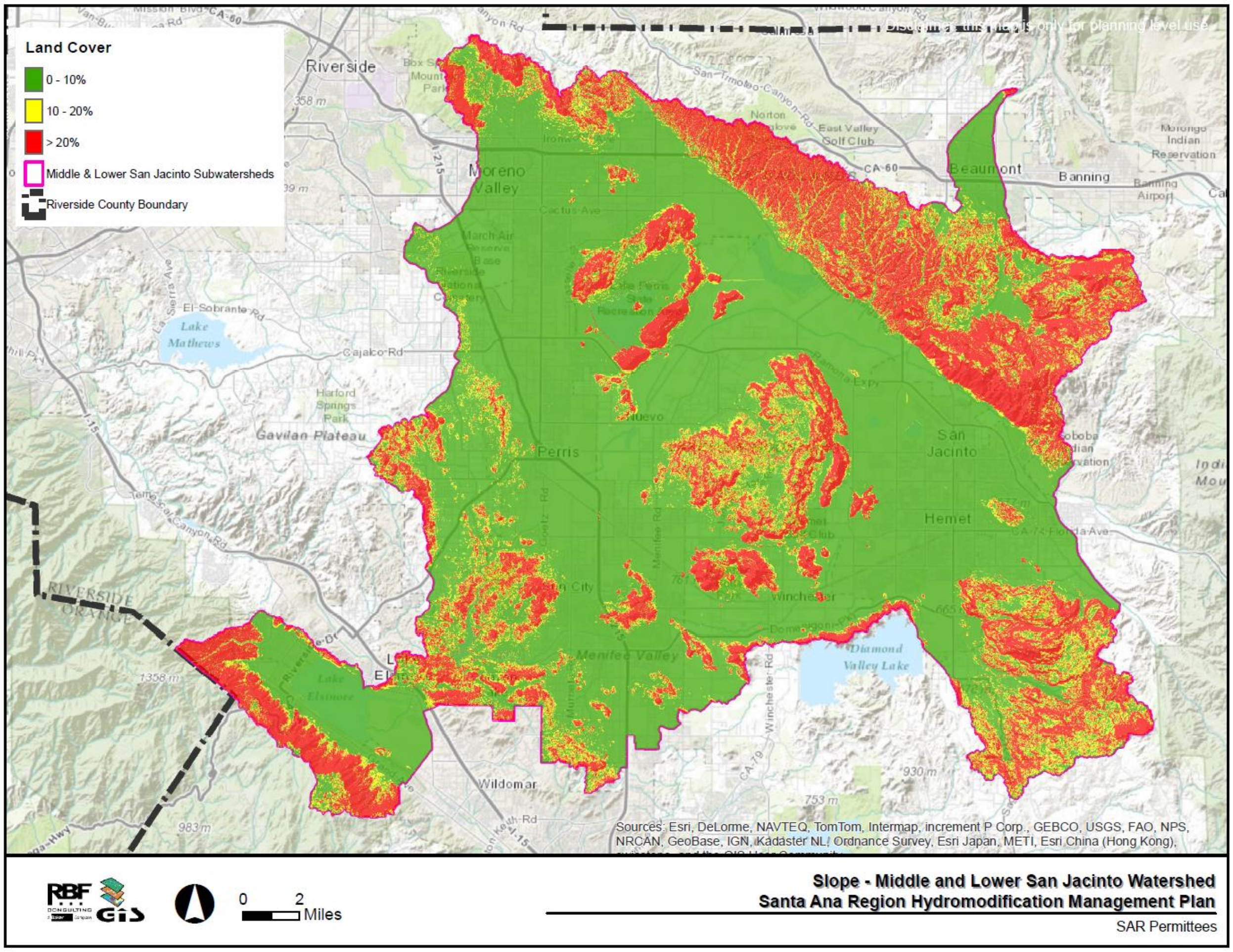


**Figure 7: Lower and Middle San Jacinto Subwatershed Hillslope Gradients**



#### *3.2.3.3 Hillslope Gradient*

The majority of reaches with the highest potential for erosion with a hillslope gradient greater than 21%, are concentrated on the upper reaches near the San Jacinto Mountains, the Santa Rosa Hills, the Lakeview Mountains, and the Sana Ana Mountains surrounding Lake Elsinore. The central (developed and agricultural) portion of the subwatershed has a hillslope gradient of 0-10% with a lower potential for sediment production. While the majority of the developed land is located in the lower sediment production areas, the construction of the debris basins have effectively obstructed a majority of the coarse sediment produced in high yield areas from reaching the downstream watercourse.

### 3.2.4 Conclusion

The majority of the urban development within the Lower and Middle San Jacinto Subwatershed is located in the lower reaches, while the upper, steeper reaches have remained in a natural condition. Generally, this would be beneficial because the steep slopes and undeveloped land would still produce significant sediment to replenish the downstream channel. The issue is that the debris basins have been constructed just downstream of the upper reaches. The debris basins have reduced the supply of coarse grained sediment from making it to the downstream channel reaches. In addition, the significant change in impervious area due to subwatershed development has increased the frequency and rate of flow in the channel.

Compared to "prior to development" conditions, the Lower and Middle San Jacinto Subwatershed has been heavily developed. But with a decrease in sediment production from the upstream reaches of the Subwatershed due to the debris basins, the hydrologic and sediment transport dynamics of the San Jacinto Subwatershed has been significantly altered. The sediment supply has been reduced, and the stream flow has been increased which has resulted in an imbalance in the sediment supply and transport capacity. This imbalance would be anticipated to result in changes in the channel stability. This can be seen in the two unprotected channel segments located respectively upstream of Canyon Lake and upstream of Interstate 215 where significant degradation and aggradation has occurred.

## 3.3 Temescal Wash

The Temescal Wash Subwatershed is located within the western part of the SAR. The 29-mile long Temescal Wash connects Lake Elsinore with the Santa Ana River. The tributary drainage area to Temescal Wash before the confluence with the Santa Ana River in Corona is 250 square miles large. Along its watercourse, several tributaries, including Wasson Canyon Wash, Arroyo Del Toro, Stovepipe Canyon Wash, Rice Canyon Wash, and Lee Lake discharge into Temescal Wash. Temescal Wash flows through an arid rain shadow zone of the Santa Ana Mountains and is ephemeral for most of its length.

### 3.3.1 Study Reach

The study reach of Temescal Wash starts approximately at Riverside Drive (Highway 74) and extends for 1.3 miles to Nichols Road within the city of Lake Elsinore. Available aerial photographs for the entire reach span from 1952 to 2013. The natural alignment of Temescal Wash has not been modified for the reach of study and urban development has occurred on adjacent land, bringing commercial and transportation infrastructures to the area. The bed and banks of Temescal Wash are vegetated but are not stabilized by adequate engineering methods, and two ephemeral pools have been conserved.

### 3.3.2 Historical Aerial Photographs

From the historical aerials (Appendix A), it can be seen that the Temescal Wash Subwatershed has observed a significant urban development within the 1952-2013 period. Historical agricultural land uses have progressively been modified for residential, commercial, and transportation purposes. The trend may be a contributing factor to the modification of the geomorphology of the wash. In addition, the implementation of a shallow dam on Lake Elsinore may have over the long run, significantly reduced the discharge from the lake. The historical aerials show the establishment of riparian vegetation over the banks of the evaluated segment between 1980 and 2013. The vegetation on the channel banks may have enhanced their ability to resist both changes in hydrologic and sediment regimes.

### 3.3.3 GIS-based Desktop Study

The following subsections summarize the results of the GIS-based desktop study for the Temescal Wash Subwatershed.

#### *3.3.3.1 Geology Type*

Geologic soils within the Temescal Wash Subwatershed are dominated by plutonic and metavolcanic rocks (52.8%) that are located on the northern slopes of Temescal Canyon (Gavilan Plateau) and southern slopes of Temescal Canyon (Santa Ana Mountains). Sedimentary rocks combine for 45.9%, and are for the most part located within the floodplain of Temescal Wash where urban development has been occurring. Urban development has reduced the potential for delivery of alluvium to the receiving waters, which may impact the morphology of Temescal Wash. Because several debris basins capture the majority of coarse grained sediment from the upper reaches, the clear reservoir outflows increase the potential for erosion along the lower reaches and Temescal Wash.

#### *3.3.3.2 Land Use*

The majority of the areas under urban development are located along the floodplain of Temescal Wash, as well as the lowlands within the city of Corona. Urban development accounts for 32.3% of all land uses within the Temescal Creek Subwatershed. The remainder of the Subwatershed is mostly undeveloped, including forest, scrub, and grassland. Agriculture and grassland remain a dominant activity within the lowlands of the subwatershed, combining for more than 49.1%. Development along Temescal Wash and within the city of Corona has resulted in a significant change in the Subwatershed imperviousness and associated increase in the frequency and flow experienced in Temescal Wash. Aerial photographs confirmed that the natural hydrologic response of the Subwatershed has been significantly altered by urban development.

#### *3.3.3.3 Hillslope Gradient*

The majority of reaches, which have the highest potential for erosion with a hillslope gradient greater than 21%, are concentrated to the northern and southern sides of Temescal Canyon, where the Gavilan Plateau and the range of Santa Ana Mountains are located, respectively. The remainder of the Subwatershed exhibit slopes lower than 10%, where the potential for erosion is much lower. The majority of development has occurred within areas of low gradient.

### 3.3.4 Conclusion

The majority of the urban development within the Temescal Wash Subwatershed is located in the lower reaches or within the floodplain of Temescal Wash, while the upper, steeper reaches have remained in a natural condition. Generally, this would be beneficial because the steep slopes and undeveloped land would still produce significant sediment to replenish the downstream channel. The issue is that several debris basins have been constructed just downstream of the upper reaches. The debris basins have cut off part of the supply of coarse grained sediment from making it to the downstream channel reaches. In addition, the significant change in impervious area due to subwatershed development has increased the frequency and rate of flow in the channel.

The subwatershed dynamics have been significantly altered. The sediment supply from the northern slopes of Temescal Canyon (Gavilan Plateau) and southern slopes of Temescal Canyon (Santa Ana Mountains) to Temescal Wash has been reduced. In addition, urbanization has resulted in increased channel flow, thus creating an imbalance in the sediment supply and transport capacity. This imbalance would be anticipated to result in changes in the channel stability. Several unimproved segments of Temescal Wash exhibit significant degradation and aggradation. Because of dry-weather runoff from agricultural and publicly-owned treatment works, the segment near Highway 74 and Corona Lake has observed a development of riparian vegetation on the channel banks. This presence of riparian vegetation may improve the channel resistance to the changes in flow and sediment regimes.

**Figure 8: Temescal Wash Subwatershed Land Cover Types**

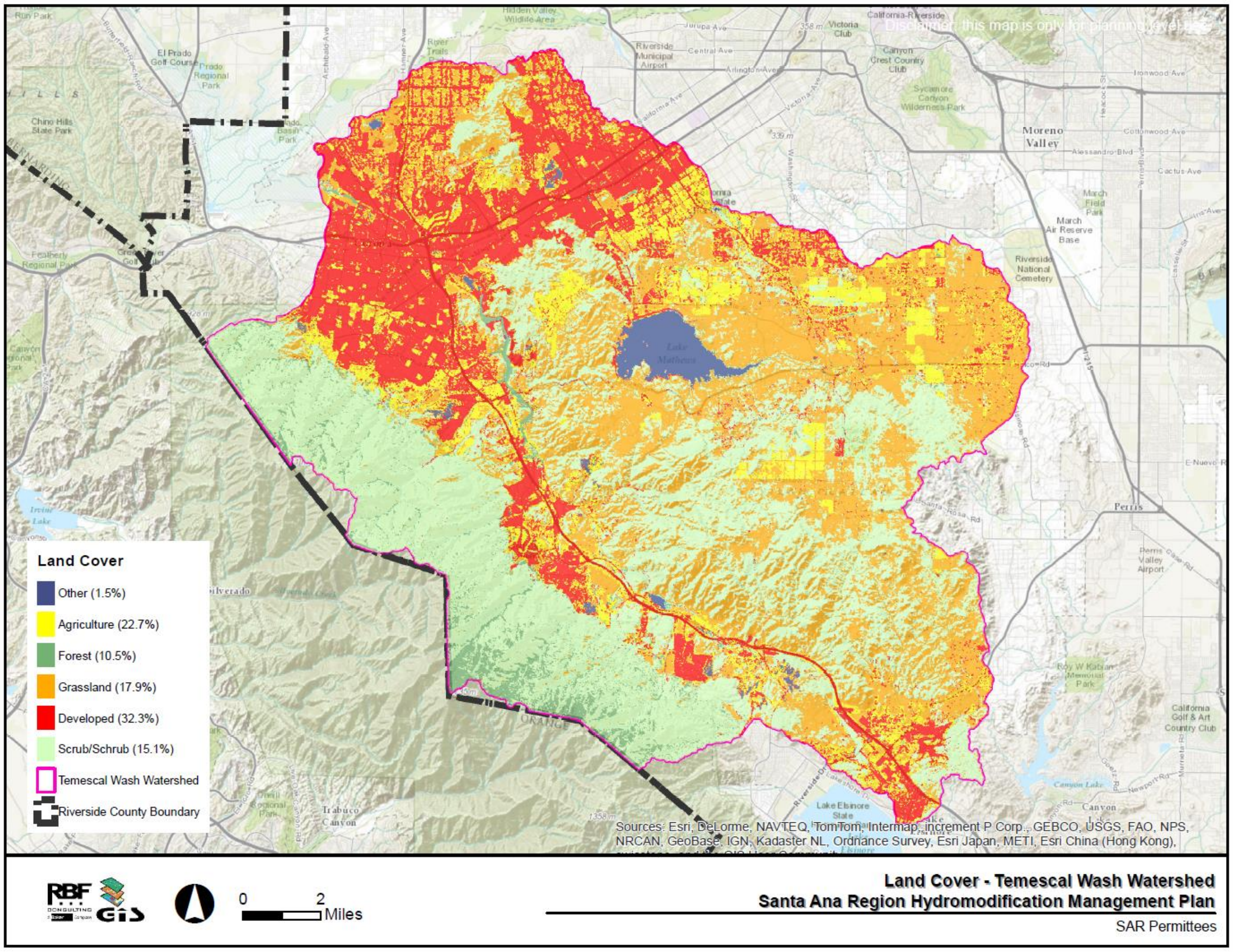


**Figure 9: Temescal Wash Subwatershed Geology Types**

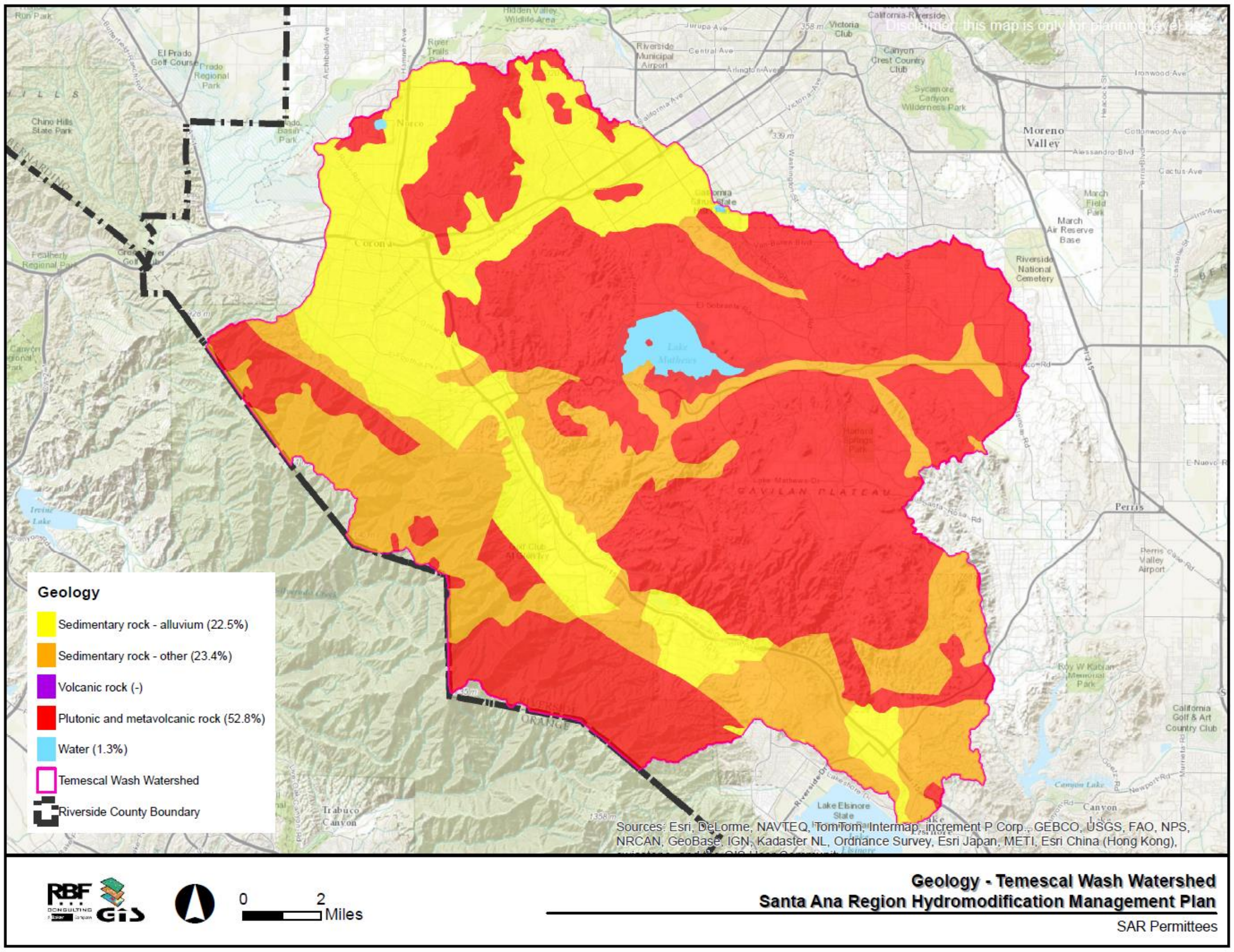
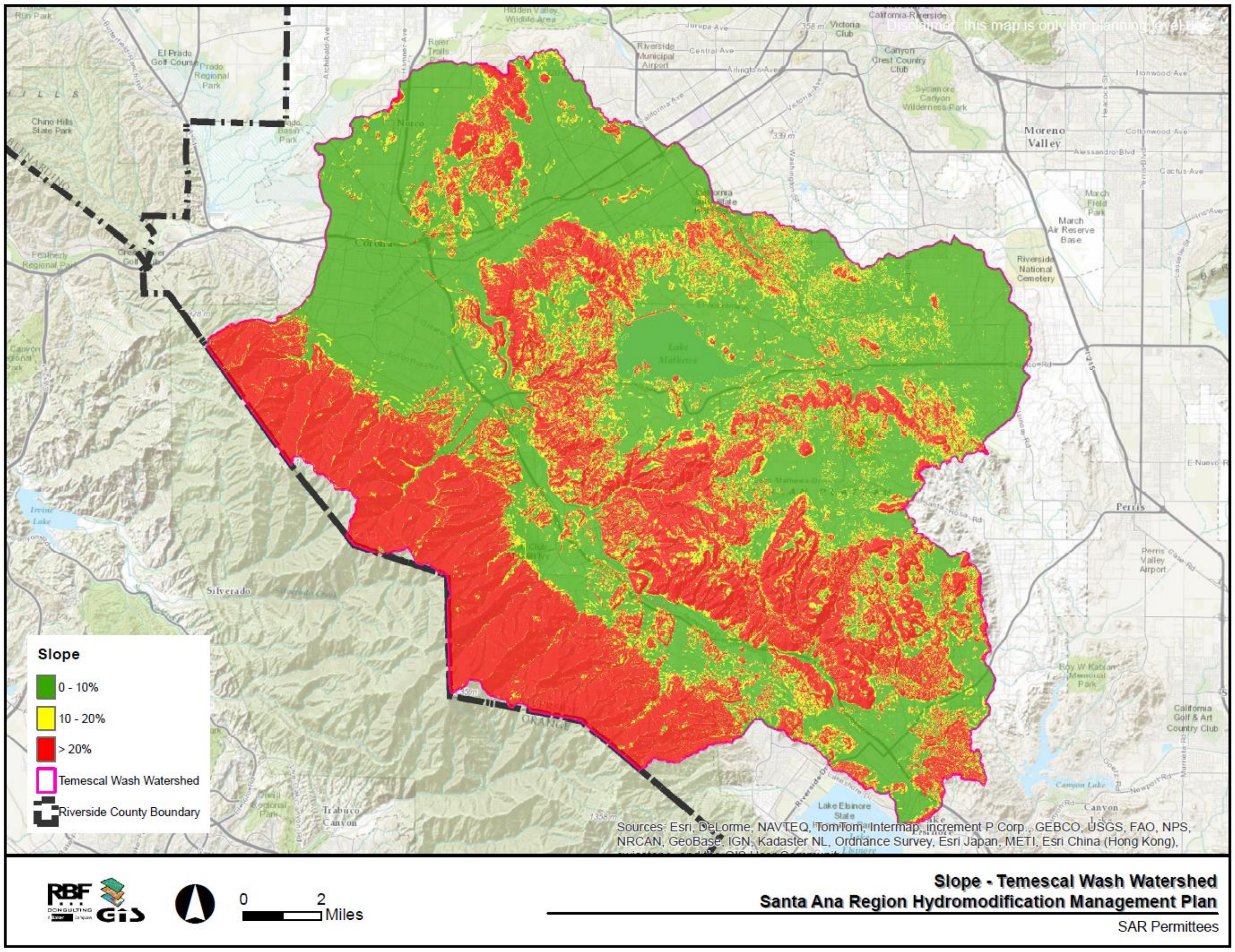


**Figure 10: Temescal Wash Subwatershed Hillslope Gradients**



## 3.4 San Timoteo Creek Subwatershed

The San Timoteo Creek Subwatershed encompasses an area of 60 square miles. Upper reaches that account for 59.9 square miles are located within the County of Riverside, whereas lower reaches are located within the County of San Bernardino. Headwaters of San Timoteo Creek within Riverside County are located in the San Bernardino Mountains, which drain to Cherry Valley. Other headwaters located within the County of San Bernardino include Yucaipa Creek and Live Oak Canyon. Upon leaving the San Timoteo Canyon, the Creek discharges into the Santa Ana River near the Interstate 10 and Interstate 215 interchange. Agricultural activities and POTW discharges to the Creek occur year-around, creating a perennial flow condition.

### 3.4.1 Study Reach

The reach of San Timoteo Creek that is evaluated extends for approximately 3.0 miles along Oak Valley Parkway, known also as San Timoteo Canyon Road. The Creek naturally meanders in the canyon upstream of Palmer Avenue, upon which the reach is conveyed along the railroad and Oak Valley Parkway. Available aerial photographs for the entire reach span from 1952 to 2013. Based on the 2013 aerial photograph, the channel bed and banks are densely vegetated, which may significantly contribute to channel stability.

### 3.4.2 Historical Aerial Photographs

From the historical aerial photographs (Appendix A), it can be seen that the Subwatershed has experienced some degree of urban development with the establishment of a residential community (Fairway Canyon) and the Tukwet Canyon Golf Course between 1980 and 2013. Historical agricultural and natural land uses have progressively been modified for residential, commercial, and transportation purposes. Based on the available aerial photography, the geomorphology and the alignment of San Timoteo Creek have not drastically changed since 1952. This may be related to the perennial flow condition caused by agricultural and POTW activities, which promotes establishment of vegetation that may protect the channel bed and banks from degradation.

### 3.4.3 GIS-based Desktop Study

The following subsections summarize the results of the GIS-based desktop study for the San Timoteo Subwatershed.

#### *3.4.3.1 Geology Type*

Sedimentary rocks account for the majority of soils (92.2%) within the San Timoteo Subwatershed; alluvium, which have the highest potential for erosion, account for 67.9% of the soils within the Subwatershed. Plutonic and metavolcanic rocks are only present in the northwestern portion of the Subwatershed that is located in Riverside County (Box Springs Mountains Range). Urban development has reduced the potential for delivery of alluvium to the receiving waters, which may impact the morphology of San Timoteo Creek in the future. The presence of debris basins is limited to the alluvial fans located downstream of Little San Gorgonio Peak area to protect the community of Cherry Valley. The future implementation of debris basins, if any, should consider the impacts that these may have on the geomorphology of the lower reaches.

#### *3.4.3.2 Land Use*

The upper reaches of the Subwatershed are primarily in agriculture land (19.0%) and grassland (24.8%). The subwatershed has observed a significant degree of urban development over the past

30 years, notably in the cities of Beaumont and Calimesa. Portions of the subwatershed that are located within the mountain ranges are still undeveloped with native vegetation, such as scrub and shrub. Urban development in the subwatershed has resulted in a change in the Subwatershed imperviousness and associated increase in the frequency and flow experienced in San Timoteo Creek. Aerial photographs show that the dense vegetation has helped stabilize the Creek under altered hydrologic and sediment regimes.

#### *3.4.3.3 Hillslope Gradient*

The majority of reaches, which have the highest potential for erosion with a hillslope gradient greater than 21%, are concentrated along San Timoteo Canyon and Wildwood Canyon. Other parts of the San Timoteo Creek Subwatershed are fairly flat, notably in the vicinity of Cherry Valley plateau; these areas exhibit a low potential for erosion.

### 3.4.4 Conclusion

The majority of the urban development within the San Timoteo Creek Subwatershed is located in the upper reaches, specifically in the vicinity of the Cherry Valley plateau. The majority of soils within the subwastershed are composed of alluvium or other sedimentary rocks, which are highly prone to erosion. Upper, steeper reaches along San Timoteo Canyon and Wildwood Canyon have remained in a natural condition. Generally this would be beneficial because the steep slopes and undeveloped land would still produce significant sediment to replenish the downstream channel. The issue is that several debris basins have been constructed just downstream of the upper reaches. The debris basins have reduced part of the supply of coarse grained sediment from making it to the downstream channel reaches. In addition, the significant change in impervious area due to urban development in the Subwatershed has increased the frequency and rate of flow in the channel.

**Figure 11: San Timoteo Creek Subwatershed Land Cover Types**

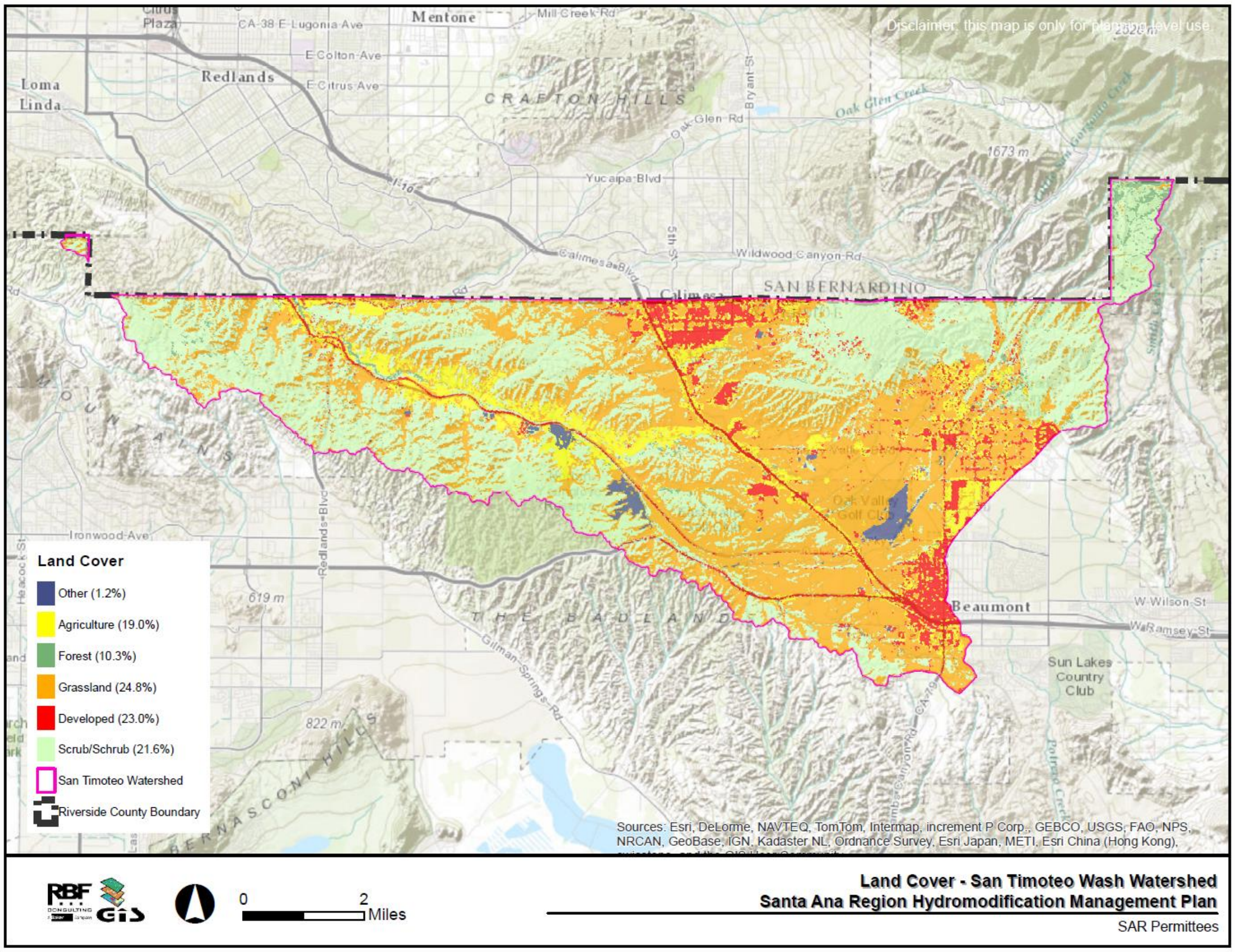


**Figure 12: San Timoteo Creek Subwatershed Geology Types**

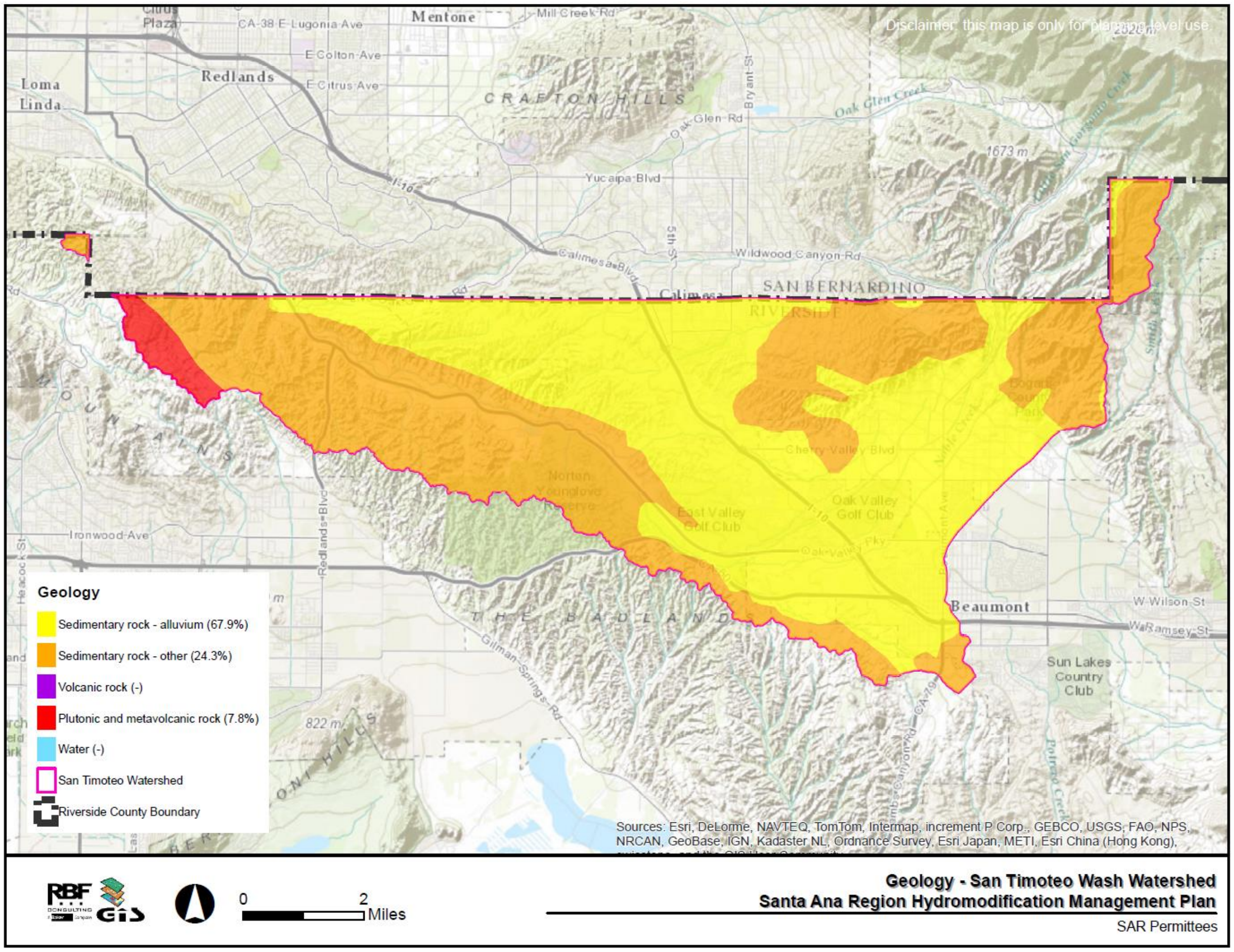
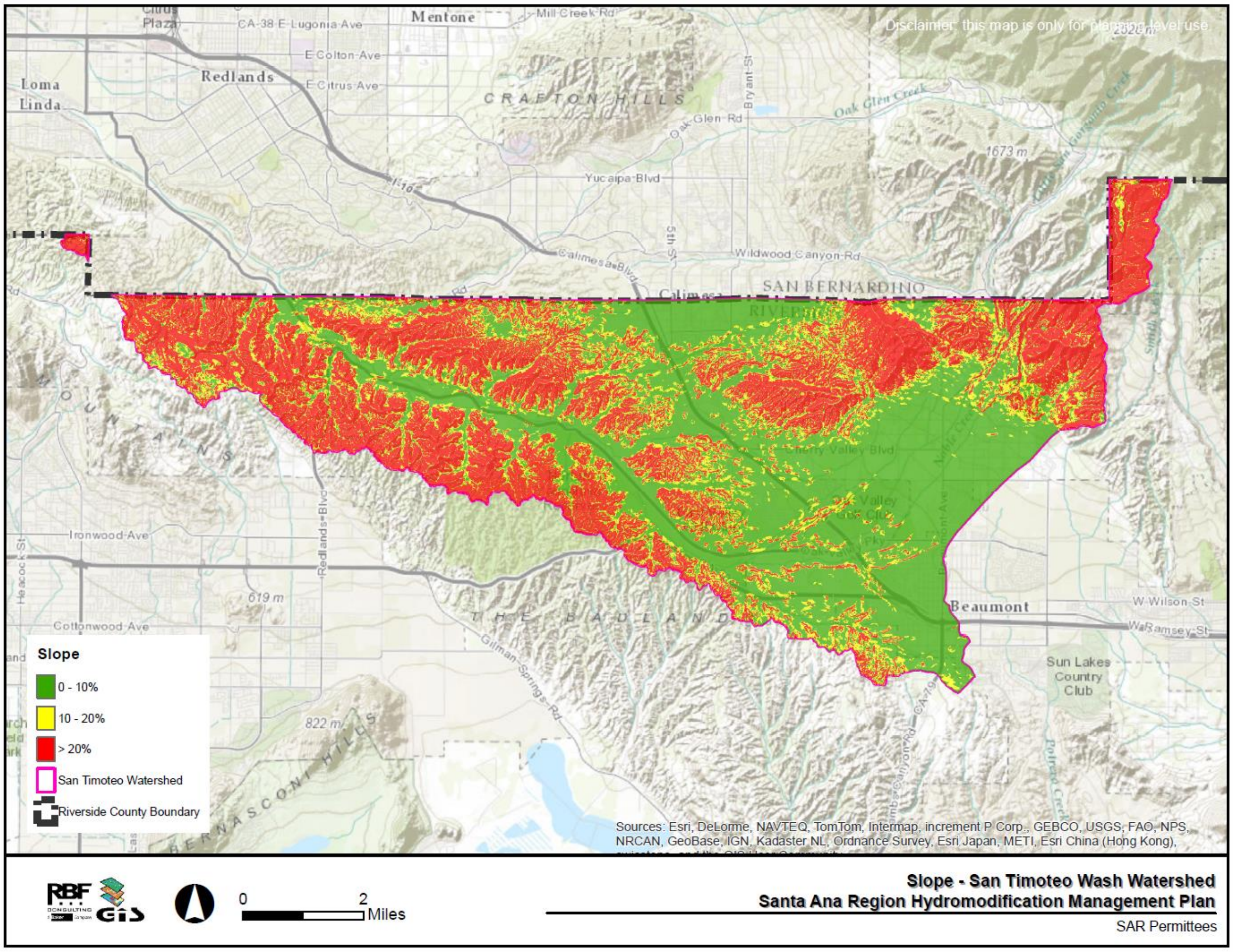


**Figure 13: San Timoteo Creek Subwatershed Hillslope Gradients**



# 4 CONCLUSION

There are three main reasons for the current level of degradation and aggradation in the four subwatersheds under investigation: the geology is vulnerable to erosion, urban development has occurred resulting in less sediment yield, and detention basins have been constructed that reduce upstream sediment supply.

The presence of sedimentary rocks, especially alluvium, is confirmed at different degrees within the four subwatersheds. This geology type is a significant factor in channel degradation and aggradation. This is especially evident in the most downstream portions of the subwatersheds where the mean grain size of the sediment will be at its smallest, and thus more likely to degrade.

The development of the land, especially in the Middle and Lower San Jacinto River Subwatershed, as well as the Temescal Wash Subwatershed, has increased the potential runoff while at the same time decreasing the sediment produced. This change caused an imbalance and increased the degradation and aggradation in the downstream reaches of the Subwatersheds.

The last major cause of degradation and aggradation, the construction of water storage/debris basins, was not part of the original GIS-based analysis, but its effect on the subwatersheds was very evident. The downstream portions of the subwatersheds rely on the coarse sediment from the upper reaches to replenish the channel bottoms. With reduced upstream sediment supply, the channels have a much higher potential for degradation. Even with the decrease in peak flow rates, an imbalance within the subwatersheds was created, resulting in downstream erosion. Additionally, the attenuation of the storm flows has caused an increased amount of time that the channels could experience degradation and aggradation.

Some additional factors that have not been assessed in this technical memorandum are the variability of storm events, the arid region, and the impacts that a significant high intensity storm may have on a dry watercourse. A historic timeline of significant events has not been performed. Other notable factors, also not included in this technical memorandum, are sediment removal operations typically located within debris basins and river systems. The sediment removal operations may be for public health and safety or commercial mining operations.

## REFERENCES


1. Bloom, Arthur L., Geomorphology: A Systematic Analysis of Late Cenozoic Landforms, 3rd Ed., 1998.

2. U.S. Army Corps of Engineers, San Antonio and Chino Creeks Channel: Feasibility Study, August 1998.

3. Southern California Coastal Water Research Project, Hydromodification Screening Tools: GIS-based Catchment Analyses of Potential Changes in Runoff and Sediment Discharge, Technical Report 605, March 2010.

# APPENDIX A

## Historical Aerials


**Upper San Jacinto River - 2013**

**Santa Ana Region Hydromodification Management Plan**

SAR Permittees


RBF CONSULTING A Baker Company GIS

0 0.4 Miles

**Upper San Jacinto River - 1980**
**Santa Ana Region Hydromodification Management Plan**

SAR Permittees


0 0.4 Miles

**Upper San Jacinto River - 1972**

**Santa Ana Region Hydromodification Management Plan**

SAR Permittees


0 0.4 Miles

**San Timoteo River - 2013**

**Santa Ana Region Hydromodification Management Plan**

SAR Permittees


**San Timoteo River - 1980**

**Santa Ana Region Hydromodification Management Plan**

SAR Permittees


0 0.4 Miles

**San Timoteo River - 1966**

**Santa Ana Region Hydromodification Management Plan**

SAR Permittees


RBF CONSULTING A Baker Company GIS

0 0.4 Miles

**San Timoteo River - 1952**

**Santa Ana Region Hydromodification Management Plan**

SAR Permittees


**Temescal Wash - 2013**
**Santa Ana Region Hydromodification Management Plan**

SAR Permittees


0 0.4 Miles

**Temescal Wash - 1980**

**Santa Ana Region Hydromodification Management Plan**

SAR Permittees


0 0.4 Miles

**Temescal Wash - 1974**

**Santa Ana Region Hydromodification Management Plan**

SAR Permittees


0 0.4 Miles

**Temescal Wash - 1952**

**Santa Ana Region Hydromodification Management Plan**

SAR Permittees


**Middle/Lower San Jacinto River - 2013**
**Santa Ana Region Hydromodification Management Plan**

SAR Permittees


**Middle/Lower San Jacinto River - 1980**

**Santa Ana Region Hydromodification Management Plan**

SAR Permittees


**Middle/Lower San Jacinto River - 1975**
**Santa Ana Region Hydromodification Management Plan**

SAR Permittees

# APPENDIX B

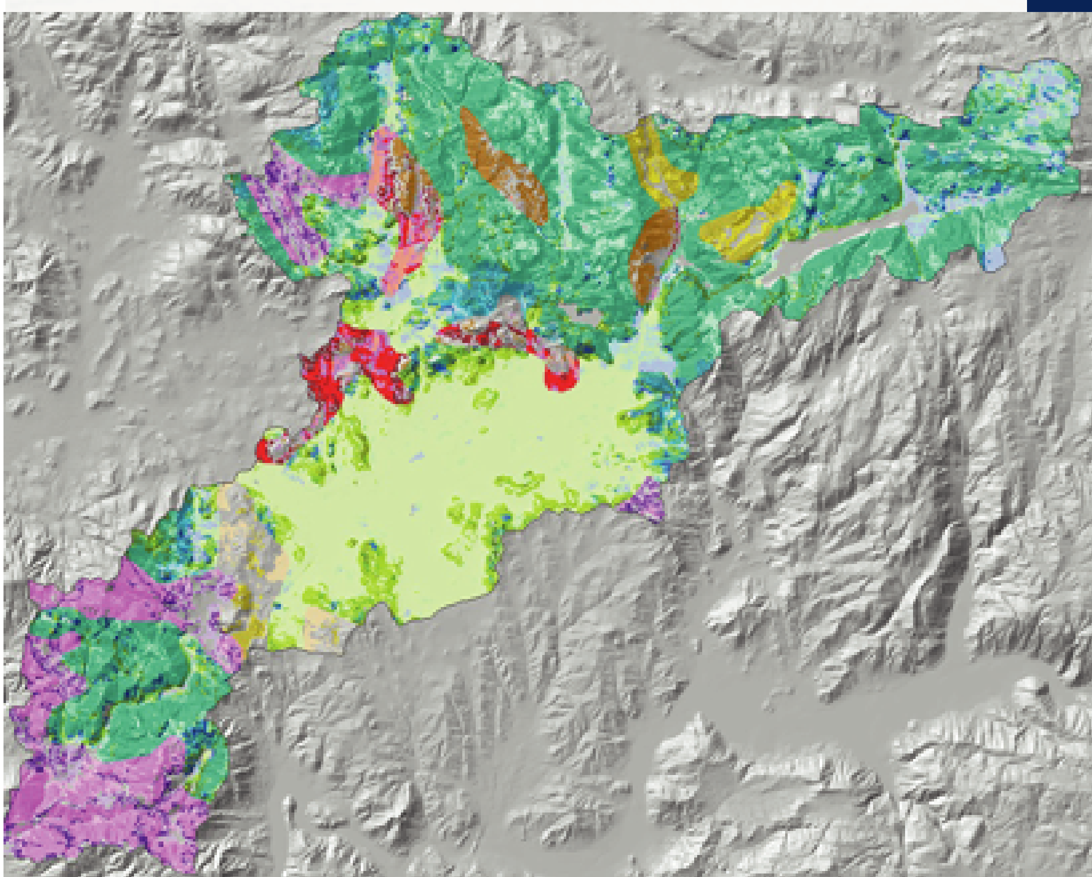
## Hydromodification Screening Tools:

## GIS-based Catchment Analyses of Potential Changes in Runoff and Sediment Discharge

**By SCCWRP**

**Technical Report 605 - March 2010**

# HYDROMODIFICATION SCREENING TOOLS: GIS-BASED CATCHMENT ANALYSES OF POTENTIAL CHANGES IN RUNOFF AND SEDIMENT DISCHARGE




Derek B. Booth
Scott R. Dusterhoff
Eric D. Stein
Brian P. Bledsoe



Southern California Coastal Water Research Project

Technical Report 605 - March 2010

# Hydromodification Screening Tools: GIS-based Catchment Analyses of Potential Changes in Runoff and Sediment Discharge


Derek B. Booth[1], Scott R. Dusterhoff[1],
Eric D. Stein[2] and Brian P. Bledsoe[3]

*[1]Stillwater Sciences, Inc., Santa Barbara, CA*
*[2]Southern California Coastal Water Research Project, Costa Mesa, CA*
*[3]Colorado State University, Fort Collins, CO*



**March 2010**

Technical Report 605

# EXECUTIVE SUMMARY

Managing the effects of hydromodification (physical response of streams to changes in catchment runoff and sediment yield) has become a key element of most stormwater programs in California. Although straightforward in intent, hydromodification management is difficult in practice. Shifts in the flow of water and sediment, and the resulting imbalance in sediment supply and capacity can lead to changes in channel planform and cross-section via wide variety of mechanisms. Channel response can vary based on factors such as boundary materials, valley shape and slope, presence of in-stream or streamside vegetation, or catchment properties (e.g., slope, land cover, geology).

Management prescriptions should be flexible and variable to account for the heterogeneity of streams; a given strategy will not be universally well-suited to all circumstances. Management decisions regarding a particular stream reach(s) should be informed by an understanding of susceptibility (based on both channel and catchment properties), resources potentially at risk (e.g., habitat, infrastructure, property), and the desired management endpoint (e.g., type of channel desired, priority functions; see Figure ES1).

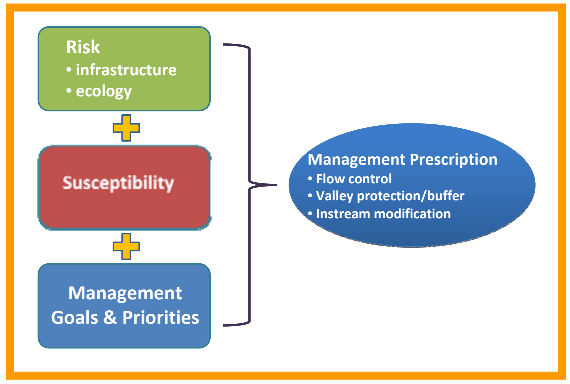



*Figure ES1: Decision nodes that influence the management prescription for a particular stream reach.*

We have produced a series of documents that outline a process and provide tools aimed at addressing the decision node associated with assessing channel susceptibility. The three corresponding hydromodification screening tool documents are:

1. *GIS-based catchment analyses of potential changes in runoff and sediment discharge* which outlines a process for evaluating potential change to stream channels resulting from watershed-scale changes in runoff and sediment yield.
2. *Field manual for assessing channel susceptibility* which describes an in-the-field assessment procedure that can be used to evaluate the relative susceptibility of channel reaches to deepening and widening.
3. *Technical basis for development of a regionally calibrated probabilistic channel susceptibility assessment* which provides technical details, analysis, and a summary of field data to support the field-based assessment described in the field manual.

The catchment analyses and the field manual are designed to support each other by assessing channel susceptibility at different scales and in different ways. The GIS-based catchment analyses document is a planning tool that describes a process to predict likely effects of hydromodification based on potential change in water and sediment discharge as a consequence of planned or potential landscape alteration (e.g., urbanization). Data on geology, hillslope, and land cover are compiled for each watershed of interest, overlaid onto background maps, grouped into several discrete categories, and classified independently across the watershed in question.

The classifications are used to generate a series of Geomorphic Landscape Units (GLUs) at a resolution defined by the coarsest of the three data sets (usually 10 to 30 m). Three factors: geology, hillslope, and land cover are used because the data are readily available; these factors are important to controlling sediment yield. The factors are combined into categories of High, Medium, or Low relative sediment production. The current science of sediment yield estimation is not sophisticated enough to allow fully remote (desktop) assignment of these categories. Therefore initial ratings must be verified in the field.

Once the levels of relative sediment production (i.e., Low, Medium, and High) are defined across a watershed under its current configuration of land use, those areas subject to future development are identified, and corresponding sediment-production levels are determined by substituting Developed land cover for the original categories and modifying the relative sediment production as necessary (Figure ES2). Conversely, relative sediment production for currently developed watershed areas can be altered to estimate relict sediment production for an undeveloped land use and used to assess the impact of watershed development on pre-development sediment production. The resultant maps can be used to aid in planning decisions by indicating areas where changes in land use will likely have the largest (or smallest) effect on sediment yield to receiving channels.

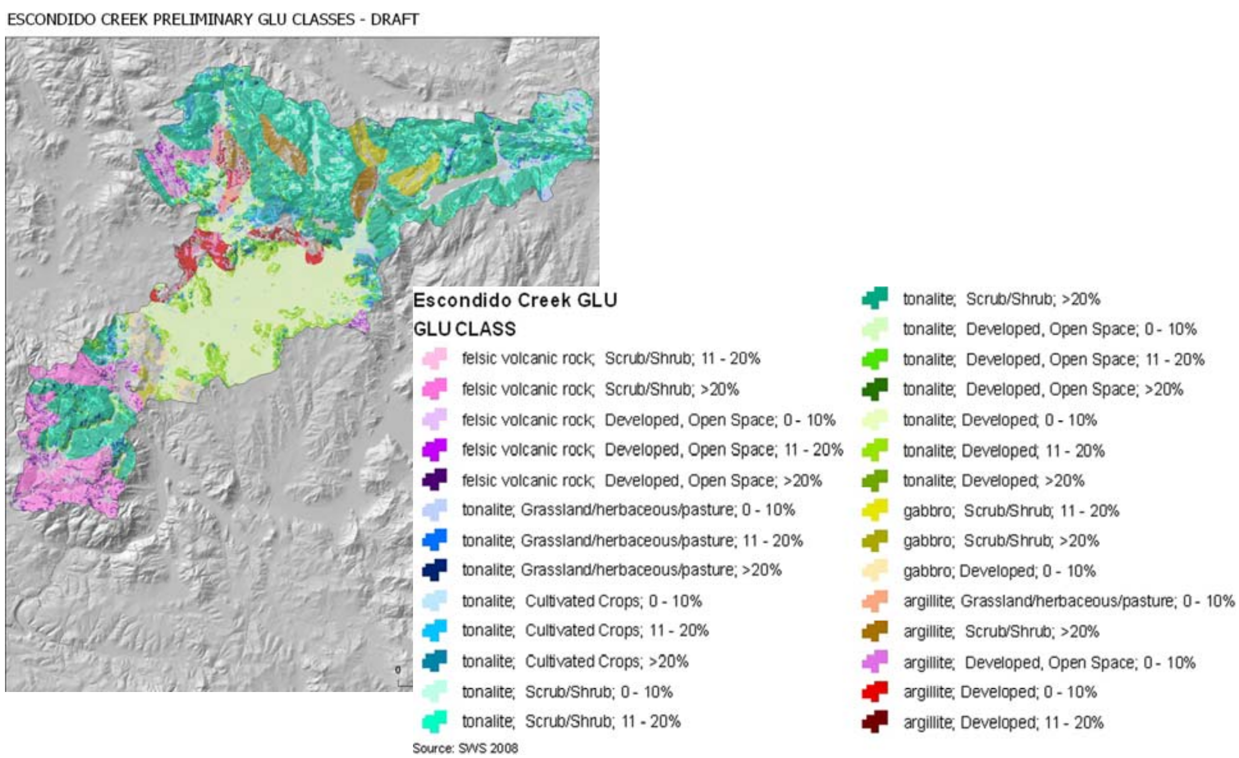



*Figure ES2: Example of Geomorphic Landscape Units for the Escondido Creek Watershed.*

The field assessment procedure is intended to provide a rapid assessment of the relative susceptibility of a specific stream reach to effects of hydromodification. The intrinsic sensitivity of a channel system to hydromodification as determined by the ratio of disturbing to resisting forces, proximity to thresholds of concern, probable rates of response and recovery, and potential for spatial propagation of impacts. A combination of relatively simple, but quantitative, field indicators are used as input parameters for a set of decision trees. The decision trees follow a logical progression and allow users to assign a classification of Low, Medium, High, or Very High susceptibility rating to the reach being assessed. Ratings based on likely response in the vertical and lateral directions (i.e., channel deepening and widening) are assigned separately. The screening rating foreshadows the level of data collection, modeling, and ultimate mitigation efforts that can be expected for a particular stream-segment type and geomorphic setting. The field assessment is novel in that it incorporates the following combination of features:

- Integrated field and office/desktop components
- Separate ratings for channel susceptibility in vertical and lateral dimensions
- Transparent flow of logic via decision trees
- Critical nodes in the decision trees are represented by a mix of probabilistic diagrams and checklists
- Process-based metrics selected after exhaustive literature review and analysis of large field dataset
- Metrics balance process fidelity, measurement simplicity, and intuitive interpretability
- Explicitly assesses proximity to geomorphic thresholds delineated using field data from small watersheds in southern California
- Avoids bankfull determination, channel cross-section survey, and sieve analysis, but requires pebble count in some instances
- Verified predictive accuracy of simplified logistic diagrams relative to more complex methods, such as dimensionless shear-stress analyses and Osman and Thorne (1988) geotechnical stability procedure
- Assesses bank susceptibility to mass wasting; field-calibrated logistic diagram of geotechnical stability vetted by Colin Thorne (personal communication)
- Regionally-calibrated braiding/incision threshold based on surrogates for stream power and boundary resistance
- Incorporates updated alternatives to the US Geological Survey (USGS; Waananen and Crippen 1977) regional equations for peak flow (Hawley and Bledsoe In Review)
- Does not rely on bank vegetation given uncertainty of assessing the future influence of root reinforcement (e.g., rooting depth/bank height)
- Channel evolution model underpinning the field procedure is based on observed responses in southern California using a modification of Schumm *et al*. (1984) five-stage model to represent alternative trajectories

The probabilistic models of braiding, incision, and bank instability risk embedded in the screening tools were calibrated with local data collected in an extensive field campaign. The models help users directly assess proximity to geomorphic thresholds and offer a framework for gauging susceptibility that goes beyond expert judgment. The screening analysis represents the first step toward determining appropriate management measures and should help inform decisions about subsequent more detailed analysis.

The GIS-based catchment-scale analysis and the field screening procedure are intended to be used as a set of tools to inform management decisions (Figure ES3). The catchment-scale analysis provides an overall assessment of likely changes in runoff and sediment discharge that can be used to support larger-scale land use planning decisions and can be applied prospectively or retrospectively. The field screening procedure provides more precise estimates of likely response of individual stream reaches based on direct observation of indicators. The field assessment procedure also provides a method to evaluate the extent of potential upstream and downstream propagation of effects (i.e., the analysis domain). In concept, the catchment-scale analysis would be completed for a watershed of interest before conducting the field analysis. However, this is not required and the two tools can be used independent of each other. It is not presently possible to describe a mechanistic linkage between the magnitude of the *drivers* of hydromodification (i.e., changes in the delivery of water and sediment to downstream channels), the *resistance* of channels to change, and the net expression on channel form. For this reason, the results of the catchment and field analyses must be conducted independently and the results cannot be combined to produce an overall evaluation of channel susceptibility to morphologic change (Figure ES3).

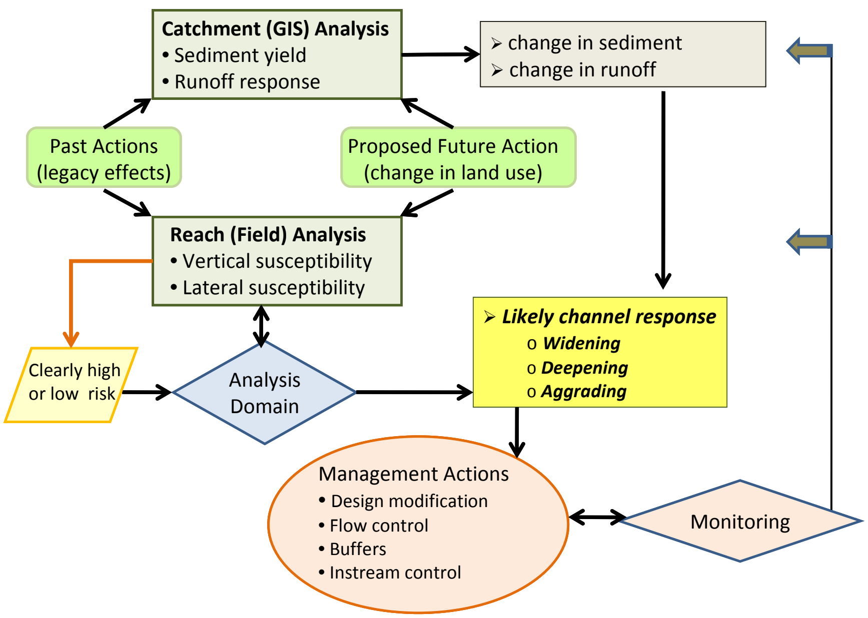



*Figure ES3: Relationship of catchment and field screening tools to support decisions regarding susceptibility to effects of hydromodification.*

Finally, it is important to note that these tools should be used as part of larger set of considerations in the decision making process (see Figure ES1). For example, the tools do not provide assessments of the ecological or economic affects of hydromodification. Similarly, they do not allow attribution of current conditions to past land use actions. Although the screening tool is designed to have management implications via a decision framework, policy/management decisions must be made by local stakeholders in light of a broader set of considerations.

# Table of Contents

## List of Figures



## List of Tables

# BACKGROUND

The magnitude and rate of hydromodification, the physical response of streams to development-induced changes in flow and sediment input, is dependent on the inherent features of potentially affected channels and the characteristics of developed areas that determine the changes to flow and sediment input to those channels. This report describes a method to assess the second of these two elements, namely how to rapidly characterize watershed-scale changes in runoff and sediment yields to stream channels as a result of urban development. In combination with a field-based assessment of channel conditions, the susceptibility of a specific stream reach can be assessed on the basis of both in-channel (i.e., local) and contributing watershed (i.e., landscape-scale) influences (Figure 1).

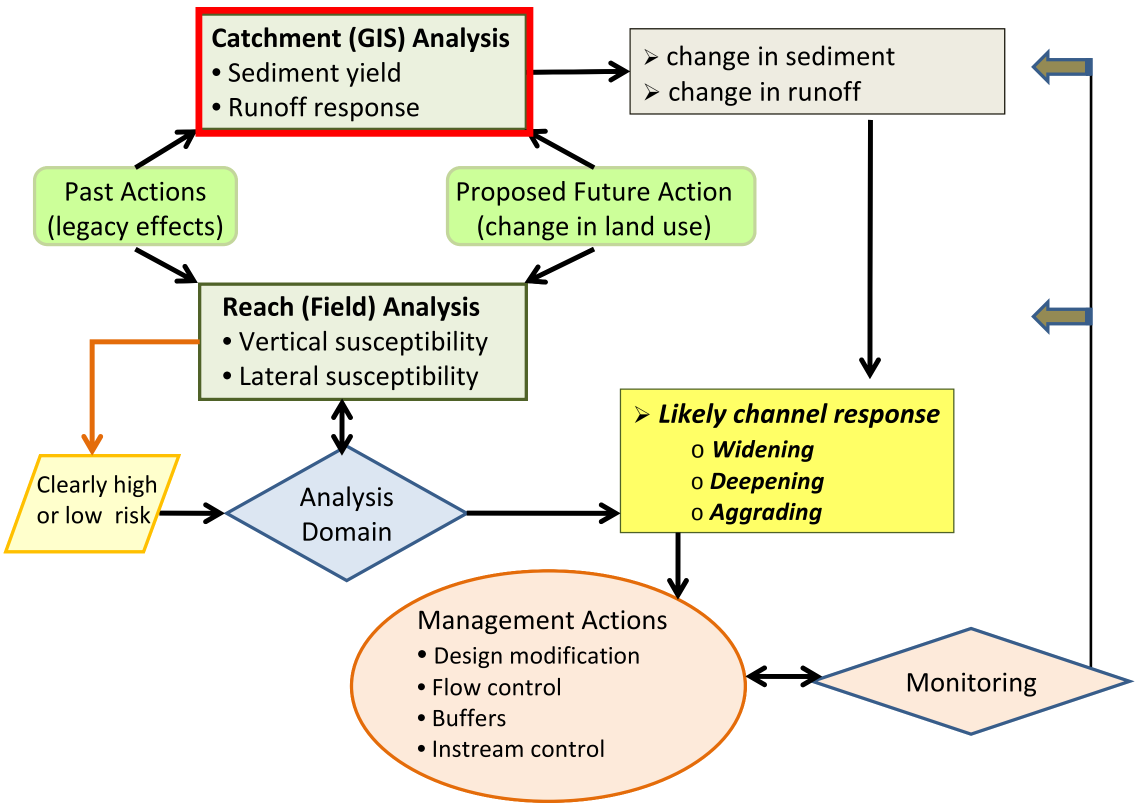



**Figure 1. Conceptual application of GIS- and field-based screening tools, and their inter-relationship in predicting potential effects of hydromodification.**

Assuming erodible boundaries and mobile sediment loads, the condition of stable stream channels reflects a balance between the capacity of the flow to transport sediment and the availability of sediment for transport. Under the broad geomorphic concept of "dynamic equilibrium," this balance is not necessarily achieved at every moment in time or at every point along the stream channel. Over a period of time, however, an observed condition of equilibrium is commonly presumed to express such a water–sediment balance. Conversely, the balance of these components is normally considered to be the defining precondition for maintaining stability in alluvial streams.

From this perspective of geomorphic stability, the ***drivers*** of channel change are the discharges of water and sediment, for which the importance of their balance in equalized channel formation has been invoked since Lane (1955). Thus, recognizing potential change(s) in these drivers, as a consequence of planned or potential landscape alteration (such as urbanization) is a necessary component of predicting hydromodification and the focus of this report. However, the intrinsic ***resistance*** of the channel form itself is no less important to determining actual outcomes, and it is the focus of the companion report by Bledsoe *et al.* (2010).

## Hydrologic Response Units (HRUs) and Their Simplified Representation in Urban Watersheds

Landscape-scale predictions of water and sediment yields have a long history. For runoff prediction, the wide variety of modern hydrologic models can be traced back over a century to the first invocation of the Rational Runoff equation (Mulvany 1851) and its explicit dependence of runoff on land cover and rainfall intensity. Subsequent models for predicting runoff have typically added soil properties and hillslope gradient to the list of important watershed factors. Grouping common hydrologic attributes across a watershed into a tractable number of Hydrologic Response Units (HRUs: a term first used by England and Holtan 1969) has become a well-established approach for condensing the near-infinite variability of a natural watershed into a tractable number of different elements. The normal procedure for developing HRUs is to identify presumptively similar rainfall–runoff characteristics across a watershed by combining spatially distributed climate, geology, soils, land use, and topographic data into areas that are approximately homogeneous in their hydrologic properties (Green and Cruise 1995, Becker and Braun 1999, Beven 2001, Haverkamp *et al.* 2005). As noted by Beighley *et al.* (2005), this process of merging the landscape into discrete HRUs is a common and effective method for reducing model complexity and data requirements.

Using watershed characteristics to predict runoff is the explicit task of hydrologic models, and there is a host of such models available for application to hydromodification evaluation. For purposes of "screening," however, the goal is simplicity and ease of application even if the precision of the resulting analysis is crude. For any given area of a watershed, the conversion of pre-developed land cover to a developed (and therefore more impervious) land cover is the most prominent change and thus is likely the most important landscape-scale hydrologic driver of downslope (and downstream) physical impacts. Other attributes, although important, are normally of much less significance.

Using imperviousness as a surrogate for the relative magnitude of hydrologic impacts due to development is well-established in the scientific and engineering literature (see Center for

Watershed Protection 2003 for a comprehensive review), and this approach has been recently reaffirmed in National Research Council (2009). Given the ready availability of classified land cover data, the amount of developed land should be a credible index for the overall magnitude of hydrologic alteration, particularly for use in screening applications. It is thus a reasonable substitute in this application for the greater complexity engendered by multi-parameter HRUs or a fully featured hydrologic model.

Although this simplistic approach is recommended here, existing data on stream channel change provide caveats to its uncritical use. For example, a 22-year assessment of stream channel changes across western Washington (Booth and Henshaw 2001) found no significant correlation between imperviousness and the magnitude of channel change across a wide range of suburban and urban watersheds. Data collection for the present study also show no statistical correlation between watershed imperviousness and observed channel instability. These findings do not invalidate the importance of imperviousness in affecting runoff patterns, but they serve as reminders that runoff change is but one of several factors that influence the response of stream channels. In any given setting there are multiple potential drivers of change (e.g., changes to the sediment supply), and their influence will be mediated by the resistance of the downstream channels to geomorphic response.

## Geomorphic Landscape Units (GLUs)

Many of the same physical properties that determine the hydrologic response of a watershed also determine the magnitude of sediment production from those same areas. These properties can be grouped into Geomorphic Landscape Units (GLUs: a term without the same degree of prior literature usage as HRUs, but entirely analogous in both definition and application). The closest pre-existing analog is that of "process domains," a conceptual framework based on the hypothesis that "spatial variability in geomorphic processes governs temporal patterns of disturbances that influence ecosystem structure and dynamics" (Montgomery 1999). A GLU-based methodology has been applied to only a few California watersheds to date, but it has seen widespread application and acceptance elsewhere, particularly in the Pacific Northwest. We note that process domains were originally defined by topography, climate, tectonic setting, and geology, but they do not include land use or any explicit effects of human activity or disturbance. Thus they are not entirely appropriate for our current application.

Erosional processes are episodic, resulting in substantial year-to-year variability (Benda and Dunne 1997, Kirchner *et al.* 2001, Gabet and Dunne 2003). Although long-term annual averages cannot predict the sediment load for any given year; nevertheless, these averages can be useful in assessing the long-term consequences of alternative management actions, because different parts of the landscape can be readily identified as to their *relative* sediment-delivery potential.

Prior work in California (Stillwater Sciences 2007, 2008) has identified three factors judged to exert the greatest influence on the variability on sediment-production rates: ***geology types***, ***hillslope gradient***, and ***land cover***. Detailed mapping procedures for GLU analysis are provided in the closing section of this report; here we offer a generalized overview. To begin, data sources for the three factors are readily available and can be compiled in a GIS over the entire watershed in question at a spatial resolution determined by the coarsest dataset (typically 30 m).

***Geology types*** are based on the best available digital geologic maps of the region, with mapped units grouped into a limited number of categories that reflect their inherent primary geologic characteristic (e.g., igneous, sedimentary, or metamorphic unit) and presumed or qualitatively observed erodibility. ***Hillslope gradients*** are generated directly from digital elevation model (DEM) of the region. Based on observed ranges of relative erosion and slope instability, prior applications have found a useful grouping of the continuous range of hillslope gradients to include just three categories, such as 0 to 10%, 10 to 20%, and steeper than 20% (alternative groupings could be based on natural breaks in the distribution frequency of slope values, but these would likely differ from watershed to watershed). Lastly, ***land cover*** categories can be based on a classified Landsat image at 30-m resolution. We have found that five grouped categories, identified by an automated classification system, provide a useful level of discrimination. Categories largely correspond to vegetation covers of forest, scrub, and agriculture and/or grassland (which includes bare soil); developed land; and miscellaneous (which includes water bodies and bare rock).

This approach provides a useful, rapid framework to identify a tractable number of categories that can serve the overarching need of a hydromodification screening tool, namely a stratification of the landscape whose relative sediment-delivery attributes can be characterized under alternative land-use conditions. As with measures of hydrologic alteration (e.g., impervious area), however, we note that no simple one-to-one correspondence between the magnitude of altered sediment delivery and the magnitude of channel change should be anticipated. Many different factors are involved, and these various data sets display no simple dominant or additive relationship to each other.

# APPLICATION

With the base data assembled, characterization of both runoff and sediment yield (i.e., the top-most box of Figure 1) at the watershed scale is relatively straightforward processes. For runoff, we affirm the common approach of using the change in either developed land or imperviousness as the index of hydrologic change. However, the once-popular concept of a “critical threshold” of imperviousness, below which no channel changes occur, has been widely abandoned in the scientific literature and is not recognized here. Unfortunately, this also eliminates the seemingly promising framework that jurisdictions once used to discriminate whether or not a potential hydrologic change would likely be significant. Although understanding the magnitude of hydrologic change is still relevant to assessing hydromodification effects, a small value clearly does not provide any guarantees of non-impact, presumably because significant sediment delivery changes can still occur and produce dramatic channel changes. For example, Figure 2 illustrates changes in channel morphology and stability associated with an in-stream grade-control structure that blocks sediment passage. Although the change in sediment supply in this example is caused by a physical blockage rather than a change in land cover, the analogy to the relative importance of watershed-scale drivers is clear: channel instability can occur even with no change in hydrology at all.

**Figure 2. Alteration in channel morphology and stability, immediately upstream (left) and downstream (right) of a grade-control structure that blocks sediment passage. The two views are less than 10 m apart in the channel, with no intervening tributary.**

Predictions of sediment production using GLUs require that the three sets of contributing data (***geology type***, ***hillslope gradient***, and ***land cover***) each be grouped into discrete categories and classified independently across the watershed in question. With the typical number of subdivisions for each of these three sets, approximately 30 to 48 different combinations are theoretically possible. In prior applications, nearly every combination of these factors were represented in any given watershed, but the vast majority of the land area is represented by only a few such combinations. Nearly all of these combinations have been observed across multiple southern California watersheds, and those observations suggest the following assignments of relative sediment production (Table 1; see Appendix for map-based example of equivalent results for the San Antonio Creek watershed, Ventura County, CA, Stillwater Sciences 2007). However, these assignments of relative sediment production are observationally determined, and our current modest range of application precludes universal or automated application without including a subsequent step of field verification.

**Table 1. Example of a full set of geomorphic landscape unit (GLU) types from Santa Paula Creek, Ventura County, CA, and assigned relative sediment production (RSP) categories based on observed field conditions (modified from Stillwater Sciences 2007 using a 3-part division of geologic units, 3 slope classes, and 5 land cover classes).**

| GLU | RSP | GLU | RSP |
|---|---|---|---|
| Unconsolidated Ag/grass/bare 0 - 10% | Low | Shale Misc. 0 - 10% | Medium |
| Unconsolidated Forest 0 - 10% | Low | Shale Misc. 10 - 20% | Medium |
| Unconsolidated Forest 10 - 20% | Low | Shale Misc. >20% | Medium |
| Unconsolidated Scrub 0 - 10% | Low | Shale **Developed** 10 - 20% | Medium |
| Shale Ag/grass/bare 0 - 10% | Low | Shale **Developed** 10 - 20% | Medium |
| Shale **Developed** 0 - 10% | Low | Shale Scrub 0 - 10% | Medium |
| Shale Forest 0 - 10% | Low | Shale Scrub 10 - 20% | Medium |
| Shale Forest 10 - 20% | Low | Shale Scrub >20% | Medium |
| Shale Forest >20% | Low | Sandstone Misc. 0 - 10% | Medium |
| Sandstone Ag/grass/bare 0 - 10% | Low | Sandstone Misc. 10 - 20% | Medium |
| Sandstone **Developed** 0 - 10% | Low | Sandstone Misc. >20% | Medium |
| Sandstone Forest 0 - 10% | Low | Sandstone **Developed** 10 - 20% | Medium |
| Sandstone Forest 10 - 20% | Low | Sandstone **Developed** >20% | Medium |
| Sandstone Forest >20% | Low | Sandstone Scrub 10 - 20% | Medium |
| Sandstone Scrub 0 - 10% | Low | Sandstone Scrub >20% | Medium |
| Unconsolidated **Developed** 0 - 10% | Low | | |
| Unconsolidated Misc. 0 - 10% | Medium | Unconsolidated Ag/grass/bare 10 - 20% | High |
| Unconsolidated Misc. 10 - 20% | Medium | Unconsolidated Ag/grass/bare >20% | High |
| Unconsolidated Misc. >20% | Medium | Unconsolidated Scrub >20% | High |
| Unconsolidated **Developed** 10 - 20% | Medium | Shale Ag/grass/bare 10 - 20% | High |
| Unconsolidated **Developed** >20% | Medium | Shale Ag/grass/bare >20% | High |
| Unconsolidated Forest >20% | Medium | Sandstone Ag/grass/bare 10 - 20% | High |
| Unconsolidated Scrub 10 - 20% | Medium | Sandstone Ag/grass/bare >20% | High |

Once these levels of relative sediment production (i.e., Low, Medium, and High) are defined across a watershed under its current configuration of land use, those areas subject to future development are identified and their future sediment production levels are similarly determined, substituting Developed land cover for the original categories and modifying the relative sediment production as necessary. Conversely, relative sediment production for currently developed watershed areas can be altered to relict sediment production for an undeveloped land use and used to assess the impact of watershed development on pre-development sediment production. For nearly all GLUs, a change of preexisting land cover to Developed is accompanied by either no change or a decrease in relative sediment production (see Table 1). Both theory and observation affirm that significant reductions in the delivery of sediment to stream channels can drive channel change. In the context of this screening application, any such predicted reduction in sediment delivery can be used to identify potential hydromodification impacts.

Although prior applications (Stillwater Sciences 2007, 2008) have developed quantitative values associated with the three relative levels of sediment production, those values were determined for specific watersheds, calibrated with nearby sediment accumulation data from debris basins and validated with nearby sediment-load gage data. These conditions cannot be expected uniformly across southern California watersheds, and so translating relative rates into precise numeric values is not presently warranted. However, this prior work has shown that the range of long-term sediment delivery rates probably spans at least two orders of magnitude, and we have used this scaling to calculate the relative change in pre- and post-development sediment production (i.e., Low = 10 to 100 tonnes/km$^2$/yr and High = 1,000 to 10,000 tonnes/km$^2$/yr). Also, we note, that it is not presently possible to describe a mechanistic linkage between the magnitude of hydromodification *drivers* (i.e., changes in the delivery of water and sediment to downstream channels), the channel *resistance* to change, and the net expression on channel form. For this reason, hydromodification drivers and channel resistance must be evaluated independently (Figure 1) in the evaluation of channel susceptibility to morphologic change.

# VALIDATION OF APPROACH

To test the applicability of the HRU- and GLU-based approaches for determining the impact of watershed development on physical channel conditions, we visited several study watersheds to compare GIS-based predictions with field-based observations. During the spring of 2009, we visited 17 watersheds and examined them from a geomorphic perspective (Figure 3). We viewed previously established channel measurement sites, as well as reaches upstream and downstream, to investigate the local and watershed-scale processes controlling geomorphic conditions at the measurement sites. A direct comparison of GIS-based and field-based channel sensitivity assessment for a study watershed is shown in this report's Appendix.

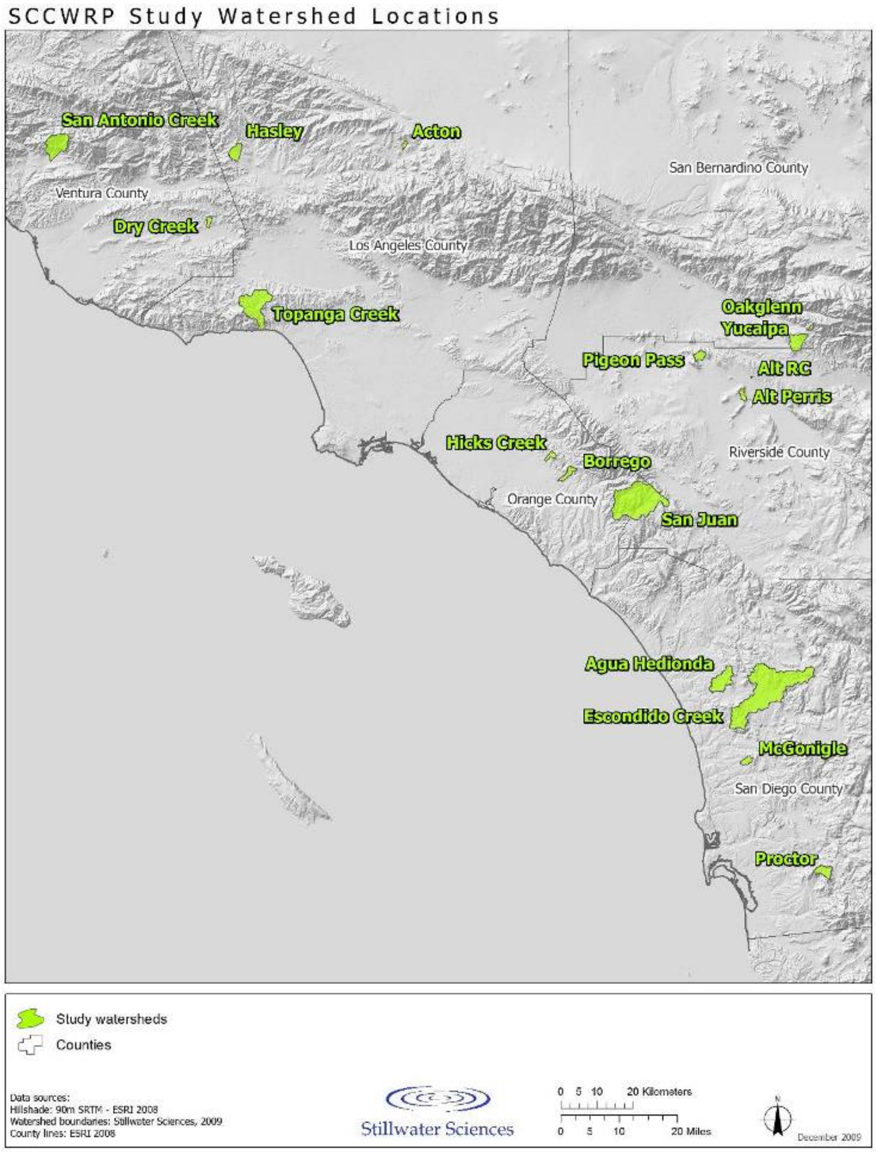



**Figure 3. Study watersheds for evaluation of GLU approach.**

The study watersheds fell into three development categories:

1) Developed (pre-2001) – watershed was developed at the time of the 2001 National Land Cover Database, and so the development is shown in the GIS layers used for the GIS-based analysis. At these sites we were able to directly relate what the GIS analysis predicts with observed channel conditions:

   - Agua Hedionda
   - Borrego
   - McGonigle
   - Pigeon Pass
   - Proctor
   - San Antonio
   - Escondido
   - Hicks
   - Topanga

2) Developed (post-2001) – watershed is developed now, but the extent of current development is not shown in the GIS land-cover layer (i.e., the development post-dates the 2001 NLCD). So, we were not necessarily able to relate directly what the GIS analysis predicted with on-the-ground channel conditions:

   - Acton
   - Dry
   - Hasley
   - Yucaipa

3) Not Developed – watershed is largely undeveloped. If channel instability was observed, it has likely been caused by local or watershed-scale factors other than those related to changes in water or sediment supply as a consequence of urbanization:

   - Alt Perris
   - Alt RC2
   - Oakglenn
   - San Juan

Overall, the multiple factors that affect development-induced watershed disturbance (the *drivers* for channel change) can be characterized by how they modify hydrology and sediment delivery to either increase impacts (i.e., factors that contribute to a High impact) of decrease impact (i.e., factors that contribute to a Low impact; Table 2). Note that neither spatial variability nor time-dependent conditions are included in this example, but the influence of either/both may be locally dominant. Also, the effects of past disturbances (i.e., legacy effects) are not included in this example because they are generally not amenable to uniform characterization and likely require site-specific, field-based analysis.

**Table 2. Channel change drivers and factors that tend to influence the magnitude of the resulting impact(s) on channel stability.**

| Driver | | Factors for High Impact | Factors for Low Impact |
|---|---|---|---|
| | % Developed | Highly developed, high total impervious area (TIA) | Moderately developed, low total impervious area (TIA) |
| **Hydrology** | Development density | Concentrated development | Distributed development |
| | Degree of upstream stormwater retention | Minimal retention of stormwater run-off | Extensive retention of stormwater run-off |
| | Upstream relative watershed sediment production | High relative sediment production | Low relative sediment production |
| **Sediment Delivery** | Relative watershed sediment production entering downstream of development | Low relative sediment production | High relative sediment production |
| | Degree of sediment transport blockage (*note: not explicitly included in this GIS-based approach*) | High number of total upstream bridges and culverts and/or close upstream proximity of undersized bridges and culverts | Low number of total upstream bridges and culverts and/or distant upstream proximity of undersized bridges and culverts |

For purposes of the validation study, these factors (where known) were combined with an assessment of the impact of development on pre-development relative sediment production. This was achieved by replacing the sediment-production values for Developed land cover in the GIS framework with the corresponding value for Scrub/Shrub land cover with the same slope and geology conditions) to arrive at a qualitative ranking (i.e., Low, Medium, High) of the impact of development on channel conditions for each of the 17 watersheds. The comparison between predicted sediment alteration and field-based observations and channel cross-section measurements of channel stability is given below:

**Table 3. Comparison of GLU-predicted and field-observed channel stability. Hypothetical = hypothetical downstream channel response to development with percent change in hillslope sediment production shown in parentheses. Observed channel stability CSU/SWS.**

| Watershed | Area (km²) | Development Status[a] | Hypothetical | Observed |
|---|---|---|---|---|
| Escondido | 156.7 | Developed (pre-2001) | Medium (-28%) | Stable |
| Hicks | 3.9 | Developed (pre-2001) | Low (<1%) | Moderately Stable |
| Topanga | 50.9 | Developed (pre-2001) | Low (-4%) | Stable |
| Borrego | 7.1 | Developed (pre-2001) | Low (-10%) | Unstable |
| Agua Hedionda | 27.1 | Developed (pre-2001) | High (-65%) | Unstable |
| Pigeon Pass | 6.5 | Developed (pre-2001) | Low (-10%) | Moderately Stable |
| McGonigle | 5.1 | Developed (pre-2001) | High (-70%) | Stable |
| San Antonio Creek | 31.1 | Developed (pre-2001) | Low (<1%) | Moderately Stable (see Appendix) |
| Proctor | 11.2 | Developed (pre-2001) | Low (-3%) | Stable |
| San Juan | 105.2 | Not Developed | Low (<1%) | Stable |
| Alt Perris | 4.0 | Not Developed | Low (<1%) | Stable |
| Alt RC | 0.2 | Not Developed | Low (<1%) | Hardened |
| Oakglenn | 1,.4 | Not Developed | Low (<1%) | Hardened |
| Acton | 2.0 | Developed (post-2001) | Medium | Unstable |
| Dry Canyon | 3.3 | Developed (post-2001) | Medium | Unstable |
| Hasley | 11.6 | Developed (post-2001) | Medium | Unstable |
| Yucaipa | 16.7 | Developed (post-2001) | Low | Stable |

[a] Developed (pre-2001) means that the current development was reflected in the land use information used in the GIS analysis; Developed (post-2001) means that the current development was not reflected in the land use information we used in the GIS analysis.

Given the multiplicity of factors that determine channel stability (both natural and man-made), the uneven performance of this metric and the lack of any obvious systematic errors in its prediction of channel stability is not surprising. Other studies of multi-determinant systems also commonly report complex interrelationships that are not amenable to simple step-wise or regression analyses (for examples that also address channel stability, see Gregory *et al.* 2008 or Moret *et al.* 2005). The challenge is thus to incorporate the value of single-factor indices, such as these assessments of change in sediment reduction or runoff, into a more complex system. This analysis is not yet at the point of specifying management or regulatory thresholds under an automated application. It does, however, suggest that the following screening steps should accompany and complement those intended to determine channel resistance:

1. Characterize the relative change in hydrology following planned development, using the change in watershed imperviousness (or developed land cover) as a surrogate.

2. Characterize the relative change in sediment production following development, using the procedure outlined above.

3. Evaluate the degree of relative risk solely arising from changes in sediment and/or water delivery. The challenge in implementing this step is that presently we have insufficient basis to defensibly identify either low-risk or high-risk conditions using these metrics. For example, channels that are close to a threshold for geomorphic change may display significant morphological changes under nothing more than natural year-to-year variability in flow or sediment load.

    a. Acknowledging this caveat, we nonetheless anticipate that changes of less than 10% in either driver are unlikely to instigate, on their own, significant channel changes. This value is a conservative estimate of the year-to-year variability in either discharge or sediment flux that can be accommodated by a channel system in a state of dynamic equilibrium. It does not "guarantee," however, that channel change may not occur—either in response to yet modest alterations in water or sediment delivery, or because of other urbanization impacts (e.g., point discharge of runoff or the trapping of the upstream sediment flux; see Booth 1990) that are not represented with this analysis.

    b. In contrast, recognizing a condition of undisputed "high risk" must await broader collection of regionally relevant data. We note that >60% reductions in predicted sediment production have resulted in both minimal (McGonigle) and dramatic (Agua Hedionda) channel changes, indicating that "more data" may never provide absolute guidance. At present, we suggest using predicted watershed changes of 50% or more in either runoff (as indexed by change in impervious area) or sediment production as provisional criteria for requiring a more detailed evaluation of both the drivers and the resisting factors for channel change, regardless of other screening-level assessments. Clearly, however, only more experience with the application of such "thresholds," and the actual channel conditions that accompany them, will provide a defensible basis for setting numeric standards.

4. Local in-channel drivers (e.g., bedrock constrictions, small-head dams, weirs) can be extremely important to downstream sediment continuity and channel stability, but they may not be readily discernable from coarse-scale spatial datasets. As with other determinants of channel resistance, field inspection of channel conditions prior to development is an inescapable component of identifying important in-channel elements that may influence the impacts of development on future channel stability.

# DETAILED MAPPING PROCEDURES FOR GLU ANALYSIS

The previous sections provided a general overview of the GLU approach. Below we offer detailed procedures for application of this approach in a GIS framework. A GLU layer is derived by overlaying hillslope, land cover, and geology, and then assigning a particular sediment-production rate to each of the resulting categories. These rates are normally categorical (i.e., Low, Medium, and High); however, if data are available, rates could be expressed as numerical values.

To maintain a useful level of standardization between GLU maps across target watersheds within a region, we favor publicly available datasets as the source of our primary GIS analysis layers. These datasets include:

- USGS National Elevation Dataset (NED): 1 arc-second and 1/3 arc-second in ArcGrid format (http://seamless.usgs.gov/products/3arc.php)
- 2001 National Land Cover Database (NLCD 2001): 30-meter pixel IMG grid (http://www.mrlc.gov/nlcd_multizone_map.php)
- 1977 Jennings Geology: 1:750,000 vector ArcInfo coverage (http://www.consrv.ca.gov/CGS/information/publications/pub_index/Pages/statewide_references.aspx)

These datasets represent statewide conditions and provide relatively coarse, but seamless, data without respect to political or watershed boundaries. However, for many areas, equally continuous coverage at much better resolution is available and preferable.

## Data Types and Acquisition

### *Data pre-processing*

Before a GLU layer can be generated, a few pre-processing steps need to be followed. The first step is to define the area of analysis. For hydromodification application these areas are watersheds, and therefore the topographic boundary of the landscape draining to the point(s) of interest becomes the area of analysis.

To delineate a particular watershed, we use the National Watershed Boundary Dataset as our primary source (in California these are maintained and distributed by CalWater). CalWater offers a free vector dataset (shapefile) with basin and sub-basin delineations organized by the commonly used 8-digit HUCs from the USGS Hydrologic Unit Maps. After the watershed of interest has been extracted, we conduct a careful examination of its boundaries against a 10-m DEM hillshade. In cases where the boundaries seem inadequate, we turn to the DEM to improve the watershed delineation using ArcInfo Hydrology routines. After the area of analysis has been sufficiently well-defined, the analysis layers are 'clipped' to its boundaries and reprojected to a common coordinate system. An example, shown for the Escondido Creek watershed (San Diego County) on an orthophoto base, is given in Figure 4.


**Figure 4. Processing the data layer.**

## *Slope classes*

The next step is to refine and classify the attributes of the analysis layers that will be used to create the GLU maps. The hillslope DEM is analyzed to produce a grid of slope values, which are subsequently classified into discrete categories. In applications to date, the following category percentages have been commonly used to categorize hillslope gradients: 0 - 10, 11 - 20, and >20%.

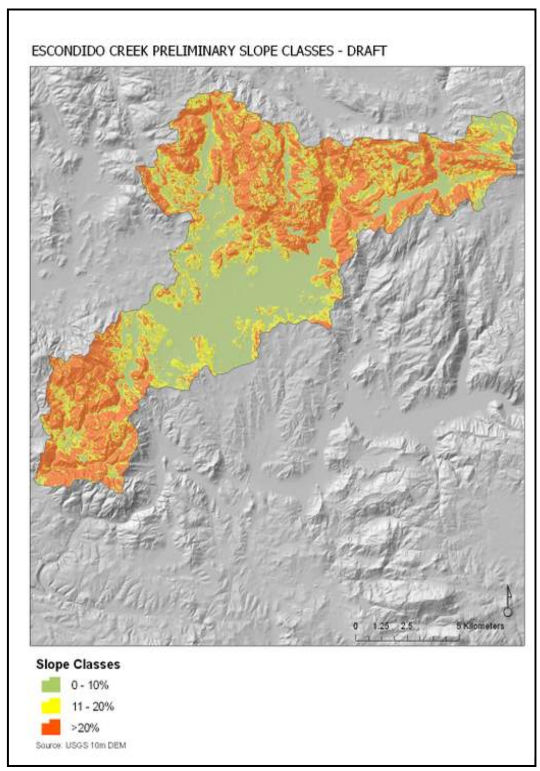



**Figure 5. DEM map with preliminary slope classes.**

There are no hard-and-fast rules for choosing particular slope breaks, but these have shown a good correlation between broad categories of observed intensity of hillslope erosion in the southern California watersheds in which they have been applied. Although uniformly flat (or uniformly steep) watersheds might display little spatial discrimination using these particular categories; however, maintaining a common framework across the entire region is likely to advance the application of this methodology more effectively than developing unique, watershed-specific categories (even those where the slope categories are chosen on the basis of more 'natural' divisions in the local distribution of values).

### *Land cover classes*

Following a similar philosophy that favors simplicity and cross-watershed uniformity, the land-cover grid categories generally include:

- Agricultural/Grass
- Developed
- Forest
- Scrub/Shrub
- Other (water, bare rock)

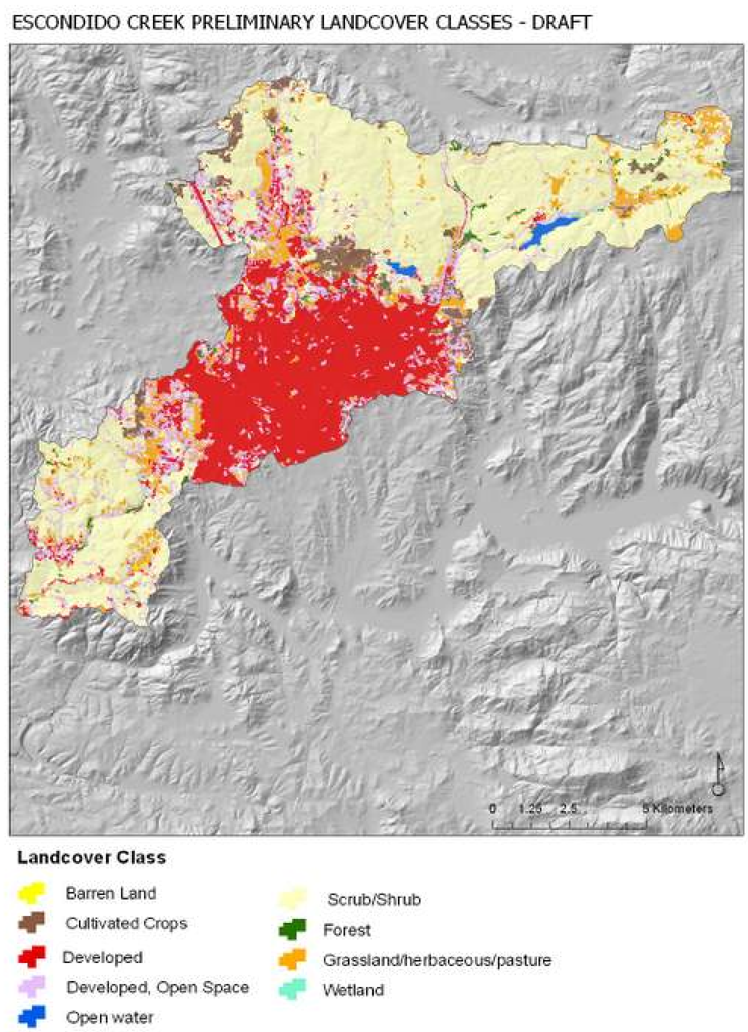



**Figure 6. DEM map with preliminary land cover classes.**

## *Geology classes*

Finally, the geology layer is categorized based on rock types or mechanical competence, the predominant sediment size generated upon erosion, and their associated erodibility. The attribution (and thus the naming) of the geology classes can vary by region, but as an example these categories might be:

- Crystalline (or other specific rock types)
- Fine-grained sedimentary, weak (i.e., easily eroded)
- Coarse-grained sedimentary, weak
- Fine-grained sedimentary, competent
- Coarse-grained sedimentary, competent

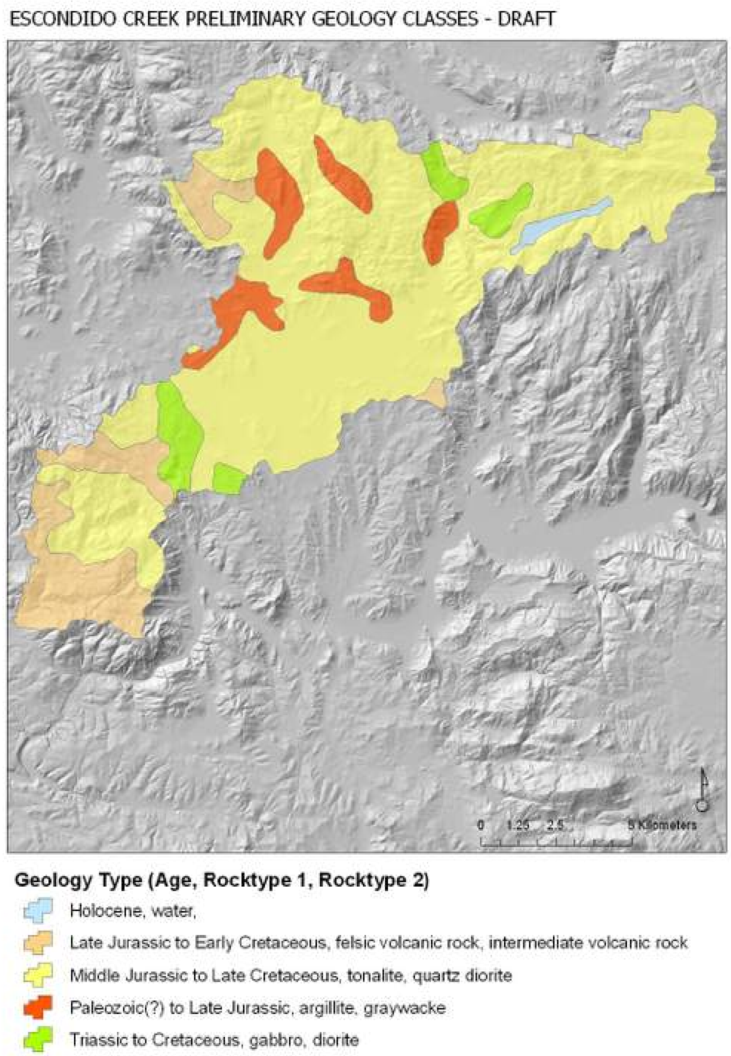



**Figure 7. DEM map with preliminary geology class types.**

The ‘geology’ categorization is the least well-defined across southern California, because literally thousands of distinct rock types are present here and they have not all been evaluated in applications of this method to date. A common-sense approach will undoubtedly be sufficient for many mapped units in most watersheds (e.g., a named sandstone unit is likely to generate coarse-grained sediment; a named shale unit will not) but, at present, there is less available guidance on how to infer relative erodibility than exists for hillslope gradient or land cover. This shortcoming is anticipated to improve as more areas are evaluated across the region, but some level of geologic acumen will normally be necessary to apply this method in any new locale.

After the analysis categories have been defined, an attribute column is added to each dataset to store that information.

Lastly, the raster datasets (i.e., hillslope and land cover) are converted to vector format for the final GLU analysis. Although GLU mapping can be done in both raster and vector formats, we have found that keeping the analysis in vector format (which keeps the final GLU layer in shapefile format) achieves the benefits of compressibility, easy distribution, and compatibility of shapefiles.

## GLU Processing

When all the individual datasets have been completed, generating a GLU layer is reasonably straightforward. With a simple overlay, the primary layers are merged into a single polygon dataset that keeps track of every unique combination of ***geology type***, ***hillslope gradient***, and ***land cover***. An additional attribute field (GLU_Type) is created in this final GLU layer to differentiate each possible combination (see Table 4 below). Note that there is no rating or ranking of these GLU categories at this stage. Each category simply represents a unique combination of slope, land cover, and geology attributes; subsequently, relative sediment production must be determined by observation, not addition of fields. Specifically, the GLU_Type field is a concatenation of each of the analysis layers GLU category, resulting in GLU types similar to those in Table 4 and graphically represented in Figure 8.

**Table 4. Example of common percentages for GLU_Type attributes.**

| GLU_TYPE |
|---|
| Volcanic rocks; Ag/Grass; 0-10% |
| Volcanic rocks; Developed; 10-20% |
| Volcanic rocks; Scrub/Shrub; 10-20% |
| Tonalite; Ag/Grass; 10-20% |
| Tonalite; Ag/Grass; >20% |
| Tonalite; Developed; 0-10% |
| Argillite; Ag/Grass; >20% |
| Argillite; Forest; >20% |
| Argillite; Scrub/Shrub; 10-20% |

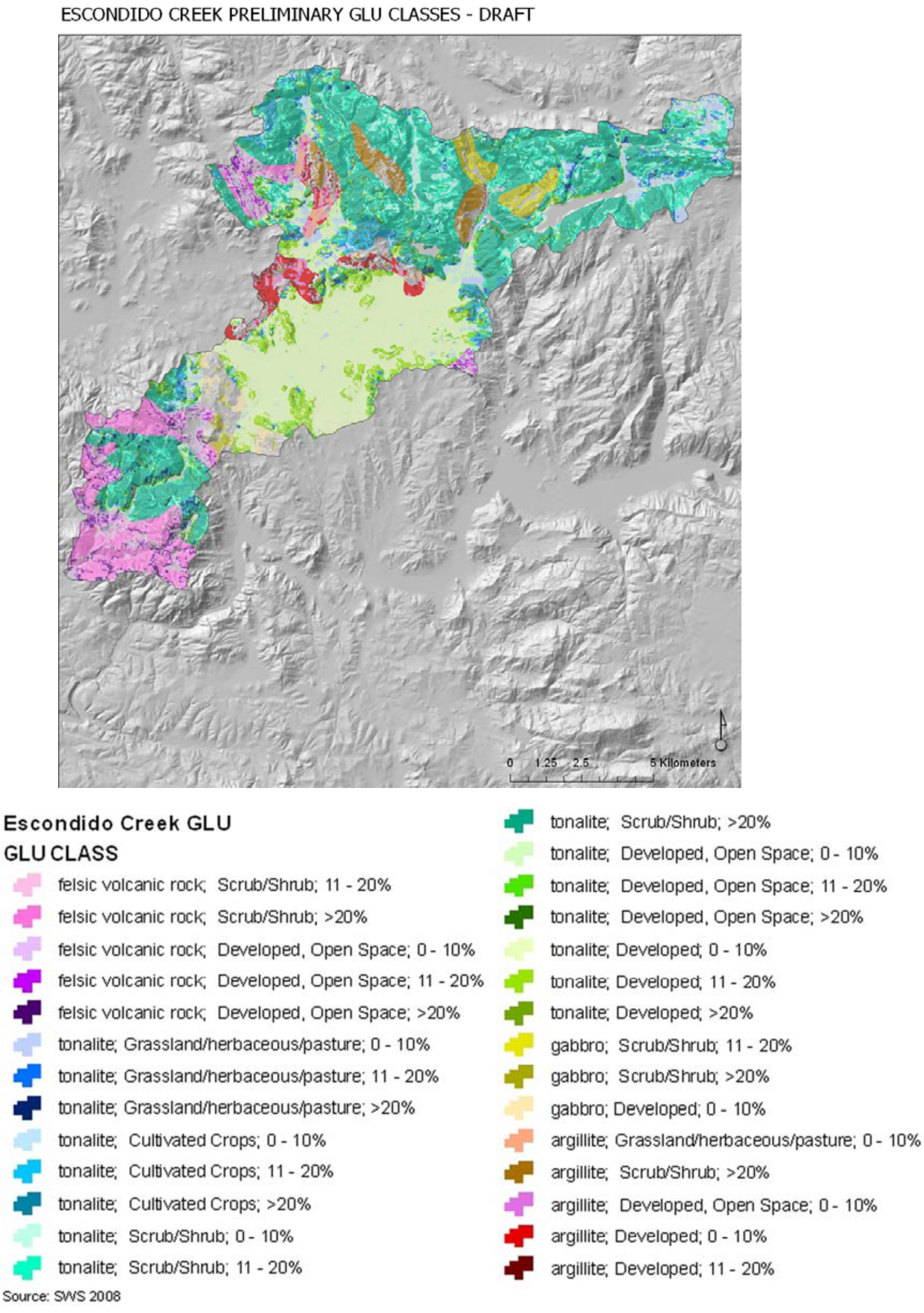



**Figure 8. DEM map with preliminary GLU layer and attribute percentages.**

## GLU Post-processing and Analysis

The combination and geoprocessing of these datasets, which are intrinsically different in format (and in many cases different in scale), is typically not free of errors or redundancy. Apart from the obvious considerations of error associated with scale (where the coarsest dataset must dictate the final scale of the analysis) and the outliers resulting from the residual artifacts produced by the manipulation of raster and vector layers, there are commonly a number of spatially insignificant GLU types that are generated in the process. In subsequent analyses, we run basic spatial statistics on each GLU type to determine their dominance in a given watershed. Calculating the percent total of each GLU type proves to be an efficient way of identifying those GLU classes whose representation will be insignificant in any final results. These generally can be omitted from subsequent analysis.

The final step is to assign each GLU type to a High, Medium or Low category based on its relative sediment production rate as observed in the field or inferred from literature information. Examples of areas from each category are provided on the next page (Figure 9). Currently, these assignments are based on field observations; although it might be anticipated that various combinations of the three factors will yield a particular outcome based on prior experience, we presently lack sufficiently widespread application to provide such a list *a priori* or to recommend its application in a new locality. Even with long-standing application, some level of field verification will always be appropriate.


**Figure 9. Examples of Low, Moderate, and High sediment production and delivery areas in the Santa Paula Creek watershed (Ventura County).**

# LITERATURE CITED

Becker, A. and P. Braun. 1999. Disaggregation, aggregation and spatial scaling in hydrological modeling. *Journal of Hydrology* 217:239-252.

Beighley, R.E., T. Dunne and J.M. Melack. 2005. Understanding and modeling basin hydrology: Interpreting the hydrogeological signature. *Hydrological Processes* 19:1333-1353.

Benda, L. and T. Dunne. 1997. Stochastic forcing of sediment supply to channel networks from landsliding and debris flow. *Water Resources Research* 33:2849-2863.

Beven, K.J. 2001. Rainfall-Runoff Modelling, The Primer. John Wiley. Chichester, UK.

Bledsoe, B., R. Hawley, E.D. Stein and D.B. Booth. 2010. Hydromodification Screening Tools: Field Manual for Assessing Channel Susceptibility. Technical Report 606. Southern California Coastal Water Research Project. Costa Mesa, CA.

Booth, D.B. 1990. Stream-channel incision following drainage-basin urbanization. *Water Resources Bulletin* 26:407-417.

Booth, D.B. and P.C. Henshaw. 2001. Rates of channel erosion in small urban streams. *In*: M. Wigmosta and S. Burges (eds.), Land Use and Watersheds - Human Influence on Hydrology and Geomorphology in Urban and Forest Areas: AGU Monograph Series. *Water Science and Application* 2:17-38.

Center for Watershed Protection. 2003. Impacts of Impervious Cover on Aquatic Systems. Center for Watershed Protection. Ellicott City, MD.

England, C.B. and H.N. Holtan. 1969. Geomorphic grouping of soils in watershed engineering. *Journal of Hydrology* 7:217-225.

Gabet, E.J. and T. Dunne. 2003. A stochastic sediment delivery model for a steep Mediterranean landscape. *Water Resources Research* 39:1237.

Greene, R.G. and J.F. Cruise. 1995. Urban watershed modeling using geographic information system. *Journal of Water Resources Planning and Management - ASCE* 121:318-325.

Gregory, K.J., G. Benito, and P.W. Downs. 2008. Applying fluvial geomorphology to river channel management: Background for progress towards a palaeohydrology protocol. *Geomorphology* 98:153-172.

Haverkamp, S., N. Fohrer and H.-G. Frede. 2005. Assessment of the effect of land use patterns on hydrologic landscape functions: A comprehensive GIS-based tool to minimize model uncertainty resulting from spatial aggregation. *Hydrological Processes* 19:715-727.

Kirchner, J.W., R.C. Finkel, C.S. Riebe, D.E. Granger, J.L. Clayton, J.G. King and W.F. Megahan. 2001. Mountain erosion over 10 yr, 10 k.y., and 10 m.y. time scales. *Geology* 29:591-594.

Lane, E.W. 1955. The importance of fluvial morphology in hydraulic engineering. *Proceedings of the American Society of Civil Engineers* 81:1-17.

Montgomery, D.R. 1999. Process domains and the river continuum. *Journal of the American Water Resources Association* 35:397-410.

Moret, S.L., W.T. Langford and D.D. Margineantu. 2006. Learning to predict channel stability using biogeomorphic features. *Ecological Modelling* 191:47-57.

Mulvany, T.J. 1851. On the use of self-registering rain and flood gauges, in making observations of the relations of rain fall and flood discharges in a given catchment. Transactions and Minutes of the Proceedings of the Institute of Civil Engineers of Ireland, Session 1850-1, v. IV, pt. II. Dublin, Ireland.

National Research Council. 2009. Committee on Reducing Stormwater Discharge Contributions to Water Pollution, Urban Stormwater Management in the United States. National Academies Press. Washington, DC.

Osman, A.M. and C.R. Thorne. 1988. Riverbank stability analysis I: Theory. *Journal of Hydraulic Engineering* 114: 134-15.

Schumm, S.A., M.D. Harvey and C.C. Watson. 1984. Incised Channels: Morphology, Dynamics, and Control. Water Resources Publications. Littleton, CO.

Stillwater Sciences. 2007. Santa Paula Creek watershed planning project: geomorphology and channel stability assessment. Prepared for California Fish and Game, Santa Paula Creek Fish Ladder Joint Powers Authority. Stillwater Sciences, Inc. Santa Barbara, CA.

Stillwater Sciences. 2008. Sespe Creek hydrology, hydraulics, and sedimentation analysis: watershed assessment of hillslope and river geomorphic processes. Draft Report. Prepared for Ventura County Watershed Protection District, California. Stillwater Sciences, Inc. Berkeley, CA.

Waananen, A.O. and J.R. Crippen. 1977. Magnitude and frequency of floods in California. US Geological Survey Water-Resources Investigations Report No. 77-21. US Geological Survey. Denver, CO.

# APPENDIX:  SAN ANTONIO CREEK EAMPLE

**The following is a summary of the GIS-based and field-based assessment of the sensitivity of San Antonio Creek to hydromodication.**

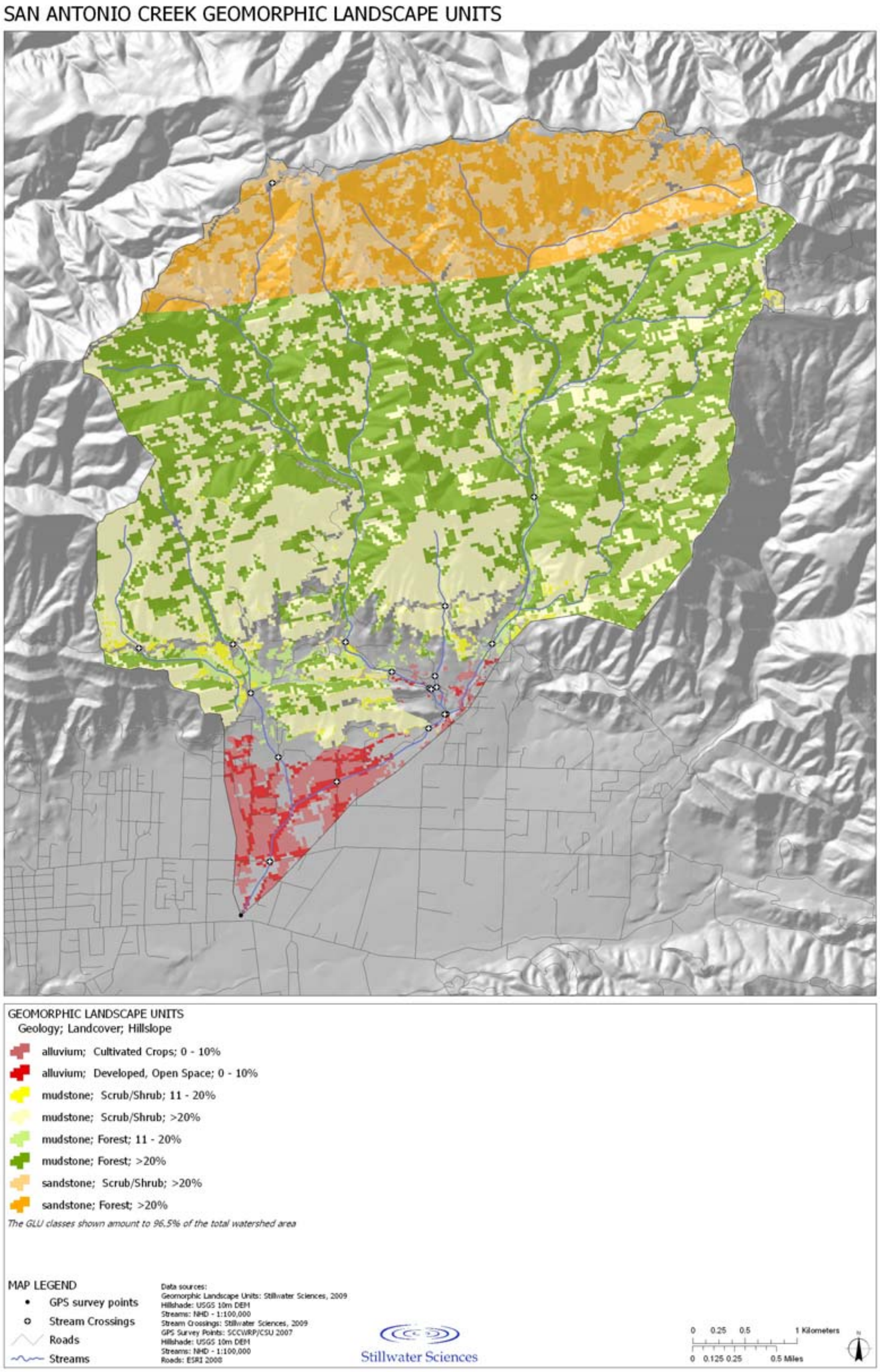
GIS-based analysis:

- The ‘pre-developed’ watershed Relative Sediment Production (determined by changing ‘developed’ GLU sediment production values to sediment production values for an undeveloped land use) is very similar to the current watershed Relative Sediment Production, indicating that the channel is not inherently receiving less sediment due to watershed development.
- Areas of ‘H’ Relative Sediment Production are interspersed with areas of ‘L’ Relative Sediment Production throughout the middle portion of the watershed.
- Development density is fairly low and concentrated towards the downstream end of the contributing watershed, so we anticipate relatively low hillslope sediment trapping potential by urban infrastructure.
- Only a few stream road crossings, so we anticipate relatively low in-channel sediment trapping potential.
- **From these data, we conclude that the San Antonio Creek study site has a “Low” sensitivity to current watershed development and is unlikely to express recent development-related changes in morphology.**

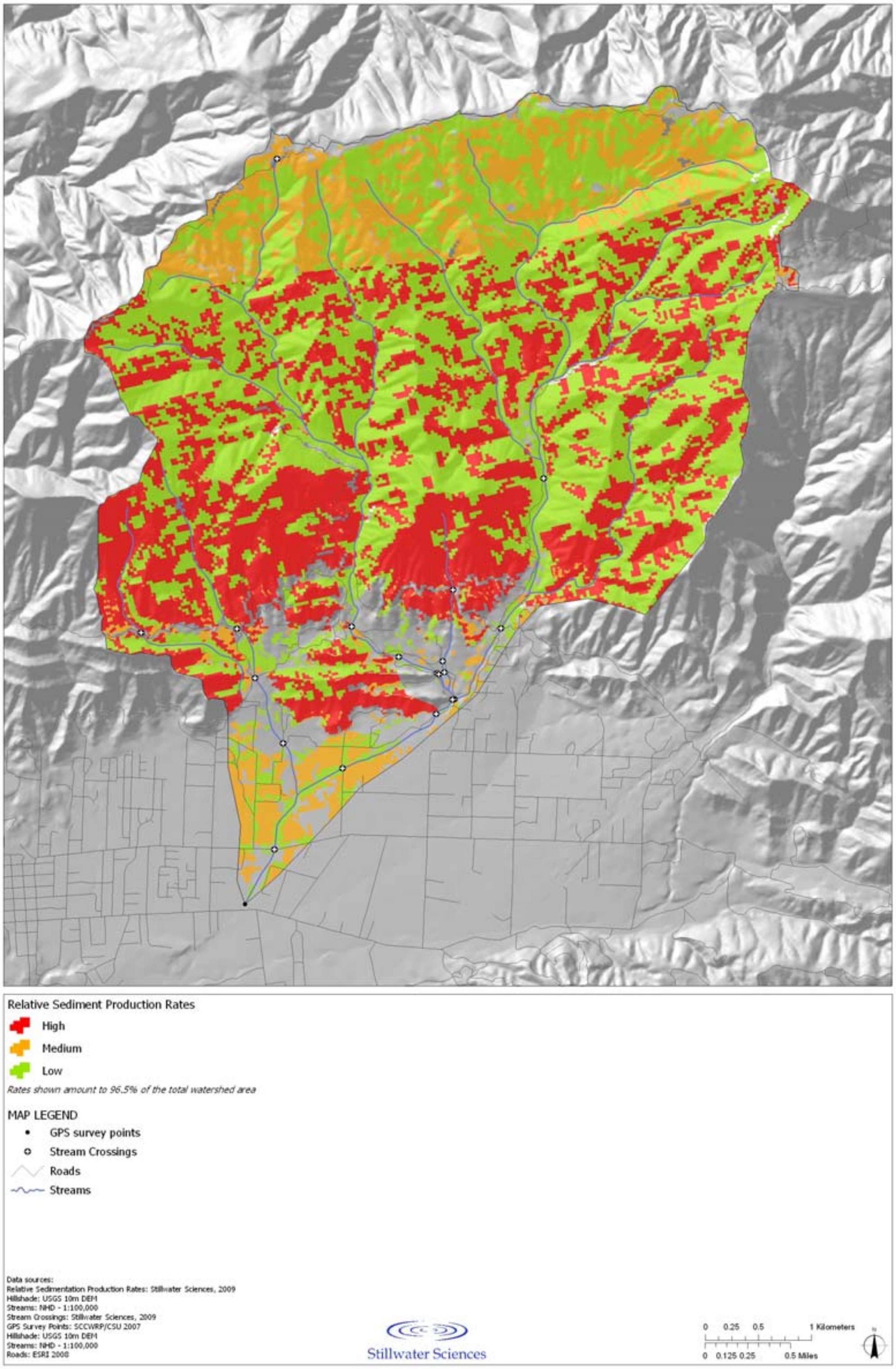
Field-based observations (see attached field photos and topographic data)

- Channel is alluvial and is transporting coarse sediment
- Channel has vegetated bars that appear stable
- Cross-sections show a ‘stable’ channel form (i.e., not incising, and displaying developed bankfull channel and stable banks)
- **From these data, concluded that the San Antonio Creek study site has had a relatively “Low” response to upstream development, expressing a “Low” sensitivity to current watershed development.**

## GLU ANALYSIS:



SAN ANTONIO CREEK RELATIVE SEDIMENTATION PRODUCTION RATES

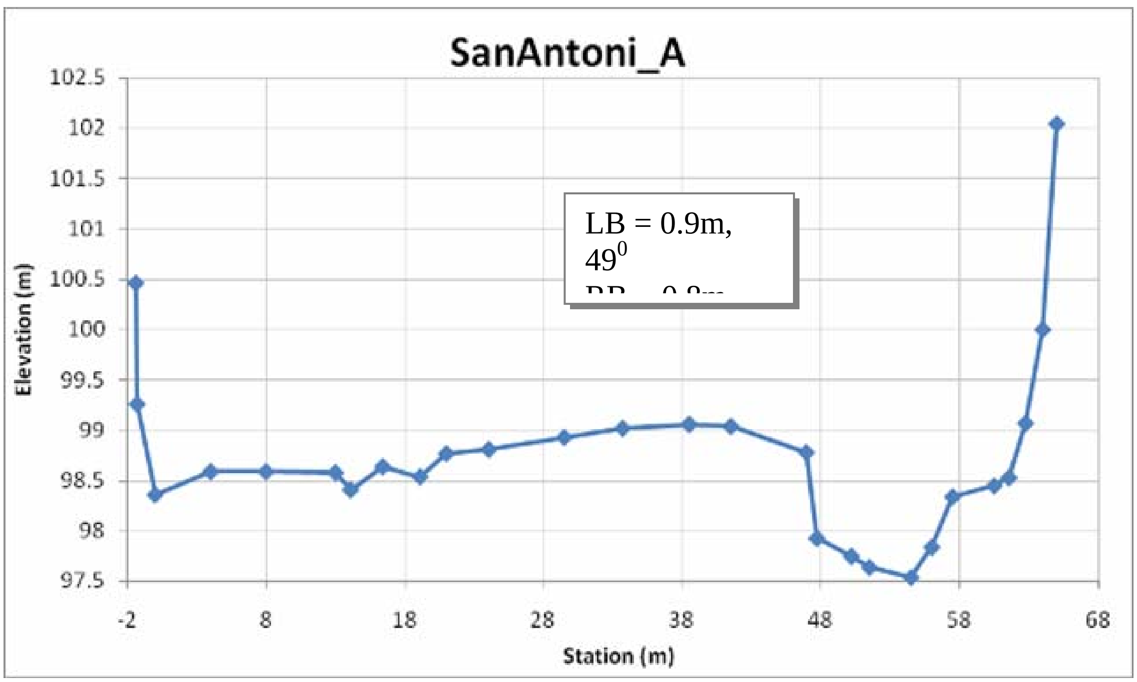


## OBSERVATIONS:

LB U-MW-UC


RB STABLE-UC


*These sites are less than 30 meters apart. Therefore, the outer banks are only counted once (see SanAntoni_B next page). Only the within the additional incision within the main channel are counted for SanAntoni_A.*



LB U-MW-PC (upper) & STABLE-UC (lower)

RB U-MW-PC (upper) & STABLE-UC (lower)