Appendix D: Causes of Degradation Technical Memorandum

San Bernardino municipalities subject to the Middle Santa Ana River Pathogen TMDL have coordinated the development of water quality monitoring programs. As a result, the program developed for purposes of implementing the Basin Plan Amendment developed by the SWQSTF (above) will suffice for implementation of the TMDL. Dischargers and stakeholders in the watershed continue to explore the potential for a single, coordinated water quality monitoring program throughout the watershed for all purposes.

TECHNICAL MEMORANDUM

Causes of Degradation

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San Bernardino County
Flood Control District

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1 INTRODUCTION

This technical memorandum is part of the larger study for San Bernardino County Flood Control District to develop the Watershed Action Plan as required by the current San Bernardino County MS4 Permit Order No. R8-2010-0036, NPDES No. CAS 618036. It identifies potential causes of stream degradation.

1.1 Background

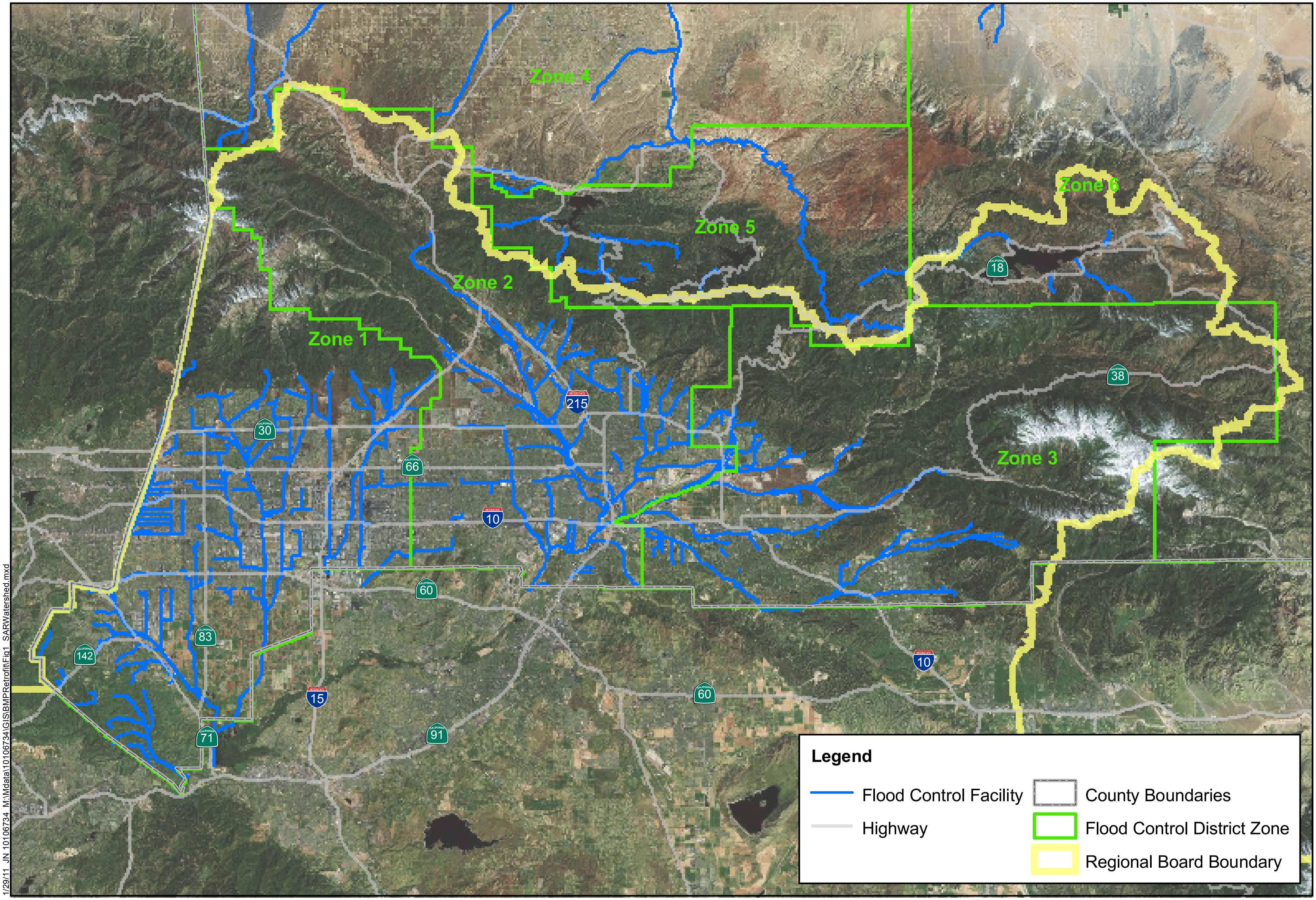
According to the County of San Bernardino (County) Stormwater Plan Proposal Summary, the County is a member of a broad, multi-stakeholder task force established to develop a regional Watershed Action Plan (WAP) that will assist its cities, water agencies, and watermasters, as well as its development and environmental communities, to integrate water quality and water supply policies and encourage the capture and infiltration of stormwater into groundwater basins. The objective of the WAP is to improve integration of water quality, stream protection, storm water management, water conservation and re-use, and flood protection, with land use planning and development processes. The WAP builds upon the requirements of the recently adopted San Bernardino County Municipal Separate Storm Sewer System (MS4) permit for the county and its cities (permittees).

As part of the WAP, the permittees are required to identify potential causes of stream degradation including a consideration of sediment yield and balance on a watershed or subwatershed basis.

According to the MS4 permit, the permittees serve a population of approximately 1.5 million, occupying an area of approximately 620 square miles (see Figure 1). The permittees MS4 systems include an estimated 378 miles of above-ground channels and 485 miles of underground storm drain channels. The MS4 regulates urban and storm water runoff from the areas within the Santa Ana Regional Board's jurisdiction, which makes up approximately seven percent (7%) of the County. All other areas are under either the Colorado River Basin Regional Board or Lahontan Regional Board.

1.2 Purpose

The purpose of this technical memorandum is to identify the potential causes of stream degradation in three major watersheds: San Antonio, Cucamonga, and Live Oak.



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0 5 10
Miles

CAUSES OF DEGRADATION

Figure 1: Santa Ana River Watershed - County of San Bernardino

Sources: Caltrans; ESRI; SB DPW; SB Permittees; Microsoft Satellite Imagery

2 METHODOLOGY

The causes of stream degradation were determined using three methods: examination of historical and current aerial photographs, site visits, 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 Google Earth. These aerials were examined to get a general idea of the existing condition of the watersheds. Specifically, the aerials were used to locate basins, areas of significant degradation and regions of dense development.

Historical aerials were purchased from Environmental Data Resources, Inc (EDR). (see Appendix A). The aerials for all three watersheds ranged from approximately year 1938 to 2005 and covered a region of approximately 100 acres. The purpose of these historical aerials was to examine a stretch of each channel to determine the timing and extent of degradation.

Also historical aerials from http://historicaerials.com/ by Nationwide Environmental Title Research (NETR) Online were examined. These aerials provided a larger view of the watersheds and were used to determine how the watersheds have physically changed over time. The aerials ranged from 1938 to 2005 and covered a region of approximately 64 square miles of each watershed.

2.2 Site Visits

Based on what was observed while examining the aerial photographs, specific locations within each watershed were visited. Pictures and general notes were taken of the current condition of each channel.

2.3 GIS-based Desktop Study

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

According to this report, 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. 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;
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 watershed 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" conditions provides evidence for the causes of degradation.

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 watersheds are structured.

2.3.1 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 watershed was divided into its respective geology types, with special consideration to areas of Cenozoic Sedimentary Rocks – Alluvium, especially in the downstream reaches of the watershed.

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. This means that less critical power, energy required to transport the existing load, is required to transport the sediment in the downstream reaches of the watershed. This results in an increased potential for the degradation of alluvial soils.

2.3.2 Land Cover

The land cover types were obtained from the National Oceanic and Atmospheric Administration (NOAA) Ocean Service, Coastal Services Center (http://www.csc.noaa.gov/crs/lca). Each watershed 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". As a watershed becomes developed, the potential for runoff increases, and the potential sediment supply decreases, creating an imbalance within the watershed.

2.3.3 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 watershed was broken up into a 10 meter by 10 meter grid, where the grids were divided into three (3) 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 and degradation.

3 WATERSHEDS

This section describes the three watersheds examined as part of this study and explains the results of the aerial photograph review, site visits, and GIS-based desktop study.

3.1 San Antonio Watershed

The San Antonio Watershed is located on the most western portion of Zone 1 within the County of San Bernardino. (See Figure 2) The watershed encompasses both the County of San Bernardino and the County of Los Angeles but only the areas within the County of San Bernardino were analyzed. The San Antonio Channel is approximately 19 miles long and ranges from the San Antonio Dam, south to Prado Dam. It crosses through the cities of Upland, Montclair, Chino Hills, and Chino. Several smaller channels and creeks are tributary to the San Antonio Channel, including English Canyon, Chino Creek, Soquel Canyon Channel, and Cypress Channel.

San Antonio Dam and Prado Dam are the two major water storage facilities within the watershed but only San Antonio Dam influences the stretch of channel being analyzed. Prior to the construction of the San Antonio Dam in 1956, the upstream portion of the watershed had a Standard Project Flood peak flow rate of 19,000 cfs. Following the construction of the Dam, the maximum outflow was restricted to 8,000 cfs at reservoir levels below the spillway crest elevation. In addition to decreasing the downstream flow rate, the Dam acts as a major debris basin.

3.1.1 Study Reach

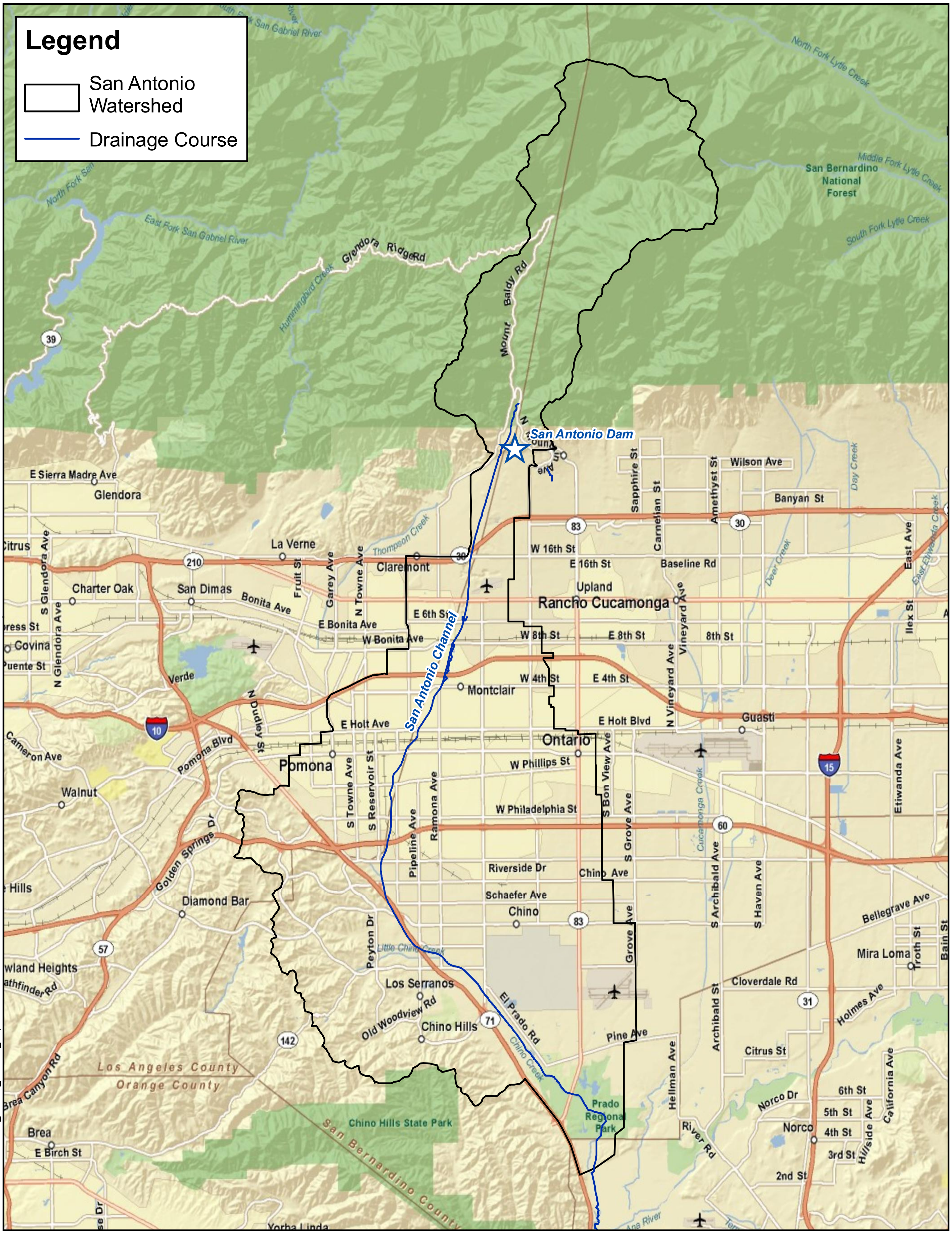
The reach of the San Antonio Channel that is under investigation starts approximately 700 feet upstream of Central Avenue in the City of Chino, CA, runs adjacent to El Prado Road, through the El Prado Golf Course and ends downstream at Prado Dam. Upstream of this reach the channel has been improved; most is concrete lined and is not at risk for degradation.

The study reach is made up a natural channel that shows signs of significant degradation, especially along the upper portion. It has a top width of approximately 60 feet and a depth of about 10 feet. Along this stretch heavy vegetation is protecting the bank but the invert is eroding and experiencing severe downcutting.

3.1.2 Historical Aerial Photographs

From the EDR historical aerials (Appendix A), it can be seen that this stretch of the channel was modified from a natural channel to a straight, earthen trapezoidal channel prior to 1968. As the watershed continued to be developed, the channel became significantly incised and cut off from its historical floodplain.

Based on the HDR historical aerials, the watershed saw significant development between 1960 and 1980. During this time the watershed transitioned from being predominantly agricultural to be predominantly developed.



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RBF CONSULTING GIS

0 1 2 4
Miles

Source: San Bernardino County

SAN BERNARDINO COUNTY

San Antonio Watershed

Figure 2 - Location Map

3.1.3 Site Visits

The channel varies between different conveyance types, from concrete-lined rectangular channels to natural channels with heavy vegetation. (See Figures 3 and 4). The natural stretches of the channel show signs of significant degradation, especially downstream of Central Avenue in the City of Chino (the most downstream section of the channel).

Figure 3: Upstream Portion of the San Antonio Watershed.

(San Antonio Dam can be seen at the base of the San Gabriel Mountains)

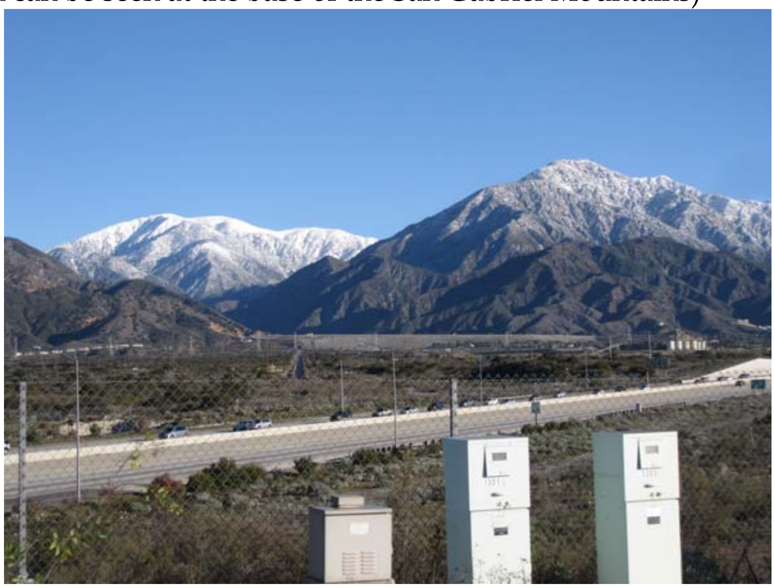


Figure 4: Natural Channel in Southern Portion of the San Antonio Watershed.

(Example of an incised reach of the channel just downstream of Central Avenue.)

3.1.4 GIS-based Desktop Study

The following subsections summarize the results of the GIS-based Desktop study for the San Antonio Watershed.

3.1.4.1 Geology Type

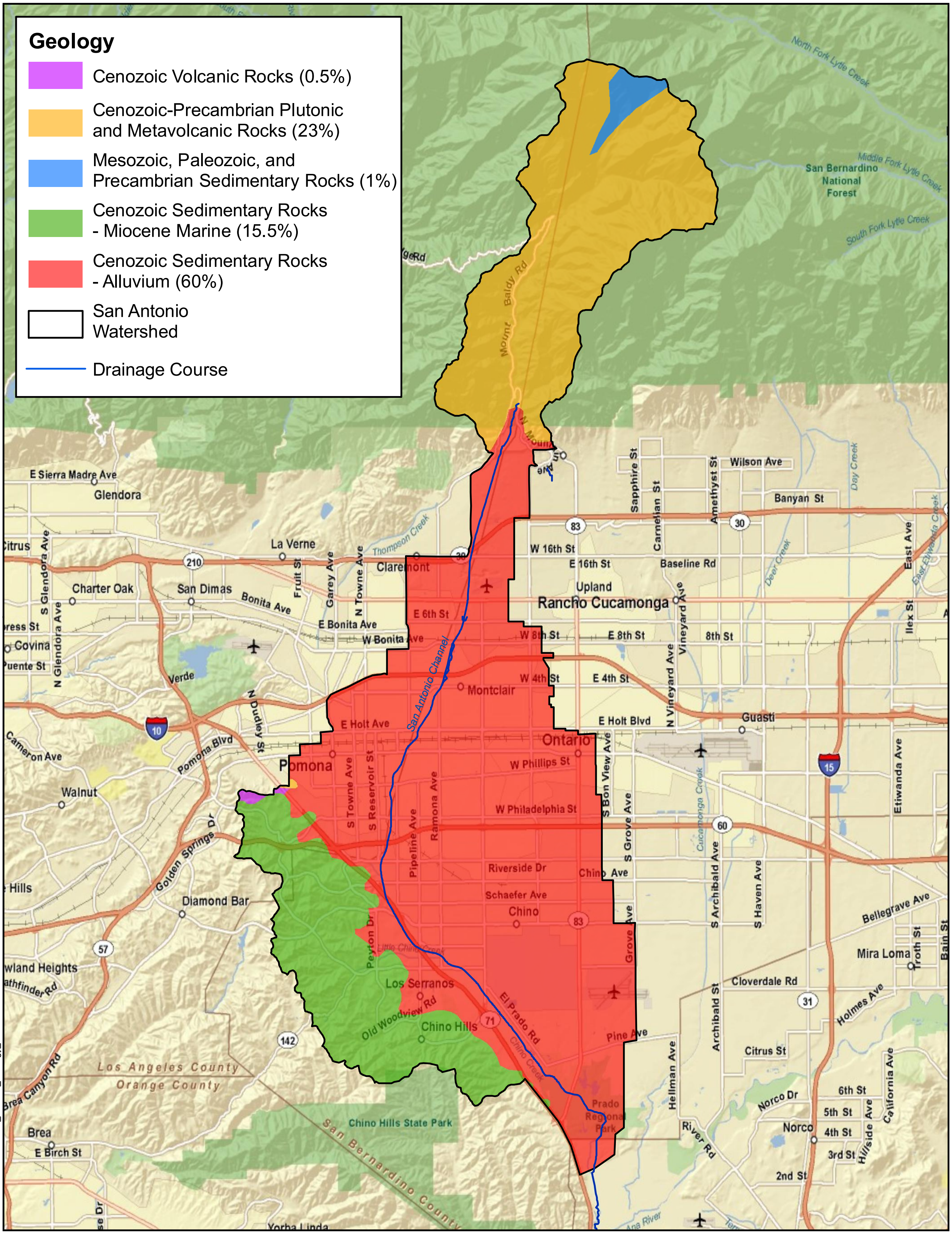
The San Antonio Watershed is dominated by Cenozoic Sedimentary Rocks – Alluvium in the lower watershed below the San Gabriel Mountains, and Cenozoic-Precambrian Plutonic and Metavolcanic Rocks within the mountain areas (See Figure 5). The Cenozoic Sedimentary Rocks – Alluvium geology type makes up the largest portion of the watershed (60%), and has the highest relative potential for erosion. This geology type covers the entire channel reach downstream of the San Antonio Dam. Because the Dam captures the majority of the upstream coarse grained sediments from the upper watershed, the clear reservoir outflow increases the potential for erosion along the lower reaches.

3.1.4.2 Land Use

The San Antonio watershed has been converted to incorporate approximately 52% of the watershed area to developed land (See Figure 6). The majority of the remaining watershed includes natural lands (Forest & Scrub/Shrub 22%) located upstream of the San Antonio Dam, and areas of agriculture (11%) and grasslands (11%) in the southern portion of the watershed. This development in the lower half of the watershed has resulted in a significant change in the watershed imperviousness and associated increase in the frequency and flow experienced in the channel. Along with the dynamics of the dam operations, the natural hydrologic response of the watershed has been significantly altered by development.

3.1.4.3 Hillslope Gradient

The upper (natural) reaches of the watershed have the highest potential for erosion with a hillslope gradient of greater than 21%, while the central (developed) portion of the watershed has a hillslope gradient of 0-10% with a lower potential for sediment production (See Figure 7). While the majority of the developed land is located in the lower sediment production areas, the construction of the San Antonio Dam has effectively removed the sediment production from the high yield areas from reaching the downstream watercourse.



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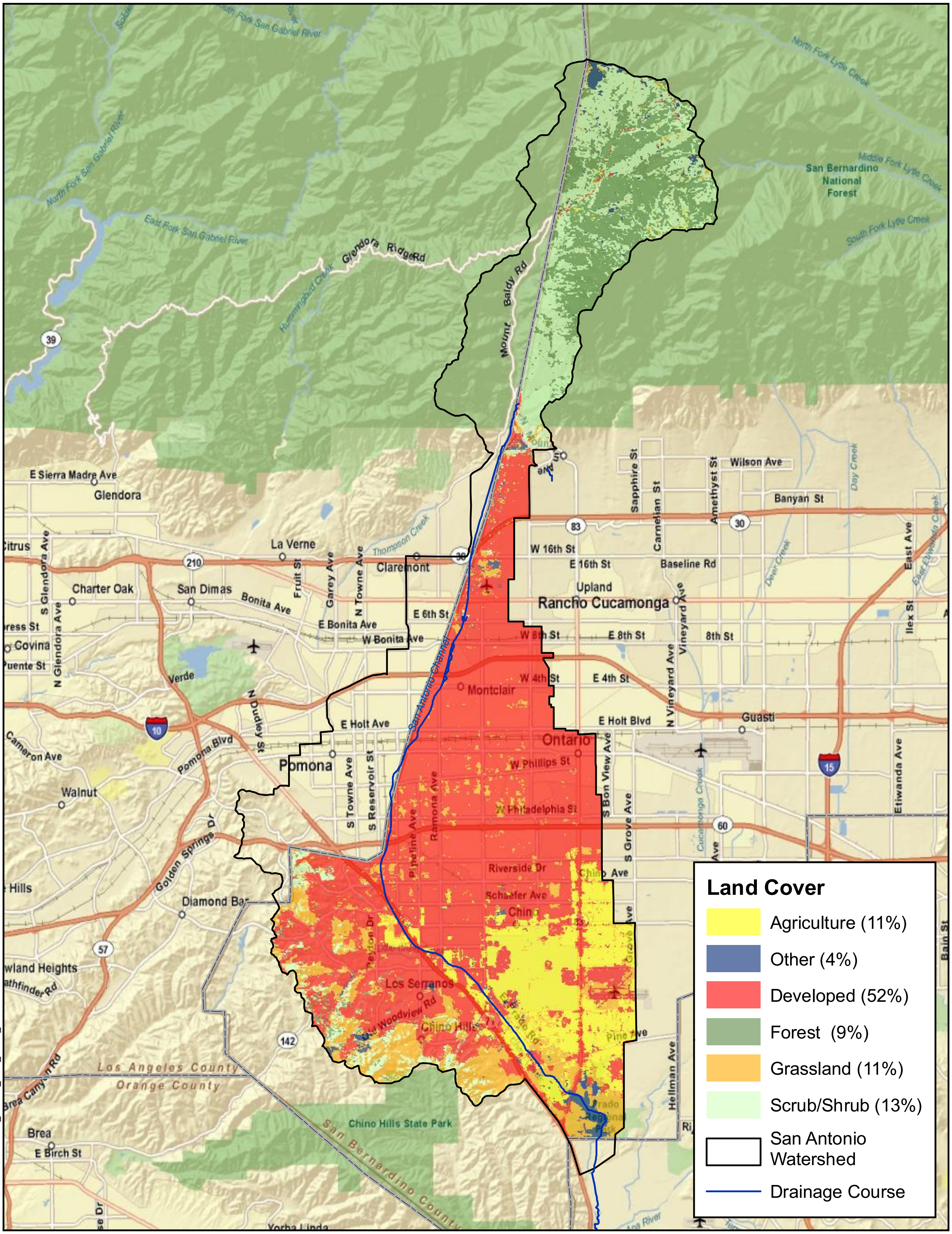
0 1 2 4 Miles

Source: San Bernardino County, CA State Dept of Geology & Mines

SAN BERNARDINO COUNTY

San Antonio Watershed

Figure 5 - Geology Types



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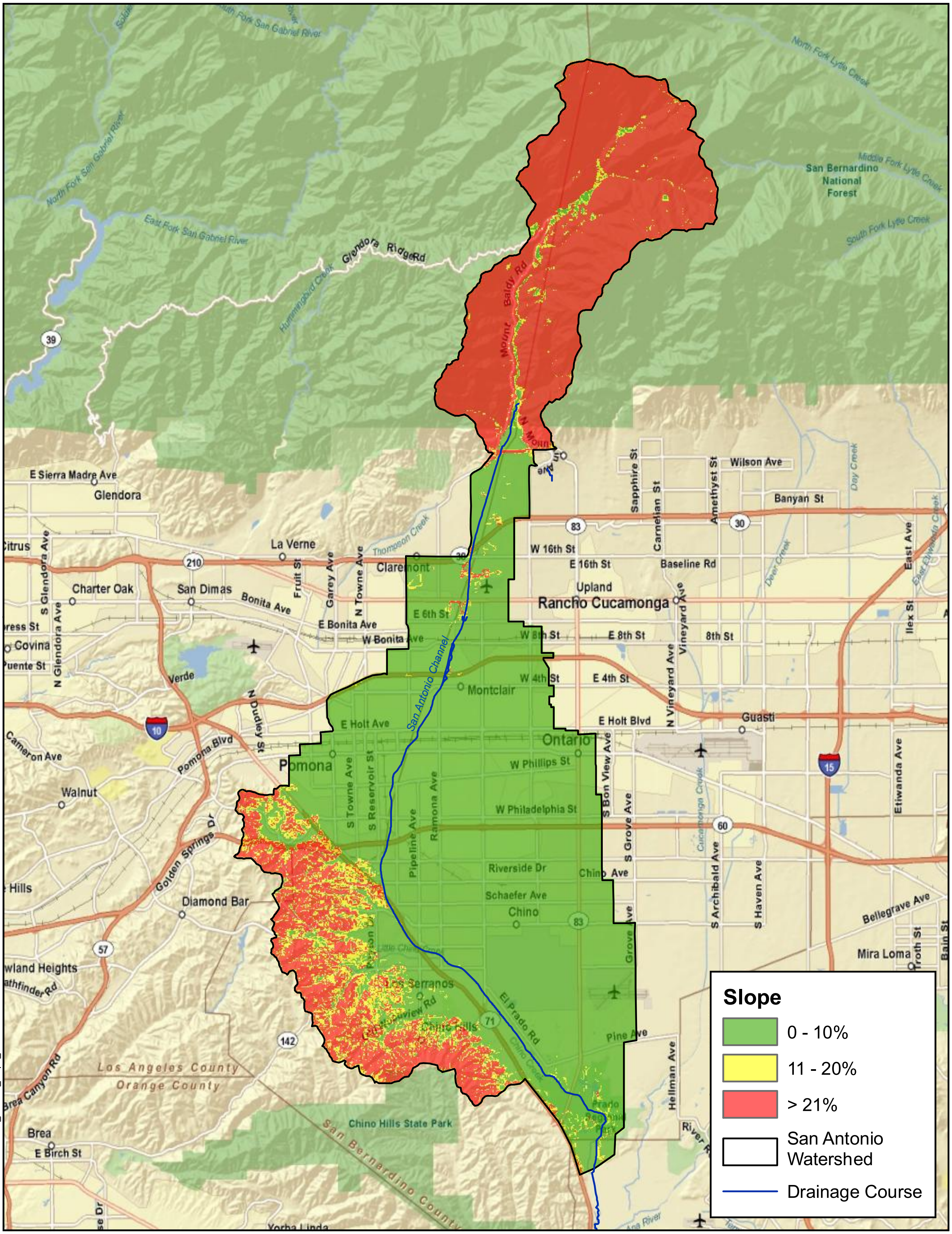
Source: San Bernardino County, NOAA

SAN BERNARDINO COUNTY

San Antonio Watershed

Figure 6 - Land Use Types



SAN BERNARDINO COUNTY

San Antonio Watershed

Figure 7 - Hillslope Gradients

0 1 2 4
Miles

Source: USGS

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3.1.5 Conclusion

The majority of the development within the watershed 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 San Antonio Dam has been constructed just downstream of the upper reaches. The Dam has cut off the supply of coarse grained sediment from making it to the downstream channel reaches. In addition, the significant change in impervious area due to watershed development has increased the frequency and rate of flow in the channel.

Compared to "prior to degradation" conditions, the geology type has remained the same. But with increased runoff from the developed areas and a decrease in sediment production from the upstream reaches of the watershed due to the San Antonio Dam, the watershed dynamics have 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 unprotected channel upstream of the Prado Dam where significant degradation and severe downcutting has occurred.

3.2 Cucamonga Watershed

The Cucamonga Watershed is located in the central portion of Zone 1 within the County of San Bernardino. (see Figure 8) The section of the Cucamonga Channel being analyzed is approximately 18 miles long and flows from the San Bernardino National Forest, south to Prado Dam. Numerous channels are tributary to the Cucamonga Channel, including Deer Creek, Demens Creek Channel, and West Cucamonga Channel.

Eight water storage facilities within the Cucamonga Watershed are specifically designed to retain the debris coming off of the San Bernardino National Forest. These basins include Cucamonga Dam, Demens Basin, Hillside Basin, Deer Creek Debris Basin and several smaller basins.

3.2.1 Study Reach

The reach of the Cucamonga Channel that is under investigation starts approximately 900 feet north of Chino Corona Road in the City of Chino, CA and ends downstream at Prado Dam. Upstream of this reach the channel has been improved, along with over 90% of the watershed; most is concrete lined and is not at risk for degradation.

The study reach is made up a natural channel that shows signs of significant degradation, especially along the upper portion. It has a top width of approximately 90 feet and a depth of about 20 feet. Along this stretch heavy vegetation is protecting portions of the bank but there are locations of significant bank and toe erosion. The channel invert is also eroding and experiencing severe downcutting.

0 1 2 4 Miles

Source: San Bernardino County

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SAN BERNARDINO COUNTY

Cucamonga Watershed

Figure 8 - Location Map

3.2.2 Historical Aerial Photographs

From the EDR historical aerials (Appendix A), it can be seen that this stretch of the channel has been modified and repaired numerous times. Also the addition of the upstream concrete-lined trapezoidal channel prior to 1977 caused significant changes to the downstream channel dimensions.

Based on the HDR historical aerials, the watershed saw significant development between 1960 and 1980. During this time the watershed transitioned from being predominantly agricultural to predominately developed.

3.2.3 Site Visits

The Cucamonga Channel varies between different conveyance types, including concrete-lined trapezoidal channels to natural channels with heavy vegetation (see Figures 9 and 10). The majority of the watershed contains engineered channels, but the portion of the Cucamonga Channel between Prado Dam and Chino Corona Road in the City of Chino is a natural channel and has been significantly degraded.

Figure 9: Upstream Portion of the Cucamonga Channel Watershed

(Looking upstream along Demens Creek Channel at the San Bernardino National Forest.)

Figure 10: Natural Channel in Southern Portion of the Cucamonga Channel Watershed

(Looking downstream at the Cucamonga Channel from the Chino Corona Road crossing in Chino, CA.)

3.2.4 GIS-based Desktop Study

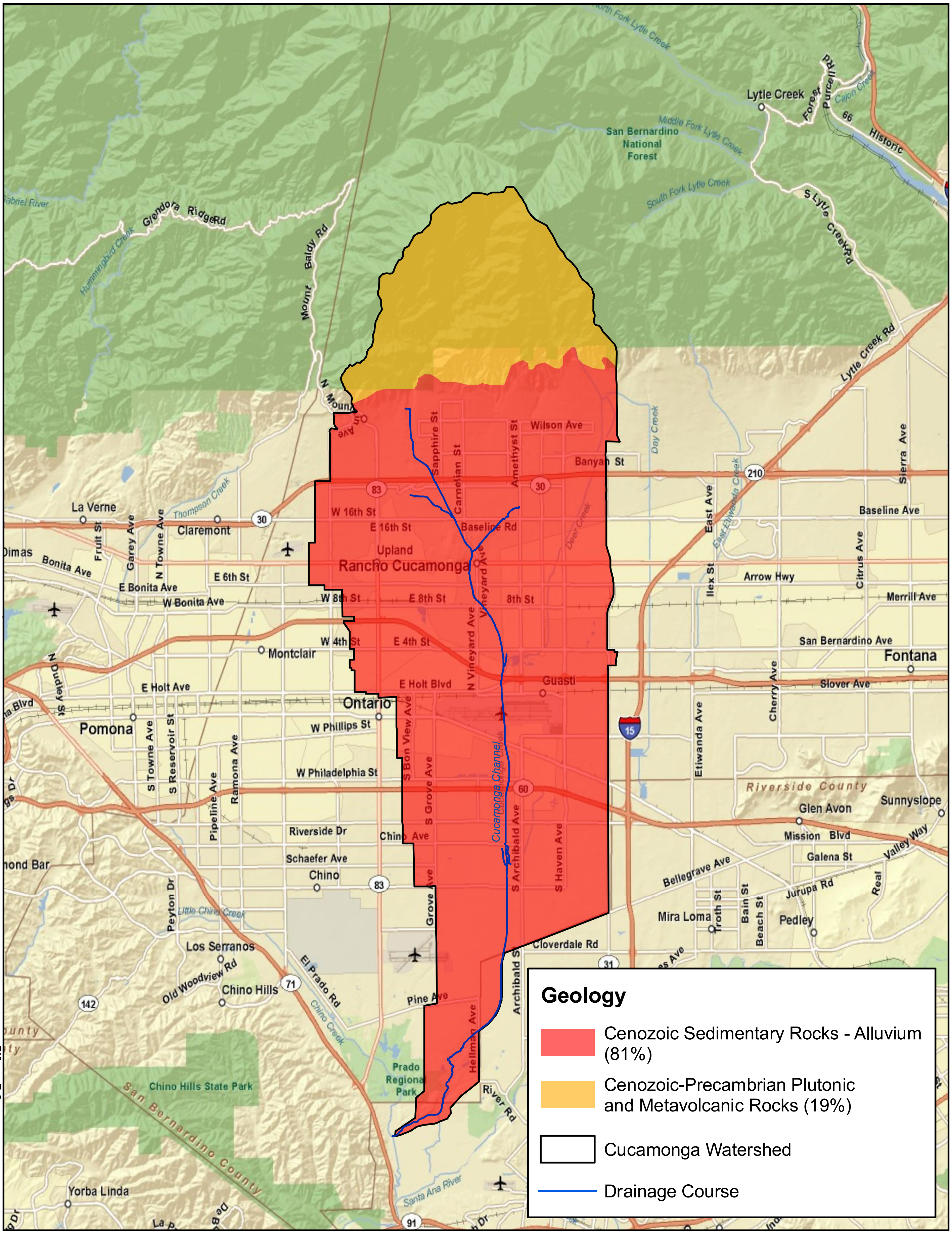
The following subsections summarize the results of the GIS-based Desktop study for the Cucamonga Watershed.

3.2.4.1 Geology Type

The Cucamonga Watershed is dominated by Cenozoic Sedimentary Rocks – Alluvium in the lower watershed below the San Bernardino National Forest, and Cenozoic-Precambrian Plutonic and Metavolcanic Rocks (19%) within the mountain areas (See Figure 11). The Cenozoic Sedimentary Rocks – Alluvium geology type makes up the largest portion of the watershed (81%), and has the highest relative potential for erosion. This geology type covers the entire channel reach downstream of the San Gabriel National Forest and debris basins. Because the debris basins capture the majority of the upstream coarse grained sediments from the upper watershed, the clear reservoir outflow increases the potential for erosion along the lower reaches.

3.2.4.1 Land Use

The Cucamonga watershed has been converted to incorporate approximately 52% of the watershed area to developed land (See Figure 12). The majority of the remaining watershed includes natural lands (Forest & Scrub/Shrub 21%) located in the San Bernardino National Forest, Grasslands (7%) in the central portion of the watershed and areas of agriculture (11%) in the southern portion of the watershed. This development in the central portion of the watershed has resulted in a significant change in the watershed imperviousness and associated increase in the frequency and flow experienced in the channel. The natural hydrologic response of the watershed has been significantly altered by development.



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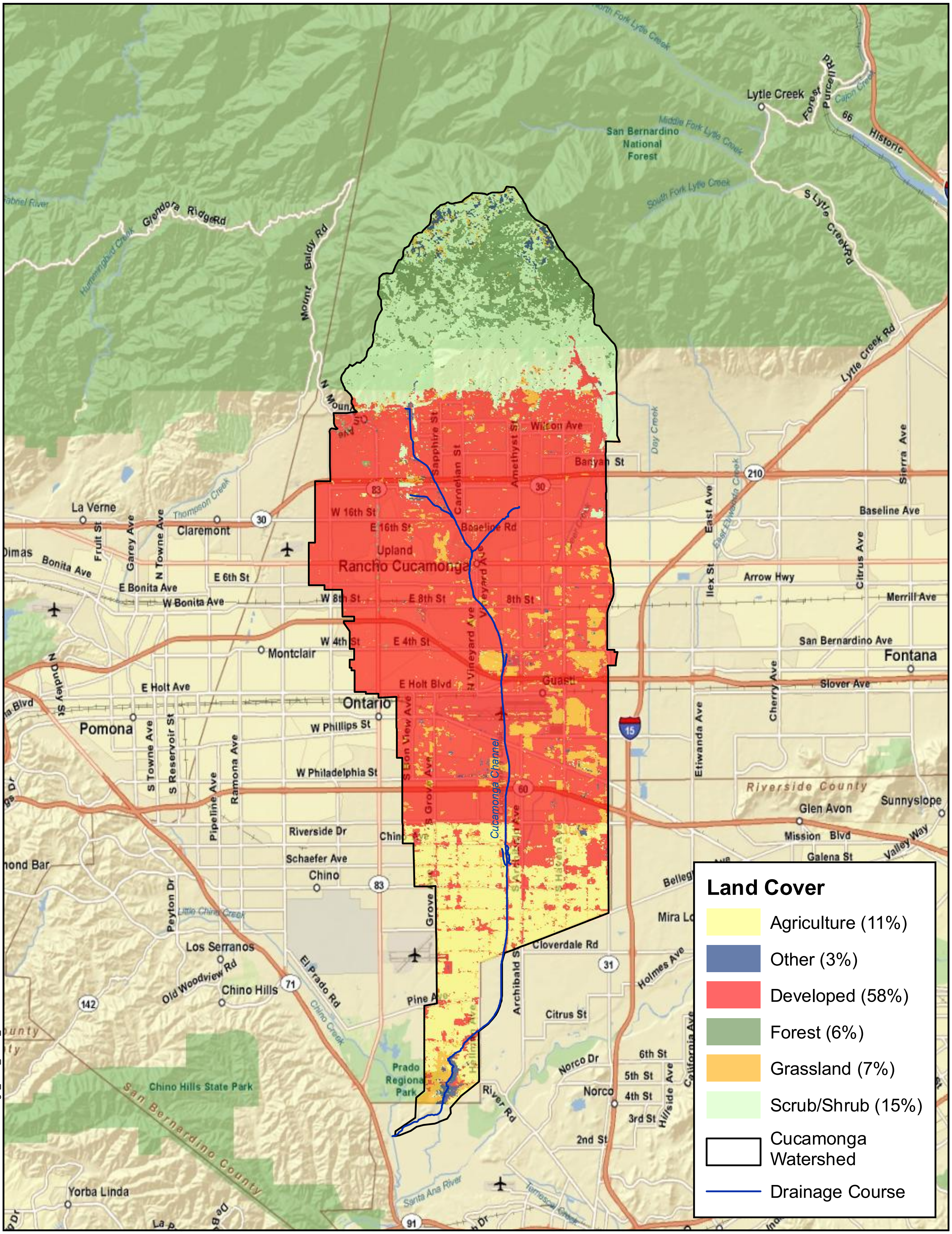
0 1 2 4 Miles

Source: San Bernardino County, CA State Dept of Geology & Mines

SAN BERNARDINO COUNTY

Cucamonga Watershed

Figure 11 - Geology Types



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RBF CONSULTING GIS

0 1 2 4 Miles

Source: San Bernardino County, NOAA

SAN BERNARDINO COUNTY

Cucamonga Watershed

Figure 12 - Land Use Types

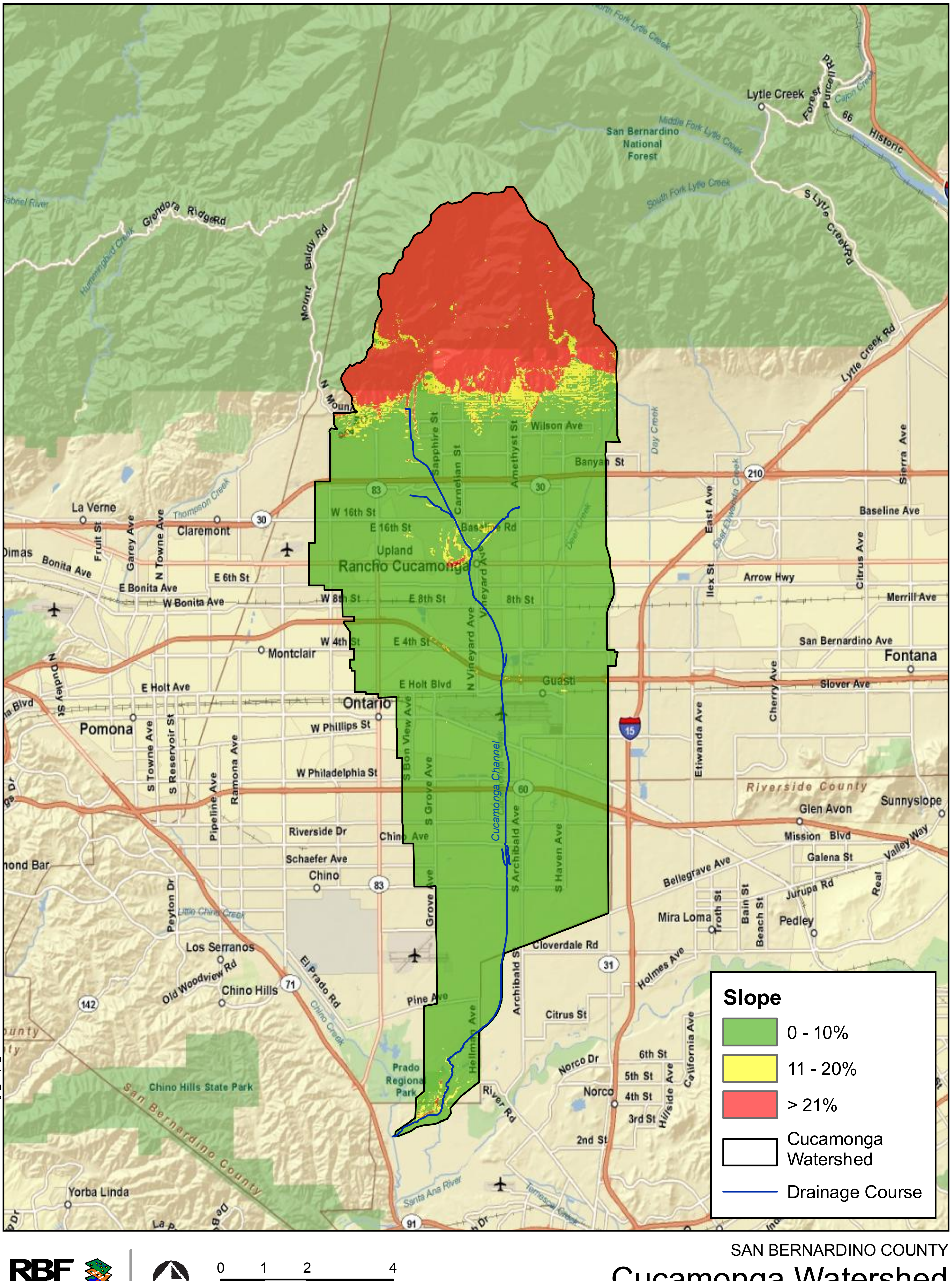
3.2.4.2 Hillslope Gradient

The upper (natural) reaches of the watershed have the highest potential for erosion with a hillslope gradient of greater than 21%, while the central (developed) portion of the watershed has a hillslope gradient of 0-10% with a lower potential for sediment production (See Figure 13). While the majority of the developed land is located in the lower sediment production areas, the construction of the debris basins have effectively removed the sediment production from the high yield areas from reaching the downstream watercourse.

3.2.5 Conclusion

The majority of the development within the watershed 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 cut off the supply of coarse grained sediment from making it to the downstream channel reaches. In addition, the significant change in impervious area due to watershed development has increased the frequency and rate of flow in the channel.

Compared to "prior to degradation" conditions, the geology type has remained the same. But with increased runoff from the developed areas and a decrease in sediment production from the upstream reaches of the watershed due to the debris basins, the watershed dynamics have 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 unprotected channel upstream of the Prado Dam where significant degradation and severe downcutting has occurred.



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RBF CONSULTING GIS

Source: USGS

SAN BERNARDINO COUNTY

Cucamonga Watershed

Figure 13 - Hillslope Gradients

3.3 Live Oak Creek

The Live Oak Watershed is located on the southeastern most portion of Zone 3 within the County of San Bernardino. The watershed stretches from east of the City of Yucaipa to the City of Loma Linda. The watershed consists of numerous waterways, including Live Oak Creek, Wilson Creek, Wildwood Creek, Yucaipa Creek, Oak Glen Creek and more. (See Figure 14)

The Live Oak Watershed contains a number of water storage facilities, but few have been designed specifically for debris capture. Most are detention basins only, with some acting as flow-by basins. Even though the basins are not specifically designed for debris capture, there would be some decrease in sediment supply from the upstream portions of the watershed and the peak flow rates would be significantly decreased when compared to natural conditions.

3.3.1 Study Reach

The reach of the Live Oak Creek that is under investigation starts at the confluence of Wilson Creek and Wildwood Creek, approximately a mile west of Interstate-10, and ends approximately one mile later at the county line. Upstream of this reach, Wilson Creek and Wildwood Creek are made up of natural, incised channels.

The study reach is made up a natural, earthen channel with little to no vegetation. The channel has become a large canyon, with: a sandy bottom, vertical banks, a top width of approximately 130 feet and a depth of 50 feet. The channel shows signs of significant degradation.

3.3.2 Historical Aerial Photographs

From the EDR historical aerials (Appendix A), it can be seen that this stretch of the channel has always shown signs of degradation. Even though it appears that Live Oak Creek has always been an incised channel, the size and amount of erosion has increased significantly over time.

Based on the HDR historical aerials, the watershed saw significant development between 1982 and 2005. During this time the watershed transitioned from being predominantly agricultural and open land.

3.3.3 Site Visits

The channels are constructed of different conveyance types, from rip-rap lined trapezoidal channels to natural, earthen channels. (See Figures 15 and 16) A number of the channels have drop structures along the invert to prevent degradation.

It is evident from the site visits that the soil is vulnerable to degradation, especially in the lower portions of the watershed where Live Oak Creek is located. Live Oak Creek is a natural channel that starts near Interstate-10 and flows west. It shows signs of significant erosion and degradation. In some areas, a +50 feet deep canyon has manifested. There is no reinforcement to protect the channel invert or banks. The channel will continue to erode in the future.

1/19/11 JN10-106734 Live_Oak_Location_Map.mxd DJ

0 0.5 1 2 Miles

Source: San Bernardino County

SAN BERNARDINO COUNTY

Live Oak Watershed

Figure 14 - Location Map

Figure 15: Upstream Portion of the Live Oak Watershed

(Looking east along Wilson Creek at the upstream reaches of the Live Oak Watershed)

Figure 16: Live Oak Creek

(Looking upstream at Live Oak Creek, approximately 1.5 miles west of Interstate 10).

3.3.4 GIS-based Desktop Study

The following subsections summarize the results of the GIS-based Desktop study for the Live Oak Watershed.

3.3.4.1 Geology Type

The Live Oak Watershed is dominated by Cenozoic Sedimentary Rocks – Alluvium (63%), see Figure 17. This geology type is located through out the watershed but specifically in the central and western portions. It has the highest relative potential for erosion and almost all of the major channels are flowing through it. The mountainous areas of the watershed, located in the north and eastern portions of the watershed, are dominated by Cenozoic-Precambrian Plutonic and Metavolcanic Rocks (33%).

3.3.4.2 Land Use

The Live Oak Watershed has been converted to incorporate approximately 20% of the watershed area to developed land. (See Figure 18) While the majority of the watershed is natural (75% is forest, grassland, or scrub/shrub), the relatively small increase in development could have had a significant effect on Live Oak Creek because it was incised prior to the watershed being developed. The development has resulted in a significant change in the watershed imperviousness and associated increase in the frequency and flow experienced in the channel. Additionally the basins within the watershed cause an attenuation of the channel storm peak flow, causing an increased time for potential degradation.

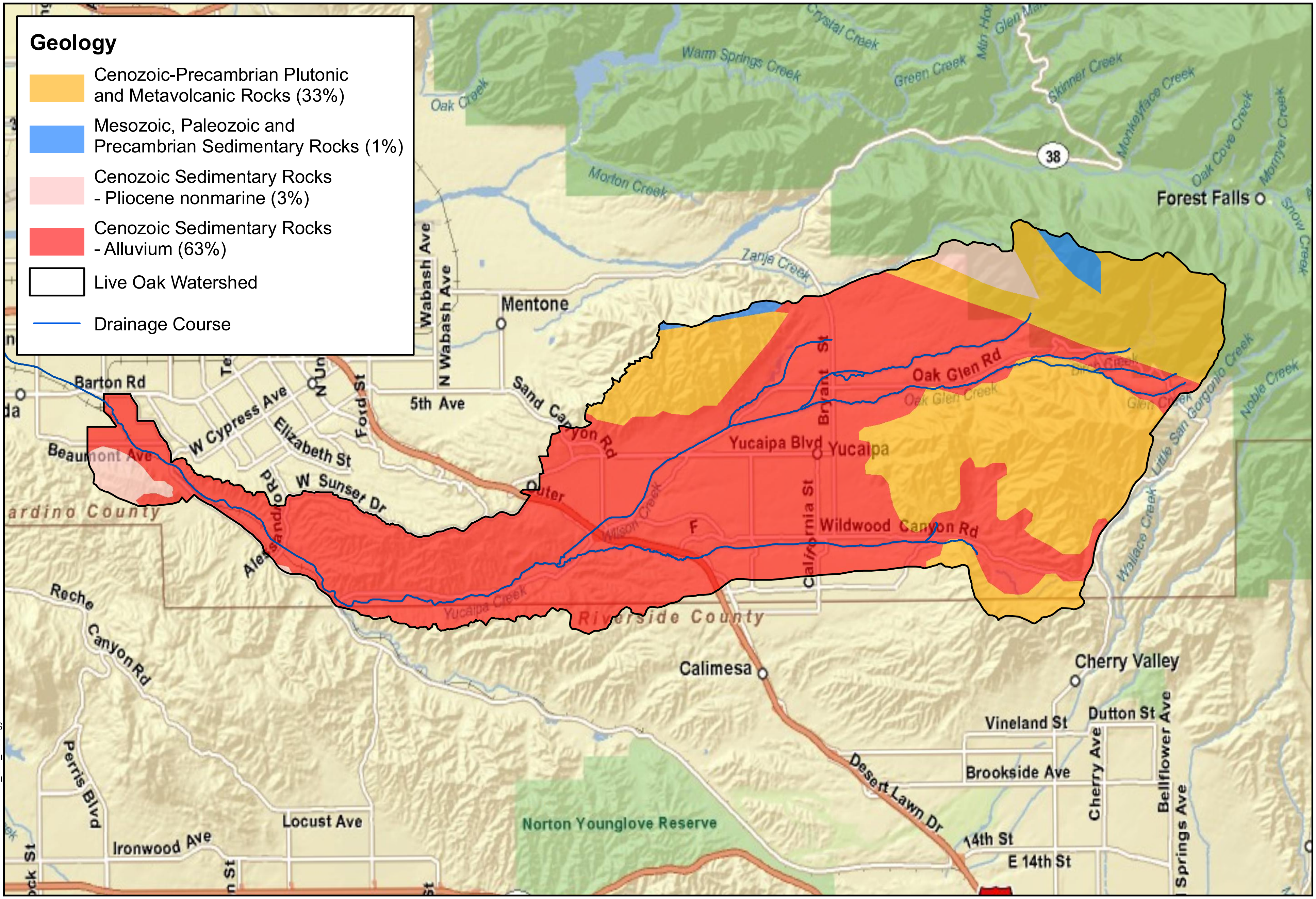
3.3.4.1 Hillslope Gradient

The outer portions of the watershed have the most potential for erosion with a steep hillslope gradient (greater than 21%). (See Figure 19) All of the development is located within the central portion of the watershed, where there is a low potential for erosion because of the relatively flat slopes (0-10%). In the western portion of the watershed, the valley is significantly smaller in size, compared to the east. The smaller and thinner dimensions of the valley could potentially cause increased degradation.

3.3.5 Conclusion

Relative to the San Antonio and Cucamonga Watersheds, the Live Oak Watershed has not experienced considerable development, 52% or 58% versus 20%. However the stream has seen more dramatic erosion compared to the other watersheds. This may be the result of specific soil conditions along the Live Oak Creek.

Compared to "prior to degradation" conditions, Live Oak Creek has experienced increased degradation with the increased watershed development. With increased runoff from the developed areas and some decrease in sediment production from the upstream reaches of the watershed due to the detention basins, the watershed dynamics have been altered. The sediment supply has been reduced, and the stream flow has been increased and the duration extended, 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 imbalance has caused the continued erosion of the Live Oak Creek.



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RBF CONSULTING GIS

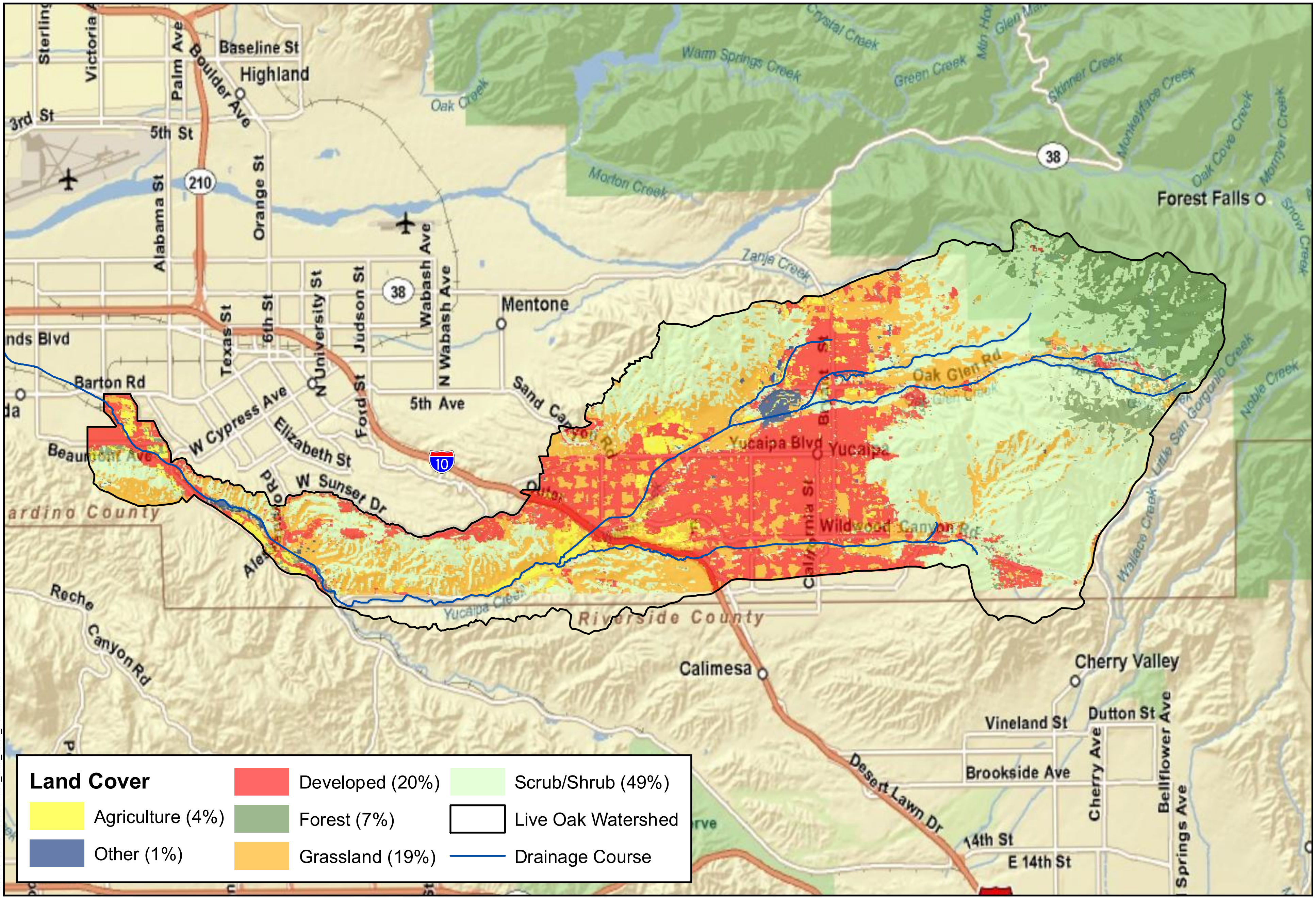
0 0.5 1 2 Miles

Source: San Bernardino County, CA State Dept of Geology & Mines

SAN BERNARDINO COUNTY

Live Oak Watershed

Figure 17 - Geology Types

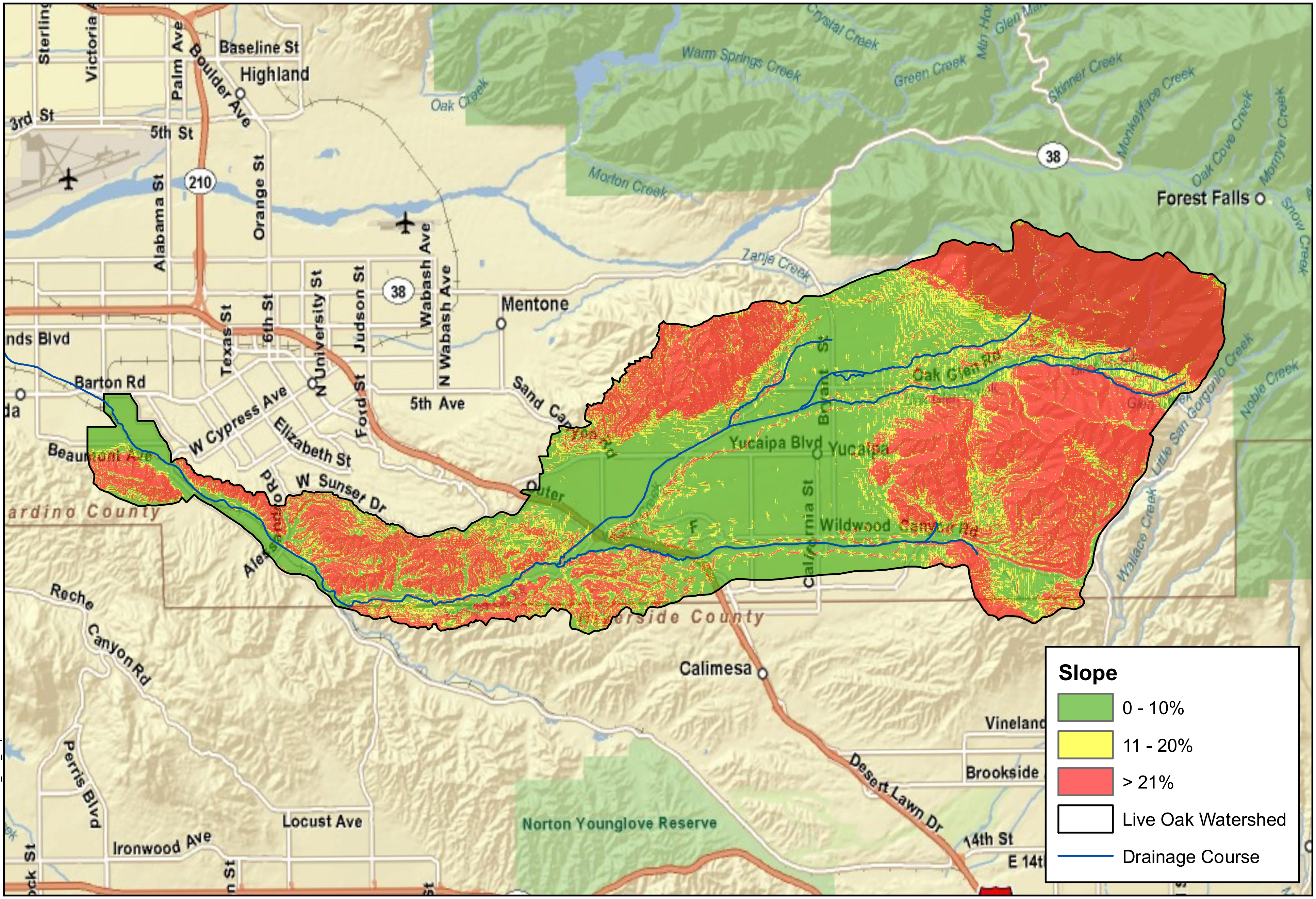


Source: San Bernardino County, NOAA

SAN BERNARDINO COUNTY

Live Oak Watershed

Figure 18 - Land Use Types



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Source: USGS

1/19/11 JN10-106734 Live_Oak_Slope.mxd DJ

SAN BERNARDINO COUNTY

Live Oak Watershed

Figure 19 - Hillslope Gradient

4 CONCLUSION

There are three main reasons for the current level of degradation in the three watersheds under investigation: the geology is vulnerable to erosion, the land has been developed resulting in less sediment yield, and basins have been constructed that cut off upstream sediment supply.

All three watersheds are dominated by Cenozoic Sedimentary Rocks – Alluvium and showing significant signs of degradation. This geology type is a significant factor in channel degradation. This is especially evident in the most downstream portions of the watersheds 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 San Antonio and Cucamonga Watersheds, has increased the potential runoff while at the same time decreasing the sediment produced. This change caused an imbalance and increased the degradation in the downstream reaches of the watersheds.

The last major cause of degradation, the construction of water storage/debris basins, was not part of the original GIS-based analysis, but its effect on the watersheds was very evident. The downstream portions of the watersheds rely on the coarse sediment from the upper reaches to replenish the channel bottoms. Without the upstream sediment supply, the channels have a much higher potential for degradation. Even with the decrease in peak flow rates, an imbalance within the watersheds 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.

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2. US Army Corp 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

San Antonio Channel
El Prado Road
Chino, CA 91710

Inquiry Number: 2966045.1
January 17, 2011

The EDR Aerial Photo Decade Package

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Target Property:
El Prado Road
Chino, CA 91710

Year	***Scale***	***Details***	***Source***
1938	Aerial Photograph. Scale: 1"=555'	Flight Year: 1938	Laval
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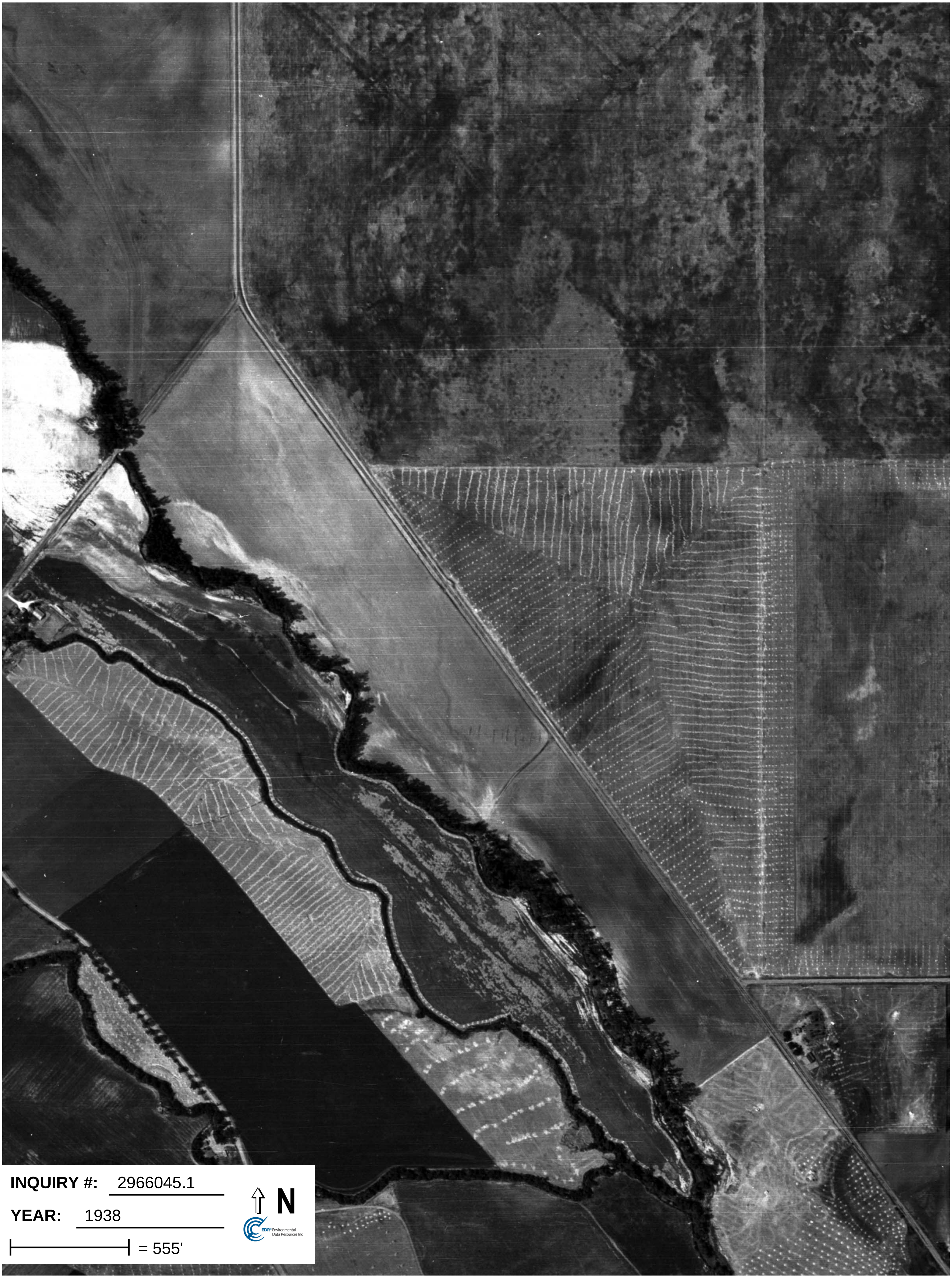
1953	Aerial Photograph. Scale: 1"=555'	Flight Year: 1953	Southwestern
1968	Aerial Photograph. Scale: 1"=480'	Flight Year: 1968	Teledyne
1977	Aerial Photograph. Scale: 1"=666'	Flight Year: 1977	Teledyne
1990	Aerial Photograph. Scale: 1"=666'	Flight Year: 1990	USGS
1994	Aerial Photograph. Scale: 1"=666'	Flight Year: 1994	USGS
2002	Aerial Photograph. Scale: 1"=666'	Flight Year: 2002	USGS
2005	Aerial Photograph. Scale: 1"=604'	Flight Year: 2005	EDR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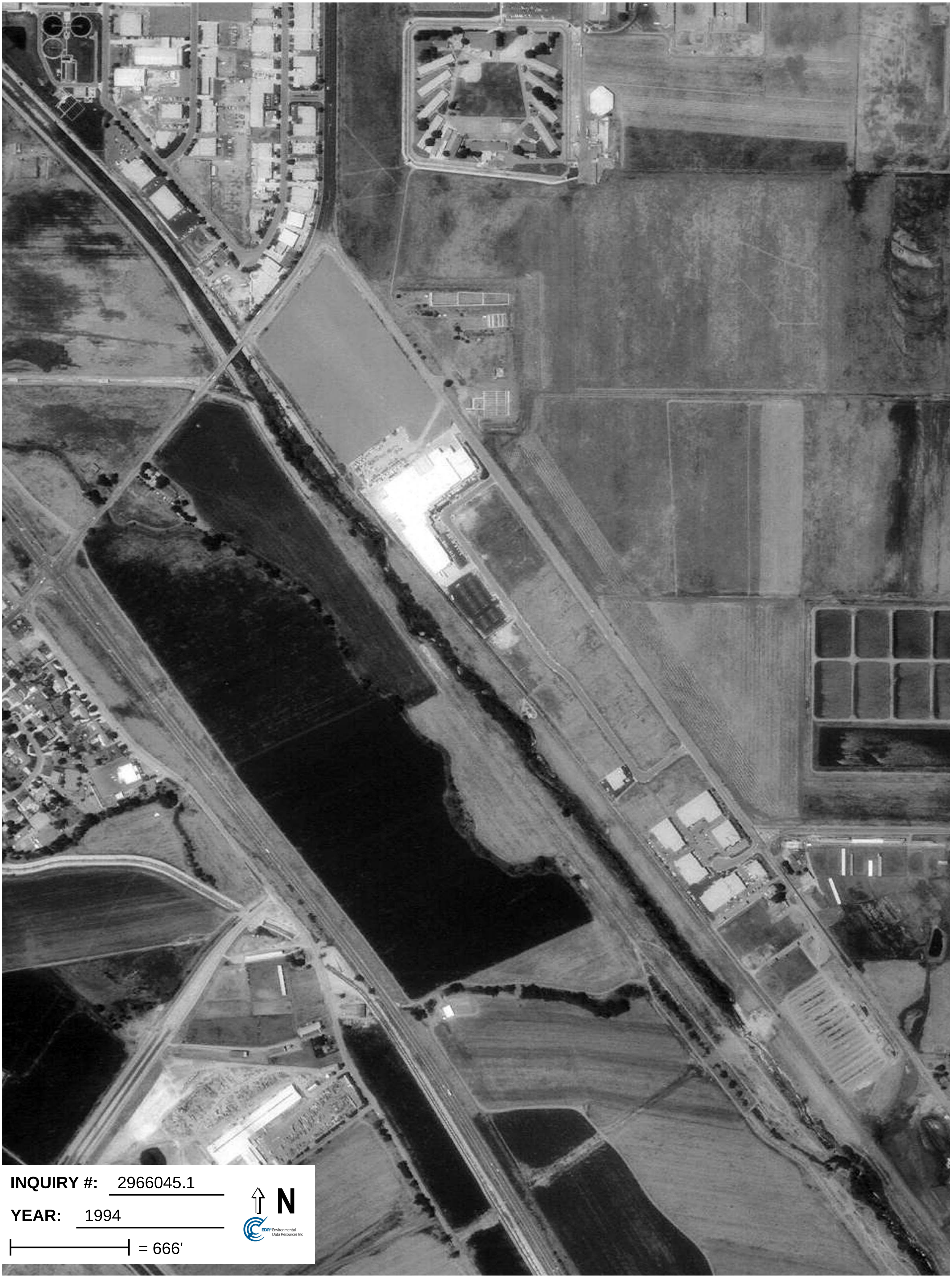

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EDR Environmental Data Resources Inc


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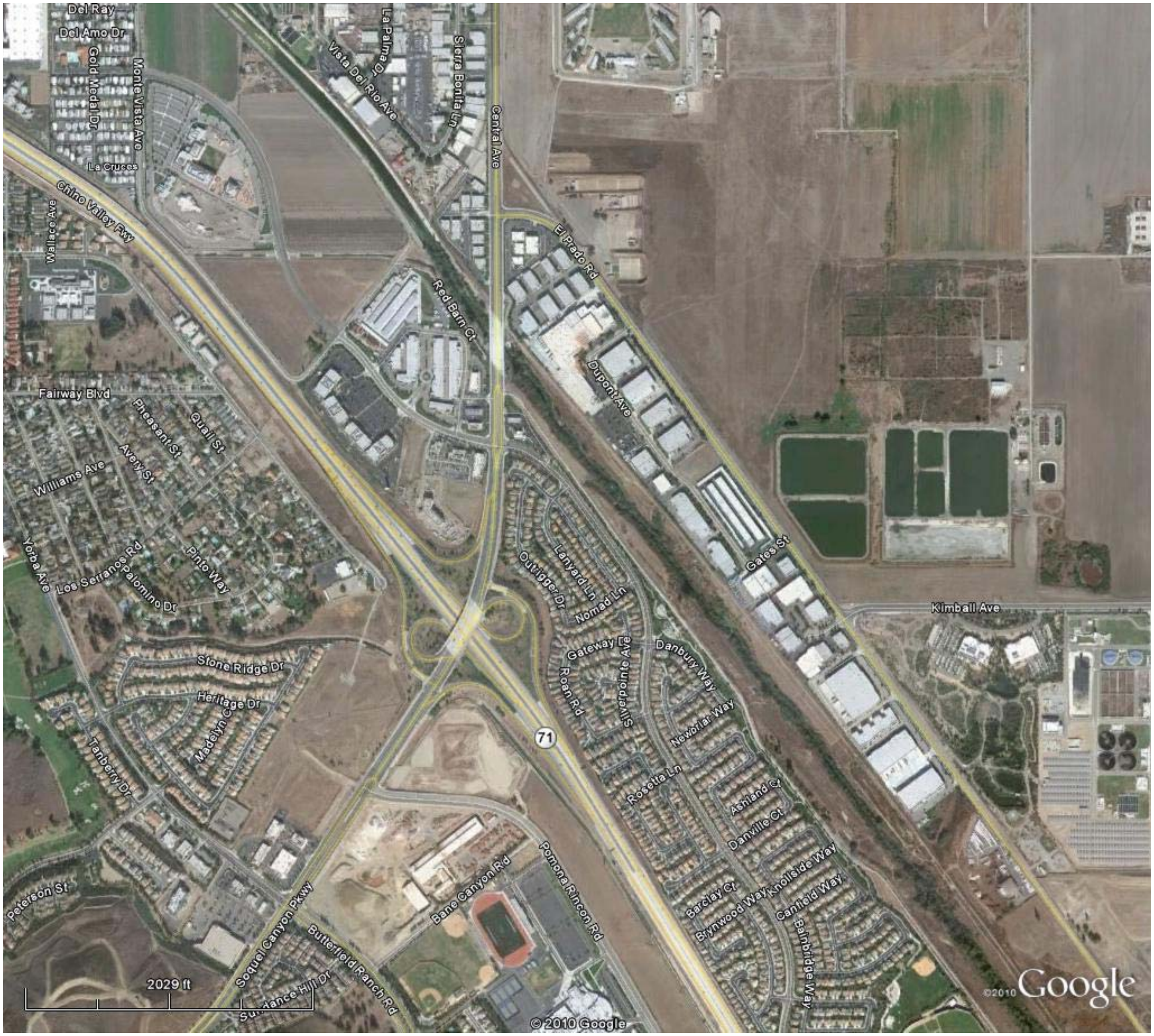

San Antonio Channel - Google Earth 2010

Cucamonga Channel
W County Road
Corona, CA 92880

Inquiry Number: 2966049.1
January 17, 2011

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W County Road
Corona, CA 92880

Year	***Scale***	***Details***	***Source***
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1977	Aerial Photograph. Scale: 1"=666'	Flight Year: 1977	Teledyne
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1994	Aerial Photograph. Scale: 1"=666'	Flight Year: 1994	USGS
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INQUIRY #: 2966049.1

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EDR Environmental Data Resources Inc


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YEAR: 2005
= 604'
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EDR Environmental Data Resources Inc

Cucamonga Channel - Google Earth 2010

Live Oak Canyon
Live Oak Canyon Road
Redlands, CA 92373

Inquiry Number: 2966050.1
January 18, 2011

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Aerial Photography January 18, 2011

Target Property:

Live Oak Canyon Road

Redlands, CA 92373

Year	***Scale***	***Details***	***Source***
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1980	Aerial Photograph. Scale: 1"=600'	Flight Year: 1980	AMI
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1994	Aerial Photograph. Scale: 1"=666'	Flight Year: 1994	USGS
2002	Aerial Photograph. Scale: 1"=666'	Flight Year: 2002	USGS
2005	Aerial Photograph. Scale: 1"=604'	Flight Year: 2005	EDR


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INQUIRY #: 2966050.1
YEAR: 2005
= 604'
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Live Oak Creek - Google Earth 2010

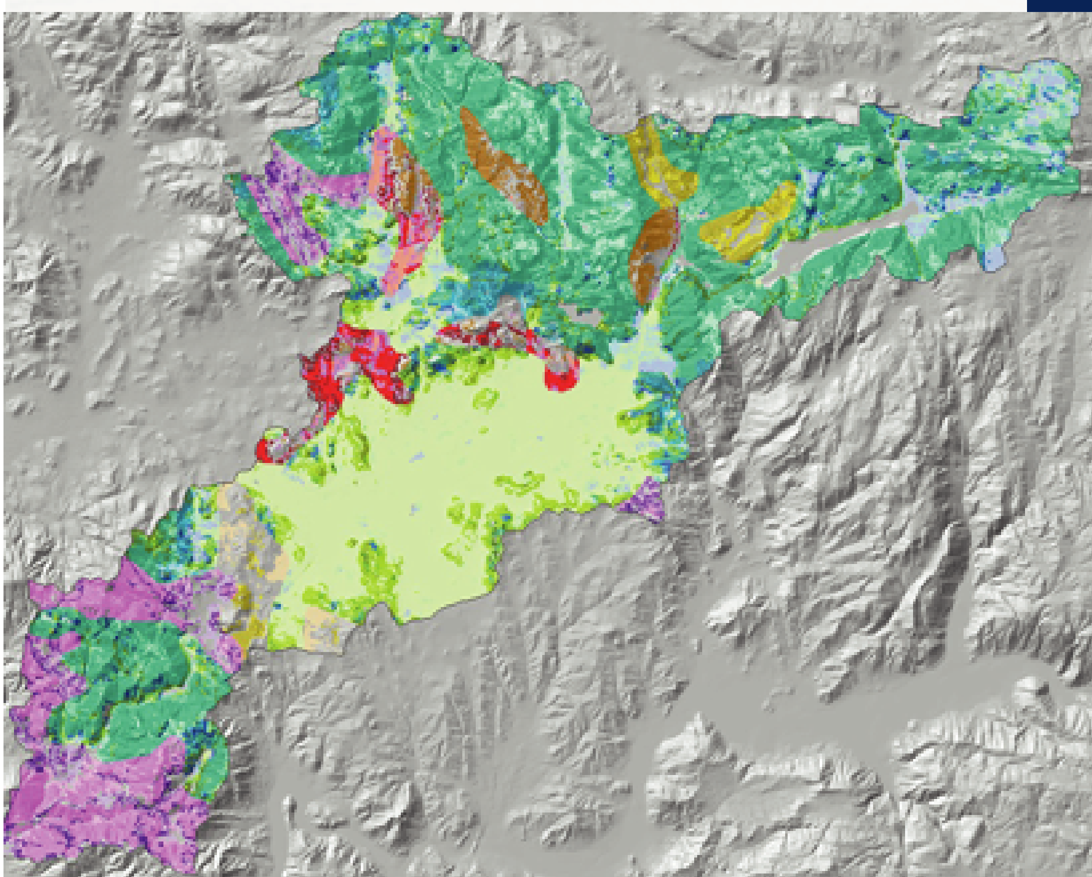
APPENDIX B

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).

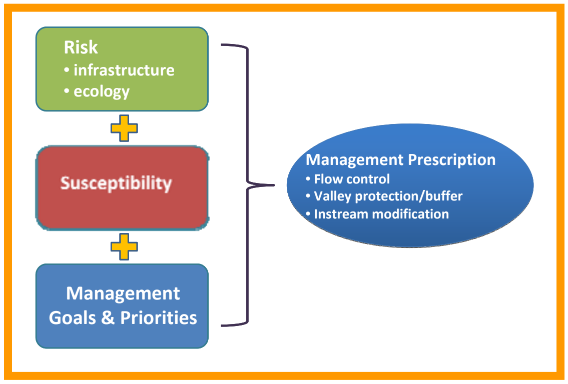


Figure ES1: Decision nodes that influence the management prescription for a particular stream reach.

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.

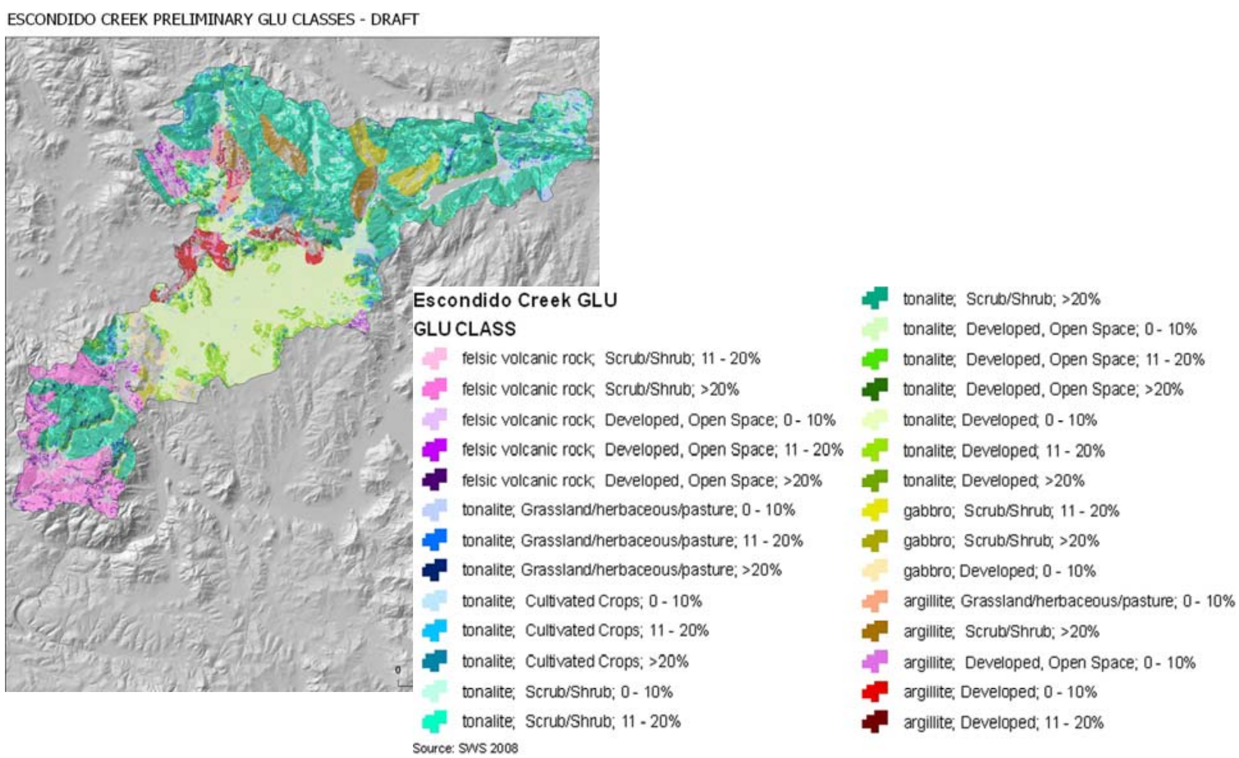


Figure ES2: Example of Geomorphic Landscape Units for the Escondido Creek Watershed.

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).

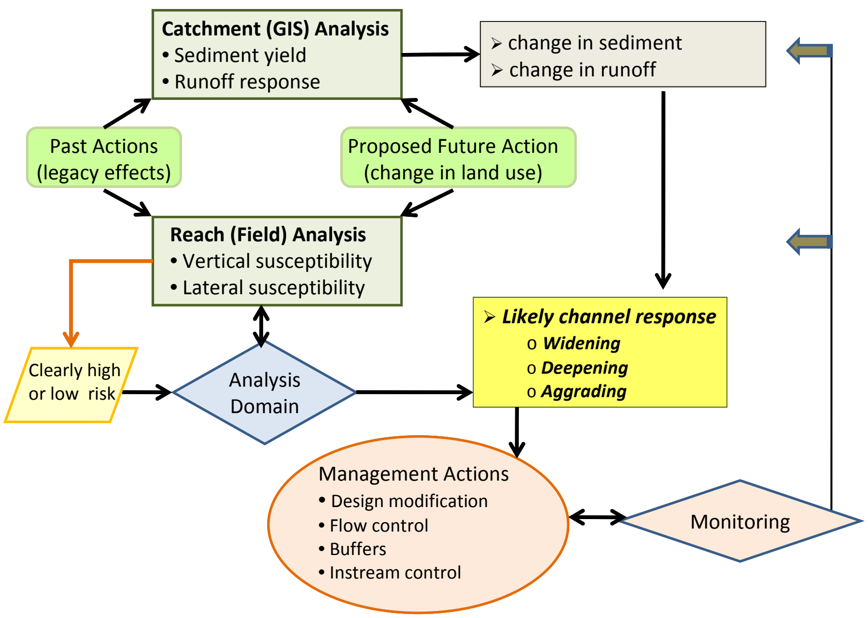


Figure ES3: Relationship of catchment and field screening tools to support decisions regarding susceptibility to effects of hydromodification.

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.

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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).

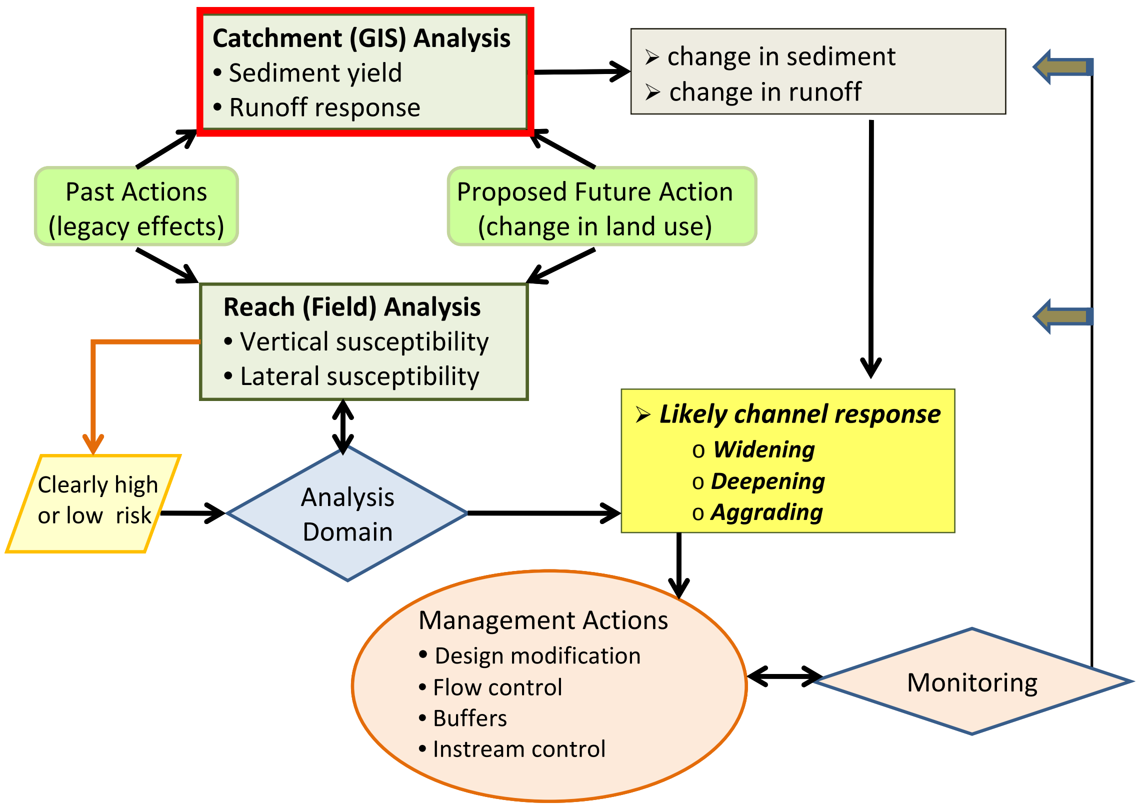

Figure 1. Conceptual application of GIS- and field-based screening tools, and their inter-relationship in predicting potential effects of hydromodification.

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.

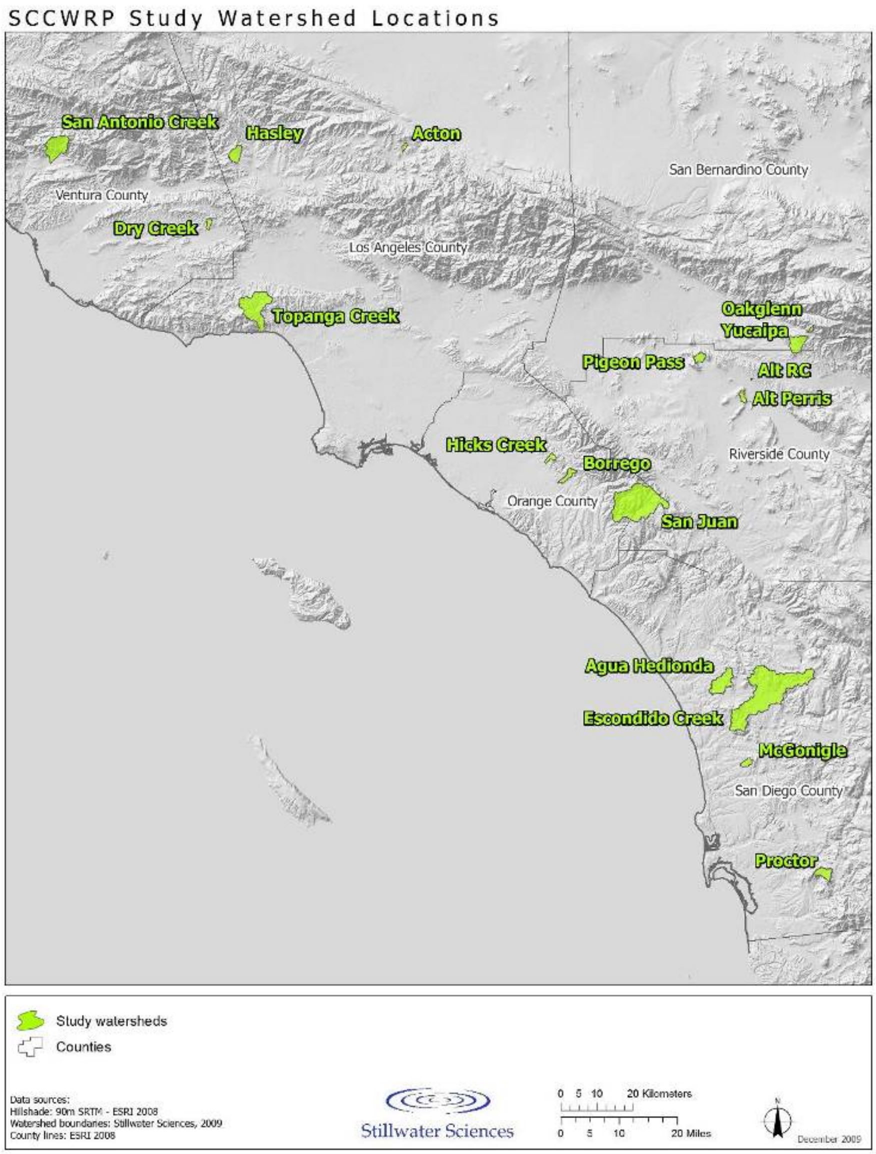

Figure 3. Study watersheds for evaluation of GLU approach.

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 (km^2)	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%.

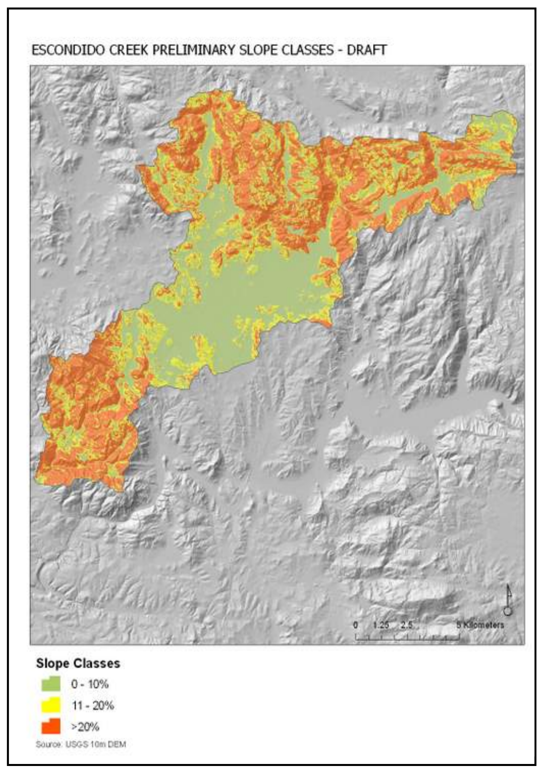

Figure 5. DEM map with preliminary slope classes.

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)

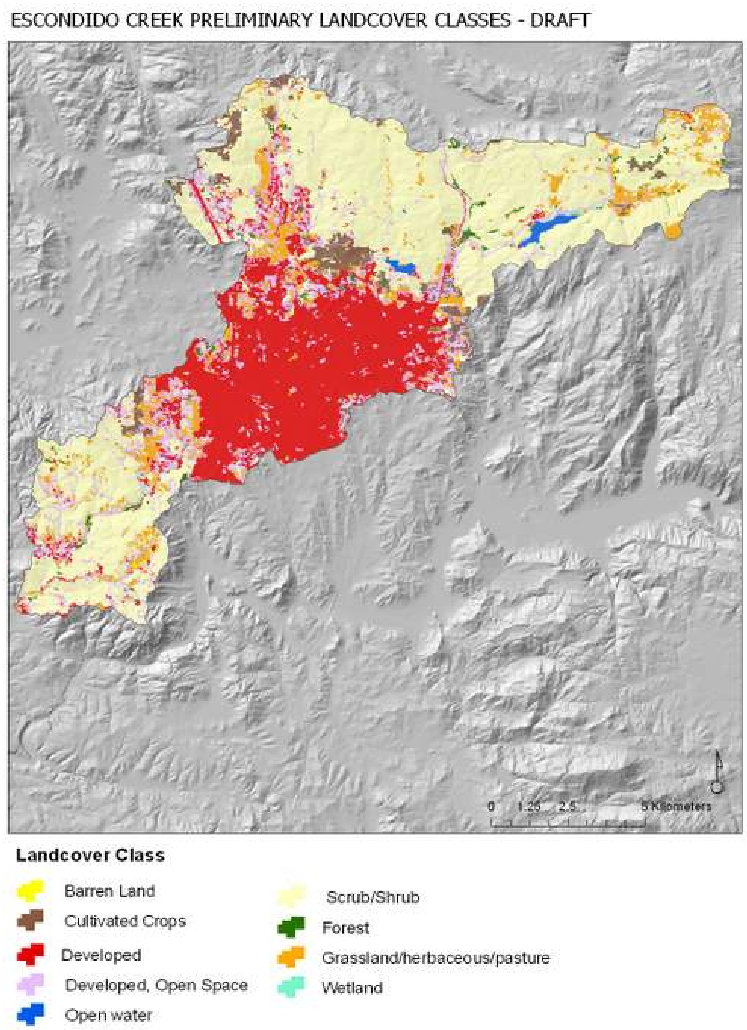

Figure 6. DEM map with preliminary land cover classes.

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

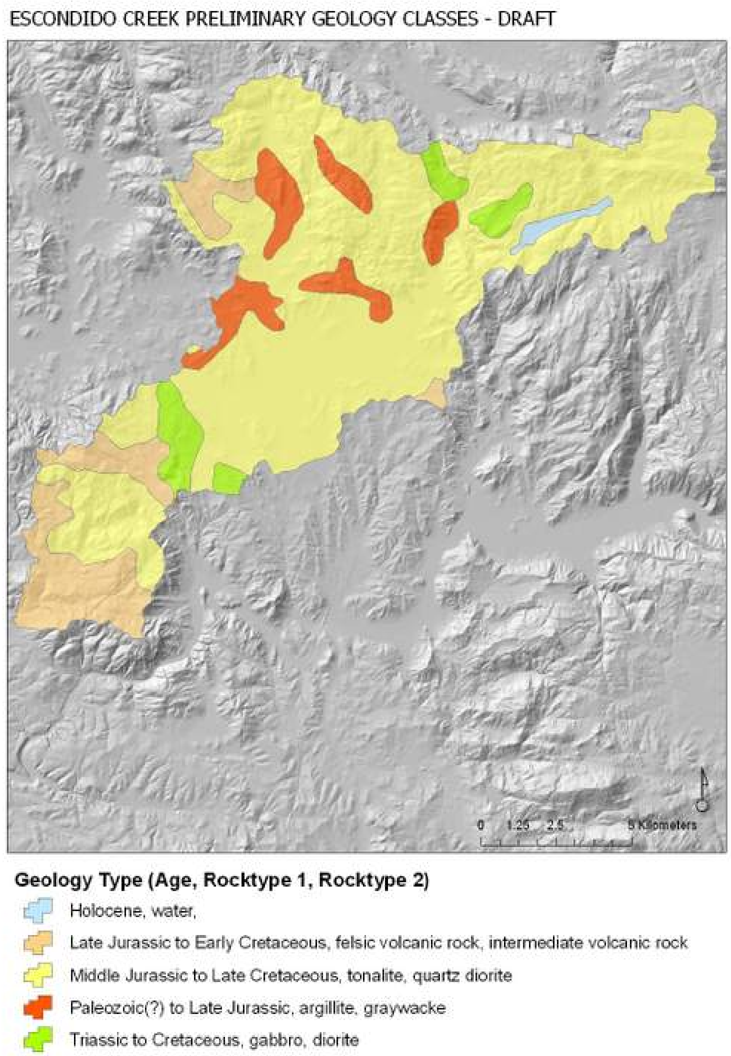

Figure 7. DEM map with preliminary geology class types.

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%

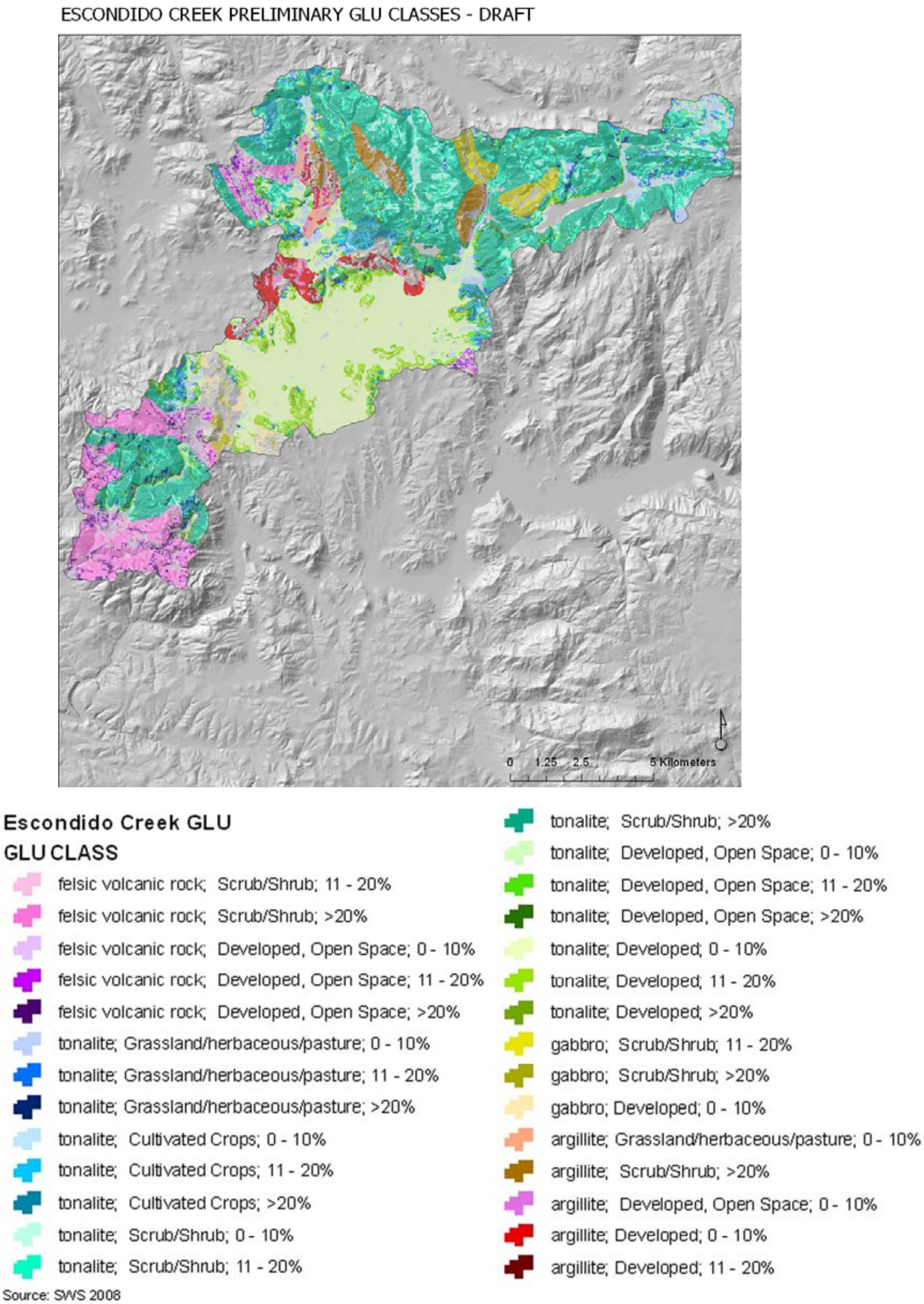

Figure 8. DEM map with preliminary GLU layer and attribute percentages.

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).

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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.

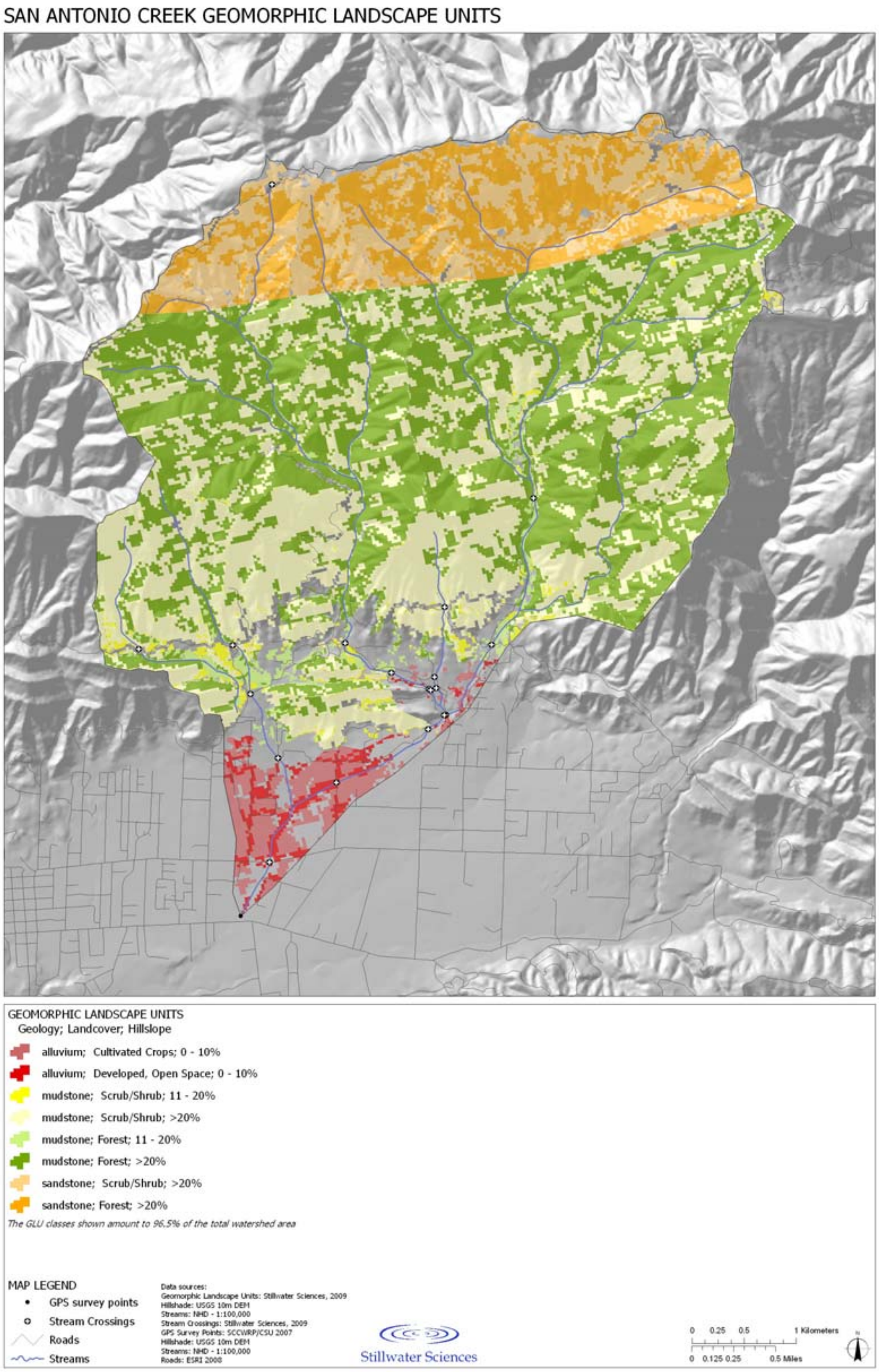
GIS-based analysis:

- 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.**

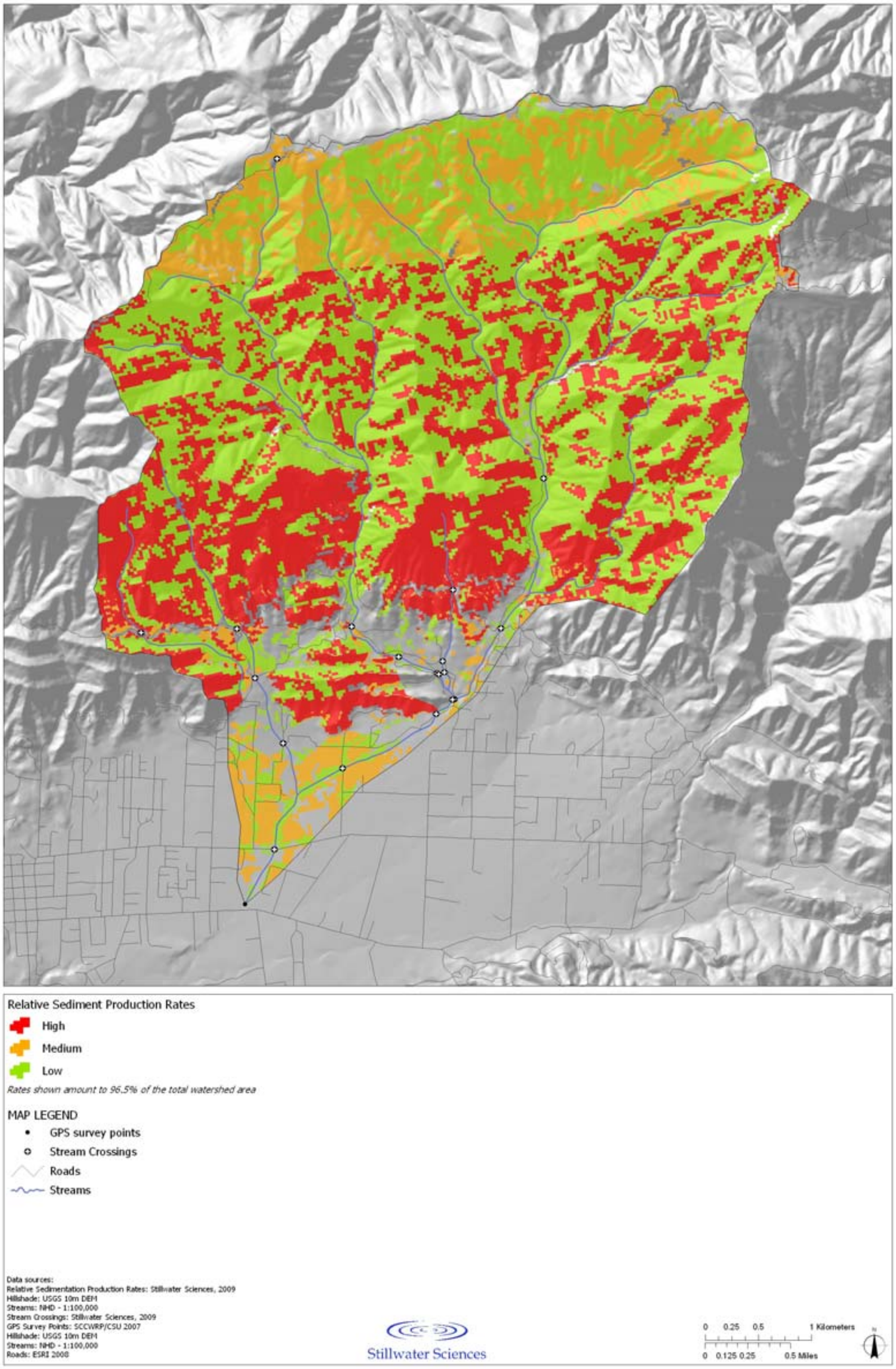
Field-based observations (see attached field photos and topographic data)

- 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

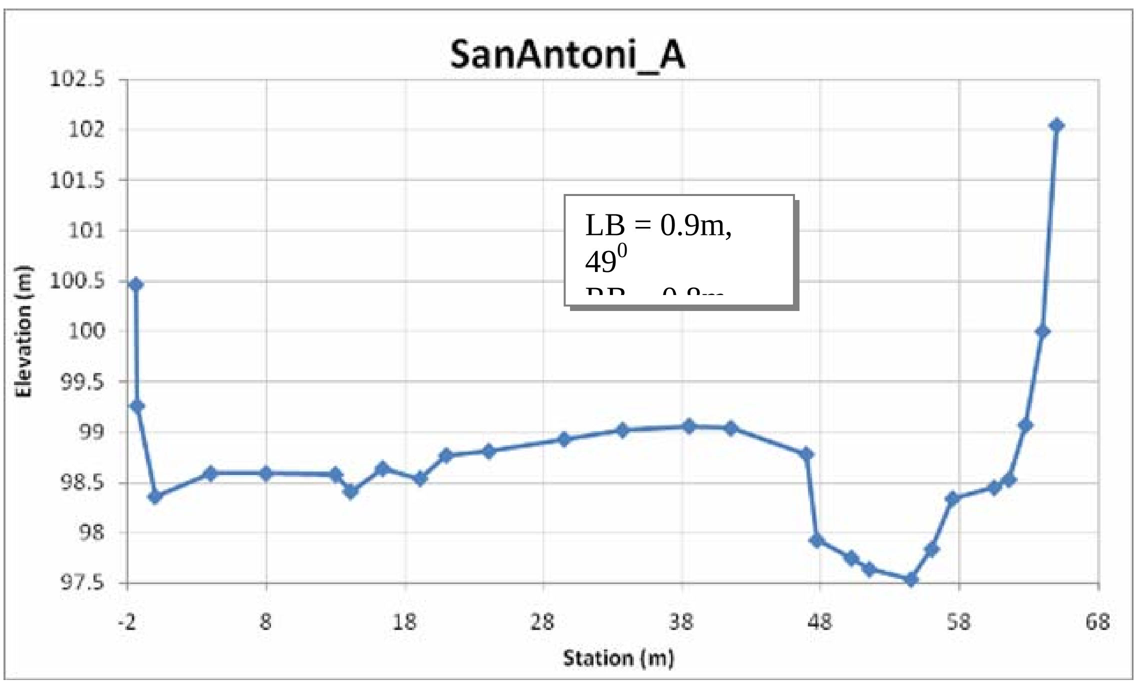


OBSERVATIONS:

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)