Caltrans Hydromodification Requirements Guidance

Storm Water Best Management Practices
Rapid Assessment of Stream Crossings
Higher Level Stream Stability Analysis

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Section 1
Introduction

1.1 Purpose

Storm water (rainfall or snowmelt precipitation) runoff from California Department of Transportation (Caltrans) rights-of-way and facilities are permitted under the provisions of the 2012, statewide, National Pollutant Discharge Elimination System (NPDES) permit (permit number CAS000003, SWRCB 2012). The permit was issued by the State Water Resources Control Board (SWRCB) as part of the NPDES permit program, which is authorized by the federal Clean Water Act and administered by the U.S. Environmental Protection Agency (EPA). The permit mandates a risk-based approach to be employed during planning and design for assessing stream stability at highway crossings and the potential impact upon existing or planned highway crossing structures. This approach involves conducting a rapid pre-project assessment of the vertical and lateral stability of the receiving stream channel related to an existing or planned highway crossing structure potentially affected by additional impervious surfaces. The approach assists the Department in assessing pre-project channel stability and implementing mitigation measures that are appropriate to protect structures and minimize stream channel bank and bed erosion. Although the assessment is based on existing conditions, the emphasis is on the downstream effects of any change in hydrology caused by the project, including the capacity of the system and any potential erosion or instability of the channels. If the rapid stability assessment (RSA) indicates potential problems, more detailed engineering analyses are required to determine if countermeasures are needed to stabilize the crossing to prevent catastrophic highway failures and the release of sediment. These analyses are referred to as Federal Highway Administration Hydraulic Engineering Circular No. 20 (HEC-20, Lagasse et al. 2012) Level 2 and Level 3 analyses. This document provides guidance for Caltrans engineers charged with conducting RSAs at each stream crossing of a proposed project. This manual is intended to serve as a training guide or short course text and as a ready reference for trained personnel. Key aspects of this guidance include an introduction to the concepts of channel stability and stream channel classification. The Level 2 and 3 analyses are introduced herein, but the HEC-20 manual (Lagasse et al. 2012) should be followed for those types of higher analysis when necessary.

This document is focused on rapid assessment, but describes the overall efforts needed for hydromodification compliance. Processes and procedures for overall management of storm water within Caltrans rights-of-way and facilities are contained in the Storm Water Quality Handbook, Project Planning and Design Guide (PPDG, Caltrans 2010), including guidance for planning and design of best management practices (BMPs) for storm water quality management.

Much of the effort required to perform a rapid stability assessment of existing crossings may be eliminated by fully utilizing information obtained under other programs such as the FHWA bi-annual bridge inspection program (http://smi.dot.ca.gov[1]) , the Storm Drain System Inventory (http://10.112.89.131/env_gis/applications.html[2]) or the Caltrans culvert inspection program

[1] Follow this link, and then select BIRIS (Bridge Inspection Reporting Information System). This is a Caltrans Intranet site, only Caltrans staff will be able to access it.

[2] This is a Caltrans Intranet site, only Caltrans staff will be able to access it.

(http://10.112.5.74/MainGISApps/culverts/[3]. With training and some experience, RSAs may be completed for very small, simple sites (for example, a 24-inch culvert with unobstructed view of the channel from the crossing) in as little as 0.5 man hours while larger, more complex sites may require up to 4 man hours. Preliminary office work will be needed prior to RSA fieldwork, and effort requirements will vary depending on accessibility of the required data and images.

In general, rapid stability assessments should be completed by or under the direction of engineers trained in basic fluvial geomorphology and channel stability assessment. Key tasks include:

1. Locate stream crossings associated with a given project.
2. Determine whether or not each crossing requires an RSA.
3. Conduct the RSA and record the results in a standard format useful to others.
4. Determine if the structure is potentially at risk based on the RSA score and assess the need for more detailed and sophisticated analyses of channel stability.

1.2 Quick Start Guide

Personnel with training and experience in channel stability assessments may wish to refer to Section 2 below for guidance on RSA requirements and proceed directly to Section 4. RSAs may be completed using the field form (Appendix A) and study of examples (Appendix B) may be helpful.

Personnel without RSA training and experience should review contents of this manual and the associated examples (Appendix B), preferably under the guidance of a short course instructor.

1.3 Definitions of Key Terms

The definitions below are unique to this manual and do not represent absolute “dictionary” definitions. A narrative definition is provided, with key terms defined in Appendix E—Glossary.

When precipitation soaks in to the ground, or infiltrates, some of it moves very slowly toward stream channels as groundwater and is gradually released over days, weeks, or months. Surface runoff movement into channels tends to be much more rapid than infiltration. Therefore, increasing the amount of impervious area in a watershed increases the total amount of water that a receiving channel must convey, and also increases the peak flow rate. Project construction can involve grading and soil compaction, an increase in impervious surfaces (roadways, roofs, sidewalks, parking lots, etc.), or a reduction of vegetative cover, all of which reduce infiltration and increase the amount of rainfall that ends up as runoff. Hydrographs become sharper and flashier as flow peaks get higher and sharper and base flows are depressed. Such changes to the hydrograph are called hydrograph modification or hydromodification.

Fluvial geomorphology is the science dealing with the shapes of stream channels and why streams have certain dimensions, shapes, or forms. A dominant paradigm in fluvial geomorphology holds that streams adjust their channel dimensions (width and depth) in response to long-term changes in sediment supplied to the channel from external sources (e.g., upstream bank erosion, landslides, or soil erosion). Sediment supply (both quantity and particle size) is related to runoff volumes and rates, which are typically influenced by development in the watershed. Hydromodification associated with development and the gradual destabilization of channels increases the loads and concentrations of sediments and associated pollutants in receiving waters. The magnitude of channel response depends on geology, land use, and channel stability at the time of watershed disturbance. Increased pollutant loads and alteration of the runoff/sediment balance can negatively affect the beneficial uses and habitats associated with

[3] This is a Caltrans Intranet site, only Caltrans staff will be able to access it.

receiving waters such as streams, lakes, wetlands, groundwater, oceans, bays, and estuaries. Accordingly, the NPDES permit seeks to regulate the impacts caused by hydromodification associated with Caltrans projects. Highways are often constructed in such a way that stream channels must be crossed, and stream flow must be conveyed under the roadway or facility using bridges or culverts. Culverts include reinforced concrete boxes, metal or concrete pipes, or other types of conduits. Locations where stream flow is conveyed under a highway or non-highway facility are called stream crossings. Erosion of the stream bed or banks upstream, within, or downstream of a stream crossing is of concern, because it may endanger or damage the embankments that support the roadway, undermine the crossing structure, or damage appurtenant structures. Furthermore, erosion represents a release of sediments and associated pollutants that can degrade downstream water quality and habitats.

The NPDES permit does not require that all Caltrans projects be subjected to an RSA. Section 2 below provides an explanation of how to determine if an RSA is required. The RSA is a means of estimating the channel response (erosion or deposition of sediments) to the hydromodification associated with the new impervious area. The assessment is based on numerical scores assigned to 13 key characteristics of the site, termed *stability indicators*. For each indicator, a numerical rating is assigned based on information obtained from maps, aerial photographs, and visual inspection of the channel and TDA. An overall rank is obtained by summing the 13 ratings. The RSA represents only a qualitative estimate of future conditions. Under the risk-based approach mandated by the NPDES permit, if the RSA does not yield a value of "Excellent" or "Good," additional analyses are required, as described in Section 5 below.

The RSA is based on the idea that stream channels tend to adjust their width,[4] depth, slope, and bed material size in response to the loads of water and sediment they receive from upstream sources. These variables mutually adjust in complex ways. Since the flow of water and input of sediment to a channel reach is constantly changing, stream dimensions are constantly responding. However, stable channels tend to have dimensions that exhibit slow and relatively small fluctuations in average width, depth, slope, and bed material size about a mean condition, corresponding to a flow rate (water discharge) that just barely fills the channel. This flow is often called the channel-forming, or dominant, discharge; the state of stability characterized by modest fluctuations about a mean condition is referred to as dynamic equilibrium. When a watershed experiences hydromodification (for instance, due to an increase in impervious area), the channel will respond by modifying its mean width, depth, or slope through erosion or deposition unless the boundaries are non-erodible or other structural controls are in place. If a channel has boundaries that prevent any adjustment, whether they are natural (like bedrock) or artificial (like concrete), it is referred to as moribund (Thorne et al. 1996a). On the other hand, if the channel responds quite rapidly and makes major changes in its dimensions or location, it is called an unstable channel. Unstable stream channels negatively affect water quality by yielding much greater quantities of sediment compared to stable channels. Scientists have developed conceptual principles about how channels respond to certain types of disturbances to eventually regain their equilibrium; these ideas are called channel evolution models. One of these models will be discussed below.

Dynamic equilibrium and channel stability are useful concepts for learning about streams. However, in reality, few channels are truly stable or remain in a state of dynamic equilibrium for very long periods. Floods, droughts, fires, earthquakes, landslides, and a host of human activities trigger channel responses that may last decades or centuries. At any point in time, the morphology of a given channel reach represents the integration of previous disturbances.

Additional important terms used in this manual are defined and discussed in Appendix E—Glossary.

[4] Note the difference between *channel* width and depth and *water* width and depth, discussed below.

1.4 Objectives

This document is intended to help Caltrans engineers and designers comply with the hydromodification requirements of the new Caltrans NPDES permit. Effective July 1, 2013, the permit requires Caltrans to conduct a rapid assessment of stream stability at highway stream crossings to be affected by added impervious surfaces as part of a new project design. The permit mandates that the RSAs be performed using Federal Highway Administration (FHWA) manuals that were written for bridge stream crossings (Johnson et al. 1999; Johnson 2005, 2006; Lagasse et al. 2001, 2012), but must now be applied to smaller structures (pipes and culverts). In this manual, these guidelines are refined for use on all types of highway stream crossings in California. Topics from the FHWA documents that are subject to interpretation are clarified through the development of RSA examples for a number of stream crossing scenarios. Examples are provided that can be followed easily in the project development process.

In addition to meeting NPDES requirements, some Caltrans projects need Clean Water Act Section 401 certifications, which may also require hydromodification-related channel stability assessments. Similar assessments may also be required to comply with the California Environmental Quality Act (CEQA) and the National Environmental Policy Act (NEPA). The guidance provided herein allows all hydromodification-related channel assessments to be performed in a consistent and efficient fashion, statewide.

1.5 Summary

Modifications of the terrain associated with development, such as the construction of roads, parking lots, and buildings, change the local hydrology by forcing more precipitation to run off and less to infiltrate into the soil. This shift is called hydromodification, and is often associated with accelerated erosion and deposition in stream channels that drain developed areas. The permit mandates that a rapid assessment be conducted during planning and design for all projects that will include 1 acre or more of net new impervious surface and for which any new impervious portion of the project drains to a stream crossing located within the project limits.

The rapid assessment involves visually assessing the vertical and lateral stability of the receiving stream channel. The purpose of the inspection is to assess the susceptibility of the channel to destabilization by the proposed hydromodification or by natural stability issues and if they will affect the structure. If the RSA indicates potential problems, more detailed engineering analyses are required. This document provides guidance for the engineers charged with performing RSAs.

Section 2

Does My Project Require A Rapid Stability Assessment?

All projects do not require an RSA. The following algorithm may be used to determine when an RSA is needed. More detail is provided below.

1. Does the project include any stream crossings? (If not, no RSA is required.)
2. Does the project include 1 acre or more of net new impervious surface? (If not, no RSA is required.).
3. Is any part of the new impervious surface within a threshold drainage area? (If not, no RSA is required.)
4. Are the stream crossings a "Water of the US" as defined by Army Corps of Engineers latest guidance on determination of jurisdiction for CWA section 404 (If no, no RSA required).

2.1 Determining Additional Impervious Surface Area

The engineer should determine the total area of impervious surface to be added by the project. Of interest is the sum of all new impervious area (which is not necessarily in one contiguous expanse of area) associated with the project. If that total area is greater than or equal to 1 acre, the steps below must be followed.

2.2 Identifying the Threshold Drainage Area

The next step is to determine whether at least part of the new impervious surface lies within a threshold drainage area (TDA). The TDA is a key concept underlying the procedure outlined in this manual. The permit text (Provision E.2.d.3).c) and should be consulted for details. The permit defines the TDA as the area draining to a location at least 20 channel widths downstream of a stream crossing (Figure 1).

The TDA for each stream crossing within the project limits should be delineated. The TDA consists of all area draining to a control point located on the stream channel of interest a certain distance downstream of the downstream end of the stream crossing. The default distance is 20 channel widths, measured along the channel centerline. Initial TDA delineation (steps 1–3 below) may be done in the office using maps and aerial photographs. This initial delineation should be field checked through visual inspection of the channel and its watershed.

Step 1. The engineer must estimate the average channel width, W. The channel width is not the water surface width. It is the horizontal distance between the top of the banks. The tops of the banks are local high points on each side of the channel. The ground surface slopes down from the top bank toward the center of the channel, and it usually also slopes downward from the top bank toward the floodplain. This topography is formed by the deposition of sediments during floods. Coarser sediments typically deposit right next to the channel, because flows decelerate when they spread across the floodplain. Channel width sometimes varies considerably along a stream reach, so an average value should be used. A visual estimate of average width may be used for very small, stable streams. For larger creeks and rivers, W should be determined based on at least 10 cross sections placed at roughly constant spacing within the

estimated limits of the representative reach. The width measurement should include bars and islands that occur along the cross section, unless their elevation is above the top bank elevation.

Alternatively, W may be found by measuring the surface area in the horizontal plane enclosed by section lines at the reach endpoints and the top banks using GIS, maps, or aerial photos, and the average width may be computed as:

W = [Area enclosed by top banks]/[reach length measured along channel centerline].

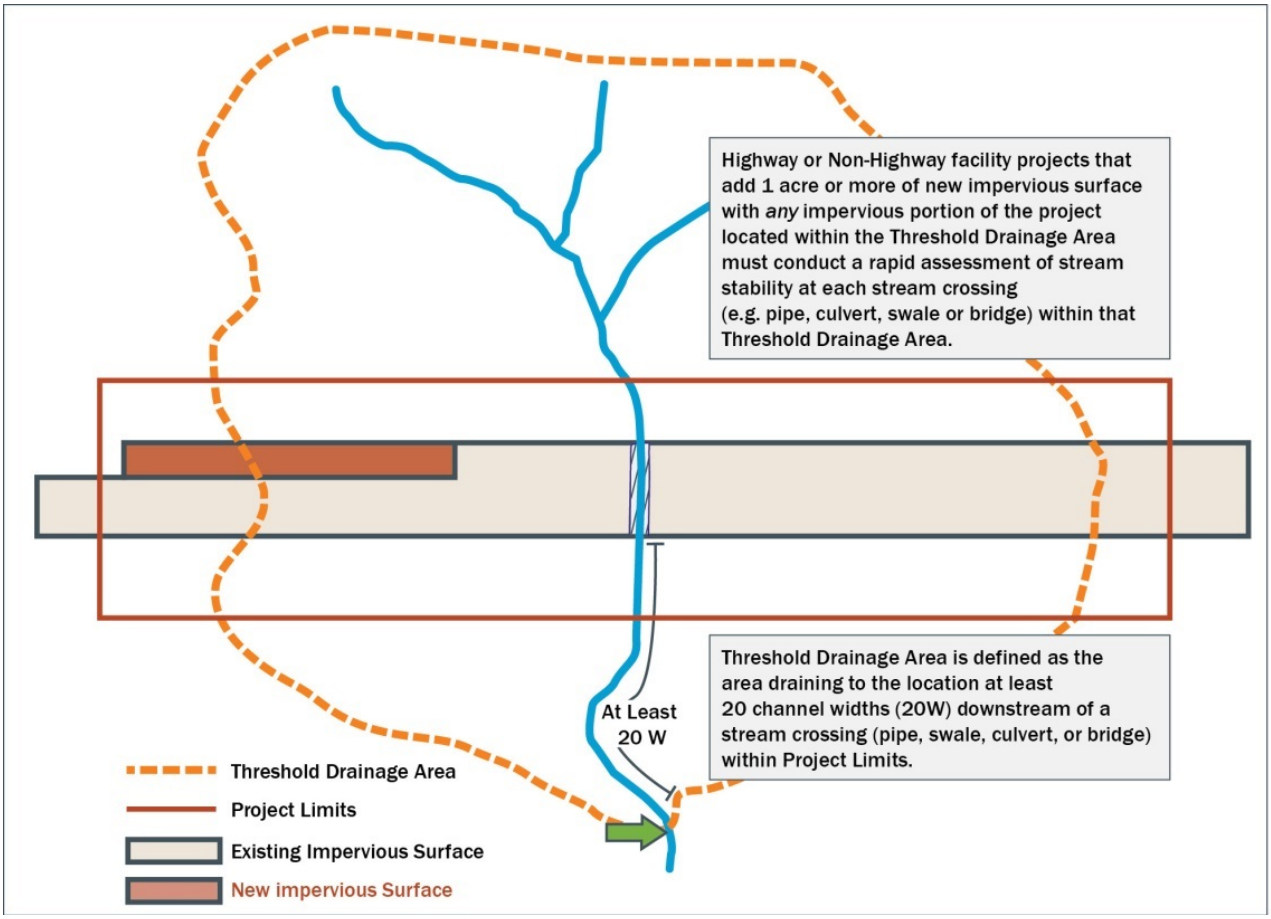

Figure 1. Definition of Threshold Drainage Area (TDA)

The TDA is delineated with a dashed line. The TDA drains to the point marked with the green arrow. The TDA drainage network is shown in blue, with the stream crossing (culvert) shown as a straight purple line

It is important to note that the purpose of determining W is to ascertain the downstream limit for the representative reach, which is to be "at least 20 channel widths upstream and downstream of a stream crossing." Herein this phrase is interpreted to mean that the representative reach is to extend at least 20W upstream (measured along the channel centerline) and 20W downstream (measured along the channel centerline) for a total representative reach length of at least 40W. For reach delineation, the value of W need not be precise. A value of W within 20% of the "true" value is usually adequate. When uncertainty exists in estimating W, the engineer should apply caution by selecting a higher value.

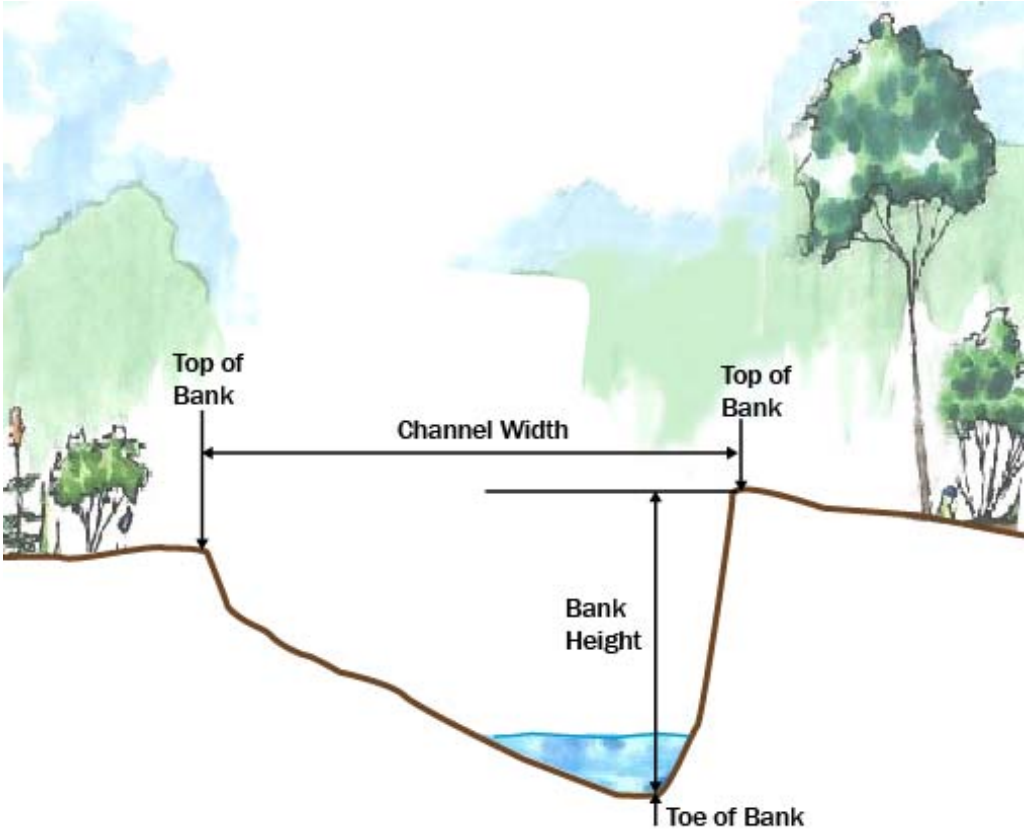

Figure 2. Definition of Top Bank and Other Channel Features

Step 2. After estimating W, the engineer should inspect the channel, starting at the downstream end of the stream crossing (bridge, pipe, or culvert) of interest and proceeding 20W (twenty widths) downstream. The downstream end of the 20W-long reach is the control point for TDA delineation (see green arrow in Figure 1). If this 20W-long reach includes any major discontinuities in channel characteristics, such as steps, culverts, grade controls, tributary junctions, or other features or structures that significantly affect the shape or behavior of the channel, the reach should extend at least 5W to 7W past the discontinuity, even if this requires a longer reach than 20W.

Step 3. When the downstream limit of the reach and thus the control point has been identified, the contributing watershed should be delineated using topographic survey maps or tools associated with GIS software and digital elevation maps. An online tool (http://streamstats.usgs.gov/california.html) provided by the U.S. Geological Survey (USGS) may be used to delineate watersheds larger than 2–3 square miles (See the link to the interactive map and use the icon labeled "Watershed delineation from a point.") Results of watershed delineation should be validated by examining aerial photographs, USGS Hydrologic Unit Code boundaries, and the National Hydrography Dataset flowlines.

After all TDAs linked to stream crossings within the project limits have been delineated, the engineer should determine whether any portion of the new impervious surface falls within a TDA. If so, an RSA is required. If the new impervious surface is not within a TDA, then no RSA is required. However, the project must implement Design Pollution Prevention Best Management Practices and Post-Construction Stormwater Treatment Controls.

Figure 3 provides some example TDA delineations.

- Figure 3a shows a project that contains a stream crossing and new impervious surface. Even though only part of the project and only part of the new impervious surface is within the TDA, if the impervious area ≥ 1 acre, an RSA will be required. Furthermore, if the new impervious surface were comprised of several small parcels with total surface area ≥ 1 acre, an RSA would be required.
- Figure 3b shows a project with multiple stream crossings, but all TDAs are contained within a single TDA when the watershed is delineated using the most downstream 20W control point. In this case the entire new impervious surface is within the TDA, although the project limits extend outside the TDA. If net new impervious area ≥ 1 acre, an RSA is required.
- Figure 3c provides an example of a project that contains a stream crossing, but the entire new impervious surface lies outside the TDA delineated from a point 20W downstream from the crossing. No RSA is required.
- Figure 3d depicts a project that does not contain a stream crossing within the project limits. No RSA is required.

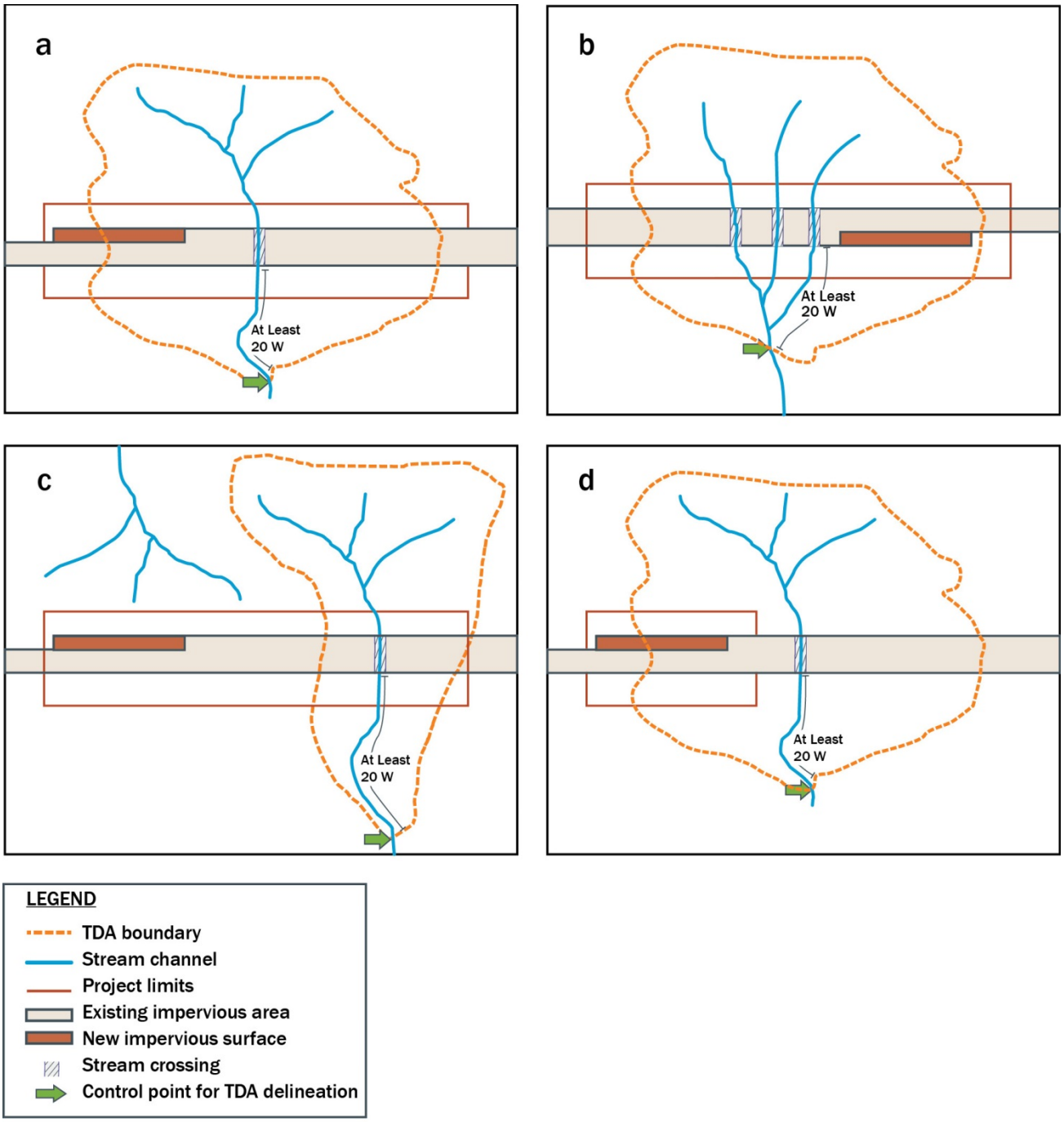

Figure 3. RSA Requirements

*Schematics illustrating Projects Involving 1 Acre or More of Net New impervious Area That Do (a and b) and Do Not (c and d) Require an RSA. **(a)** > 1 acre of new impervious area within TDA, RSA required; **(b)** Several TDAs that are tributary to a larger one, and > 1 acre new impervious area within largest TDA, RSA required; **(c)** New impervious area entirely outside TDA, RSA not required; **(d)** Project does not contain any stream crossings, RSA not required. See text for more detail.*

Section 3

Basic Concepts and California Earth Science

This section provides a description of basic concepts and defines additional terms used in the Rapid Stability Assessment. Fluvial geomorphology is a broad topic, so coverage here is quite elementary. The reader is encouraged to refer to Lagasse et al. (2012, HEC-20) for more information.

3.1 Equilibrium

As noted above, fluvial geomorphology is the science dealing with the shape of stream channels. A more sophisticated definition would include mention of the study of physical processes within river systems, such as bank erosion, sediment transport, bed material sorting, etc. Channel networks are tightly linked to their contributing watersheds. The watershed is the basic systemic unit, and the channel network is a subsystem of the watershed. The watershed receives climatic inputs and is constrained by geological features and processes. All watershed and channel behavior is consistent with the basic laws of physics, but since these are such complicated systems we often resort to empiricisms that describe the systems rather than analyzing physical forces and processes acting on each component. If inputs and constraints were constant through time, the channel system would reach a state of equilibrium characterized by fairly constant average dimensions and no net erosion or deposition when viewed at the reach scale, although local erosion (e.g., the outside of bends) would occur and would be balanced by deposition elsewhere in the reach (e.g., on bars). However, since climatic inputs and geological constraints vary in time, true static equilibrium is impossible. A key principle of fluvial geomorphology is that changes in the independent variables of discharge, sediment load supplied to a reach, and valley slope give rise to adjustments in the dependent variables of sediment load and particle size, hydraulic characteristics, and channel forms, all of which interact with each other. When viewed over appropriate time scales (decades to centuries), some channels achieve a state of “steady-state equilibrium,” in which dimensions vary or oscillate about a constant mean as the system responds to floods, droughts, and other events (Figure 4). When viewed over longer periods (centuries to millennia), even under the influence of a stable climatic regime, episodic perturbations (glaciers) and long-term erosion processes modify the channel slope, and all other morphologic properties respond accordingly. It is important to note that our definition of geomorphically stable channels (nearly constant average width, depth, and slope) does not require that the channel *location* remain constant. Channel width may remain stable as a meander bend migrates across a floodplain due to the compensating processes of erosion on the outside of the bend and deposition on the inside. However, a geomorphically stable channel that exhibits rapid lateral migration in the vicinity of a stream crossing would not receive a rating of “Excellent” stability in an RSA.

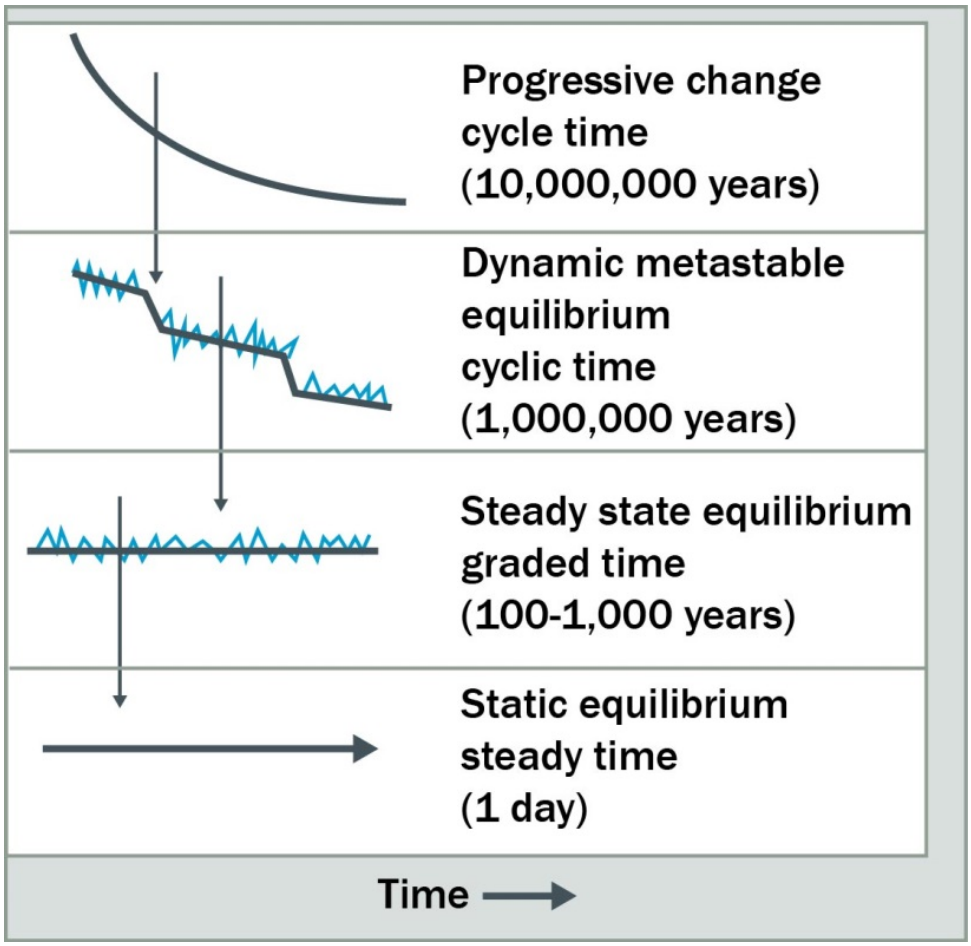

Figure 4. Time Scales in Geomorphic Systems

(Boyer and Shields 2007)

Even though scientists realize that channels respond to changes in inputs of water and sediment, exact predictions of response are very difficult because there are so many variables involved. Furthermore, the relationships between these variables are highly nonlinear and often exhibit threshold-type behavior. For example, a channel may maintain the same average width, depth, and slope for many years, even as the peaks of storm hydrographs increase steadily due to upstream development. Then, when a slight additional increase in peak flow occurs, a geomorphic threshold is crossed, and the channel width may increase by 50% in a short period.

Threshold behavior varies greatly from one watershed to another and even varies among channels within the same watershed. The *sensitivity* or *susceptibility* of channels to disturbances varies greatly because of differences in the resistance of their boundaries (bed and banks) to erosion, ongoing responses to previous disturbances (legacy effects), and the proximity of each system to a threshold. Furthermore, channels may respond differently to similar disturbances. For example, one channel may widen when peak flows increase after its forested watershed is cleared, whereas another may deepen. In the first case, the presence of erosion-resistant material on the bed (bedrock or large cobble, for example) deflects erosive forces toward the less resistant banks, while in the other channel, well-vegetated, cohesive banks were more resistant than the sandy bed.

3.2 Disturbances

Despite the variation in channel response to hydromodification, some generalizations may be drawn. Hydromodification results from both natural events and human activities. Several examples, along with their direct impacts on the fluvial system, are listed in Table 1. An important lesson to be learned from studying Table 1 is that predicting hydromodification effects for a given channel reach is difficult—variables interact in a complex way across a range of spatial and temporal scales. Another lesson is that all channels are in some stage of response or recovery to previous disturbances. For example, many channels in the eastern US cut deeply into floodplain deposits that formed behind mill dams which have since been removed; the legacy impacts of those dams are still manifest more than a century after they were built. Furthermore, most channels are responding to the cumulative effects of more than one natural or human disturbance.

Disturbances include natural events (tectonics, landslides, forest fires, volcanic eruptions) and those caused by humans (Instream or floodplain mining, channelization, dam construction, watershed development). Some locations are not necessarily "disturbed," but they are inherently dynamic and unstable. When stream channels flow from steep, narrow canyons onto broader, more open valleys with more gradual slopes, coarse sediments deposit in a cone- or fan-shaped deposit known as an alluvial fan (Table 2). Channels crossing alluvial fans often shift or change courses quite suddenly during high flow events. See Lagasse et al. (2012) for more detailed information. Sand bed channels tend to be more dynamic than those with coarser beds, particularly if they are braided with mid-channel bars and islands

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Table 1. Typical Causes of Hydromodification and Associated Channel Responses		
Primary Cause	**Typical Effects on Inputs to Fluvial System**	**Typical Channel Response**
Urban development of watershed, adding impervious area, or clearing of forested area or fire	Flow volumes, especially peaks, may increase. Sediment inputs to channel increase due to increased runoff and unprotected soils.	Channel will erode within the affected reach, but sediments may deposit in downstream reaches. Whether widening, deepening, or both occur depends on the relative resistance of beds and banks.
Flood	Flooding represents increased input of water and sediment.	Channel response to a single event varies widely, from no erosion to significant erosion. Greatest effects are associated with channel avulsions or cutoffs because they change the channel slope.
Prolonged drought	Drought implies less water and sediment input.	Channel may narrow due to vegetative encroachment. Bed sediments may grow finer because of lower bed shear stress and transport capacity.
Removal of large wood	No direct impact on inputs; increase in sediment input occurs if erosion is triggered.	Channel geometry may become more uniform. Local deposits that were stabilized by wood may erode.
Channel enlargement	No direct impact on inputs; increase in sediment input occurs if erosion is triggered.	Erosion or deposition may take place in the enlarged reach; headcutting may occur upstream and deposition downstream.
Channel straightening	No direct impact on inputs; increase in sediment occurs input if erosion is triggered.	Erosion may take place in the straightened reach; headcutting and dramatic erosion may occur upstream and deposition downstream.
Diversion of flow out of channel	Diversion represents a reduction in water flow; diversions often remove disproportionate amounts of sediment and water. For example, a diversion might capture half of the water, but only one fourth of the sediment from the main channel.	Sedimentation may occur downstream of the diversion.
Diversion of flow into channel	Diversion represents an increase in flow and perhaps sediment.	Channels will erode within the affected reach, but sediments may deposit in downstream reaches. Whether widening, deepening, or both occur depends on the relative resistance of beds and banks.
Lowering of base level[5]	No direct impact on inputs; increase in sediment input occurs if erosion is triggered.	Erosion may take place in the straightened reach; headcutting and dramatic erosion may occur upstream and deposition downstream.
Placement of flow constriction, dam, or control structure	Dams reduce sediment transport downstream and change hydrology.	Sedimentation may occur upstream, while bed lowering (deepening) generally occurs downstream; downstream response may be quite complex.

Modified from USACE (1994)

[5] For example, when a dam or highway stream crossing is removed, or when a downstream reach is straightened.

3.3 The Stream Balance – Lane's Relation

Although complex models and considerable professional judgment is needed for precise prediction of fluvial response to hydromodification at a given site, Lane's relation is very useful for understanding how and why channels behave as they do (Figure 5). This simple relation is a key tool for rapid stability assessments (Lagasse et al. 2012). Lane's relation (Lane 1955) states that the driving and resisting forces in a fluvial system respond to each other to create a balance. The driving forces may be expressed as the product of water discharge and channel slope, and the resisting forces as the product of sediment discharge and sediment size. Mathematically, the Lane relation is

$$QS \sim Q_s\, D_s$$

where

Q = water discharge. Usually this is a "dominant" or channel-forming discharge that occurs with a moderate frequency, such as the 1- to 2-year return interval event.

S = channel slope.

Q_s = sediment discharge. This is the discharge of sediment that is the same size as that composing the channel bed. For example, in a gravel-bed stream, Q_s would not include the discharge of suspended clay and silt.

D_s = sediment size. Usually a representative size is used, such as the median (D_{50}).

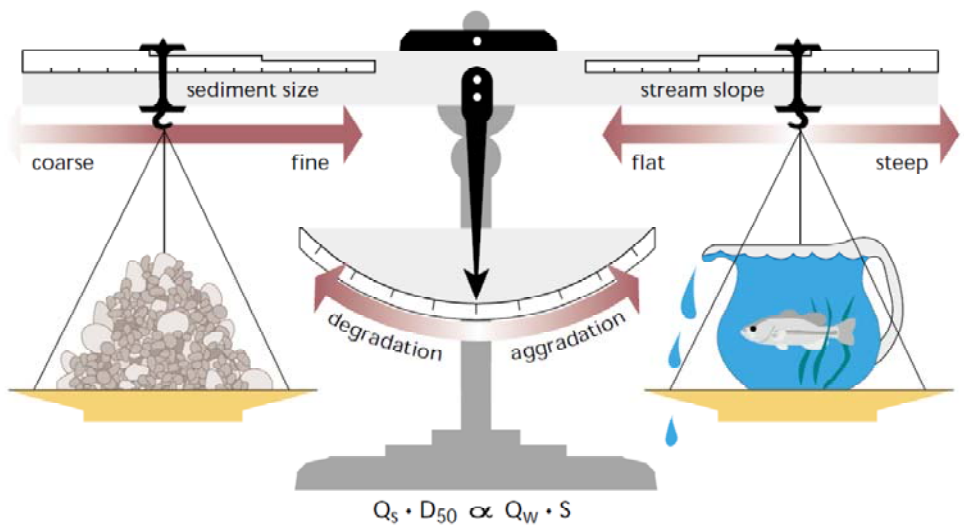

Figure 5. Schematic Illustrating Lane's Relation

In Alluvial Channels that are free to adjust their boundaries through erosion and sedimentation, changes in any of the four quantities in the relation will produce adjustments in the other three to maintain equilibrium (Federal Interagency Stream Restoration Working Group 1998)

Note that the relation is a proportion (~), not an equation (=). The relationship holds only for fully alluvial channels that are free to erode their boundaries in response to changes in inputs. The Lane relation has often been illustrated by sketches similar to the one in Figure 5. Increasing either water discharge or slope (left side) will trigger increased sediment discharge or bed sediment coarsening (right side), or both. This relation can be useful for predicting the types of adjustment that will occur in a fluvial system and for explaining previous or ongoing channel responses. However, it cannot be used to quantify the magnitude or speed of the response, since it is only a relation and not an equation.

3.4 Lateral Instability

Streambank erosion is a natural process, and almost all streams erode their banks to some degree. Even channels in which there is a net deposition of sediment rather than erosion may erode their banks as sediment deposits (bars) deflect flows against the banks. As noted above, many stable channels (i.e., with no net erosion or deposition at the reach scale, when viewed over several years) migrate laterally by depositing sediments on convex banks as concave banks are eroded. Laterally unstable channels may exhibit bank erosion processes similar to those of stable channels, but these processes act much more rapidly, resulting in *excessive* erosion, leaving visual clues that may be noted by a careful, trained observer (Brice 1982, Copeland 1994, Thorne et al. 1996b). Streambank erosion processes fall into two groups: *fluvial erosion,* in which sediments are removed grain by grain or in relatively small aggregates by channel flow, and *mass failure* (also called mass wasting or slope instability), in which large blocks of sediment are detached from the bank and fall into the channel. Mass failure can be triggered by a variety of geotechnical processes, including subsurface seepage. Several types of mass failure are illustrated in Figure 6. Lateral instability may be local, such as the erosion on the outside of a bend or erosion in response to a local contraction (like a culvert) or deflection of flow by an obstruction. In contrast, general instability is much more serious and much harder to control. An example of general lateral instability is channel widening caused by increased water discharge or large-scale removal of bank vegetation by grazing, clearing, drought, or fire.

Frequently, bank erosion in urbanizing watersheds is evidence of a particular type of vertical instability known as channel incision, which is described below.

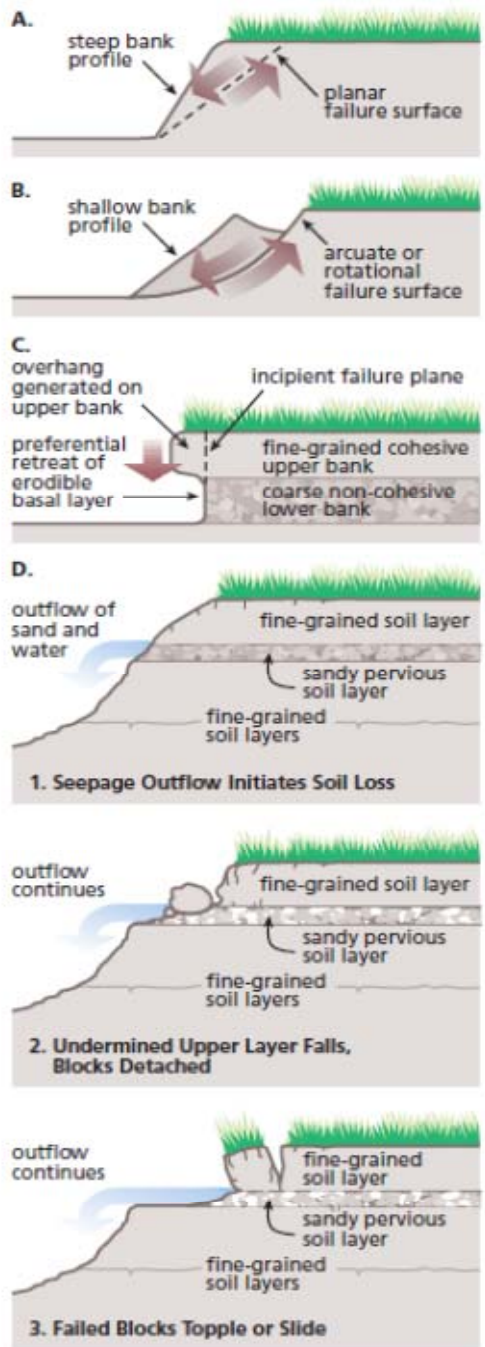

Figure 6. Common Mechanisms for Mass Failure of Streambanks

(FISRWG 1998)

3.5 Vertical Instability

Vertical instability is a condition defined by a change in streambed elevation over time when viewed at the scale of a reach many channel widths long. Although streambed elevation varies almost continuously at a given point, only a general lowering (degradation or incision) or raising (aggradation) of the bed

elevation along the reach is classified as vertical instability. Vertical instability is common in urbanizing watersheds, on alluvial fans and downstream from dams. For urbanizing watersheds, there is usually an initial increase in sediment loading during development which may produce bed aggradation. Following development, however, the higher peak flows associated with more impervious area often trigger erosion. If beds are more erodible than banks, channel incision will occur. Incision of a main channel lowers the base level for all tributaries, increasing their slope—the S on the left side of the Lane relation. Channels respond to higher S values by increasing either or both of the factors on the right side of the Lane relation: sediment discharge (via erosion) or sediment size (if larger sediment is available in the bed). Refer to Lagasse et al. (2012) for a more extensive discussion of the causes and symptoms of vertical instability.

3.6 Conceptual Models of Channel Evolution

Patterns of erosion associated with channel incision seem to follow a sequence of steps that have been described in a conceptual channel evolution model (CEM), shown in Figure 7. There are several versions of the CEM, but the one presented here is representative. The long profile at the bottom of Figure 7 is typical of the changes that may be observed as one moves from place to place along an actively incising stream; the smaller cross-sectional drawings are typical for each class or stage, but also depict the sequence of changes that occur at a fixed location as time passes. First, natural or "premodified" channels will be sinuous, with more or less stable banks, and may even be slightly aggradational (Class or Stage I). Recent work published by Cluer and Thorne (2012) suggests that CEM Class I is preceded by a braided or anastomosing stage (multiple channels divided by bars and vegetated islands). Other recent research has modified the standard CEM for streams characteristic of southern California, including transitions from single-thread to multithread and braided evolutionary endpoints (Hawley et al. 2012). Straightening (channelization) places a channel in Class II, but this stage often triggers vertical adjustment in the form of general bed lowering or the formation of steps or waterfalls in the bed (known as knickpoints or headcuts), which migrate upstream (Class III). Unless prevented by some erosion-resistant material in the bed (e.g., boulders, concrete, bedrock) or by a structure such as a dam, weir, or culvert, the headcut will continue to move upstream until the watershed is so small and flows are so low that the stream no longer has sufficient power to erode the bed (stream power = QS, the left side of the Lane relation). If the headcut deepens the channel enough to force banks to exceed a critical bank height, h_c, for geotechnical stability, extremely rapid channel widening via mass failure results, defined as Class IV. Bank failure may be exacerbated in some ecoregions because channel incision may lower the water table along the stream which causes adverse impacts on riparian vegetation. Class IV channels often exhibit erosion of both banks. When channels become so wide that they cannot transport the sediment load from upstream, vertical processes shift from degradation to aggradation, even though some bank erosion may continue (Class V). When deposited bars become high enough to support woody vegetation, a new channel within the enlarged, incised channel, and a Class VI form may be identified. Recent research suggests that this CEM should be expanded to include a form that often develops after Class VI that is braided (Cluer and Thorne 2013).

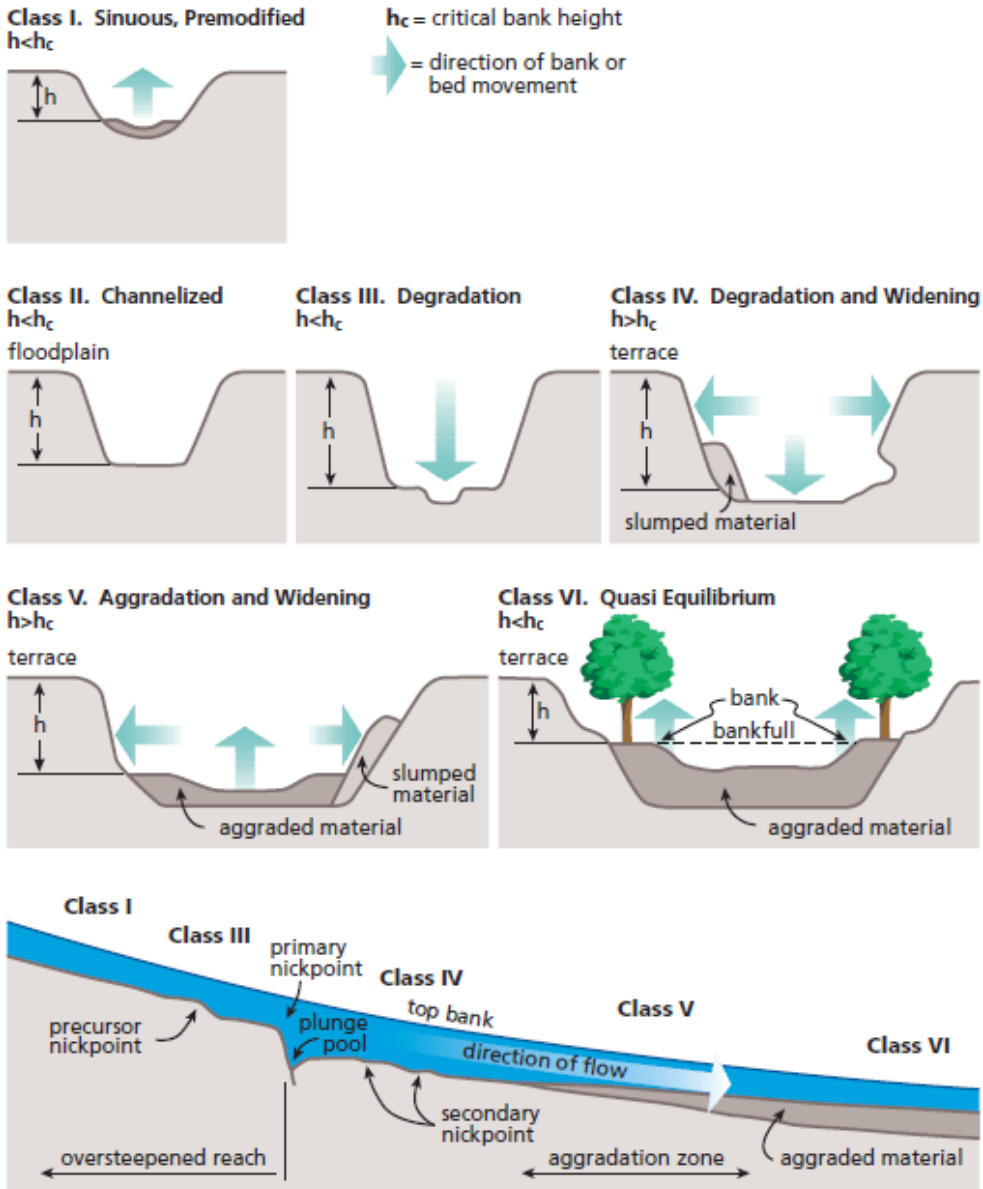

Figure 7. Schematic of Conceptual Channel Evolution Model (FISRWG 1998)

Model from Schumm et al. (1984), and Simon (1989)

The CEM is idealized. Actual fluvial systems may shift among Classes III, IV, and V repeatedly as pulses of sediment pass downstream and series of headcuts moves upstream. Nevertheless, it is quite important to note that instability can rapidly progress upstream in an incising system. A reach that has remained stable for many years can suddenly deepen and widen several fold, when a migrating headcut passes through.

3.7 Highways and Channel Instability

More rapid transmission of precipitation through the drainage network results in higher peak discharges and resultant increases in stream power (the left side of Lane's relation). Unstable channels may threaten stream crossings by eroding embankments or approaches, undermining piers, or destroying culvert foundations. As channels shift, the flow path of floodwaters may be directed at an unfavorable angle to structural piers and abutments. Piers originally founded in overbank floodplain areas can become main channel piers due to channel migration. Footings and foundations may be exposed and undermined by local scour or channel degradation. Concave banklines (outsides of meanders) typically migrate downvalley, and may impinge on approach embankments or abutments (Figure 9).

Headcuts pose a particularly serious hazard to highway infrastructure (Figure 8). For example, in 1995, a railroad bridge near Kingman, Arizona, collapsed as a passenger train passed over it, injuring more than 150 people. The bridge collapse was caused by upstream migration of a headcut following heavy rains and the failure of a downstream check dam (Johnson 2006). Sediments and large wood brought into channels (particularly Classes III and IV) as a result of incision are deposited downstream in Class V and VI reaches. Accelerated deposition can fill a channel, forcing flows over the banks and damaging or destroying roadways or embankments. Excessive amounts of large wood can also lodge on bridge piers or block entrances to pipes and culverts. Even dynamically stable channels can threaten highway rights-of-way when upstream meanders migrate toward them (Figure 9). A fuller description of the implications of stream channel instability for highway structures is provided by Lagasse et al. (2012). The FHWA publication, *A Field Guide for Bridge Inspectors* (FHWA 2009) is a handy, well-illustrated pocket guide with checklists for assessing symptoms of instability. Caltrans guidance is available for culvert inspections also (Caltrans 2008).

Figure 8. Headcut in Consolidated Cohesive Bed Approaching County Road Bridge

Big Creek, MS, 1997

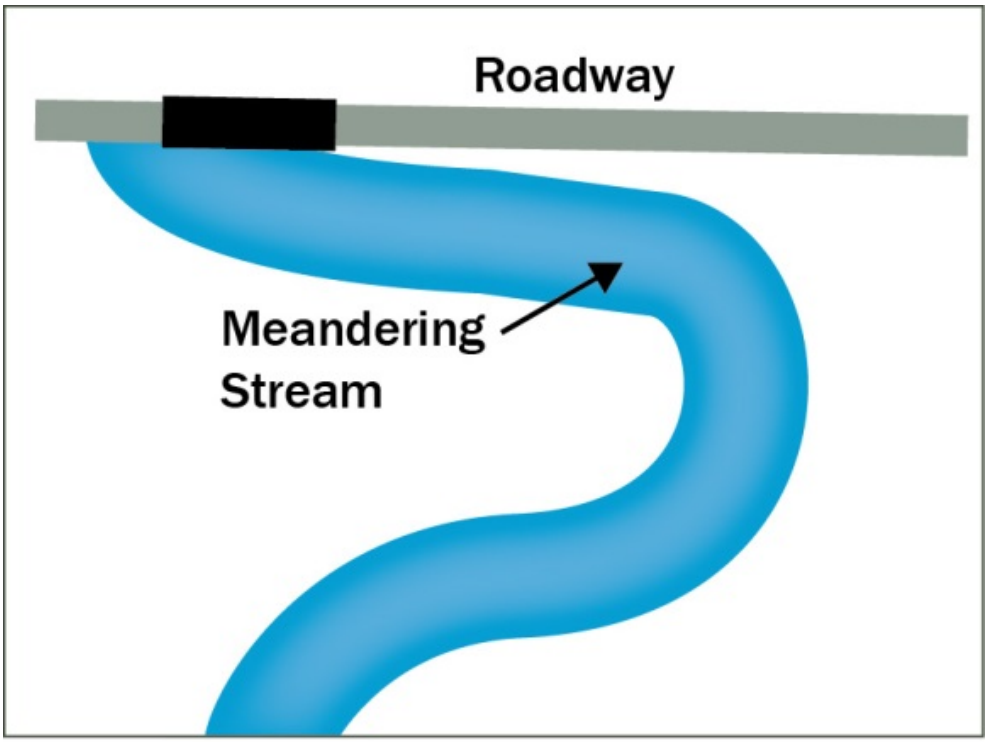

Figure 9. Meander Threatening a Roadway

Most rapid erosion along a bend occurs on the concave bank just downstream of the bend apex.

3.8 Stream Channels Types

3.8.1 Available Classification Systems

Since channel networks in fluvial systems exhibit mutual adjustments of their key characteristics (slope, channel dimensions, planform, bed material size, etc.), certain characteristics tend to occur together. For example, very steep channels tend to have beds of boulders or cobbles, whereas those with very mild slopes have beds of sand and finer materials. Accordingly, scientists have repeatedly attempted to develop comprehensive classification systems for streams and rivers (Niezgoda and Johnson 2005). These systems are very useful when describing a given channel reach to others and, in some cases, they allow predictions about the sensitivity of a channel to hydromodification. For example, a system proposed by Schumm (Federal Interagency Stream Restoration Working Group [FISRWG] 1998) is based on the way a river transports sediment and the pattern (or *planform*) of the river when viewed from above (Figure 10). Also, the aforementioned CEM has been used to classify reaches in watersheds experiencing channel incision. Classification systems vary from simple (three categories of stream types) to complex (several dozen categories). In scientific circles, classification systems have been controversial, and no system is universally accepted. Engineers using stream classifications should be aware that they are artificial constructs, and no strict taxonomy (such as used in biology) is possible. Although we may assign channel reaches to discrete categories based on arbitrary thresholds of slope, sinuosity, bed material size, width-depth ratio, etc., these quantities vary continuously, and channels tend to behave in rather individualistic fashion. Nevertheless, classification systems are useful for preliminary work such as RSAs.

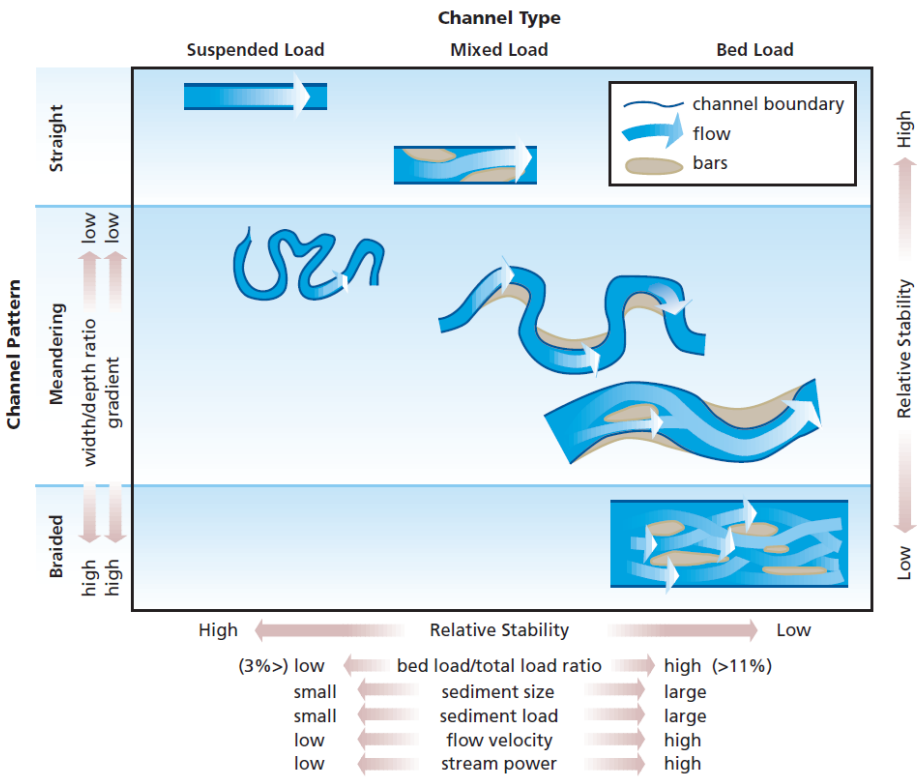

Figure 10. Simple Stream Classification System

The classification system proposed by Schumm categorizes river reaches based on pattern (planform) and sediment load. Stability varies based on these characteristics.

From FISRWG (1998).

3.8.2 Simple Stream Classification System

Since the sensitivity of channel systems varies widely, several authors have attempted to classify their susceptibility to instability when subjected to hydromodification. The Schumm system shown in Figure 10 rates relative stability for various channel types; presumably, sensitivity to hydromodification is greatest for the most unstable types of channel. The U.S. Army Corps of Engineers (USACE) (1994) has classified stream types based on channel planform; this system offers the advantage of including engineered (channelized) systems (Table 2). In another example, Montgomery and Buffington (1997) classified stream channel reaches into seven categories based on the nature and organization of the bed material (Table 3). For five of these seven channel types that are single thread, alluvial channels, Montgomery and MacDonald (2002) tabulated the channels' sensitivity to an increase in water and sediment inputs (Table 4). They suggest that pool-riffle streams are the most sensitive to hydromodification. Pool-riffle channel dimensions (depth and width) and bank stability are very sensitive to changes in coarse sediment supply and to increases in discharge. Bed material in these channels is also very responsive to changes in sediment supply and water discharge. By comparison, cascade and step-pool channels are not as sensitive and will maintain their dimensions and bank stability despite changes in sediment and water supply.

For the purposes of this manual, we follow the example of Johnson (2006), as specified in the NPDES permit, and recognize only three categories of stream channel reaches (Table 5). The categories in Table 5 are primarily process-based groupings of the Montgomery and Buffington categories, with reference to the relative sensitivities proposed by Montgomery and MacDonald (2002) shown in Table 4.

Table 2. US Army Corps of Engineers Stream Channel Classification System
Mountain Torrents. High-velocity streams on steep slopes with a drop-and-chute structure often achieved by obstacles such as large boulders or debris. These streams are subject to scour and degradation caused by flood events. Very steep slopes can lead to debris flows that produce substantial movement of boulders and gravels.
Alluvial Fans. Occur usually in arid and semiarid lands where a stream flowing through a stream valley enters a flat area. The coarse sediment carried by the stream deposits in a delta-like configuration characterized by multiple channels subject to shifting. The chief stability problem is caused by the unpredictability of the flow paths, which may cause erosion and deposition in unexpected places.
Braided Rivers. The main characteristic of these streams is a series of interlaced channels defined by bars and islands. Braided streams often occur in upper and middle zones of the watershed and usually involve gravel and cobbles, although braiding may also occur in sands. Scour and deposition often cause shifting of the main channel.
Arroyos. Present in arid and semiarid lands, these are streams that remain dry most of the time and carry flow only during flood events. Discharge and sediment transport can be substantial during flow episodes. Incising channels, width enlargement, and deposition are typical problems associated with arroyos.
Meandering Alluvial Rivers. These occur primarily in the middle and lower portion of the watershed. The planform of the stream is characterized by meanders that erode the streambank in the outer side of the bend and deposit material on the inner side. Meanders may migrate in the floodplain and can often become cut off periodically when two bends advance toward each other and curvatures becomes severe. Cutoff meanders become isolated features called “oxbow lakes” that eventually fill with sediment. Traces of old meanders (scrolls) are easily distinguishable in aerial photographs. Measures that alter the supply of water or sediment have the potential to change cross sections, planforms, and gradients.
Modified Streams. This term generically encompasses those streams whose natural configuration has been severely modified by human intervention. These modifications include straightening, channelizing, enlargement, and base level changes caused by regulation of the receiving stream. Increased runoff from surrounding development also introduces modifications.
Regulated Streams. Regulation of tributaries by upstream reservoirs reduces flood flows and increases baseflow. These changes in the flow regime translate into reduced morphological activity. If regulation facilitates sediment deposition in the channel and vegetation growth, the stream cross section will be reduced. However, if the stream carries substantial sediment loads that become trapped in the reservoir, the stream may cause erosion downstream of the dam.
Deltas. These features occur on flat slopes of the lower portion of the stream where it empties into relatively quiescent water such as the ocean or a lake. Sediment deposition due to reduced velocity forces the river to split into distributaries whose base level rises as the delta progresses into the water body. Deltas also exhibit the formation of natural levees along the distributaries.
Under Fit Streams. These are streams common in regions whose landscape formed as a result of glacial activity. Under fit streams occur in wide valleys formerly shaped and occupied by larger streams, usually the outlet to glacial lakes. Under fit streams are also found in abandoned riverbeds or channels downstream from reservoirs. Flat slopes, low velocities, and established vegetation make under fit streams generally stable.
Cohesive Channels. These are channels cut in cohesive materials such as marine clays, silted lakes, and glacial till plains. In marine deposits, these streams behave somewhat like meandering alluvial streams, although the meanders are flatter, wider, more uniform, and usually more stable. In glacial till, the plan form tends to be irregular.

Source: *USACE 1994*

Table 3. Montgomery-Buffington Stream Classification System

	Cascade	Step-pool	Plane-Bed	Pool-Riffle	Dune-Ripple	Braided	Bedrock
Typical bed material	Boulder	Cobble, boulder	Gravel, cobble	Gravel	Sand	Variable	N/A
Bedform pattern	None	Vertically oscillatory	None	Laterally oscillatory	Multilayered	Laterally oscillatory	N/A
Reach type	Transport	Transport	Response	Response	Response	Response	Transport
Dominant roughness elements	Grains, banks	Bedforms, grains, large woody debris (LWD), banks	Grains, banks	Bedforms, grains, LWD, sinuosity, banks	Sinuosity, bedforms	Bedforms	Boundaries
Dominant sediment sources	Fluvial, hill slope, debris flow	Fluvial, hill slope, debris flow	Fluvial, bank failure, debris flows	Fluvial, bank failure, inactive channel, debris flows	Fluvial, bank failure, inactive channel	Fluvial, bank failure, debris flow	Fluvial, hill slope, debris flow
Sediment storage elements	Lee and stoss sides of flow obstructions	Bedforms	Overbank, inactive channel	Overbank, bedforms, inactive channel	Overbank, bedforms, inactive channel	Overbank, bedforms	N/A
Typical slope (ft/ft)	$0.08 < S < 0.30$	$0.03 < S < 0.08$	$0.01 < S < 0.03$	$0.001 < S < 0.02$	$S < 0.001$	$S < 0.03$	Variable
Typical confinement by valley walls	Confined	Confined	Variable	Unconfined	Unconfined	Unconfined	Confined
Pool spacing (channel widths)	< 1	1 to 4	None	5 to 7	5 to 7	Variable	Variable

Source: *Johnson (2006)*

Table 4. Relative Sensitivity to Hydromodification, by Channel Type, after Montgomery and MacDonald (2002)[6]					
Response Variables	Cascade	Step-pool	Plane-bed	Pool-riffle	Dune-ripple
Channel width and depth	2, 1, 2	2, 1, 2	3, 1, 3	3, 2, 3	2, 2, 3
Bed material size[7]	1, 1, 1	2, 1, 1	3, 2, 1	3, 2, 2	3, 1, 1
Pool volume	2, 1, 2	3, 2, 2	N/A	3, 3, 3	2, 3, 1
Bank erosion	2, 1, 2	2, 1, 3	2, 1, 3	3, 2, 3	2, 3, 3
Channel scour	2, 1	2, 1	3, 1	3, 2	2, 2

Each cell contains three integers (1, 2, or 3). The first represents relative sensitivity to a chronic increase in the supply of coarse (> 2 mm (.08 in.)) sediment. The second represents relative sensitivity to a chronic increase in the supply of fine (< 2 mm (.08 in.)) sediment. The third represents relative sensitivity to a chronic increase in the frequency or magnitude of peak flows. 1 = little or no response, 2= secondary or small response, 3 = very responsive.

Table 5. Simplified Channel Reach Classification System, after Johnson (2006)		
Stream channel types	Sediment transport regime	Sensitivity
Pool-riffle, plane-bed, dune-ripple and engineered (channelized) channels	Aggradational/degradational	Responsive to loadings
Bedrock, cascade and step-pool	Transport	Not sensitive to loadings
Braided	Usually aggradational	Very responsive; more common in West and Southwest

[6] Montgomery and MacDonald (2002) present a more comprehensive list of response variables.

[7] D_{84} of bed sediment. This is the size (sieve diameter) for which 84% of the bed sediment is finer, by weight. It represents the larger bed particles.

3.9 Physiographic Subregions of California

Stream channels reflect the influences of larger-scale forms and processes that are evident at a regional scale. Earth scientists use landscape geology and topography to divide terrestrial areas into physiographic regions, which are further divided into subregions. Stream channel morphology reflects the action of erosion and deposition interacting with geology. Although different types of streams occur within a given subregion, the similar terrain and geology lead some types to be more common than others. There are eight major physiographic regions in the lower 48 states of the US; these are further divided into 25 subregions (http://tapestry.usgs.gov/physiogr/physio.html). The boundaries of these regions are not strictly defined. Johnson (2006) demonstrated the importance of regional physiography in stream channel stability assessment at a national scale. California includes all or part of four subregions, which are further subdivided into 11 sections as described below (Dellinger 1989, McNab and Avers 1994, California Geological Survey 2002, McNab et al. 2005).

3.9.1 Cascade-Sierra Mountains

This subregion includes the Sections labeled "Cascade Range" and "Sierra Nevada" in Figure 11.

Figure 11. Physiographic Subregions of California

From California Geological Survey (2002).

3.9.1.1 Cascade Range (Southern)

The Cascade Range, a chain of volcanic cones, extends through Washington and Oregon into California. In California, the Section is dominated by Mt. Shasta, a glacier-mantled volcanic cone, rising 14,162 feet above sea level. The southern termination is Lassen Peak, which last erupted in the early 1900's. These volcanic mountains are variously eroded; there is no distinct range. Elevation varies from 1,500 to 14,000 ft. The Cascade Range is transected by deep canyons of the Pit River. The river flows through the range between these two major volcanic cones, after winding across interior Modoc Plateau on its way to the Sacramento River. Lithology comprises Cenozoic volcanic rocks. Vegetation has been mapped as Sierran montane forest, sagebrush steppe, yellow pine–shrub forest and northern yellow pine forest. Average annual precipitation ranges from 20 to 80 inches. The growing season lasts 30 to 200 days. There are many slow and moderately rapid rivers and streams. Rivers flow in alluvial or weak bedrock channels westerly to the Klamath and Sacramento Rivers, and easterly to basins in the Modoc Plateau Section. Wide fluctuations in precipitation and temperature for periods of years result in significant or catastrophic changes in biological communities. This Section contains locations in which eruptive activity (lava flows and ash fall) has occurred within the past 200 years.

3.9.1.2 Sierra Nevada

The Sierra is a tilted fault block nearly 400 miles long. Its east face is a high, rugged multiple scarp, contrasting with the gentle western slope (about 2°) that disappears under sediments of the Great Valley. Deep river canyons are cut into the western slope. Their upper courses, especially in massive granites of the higher Sierra, are modified by glacial sculpturing, forming such scenic features as Yosemite Valley. The high crest culminates in Mt. Whitney with an elevation of 14,495 feet above sea level near the eastern scarp. The metamorphic bedrock contains goldbearing veins in the northwest trending Mother Lode. The northern Sierra boundary is marked where bedrock disappears under the Cenozoic volcanic cover of the Cascade Range. Elevation ranges from 1,000 to 14,495 ft, and local relief ranges from 500 to 2,000 ft. There are Mesozoic granitic and ultramafic rocks, Paleozoic and Mesozoic strongly metamorphosed sedimentary and volcanic rocks, and Cenozoic volcanic rocks. Natural vegetation communities are ponderosa pine, ponderosa pine–mixed conifer, Douglas fir–mixed conifer, white fir–mixed conifer, red fir, lodgepole pine, Jeffrey pine, big sagebrush, canyon live oak, white alder, mountain alder, huckleberry oak, carex, and aspen series. Precipitation ranges from 20 to 80 inches during fall, winter, and spring. It occurs mostly as snow above 6,000 ft. Rain on snow is common. Summers are dry, with low humidity. The growing season lasts 20 to 230 days. There are many rapid rivers and streams. Rivers flow west from the crest, in deeply incised canyons with bedrock-controlled channels, to the Great Valley Section and Pacific Ocean. Rivers also flow east from the crest, in mostly bedrock-controlled channels, terminating in basins in the Mojave Desert, Mono, or northwestern Basin and Range Sections. Numerous lakes and wet meadows are associated with glaciated areas above 5,000 ft.

3.9.2 Basin and Range

This subregion is primarily arid to semiarid. Thus, rivers in the Basin and Range subregion tend to be ephemeral or intermittent. Alluvial fans are common in the Basin and Range. They develop when sediment transported along steep mountain channels deposits on shallower slopes at the base of the mountains. Streams in alluvial fans are typically highly unstable in terms of lateral position.

This subregion includes the Sections labeled "Modoc Plateau," "Basin and Range," and "Transverse Ranges" in Figure 11.

3.9.2.1 Modoc Plateau

The Modoc Plateau is a volcanic table land (elevation 4,000 - 6,000 feet above sea level) consisting of a thick accumulation of lava flows and tuff beds along with many small volcanic cones. Occasional lakes, marshes, and sluggishly flowing streams meander across the plateau. The plateau is cut by many north-south faults. The province is bound indefinitely by the Cascade Range on the west and the Basin and Range on the east and south. This area comprises northwesterly trending fault-block mountains and ridges, with intervening basin-like grabens commonly interspersed with lake bed deposits, shield volcanoes, cinder cones, or lava flows. Lithology is characterized by Cenozoic volcanic and nonmarine sedimentary rocks and alluvial deposits. Natural vegetation communities include yellow pine–shrub forest, juniper-shrub savannah, Sierran montane forest, sagebrush steppe, upper montane–alpine forests, and northern Jeffrey pine forest. Predominant potential natural communities are ponderosa pine, mixed conifer, western juniper, white fir, big sagebrush, low sagebrush, and carex series. Precipitation ranges from 12 to 30 inches per year. The growing season lasts 70 to 140 days. There are a few slow rivers and a few slow to moderately rapid streams, although most streams do not flow throughout the summer. Rivers and streams flow in alluvial and bedrock-controlled channels to the Sacramento and Klamath Rivers, or to basins within the Modoc Plateau or the northwestern Basin and Range Sections. Numerous small to very large lakes and reservoirs occur throughout the Section.

3.9.2.2 Basin and Range

The Basin and Range is the westernmost part of the Great Basin. The province is characterized by interior drainage with lakes and playas, and the typical horst and graben structure (subparallel, fault-bounded ranges separated by downdropped basins). Death Valley, the lowest area in the United States (280 feet below sea level at Badwater), is one of these grabens. Another graben, Owens Valley, lies between the bold eastern fault scarp of the Sierra Nevada and Inyo Mountains. The northern Basin and Range Province includes the Honey Lake Basin.

3.9.2.3 Transverse Ranges

The Transverse Ranges are an east-west trending series of steep mountain ranges and valleys. The east-west structure of the Transverse Ranges is oblique to the normal northwest trend of coastal California, hence the name "Transverse." Its eastern extension, the San Bernardino Mountains, has been displaced to the south along the San Andreas Fault. Intense north-south compression is squeezing the Transverse Ranges. As a result, this is one of the most rapidly rising regions on earth. Great thicknesses of Cenozoic petroleum-rich sedimentary rocks have been folded and faulted, making this one of the important oil-producing areas in the United States. The ranges are rugged, with peak elevations as high as 11,500 ft and densely populated urban centers in valleys and along coastal plains. The native plant communities of the Transverse ranges include coastal sage scrub, chaparral (lower chaparral, upper chaparral, and desert chaparral), oak woodland and savanna, and pinyon-juniper woodland at lower elevations, and yellow pine forest, Lodgepole Pine forest, and subalpine forest at higher elevations. Chaparral is a common feature of the Transverse Ranges. Common plant associates in chaparral, especially in the transition between coastal chaparral and coastal sage scrub, include California sagebrush and Toyon, the latter shrub having its southern distribution limit defined by the Transverse Ranges.

3.9.3 Pacific Coastal

The Pacific Coastal subregion in California is characterized by a wide variety of channel types that include arroyos and alluvial fans. These stream types tend to be unstable both laterally and vertically. Human alterations of stream channels in this region are widespread and have changed erosion and deposition patterns. Streams may be ephemeral, intermittent, or perennial. Sections in this region include those labeled “Klamath Mountains,” “Great Valley,” and “Coast Ranges” in Figure 11.

3.9.3.1 Klamath Mountains

The Klamath Mountains have rugged topography with prominent peaks and ridges reaching 6,000-8,000 feet above sea level. In the western Klamath, an irregular drainage is incised into an uplifted plateau called the Klamath peneplain. The uplift has left successive benches with gold-bearing gravels on the sides of the canyons. The Klamath River follows a circuitous course from the Cascade Range through the Klamath Mountains. The province is considered to be a northern extension of the Sierra Nevada. Elevation ranges from 1,500 to 8,000 ft. There are Paleozoic sedimentary and volcanic rocks and Mesozoic ultramafic, granitic, sedimentary, and volcanic rocks. Natural vegetation is primarily coniferous montane forest. Predominant potential natural communities are Douglas-fir, ponderosa pine, mixed conifer, Jeffrey pine, white fir, and red fir series. Average annual precipitation ranges from 40 to 120 inches. Many rapid or moderately rapid rivers and streams are found in this Section. Most rivers flow westerly in deeply incised canyons with bedrock-controlled channels. Some easterly flowing streams in deeply incised canyons flow inland to the Sacramento River. There are numerous lakes and meadows associated with glaciated areas above 5,000 ft. The western part of the Section is seismically active, with strong shaking and ground rupture. Wide fluctuations in precipitation and temperature for periods of years result in significant or catastrophic changes in biological communities.

3.9.3.2 Great Valley

The Great Valley is an alluvial plain about 50 miles wide and 400 miles long in the central part of California. Its northern part is the Sacramento Valley, drained by the Sacramento River and its southern part is the San Joaquin Valley drained by the San Joaquin River. The Great Valley is a trough in which sediments have been deposited almost continuously since the Jurassic (about 160 million years ago). Great oil fields have been found in southernmost San Joaquin Valley and along anticlinal uplifts on its southwestern margin. In the Sacramento Valley, the Sutter Buttes, the remnants of an isolated Pliocene volcano, rise above the valley floor. This area has Cenozoic nonmarine sedimentary rocks and alluvial deposits. The Great Valley Section has been highly developed for irrigated agriculture. Most of the Section is intensely cultivated, but natural vegetation may be characterized as California prairie, riparian forest, tule marsh, San Joaquin saltbush and valley oak savanna. Predominant potential natural communities are Valley Oak, Valley Needlegrass, and Saltbush series. Composition and successional sequence of some communities (especially grassland communities) has changed because of plant and animal species introduced between the early 1800's and early 1900's. These changes related to grazing, agriculture, and urbanization. Rapidly expanding urbanized areas are scattered throughout the Section. Flood control has decreased the duration and extent of wetlands. Precipitation ranges from 5 to 30 inches and the growing season lasts 230 to 350 days. Many slow moving rivers flow to the delta east of San Francisco Bay via the Sacramento and San Joaquin River systems. Flows to these leveed, alluvial channel river systems are regulated throughout the year by dams and reservoirs. Constructed deep water ship channels also connect to Sacramento and Stockton. Many rivers and perennial streams flow west from the Sierra Nevada foothills Section to the Sacramento and San Joaquin Rivers. The many alluvial channels that flow eastward from the Coast Ranges to the Sacramento and San Joaquin Rivers are mostly dry during summer months; only a few are perennial streams. The southern part of the San Joaquin Valley drains to basins and does not reach the San Joaquin River. Many of the channels in the Valley are highly engineered and have very low slopes relative to those draining the adjacent mountainous areas.

3.9.3.3 Coast Ranges (North)

The Coast Ranges are subparallel to the active San Andreas Fault. The San Andreas is more than 600 miles long, extending from Pt. Arena to the Gulf of California. The northern and southern ranges are separated by a depression containing the San Francisco Bay. Strata dip beneath alluvium of the Great Valley. The northern Coast Ranges are dominated by irregular, knobby, landslide-topography of the Franciscan Complex. The eastern border is characterized by strike-ridges and valleys in Upper Mesozoic strata. In several areas, Franciscan rocks are overlain by volcanic cones and flows of the Quien Sabe, Sonoma and Clear Lake volcanic fields. This Northern Coast Range Section has parallel ranges, and folded, faulted, and metamorphosed strata; there are rounded crests of subequal height. Elevation ranges from 200 to 7,500 ft. Predominant potential natural vegetation communities are Douglas-fir, white fir, ponderosa pine, tanoak, interior live oak, coast live oak, blue oak, mixed chaparral, and valley needlegrass series. Average annual precipitation ranges from 20 to 80 inches. The growing season lasts 80 to 270 days. There are many rapid or moderately rapid rivers and streams in deeply incised canyons with weak bedrock channels; they flow westerly to the Pacific Ocean. Streams draining the interior range may be characterized as rapid perennial or intermittent streams flowing in deeply incised canyons with weak bedrock channels; they flow easterly to the Sacramento River. Reservoirs for irrigation water and flood control are common. This is a seismically active area, with strong shaking and ground rupture. Wide fluctuations in precipitation and temperature for periods of years result in significant or catastrophic changes in biological communities.

3.9.3.4 Coast Ranges (South)

This Section is divided from the northern Coast Ranges by the San Andreas Fault. The Section has a landscape of narrow ranges of low elevation with alluvial lowlands and coastal terraces on geologic formations and nonmarine sedimentary rocks. Vegetation includes sagebrush, chaparral-mountain shrub, and western hardwoods cover types. Few slow and moderately slow moving rivers and streams flow northerly to Monterey Bay via the Salinas River. Few streams in alluvial or weak bedrock channels flow directly toward the Pacific Ocean. Many streams that flow eastward in alluvial or weak bedrock channels to the Great Valley Section do not flow throughout the summer. Reservoirs for irrigation and flood control are common.

3.9.4 Lower California

This subregion includes the sections labeled “Peninsular Ranges,” “Mojave Desert,” and “Colorado Desert,” in Figure 11.

3.9.4.1 Peninsular Ranges

A series of ranges is separated by northwest trending valleys, subparallel to faults branching from the San Andreas Fault. The trend of topography is similar to the Coast Ranges, but the geology is more like the Sierra Nevada, with granitic rock intruding the older metamorphic rocks. The Peninsular Ranges extend into lower California and are bound on the east by the Colorado Desert. The Los Angeles Basin is included in this province. There are narrow ranges and broad fault blocks, alluviated lowlands, and dissected westward sloping granitic uplands. Elevation ranges from 500 to 11,500 ft. Naturally-occurring vegetation includes southern oak forest, coastal sagebrush, chaparral and southern yellow pine forest. Predominant potential natural communities include Chamise, Ceanothus, Mixed Chaparral, Scruboak, Coast Live Oak, Englemann Oak, Needlegrass, Jeffrey Pine, Canyon Oak and Big Cone Douglas-Fir. Average annual precipitation ranges from 10 to 40 in. The growing season lasts 100 to 200 days. Rivers and streams are common, but most do not flow throughout the year. Rivers and streams flow in alluvial and weak bedrock channels westward to the Pacific Ocean, or eastward to basins in the Mojave Desert or Sonoran Colorado Desert Sections. Many reservoirs for municipal water supply and flood control occur below steep mountains throughout the Section.

3.9.4.2 Mojave Desert

The Mojave is a broad interior region of isolated mountain ranges separated by expanses of desert plains. It has an interior enclosed drainage and many playas. This Section is desert bordered by mountain ranges that delineate the landscape and serve as barriers to the migration of sediments (carried both by water and wind). Adjacent to each range are corresponding valleys that are filled with sediments. The Mojave Desert region is within a great inland (isolated) drainage basin. During the past Ice Ages, great lakes filled many of the lower valleys; many of these lake basins overflowed into adjacent valleys, and some eventually spilled into Death Valley. However, the region has dried up, leaving behind great dry lakebeds exposed to erosion by the wind. Between the ranges and the lakebeds are regions covered by coalescing alluvial fans (called bajadas) or extensive flat regions of barren, weathered bedrock (called pediments). Freezing temperatures occur during the winter, particularly in higher elevation regions. Summers tend to be hot, dry, and windy. Average precipitation in the region is less than 5 inches, but is highly variable from one year to the next. Many streams are ephemeral. Almost all precipitation arrives in the winter, but the region also experiences rare, intense summer thunderstorms that can produce rapid changes in stream morphology and even landscapes. Precipitation is greater for higher elevations, which receive snow as well as rain. Vegetation is sparse and comprised of an assemblage of desert species. The perennial vegetation is composed mostly of low shrubs; annuals carpet the ground in wet years. Few succulents and trees grow there. The only common tree species is the characteristic Joshua Tree (*Yucca brevifolia*), an arborescent (treelike) yucca that forms extensive woodlands above 3,000 ft elevation.

3.9.4.3 Colorado Desert

The Colorado Desert is a very hot, low-lying barren desert basin, about 245 feet below sea level. The Salton Sea is a major geomorphic feature. The province is a depressed block between active branches of alluvium-covered San Andreas Fault with the southern extension of the Mojave Desert on the east. It is characterized by the ancient beach lines and silt deposits of extinct Lake Cahuilla.

Section 4

Performing a Rapid Stability Assessment

4.1 Stability Indicators

A RSA consists of assigning, for each site in question, numerical values between 1 and 12 to each of 13 channel characteristics that are indicators of present channel stability. The 13 characteristics are as follows:

1. Watershed and floodplain activity and impacts
2. Flow characteristics
3. Channel pattern
4. Entrenchment/channel confinement
5. Bed material
6. Bar development
7. Obstructions
8. Bank soil texture and coherence
9. Average bank slope angle
10. Vegetative or engineered bank protection
11. Bank erosion
12. Mass wasting or bank failure
13. Stream crossing alignment with flow

Indicators 4 to 6 are linked to vertical channel stability, whereas indicators 8 to 13 describe lateral stability. Conditions associated with high levels of stability receive Excellent ratings (values between 1 and 3), while those associated with the most unstable behavior are assigned Poor ratings (values between 10 and 12), as shown in Table 6. The 13 indicator scores are summed to produce scores between 13 and 156, yielding an overall assessment of reach stability. Additional judgment is required, as described below, to use the channel's current status in estimating site susceptibility to hydromodification-driven instability or to natural instabilities.

Although the focus of the RSA is on particular sites (reaches), it should be self-evident that channels are embedded in watershed systems. The engineer should strive to view the site in its overall context, and observations made at sites up- and downstream should inform the overall RSA rating in order to reduce spatial bias driven by focus on a short reach (Lagasse et al. 2012). Temporal bias can be reduced by revisiting the site at different times of year to observe flow and channel conditions at both high and low stages.

Susceptibility to hydromodification-driven disturbance is directly related to the spatial context of the channel, which is related to physiographic characteristics (see above). Headwater reaches near watershed divides in steep or mountainous settings may be governed by inputs of wood, landslides, and debris flows, and may be confined within narrow valleys. Lower-gradient, higher-order channels may experience natural cutoffs and meander migration, and floodplains adjacent to these reaches typically invite more intense development. The distance of the reach in question from sources or sinks of water

and sediment is important. Reaches below large wetlands or reservoirs may have dampened high flow peaks and longer, more stable baseflows.

4.2 Preparing for the RSA

An initial assessment of site stability status should be worked up, using evidence available in the office, then revised and completed based on field inspections. The field form (Appendix A) should be completed in the office prior to going to the field, using pencil or other media suitable for revision. The form is set up to accept only two values for the first two indicators (watershed activity and flow characteristics)—one for the reach upstream from the crossing and one for the downstream reach. Only one value is needed for indicator 13 (stream crossing alignment), but the other 10 indicators should be evaluated at regularly-spaced cross sections if possible. When scoring a given cross section, the observer should consider conditions one channel width on either side of the cross section. When scoring the third indicator, channel pattern, conditions for a reach centered on the scored cross section that is several channel widths long should be considered. With training and some experience, RSAs may be completed for very small, simple sites (for example, a 24-inch culvert with unobstructed view of the channel from the crossing) in as little as 0.5 man hours while larger, more complex sites may require up to 4 man hours (Simon and Downs 1995). Preliminary office work will be needed prior to RSA fieldwork, and effort requirements will vary depending on accessibility of the required data and images.

Table 6. Stability Indicators, Descriptions, and Ratings[8]

Stability Indicator	Excellent (1–3)	Good (4–6)	Fair (7–9)	Poor (10–12)
1. Watershed and floodplain activity and impacts	Stable, forested, undisturbed watershed	Occasional minor disturbances in the watershed, including cattle activity (grazing and/or access to stream), construction, logging, or other minor deforestation; limited agricultural activities	Frequent disturbances in the watershed, including cattle activity, landslides, channel sand or gravel mining, logging, farming, or construction of buildings, roads, or other infrastructure; urbanization over significant portion of watershed	Continual disturbances in the watershed. Significant cattle activity, landslides, channel sand or gravel mining, logging, farming, or construction of buildings, roads, or other infrastructure; highly urbanized watershed
2. Flow characteristics	Perennial stream with no flashy behavior	Perennial stream or ephemeral first-order stream[9] with slightly increased rate of flooding	Perennial or intermittent stream with flashy behavior	Extremely flashy; flash floods are prevalent mode of discharge; ephemeral stream other than first-order stream
3. Channel pattern	Straight to meandering with high radius of curvature; primarily suspended load	Meandering, moderate radius of curvature; mix of suspended and bed loads; well-maintained engineered channel	Meandering with some braiding; tortuous meandering; primarily bed load; poorly maintained engineered channel	Braided; primarily bed load; engineered channel that is not maintained
4. Entrenchment/channel confinement	Active floodplain exists at top of banks; no sign of undercutting infrastructure; no levees	Active floodplain abandoned, but is currently rebuilding; minimal channel confinement; infrastructure not exposed; levees, if present, are low and set well back from the river	Moderate confinement in valley or channel walls; some exposure of infrastructure; terraces exist; floodplain abandoned; levees, if present, are moderate in size and have minimal setback from river	Knickpoints visible downstream; exposed water lines or other infrastructure;; deeply confined; no active floodplain; levees, if present, are high and along the channel edge
5. Bed material Fs = approximate fraction of sand in bed sediments	Assorted sizes tightly packed, overlapping, and possibly imbricated; most material >4 mm (0.16 in.) ; Fs<20%, mostly boulders/cobbles/coarse gravel	Moderately packed with some overlapping; very small amounts of material <4 mm (0.16 in.); 20< Fs<50%, mostly cobbles to fine gravel	Loose assortment with no apparent overlap; small to medium amounts of material <4 mm (0.16 in.); 50<Fs<70%, mostly sands	Very loose assortment with no packing; large amounts of material <4 mm (0.16 in.); Fs>70% , mostly fine sand and silt or clay

[8] H = horizontal, V = vertical, Fs = fraction of sand, S = slope (in units of ft/ft), W/D = width-to-depth ratio, with width and depth as defined in glossary.

[9] A small headwater stream that has no tributaries depicted on standard (say, 1:24000 scale) topographic maps.

Table 6. Stability Indicators, Descriptions, and Ratings[8]

Stability Indicator	Excellent (1–3)	Good (4–6)	Fair (7–9)	Poor (10–12)
6. Bar development	For S<0.02 and W/D>12, bars are mature, narrow relative to stream width at low flow, well vegetated, and composed of coarse gravel to cobbles; for S>0.02 and W/D<12, no bars are evident	For S<0.02 and W/D >12, bars may have vegetation and/or be composed of coarse gravel to cobbles, but minimal recent growth of bar is evidenced by lack of vegetation on portions of the bar; for S>0.02 and W/D<12, no bars are evident	For S<0.02 and W/D>12, bar widths tend to be wide and composed of newly deposited coarse sand to small cobbles and/or may be sparsely vegetated; bars forming for S>0.02 and W/D<12	Bar widths are generally greater than half the stream width at low flow; bars are composed of extensive deposits of fine particles up to coarse gravel with little to no vegetation; no bars for S<0.02 and W/D<12
7. Obstructions, including bedrock outcrops, armor layer, LWD jams, grade controls, bridge bed paving, revetments, dikes, vanes, or riprap	Rare or not present	Occasional obstructions, causing cross currents and minor bank and bottom erosion	Moderately frequent and occasionally unstable obstructions, causing noticeable erosion of the channel; considerable sediment accumulation behind obstructions	Frequent and often unstable obstructions, causing a continual shift of sediment and flow; traps are easily filled, causing channel to migrate and/or widen
8. Bank soil texture and coherence	Clay and silt; cohesive material	Clay loam to sandy clay loam; minor amounts of noncohesive or unconsolidated mixtures; layers may exist, but are cohesive materials	Sandy clay to sandy loam; unconsolidated mixtures of glacial or other materials; small layers and lenses of noncohesive or unconsolidated mixtures	Loamy sand to sand; noncohesive material; unconsolidated mixtures of glacial or other materials; layers or lenses that include noncohesive sands and gravels
9. Average bank slope angle (where 90° is a vertical bank)	Bank slopes <3H:1V (18°) in noncohesive or unconsolidated materials, to <1:1 (45°) in clays, bedrock or armored banks, on both sides	Bank slopes up to 2H:1V (27°) in noncohesive or unconsolidated materials, to 0.8:1 (50°) in clays, bedrock or armored banks on one or occasionally both banks	Bank slopes 1H:1V (45°) in noncohesive or unconsolidated materials, to 0.6:1 (60°) in clays, bedrock or armored banks, common on one or both banks	Bank slopes over 45° in noncohesive or unconsolidated materials, or over 60° in clays, bedrock or armored banks, common on one or both banks
10. Vegetative or engineered bank protection	Wide band of woody vegetation with at least 90% density and cover; primarily hardwood, leafy, deciduous trees with mature, healthy, and diverse vegetation located on the bank; woody vegetation oriented vertically; in absence of vegetation, both banks are lined or heavily armored	Medium band of woody vegetation with 70–90% plant density and cover; a majority of hardwood, leafy, deciduous trees with maturing, diverse vegetation located on the bank; woody vegetation oriented 80–90° from horizontal, with minimal root exposure; partial lining or armoring of one or both banks	Small band of woody vegetation with 50–70% plant density and cover; a majority of softwood, piney, coniferous trees with young or old vegetation lacking in diversity located on or near the top of bank; woody vegetation oriented 70–80° from horizontal, often with evident root exposure; no lining of banks, but some armoring may be in place on one bank	Woody vegetation band may vary depending on age and health, with less than 50% plant density and cover; primarily softwood, piney, coniferous trees with very young, old, and dying vegetation and/or monostand vegetation off of the bank; woody vegetation oriented at less than 70° from horizontal with extensive root exposure; no lining or armoring of banks

Table 6. Stability Indicators, Descriptions, and Ratings[8]

Stability Indicator	Excellent (1–3)	Good (4–6)	Fair (7–9)	Poor (10–12)
11. Bank erosion	Little or none evident; infrequent raw banks, insignificant percentage of total bank	Some intermittently along channel bends and at prominent constrictions; raw banks are minor portion of bank in vertical direction	Significant and frequent on both banks; raw banks are large portion of bank in vertical direction; root mat overhangs	Almost continuous cuts on both banks, some extending over most of the banks; undercutting and sod-root overhangs
12. Mass wasting or bank failure	Little or no evidence of potential or very small amounts of mass wasting; uniform channel width over the entire reach	Evidence of infrequent and/or minor mass wasting, mostly healed over with vegetation; relatively constant channel width and minimal scalloping of banks	Evidence of frequent and/or significant occurrences of mass wasting that can be aggravated by higher flows, which may cause undercutting and mass wasting of unstable banks; channel width quite irregular, and scalloping of banks evident	Frequent and extensive mass wasting; considerable potential for bank failure, as evidenced by tension cracks, massive undercuttings, and bank slumping; channel width is highly irregular, and banks are scalloped
13. Stream crossing alignment with flow and distance from stream crossing to upstream meander impact point, and alignment	>150 ft; crossing is well aligned with river flow	75-150 ft; crossing is aligned with flow	50-75 ft; crossing is skewed to flow, or flow alignment is otherwise not centered beneath crossing	<50 ft; crossing is poorly aligned with approaching flow

Source: *Johnson (2006)*

4.2.1 Maps and Aerial Photos

The first step in preparation is to study the project site and its topographic maps (paper or digital). Recent, high-resolution aerial photos should then be consulted (DHIPP). Soil maps are available through Caltrans intranet website http://svctenvims.dot.ca.gov/wqpt/wqpt.aspx, online at websoilsurvey.nrcs.usda.gov and from the California Soil Resource Lab, which provides a Google Earth layer at calsoilresource.lawr.ucdavis.edu. Additional resources for pre-field preparation include as-built plan sheets for existing highways to show existing stream crossings, FHWA bi-annual bridge inspection reports, and in some cases, survey data such as channel cross sections and longitudinal profiles. An inventory of culverts and bridges with preliminary design information is currently (2013) under development by Caltrans.

Using these resources, stream crossings and threshold drainage areas should be delineated as described above. The locations of drainage networks, land use patterns, and existing infrastructure, including storm drainage, should be noted within each TDA. Unless the channel is completely obscured by tree canopy, the planform should be identified and the reach should be classified using the USACE system (1994) (Table 2) and the Montgomery-Buffington system (Table 3). The latter is used on the field form (Appendix A), with channelized or engineered reaches added as an additional classification.

4.2.2 Other Inspections

As noted above, much of the effort required to perform a rapid stability assessment of existing crossings may be eliminated by fully utilizing information obtained under other programs such as the FHWA bi-annual bridge inspection program (http://smi.dot.ca.gov/[10]) or the Caltrans culvert inspection program (http://10.112.5.74/MaintGISApps/culverts/[11]).

4.2.3 Determining Limits of the Representative Reach for Field Data Collection

The NPDES permit states, "The assessment will be conducted within a representative channel reach to assess lateral and vertical stability. A representative reach is a length of stream channel that extends at least 20 channel widths upstream and downstream of a stream crossing. For example, a 20 foot-wide channel would require analyzing a 400 foot distance upstream and downstream of the discharge point or bridge. If sections of the channel within the 20 channel width distance are immediately upstream or downstream of steps, culverts, grade controls, tributary junctions, or other features and structures that significantly affect the shape and behavior of the channel, more than 20 channel widths should be analyzed." For purposes of this manual, we interpret this wording to mean that a minimum total channel length of 40W is to be evaluated—at least 20W upstream and 20W downstream of the crossing. However, as noted above, channel nonuniformity may require adding additional distance to extend the inspected representative reach.

Methods for initial reach delineation are provided in Section 2.2. Initial reach delineation should be done in the office, as described. In some cases, more than one reach should be delineated for a given stream crossing. For example, conditions (CEM class, channel width, depth, bed material, bank height, riparian land use, etc.) may change sharply along the representative reach so that more than one RSA score is needed to adequately describe the channel stability. It may also be efficient to determine locations for 10 cross sections where indicators 3 through 12 will be scored. Assuming the first cross section is placed at the downstream end of the representative reach, subsequent cross sections will be located at intervals of $(W_{down} + L_{crossing} + W_{up})/9$ where W_{down} and $L_{crossing}$ are the lengths of the downstream and

[10] Follow this link, and then select BIRIS (Bridge Inspection Reporting Information System). This is a Caltrans Intranet site, only Caltrans staff will be able to access it.

[11] This is a Caltrans Intranet site, only Caltrans staff will be able to access it.

upstream reaches, representatively (normally at least 20W each) and $L_{crossing}$ is the dimension of the crossing structure in the streamwise direction. For culverts, $L_{crossing}$ will be the length of the culvert.

4.2.4 Plan the Field Trip

A final preparation step is to plan the field trip. In general, field assessments should be performed at low flow so that the channel boundary is visible. However, when there is an opportunity to view the channel during high flows, observations of current velocity, turbulence, eddies, erosion, trash accumulations, etc. can be most revealing. Travel routes and channel access points should be identified prior to the trip; as a result, access agreements with private and public landowners should be secured in advance. If all other factors are equal, the best overview of channel conditions may be gained by walking the representative reach continuously from downstream to upstream. It will be necessary to view both banks, the stream bed, and adjacent riparian zones at several points along the reach. In some cases, for safety reasons the inspection may have to be completed from the bridge, roadway or fence line if the required length of channel is visible from this point. This approach is appropriate for very small culverts where the channel is not contained within the Caltrans right of way. Equipment assembled and packed for the field trip should include a camera, field forms, maps, and aerial photos. A handheld GPS unit or GPS-enabled cell phone may also prove useful. Maps or aerial photos may be marked with field notes. Tape measures or hip chains are useful for measuring distances (e.g., channel width). A safety plan for addressing field work and basic safety considerations should be taken into account: wear suitable shoes and clothing, have cell phones charged and available, and pack sunscreen, water, insect repellent, and local information about hazardous plants and animals. The works of Thorne (1998) and Harrelson et al. (1994), while somewhat dated, are additional sources of information about field assessments and may be consulted in the preparation phase.

4.3 Collecting Information in the Field

4.3.1 Access Safety

The access to the stream reach should be safe for the inspectors, and it is not expected that all locations will be accessed by foot. For example, if the discharge location of a culvert is a cliff, then the RSA should be done with photos or from the guard rail. If streams or rivers are at high flows where they might pose a danger to enter, then assessments should be done from the bank or bridges as appropriate.

4.3.2 Personnel

The field inspection is the core of an RSA. For safety and efficiency, the RSA should be performed by two or three people; safety reasons may dictate additional persons. Because the field visit provides only one “snapshot in time,” a local informant, such as a landowner with many years’ experience in observing the channel, is a valuable addition to the team, and may be considered for inclusion when working potentially unstable sites or larger streams. Personal bias on the part of such informants should be expected. All members should be fully aware of the purpose of the field assessment: to evaluate the susceptibility of the channel reach to instability driven by future hydromodification.

4.3.3 Field Form

The form provided in Appendix A can be used to record information for each site. One person should be charged with responsibility for completing the field form. The site inspection should be regarded as a nearly unique opportunity, so notes should be legible and complete. A photo log with the approximate time, location, and subject of each photo can be extremely valuable. All applicable parts of the form (Appendix A) should be completed. The form may be used in either of two fashions. For larger streams that are potentially unstable, the inspector should record scores for indicators 3 to 12 at up to 10 equally-spaced cross sections along the $\geq$40W-long representative reach. However, for RSA of very small

streams such as those conveyed through small culverts, the engineer may record overall values for reaches up- and downstream of the crossing in the columns on the right side of the form. These two columns may also be used if it is not possible or not safe to access the representative reach on foot. In any event, only overall values are needed for indicators 1 and 2 (watershed development and flow characteristics), and only one value is possible for indicator 13 (Stream crossing alignment with flow and distance from stream crossing to upstream meander impact point). Inspectors may find it useful to duplicate Table 6 and have it available for ready reference while scoring a reach. If the inspection finds differences from the preliminary assessments made using maps or aerial photos in the office, brief explanatory notes should be provided on the form.

4.3.4 Reach Classification

Before detailed notes and photographs are collected, the engineer should verify the stream channel classification that was determined in the office. Table 3 should be used as a guide for assigning channel type, keeping in mind that channelized ("engineered") reaches are assigned to the first category, and that the ultimate goal is to simply assign the reach to one of the three categories shown in Table 5:

- Pool-riffle, plane bed, dune-ripple, and engineered (channelized) channels;
- Bedrock, cascade and step-pool channels; or
- Braided channel.

4.3.5 Stability Indicators

4.3.5.1 Watershed and Floodplain Activity and Impacts

The first indicator has to do with watershed land use. An Excellent rating is reserved for watersheds in pristine condition with natural climax vegetation. The land surface is generally undisturbed by roads, logging, mining, construction, or other types of disturbance. Higher scores are assigned based on the departure of the watershed from such ideal conditions, with emphasis on types of disturbance that produce hydromodification (Table 6). For example, higher scores are assigned to watersheds with steeper slopes, highly erodible soils, landslide potential, or disturbances that are expanding in scope, such as subdivision construction or expanding surface mines. A pristine watershed in Yosemite National Park, which would receive a score of 1 or 2 for this indicator, is shown in the top frame of Figure 12. The middle frame is a channel within the Russian River watershed. Although substantial amounts of forest cover are visible, much of the forest has been cleared and is now grassland. Furthermore, homes and a highway are visible. In order to assign a score for a reach in this area, the entire TDA should be evaluated, but the land use shown would indicate a score in the Good (4 to 6) or Fair (7 to 9) range. The lowest frame shows a watershed disturbed by large-scale grading and construction of condominiums. The ephemeral channel in the center of the frame is choked with sandy sediment. This watershed/floodplain condition would receive a Poor (10 to 12) score. See Example 1 in Appendix B for a case where this indicator received a low score due to a very nonurban setting.

Figure 12. Watershed Examples

From top: excellent, good to fair, and poor watershed and floodplain conditions

4.3.5.2 Flow Characteristics

The second indicator is a measure of stream flow variability when viewed across a year or longer period (Figure 13). Hydromodification tends to reduce the percentage of stream flow that is contributed by shallow groundwater and increase the amount of direct runoff. Accordingly, ephemeral, flashy (rapid rise and fall) hydrographs are given higher (less stable) ratings. Since the field inspection portion of the RSA is typically a one-time event at baseflow, this indicator is best assessed using actual gage data, obtained as described in the section below on Level 2 analysis. In the absence of such data, flow characteristics may be roughly assessed based on the appearance of the channel and its environs when the field inspection is conducted. Channels with stable, perennial flows and no flashy behavior (Table 6) tend to have well-defined, densely vegetated banks.

Although the channel will not be full at baseflow, the bed should be mostly covered with water. Evidence of groundwater contributions (seeps and small springs discharging into the channel, and wet, marshy areas on the floodplain) is often present. Flashy, ephemeral channels tend to be dry or mostly dry, particularly during summer months, with ragged or absent bank vegetation. Fresh trash and debris may be lodged at locations high on the bank or floodplain. Channel incision is often associated with flashy hydrology. See Example 4 in Appendix B for a case where a perennial stream in an urban setting is assigned a score of 8 for this indicator (perennial or intermittent stream with flashy behavior, Table 6) based on gage records and numerous stormwater outfalls.

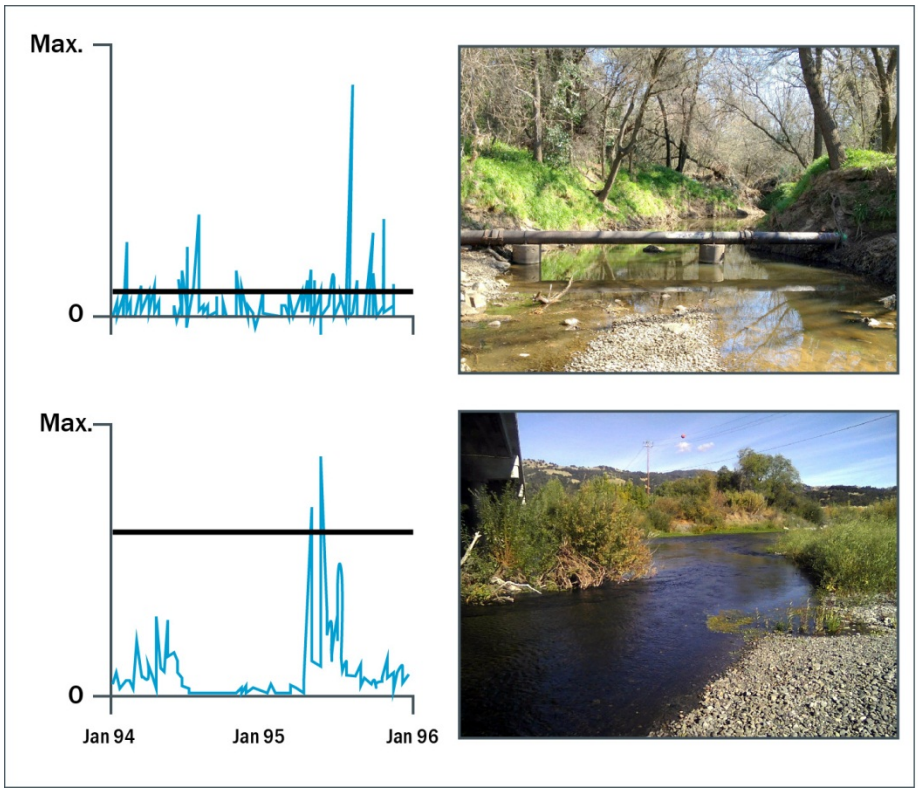

Figure 13. Flow Characteristic Examples

Flashy discharge hydrograph from incised channel in urban area (Top Plot), and hydrograph of perennial stream draining natural area fed by snowmelt, with no flashy behavior (Bottom Plot). Horizontal lines indicate discharge levels that transport the most sediment. Photos to the right of each plot illustrate typical conditions for flashy and stable-flow channels, but are not from the same locations as the hydrographs.

4.3.5.3 Channel Pattern

The third indicator, channel pattern, refers to the planform, or the way the channel appears from above (Figure 14). A wide range of meandering and braided channel patterns have been identified (USACE 1994, Figure 2-11), but herein we classify channels simply as straight, meandering, or braided. A straight channel has roughly parallel top banks, with no major bars evident at baseflow. Note that artificially straightened, channelized, or engineered channels (Table 6) are rated separately from straight channels. A meandering channel has a single thread at baseflow that follows a sinuous course. Typically, the degree of sinuosity is quantified by the ratio of the distance measured along the channel centerline by the straight line distance between the same two points: sinuosity, *P* = channel length/valley length, as shown in Figure 15. The example shown in Figure 15 has a sinuosity of 1.22, which places it on the borderline between straight and meandering and would produce a low (Excellent) score for this indicator. A score of 1 would be reserved for a perfectly straight channel or one with very smooth bends; the presence of two moderate bends in the reach would elevate the score to 3 or possibly 4. Fully meandering channels receive ratings of Good (4 to 6) or Fair (7 to 9) based on channel pattern and sediment load type. Bank stability, radius of bend curvature, and presence of bars are indicators of sediment load type, as shown in Figure 10. Braided channels have multiple interlacing flow threads, and are typically unstable and quite sensitive to hydromodification. Accordingly, braided channels receive Poor (10 to 12) ratings for this indicator. Channels with braided patterns that have flow threads separated by stable, well-vegetated islands are sometimes called anastomosing channels, and may be assigned Good or Fair ratings if they appear to be quite stable. Engineered channels may be rated Good, Fair, or Poor depending on evidence of bed or bank erosion, bank vegetation, and debris accumulations, with well-maintained channels receiving the lowest scores and Good to Excellent ratings. Example 3 in Appendix B is based on an engineered channel that alternates between braiding and single thread meanders based on the water surface elevation and the location along the reach. Scores for individual cross sections varied from 3 to 9, and the site received an overall average score of 5.8.

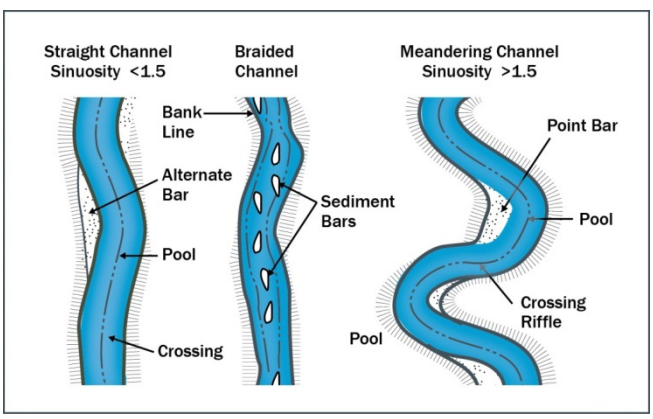

Figure 14. Plan View of Major Channel Patterns

Note that the threshold given in the figure between straight and meandering (P = 1.5) is slightly different than the one used herein (P = 1.25).

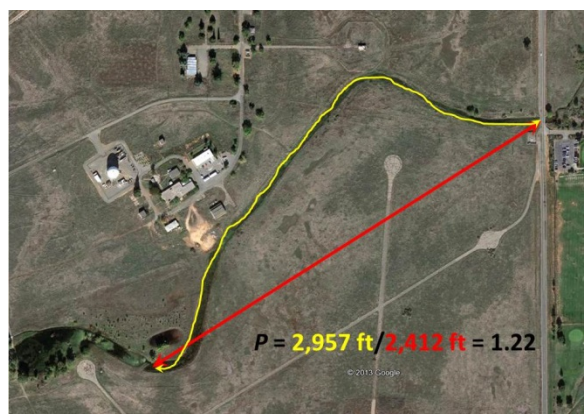

Figure 15. Definition of Channel Sinuosity, P

4.3.5.4 Entrenchment/Channel Confinement

The fourth indicator, entrenchment, or channel confinement, refers to the vertical distance between the bottom of the channel and the adjacent floodplain. Stable alluvial channels typically have an active floodplain at the top of banks and display evidence of overflow that occurs at least biannually. In perennial streams, baseflow water depth is generally ≥ 20% of the average channel depth. The floodplains of stable channels are broad relative to channel width and composed of alluvial soils, or at least have substantial sediment deposits. Evidence of recent downcutting, such as exposed bridge pier footings, exposed (formerly buried) pipelines, perched outfalls, and trees with undermined rootwads, is absent. Such channels receive an Excellent (1–3) rating. Confined or entrenched channels are tightly hemmed in by artificial levees, are constrained by the walls of valleys so narrow that floodplains cannot develop, or have eroded so deeply that they are confined between steep, high banks and rarely, if ever, overflow.

The most common cause of artificial entrenchment is channel incision (downcutting) in response to hydromodifications associated with development. Incision indicators are consistent with the CEM (Figure 7) and include the following (Castro 2003):

- Headcuts—vertical drops or offsets in the channel bed, “waterfalls” at baseflow. Also called knickpoints, a headcut formation is most obvious in streams with cohesive beds and banks (Figure 16) because headcuts remain fairly vertical as they progress upstream, and are thus readily visible. In sand or gravel-bedded rivers, discrete headcuts do not form, and regions of active downcutting may extend over hundreds or thousands of feet (“knickzones”).

Figure 16. Headcut Formed in Cohesive Streambed

- No bars or sediment deposits— erosion of the channel bed down to bedrock or other resistant soil layer. Sometimes banks on both sides of the channel will be near vertical, raw, and eroding (Figure 17).

- Toe of bank is vertical—lack of a sediment facet at the interface between the streambed and banks.
- Cultural features exposed—exposed bridge footings or aprons, exposed pipelines, or perched culverts. However, note that local scour may lower the bed immediately downstream of a culvert without reach-scale channel entrenchment or incision.
- Historical reference—individual accounts, historical photos, and old maps or surveys may indicate incision.
- Lack of pools—long reaches of riffle or run, no pool areas.
- Dead or dying riparian vegetation in drier regions—loss of riparian vegetation due to lowering of shallow aquifer.
- Dewatering of aquifers—effluent from banks and evidence of dewatering from wells and piezometers.
- Upland species encroaching into floodplain—change in moisture conditions resulting in plant community changes. Older individuals of hydrophytic species that initially germinated in frequently flooded zones will now be located high on the banks.
- Trees falling into the channel from both sides for significant reach lengths.
- In perennial flow streams, baseflow water depth will be < 10% of average channel depth.

Additional symptoms related to bridges are noted by FHWA (2009):

- Exposure of bridge substructure elements (e.g. soil stains on piers that are above the existing streambed).
- Exposure of upstream/downstream buried utility crossings or upstream/downstream bridge or culvert substructure elements.
- Headcuts or gullying of tributaries. Also, ditches or tributaries that are "perched," i.e., their inverts are above the main channel bed elevation, are diagnostic of degradation.

Figure 17. Channel Entrenchment Examples

Top: Deeply incised channel with cohesive banks and lacking any sediments in channel bed. Bottom: Non-incised channel with berms or floodplains several times as wide as the channel on both sides. No signs of undercutting infrastructure or oversteepened banks.

Channels that exhibit two or more of the symptoms of incision listed above should be rated Fair or Poor for this indicator. In contrast, channels that receive Excellent ratings (1 to 3) have low banks and broad floodplains that are frequently inundated. Additional indicators of a stable channel include vegetated bars and banks, limited bank erosion, older bridges, culverts and outfalls with inverts at or near grade, no exposed pipeline crossings, and tributary mouths at or near existing main stem stream grade. Channels that receive Good ratings (4–6) do not exhibit periodic connectivity with the active floodplain but do have sediment deposits or low terraces forming within the incised channel, indicating that the floodplain is reforming. Generally, infrastructure is not exposed. Such channels generally correspond to CEM Class V (Figure 7). Poor ratings are assigned to channels that follow characteristics of CEM Class III–IV, or that are tightly and deeply confined by levees or valley walls. Maximum scores (12) should be assigned to reaches that are upstream of advancing headcuts or knickzones. (CEM Class II, Figure 7). See Example 4 for a case where an urban stream gives evidence of moderate, systemic entrenchment with an overall score of 7.8 for this indicator. Example 3 in Appendix B is for a stream that is not deeply incised, but has one cross section just upstream from a knickzone that receives a score of

4.3.5.5 Bed Material

The fifth indicator, bed material, is based on the size of bed sediments and how tightly they are consolidated or interlocked (Figure 18). Table 6 uses the variable Fs, or the fraction of the bed composed of sand, as a key discriminant for this indicator. Strictly speaking, if sand-sized sediment is present on the bed in mixture with other sizes, a sample must be collected and subjected to sieve analysis to generate reliable estimates of Fs. However, for the purposes of an RSA, a simple visual estimate of the fraction of bed surface that is sand is adequate. The engineer should examine the channel from the top bank where it affords an unobstructed view of the bed, or from near the channel centerline, to make this estimate. Each estimate should apply to a given cross section, and an overall average should be determined based on at least 10 cross sections placed at constant spacing along the ≥40W-long representative reach.

Figure 18. Examples of Bed Material

Top: Excellent bed material. Large gravel and cobble, tightly packed. Middle: Good bed material. Writing pen in center for scale. Bed is covered with 10–30 mm (0.4 – 1.2 in.) gravel at this point, but sand appears elsewhere along the cross section (outside the photo). Sediments are only slightly imbricated (overlapped and packed). Bottom: Poor bed material. Coins for scale. 90% sand, D_{50} ~ .20 mm.

Table 6 also frequently refers to the amount of bed material larger or smaller than 4 mm (0.16 in.), the size that corresponds to the boundary between very fine gravel and fine gravel. Channels with bed material that is gravel size and larger receive low scores because of the inherent stability of larger sediments. Finally, the rating of bed material also accounts for the degree of packing, interlocking, overlapping, and imbrication (shingling) of the gravel and cobble sediments. Channels with beds of consolidated silt, clay, or bedrock may be rated Excellent or Good, but the rating should reflect the resistance of the material when subjected to high flows. Zones of active bed erosion (such as headcuts) indicate that the cohesive material is not sufficiently resistant, and should be assigned a Fair or Poor rating. A very soft bed of fine-grained muck or mud should be assigned a Fair or Poor rating. Such sediments may be eroded easily if subjected to higher velocities, and may also indicate that the channel is in a depositional/aggradational state that will tend toward disequilibrium if sediment loading is increased. Refer to Example 1 in Appendix B for a case where coarse bed material results in a very low score for this indicator.

Figure 19. Examples of Bar Development

All sites have slopes < 0.02 ft/ft and W/D > 12. ***Top:*** *Excellent score for bar development as bars are absent or narrow relative to stream width, well vegetated and composed of cobbles.* ***Middle:*** *Fair bar development. Bar is small and sparsely vegetated, comprised of coarse sand, but appears to be partially blocking culvert, lowering score.* ***Bottom:*** *Poor score for bar development as bars are very wide relative to stream width at low flow and little to no vegetation.*

4.3.5.6 Bar Development

Bar development is the sixth stability indicator. Bars, their sediment size, and their vegetation, as described in Table 6, are diagnostic of relative stability (Figure 19). Channels with greatest sensitivity to hydromodification are likely to have large bars composed of sandy sediments with minimal vegetation. It should be noted that bar vegetation can reflect antecedent flow and weather conditions as much as channel stability. Even unstable channel bars may be heavily colonized during droughts by invasive herbaceous species, which will only be washed away during the next high flow.

To apply this indicator, the engineer must estimate whether the channel bed slope (S) is greater than or less than 0.02 ft/ft. The engineer must also estimate whether the ratio of the top width to the average channel depth (W/D) is greater than or less than 12. Channel slope (S) may be estimated using maps or previous surveys, or measured from channel profiles collected using levels, total stations, or survey-grade GPS. Estimates may be generated by dividing the change in elevation between two points on the channel by the horizontal distance (not the straight line distance) between the same two points, measured along the channel. Elevation may be estimated by taking vertical measurements at points of known elevations (such as bridge decks or culvert headwalls). Top width (W) may be determined as described in section 2.2 above. Mean depth (D) is the ratio of channel cross sectional area to top width; this may be estimated at 10 or more equally spaced cross sections above and below the stream crossing, or computed from surveys of several representative cross sections. Different criteria apply for wide (W/D > 12) channels with gradual slopes (S < 0.02 ft/ft) than for steeper, narrower channels. Consult Table 6 for scoring guidelines.

Stream crossings experiencing channel aggradation (vertical accumulation of sediments) should receive poor scores for this indicator. Such crossings often exhibit large sediment accumulations (bars) that may partially occlude bridge openings or pipe or culvert entrances. Aggradation is also associated with localized channel widening, unexpected lateral shifting and may be evident on past bridge inspection reports or when previous surveys are compared with current conditions (FHWA, 2009). Aggradation is driven by changes in watershed land use that elevate sediment yield (e.g., forest fires, logging, construction), excessive sediment delivery from landslides or debris flows upstream or on tributaries, alluvial fan deposits, sediment deposition at the upstream end of a reservoir pool, or accumulation upstream from a culvert or grade control structure (FHWA, 2009). Examples are provided in Appendix B. Example 1 is a perennial stream with ratings of Excellent to Good (average 3.8) for this indicator, while Example 2 is an ephemeral desert wash with bar development scores of 9 to 12 (average 10.4) since the bars are large relative to the channel and support no vegetation.

Figure 20. Examples of Obstructions

Top: Excellent condition for obstruction. Small amounts of vegetation and one piece of metal debris in approach channel to culvert. Middle: Good obstruction. Pipeline crossing (with concrete piers) is only major obstruction in reach, but local deposition and scour caused by obstruction are evident. Bottom: Poor obstruction condition. Railroad bridge crosses channel at an angle so that pile bents are oriented at an angle to approach flow, collecting debris and trash and impacting entire reach. Riprap bank protection and vegetation add minor obstruction. Sediment accumulation downstream from obstruction is evident.

4.3.5.7 Obstructions

This indicator is based on the presence or absence of solid objects that obstruct higher flows (flows approaching bankfull). Examples of flow obstructions include large wood formations, bedrock outcrops, river training dikes, spurs, vanes, barbs or groins, beaver dams, grade control structures or weirs, water intakes or outfalls that project into the flow, and human-made objects such as junked cars (Figure 20). Riprap revetment or bed armor constitutes a minor flow obstruction. Although natural stable channels often feature large wood or rock obstructions that stabilize local sediment deposits and maintain channel alignment, an Excellent rating for this indicator requires that obstructions of all types be rare or absent. Obstructions can deflect flows and promote local scour, particularly if peak flow rates increase. Furthermore, some types of obstructions (such as large wood accumulations) are indicative of upstream erosion. Higher scores for this indicator are warranted when obstructions are associated with in-channel erosion and deposition, and especially when associated with changes in channel alignment. Channels that carry high loads of large wood should receive higher scores for this indicator as the potential for formation of obstructions—either jams in the channel or large wood accumulations on the crossing structure—is significant. Additional detail on forecasting debris loading for highway structures is provided by Lagasse et al. (2012). Example 4 in Appendix B is a complex project in an urban channel that is frequently obstructed by pipes and debris and receives an average score of 9.3 for this indicator.

4.3.5.8 Bank Soil Texture and Coherence

The eighth indicator is based on the texture and coherence of bank soils. Excellent ratings and low scores are assigned to channels with erosion-resistant, cohesive banks, whereas those with unconsolidated sands and gravels receive higher scores because of their sensitivity to the higher and more variable flows associated with hydromodification. It should be noted that, although soil survey maps (available online at websoilsurvey.nrcs.usda.gov) may be useful in the preliminary assessment of this indicator, the soil survey provides information on the floodplain surface only. Field assessment should include examination of both banks at no fewer than 10 cross sections placed at constant spacing along the ≥40W-long reach. When banks are stratified with different types of soils in layers, emphasis should be placed on the weakest layers. When one bank is fronted by a large bar reaching half the bank height, it may be omitted. Example 3 in Appendix B is an urban, channelized stream with very sandy banks that received a score of 11.1 for this indicator.

4.3.5.9 Average Bank Slope Angle

The average bank slope angle is the angle from horizontal of a line running from the point where the streambank and streambed meet to the top of bank. A vertical bank has an angle of 90 degrees.

Stream banks may erode as individual grains or aggregates of soil are removed by water flowing past the bank, or they may fail as large blocks of soil break free and tumble into the channel (mass failure). Bank resistance to mass failure is directly related to soil shear strength and inversely related to bank height and angle. Higher, steeper banks are less stable. Accordingly, scores for this indicator are higher for steeper banks. However, bank angle is not important for very low banks, and even steep banks may be assigned low numerical scores if the bank height is less than about 2 ft. Bank angles should be measured at several cross sections and averaged, but banks may be omitted if they are fronted with large bars reaching half of bank height or more. Angles may be visually estimated, measured from survey cross sections, or measured in the field using a Brunton compass or equivalent. Stability ratings vary with bank soils, as noted in Table 6 and Table 7 (Figure 21). When ratings are different for left and right banks, the higher of the two scores should be recorded. Example 3 is an urban, channelized stream with rather steep banks that received a score of 10 for this indicator.

Table 7. Rating for the Bank Slope Angle Stability Indicator Based on Bank Slope and Bank Soils

Rating	Bank soils	
	Noncohesive or unconsolidated materials	Cohesive soils, armored banks, bedrock
Excellent	<3H:1V (18°)	<1H:1V (45°)
Good	<2H:1V (27°)	<0.8H:1V (50°)
Fair	<1H:1V (45°)	<0.6H:1V (60°)
Poor	>1H:1V (45°)	>0.6H:1V (60°)

Figure 21. Examples of Bank Slope Angle

Top: Excellent score. Average bank slope is 5H:1V, cohesive soils, bank heights ~ 6 ft.

Middle: Good score. Bank soils are silty clay and average angle is 2H:1V.

Bottom: Poor bank slope score. Soils are silty sands, only moderately cohesive and average bank angle >45o, (1H:1V).

4.3.5.10 Vegetative or Engineered Bank Protection

Stable, well-protected banks are less susceptible to erosion due to hydromodification than those already exhibiting signs of stress. Bank protection may consist of artificial structures, such as riprap revetment, or a band of dense, healthy riparian vegetation (Figure 22). Excellent scores are reserved for sites with either (1) both banks protected by intact revetment or lining (asphalt or concrete) or (2) both banks heavily vegetated with erect, mature hardwoods. Departures from these conditions warrant higher numerical scores (Table 6). Scores for this indicator should be determined by examining at least 10 cross sections placed at constant spacing along the >40W-long reach. If vegetation is present, attention should be paid to signs of distress, such as exposure of roots and the orientation of trunks with respect to vertical. Higher scores are assigned to softwoods, coniferous species, and monocultures. In similar fashion, higher scores should be assigned to banks with damaged revetment or other damaged countermeasures. Refer to Example 4 in Appendix B for a case where an overall score of 7.7 was assigned to an urban channel without any engineered bank protection, but a thin but fairly dense band of trees growing at the top of both banks.

4.3.5.11 Bank Erosion

Bank erosion is rated based on its extent along the reach and its severity (Figure 23). Streambank erosion is a natural process, and alluvial channels will exhibit raw (unvegetated) banks in certain locations, especially at elevations below normal baseflow and on the outside of bends. However, when bank condition is assessed for an entire >40W-long reach, stable channels that receive Excellent ratings for bank erosion will exhibit only small areas of active erosion. Poor ratings are associated with near-continuous raw banks, both in a streamwise direction and up and down the bank at a given cross section. Bank vegetation can be a strong indicator of rapid erosion, the engineer should look for undercut root mats and sod. Especially notable are local zones of distress, such

Figure 22. Bank Protection Example

Top: Good score for vegetative or engineered bank protection indicator due to bank stability, partial coverage of banks by woody species, and partial protection of bank with stone. Middle: Fair bank protection. Small band of woody vegetation at top of bank. Trees leaning over channel, root exposures, some riprap at toe of left bank. Bottom: Poor bank protection. Very little woody vegetation along banks, no structural lining or armor.

as gullies that form where runoff flows over the bank, bank scour at obstructions or downstream of channel constrictions, and "pipes" where groundwater emerging from the bank face has created a void that may cave in. Failure blocks along the bank face are evidence of mass wasting and thus geotechnical slope instability, and should be evaluated using the next indicator rather than this one. Example 1 in Appendix B is a site with very stable banks (overall score for this indicator was 2) while Example 4 is an urban, incising channel with frequent raw soil exposures and root mat overhangs that received an overall score of 7.3.

Figure 23. Bank Erosion Examples

Top: Excellent score. Bank erosion limited to insignificant footpath along upper bank due to bedrock and boulders along lower bank. Middle: Good score. Raw area is prominent on right bank, but there are no undercut roots, and much of the bank is well vegetated with herbaceous species. Bottom: Poor score. Almost continuous exposed soil and cuts along both banks.

4.3.5.12 Mass Wasting or Bank Failure

In contrast to the bank erosion described by the previous indicator, mass wasting or bank failure is indicated by the removal of large blocks of material from the bank face (Figure 6 and Figure 24). Mass wasting may occur when portions of the bank are undercut by toe erosion, when banks become so high and steep that they slump or slide, or when subterranean erosion by shallow groundwater works in concert with other processes to weaken a large section of bank that then slumps, caves, or slides. Banks experiencing mass wasting are typically high and steep and composed at least in part of cohesive soils; also, failure blocks are often present along the toe of bank. These failure blocks gradually disintegrate through cycles of wetting and drying, and the resulting smaller particles are removed by high flows. Leaning or fallen trees along the bank are often indicative of mass wasting; in some cases failure blocks may rotate back toward the bank as they fall, causing trees to lean away from rather than toward the channel. Sandy banks do not produce failure blocks, but can experience mass wasting as shallow, planar slides of material when bank toes are undercut. Mass wasting can be a rapid process. Usually banks subject to mass wasting have tension cracks along the top bank that run parallel to the channel 1–3 ft from the bank face. Because mass failures do not occur simultaneously all along a given channel, banks subject to mass wasting often display a scalloped appearance, giving rise to variable top bank widths. Example 2 in Appendix B is an ephemeral, desert wash with unstable banks that exhibited mass wasting in the form of shallow, planar slides.

Figure 24. Examples of Mass Wasting or Bank Failure

Top: Excellent score. Low, well-vegetated banks with no evidence of mass failure. Middle: Fair score. Evidence of frequent and significant mass wasting. Channel width irregular, scalloping of left bank. Presence of bank vegetation slightly reduces score. Bottom: Poor score for mass wasting indicator. High banks with recent failure blocks at toe, regular bank slumping, irregular channel width (not visible from this photo point).

4.3.5.13 Stream Crossing Alignment with Flow

Most stream channels are not straight, and flow forces on banks are typically greatest just downstream of the apex of a bend, at a point that coincides with the intersection of flow lines or the channel centerline at the bend entrance and the bankline (Figure 25). This point is called the meander impact_point, and often corresponds with a zone of rapid bank migration. Meander migration typically occurs in a downvalley direction, so the proximity of upstream impact points to stream crossings is of concern in the RSA. Rapidly migrating bends can impinge on embankments or approaches to bridges or culverts. Tight bends upstream of crossings will produce poor alignments, such that flow must turn sharply to pass through the crossing. Ideally, flow should be aligned so that high-flow vectors pass directly through the bridge or culvert with no redirection or deflection required. The examples presented in Appendix B generated low scores when upstream impact point locations were considered. However, Example 2 presented a complex case of stream channel flow alignment: "although the top bank alignment upstream from the bridge was well aligned, there was a small gully that joined the main channel immediately upstream from the bridge that made a sharp angle with the main channel and a large bar at the confluence of the two channels. A score of 9 was assigned to this indicator.

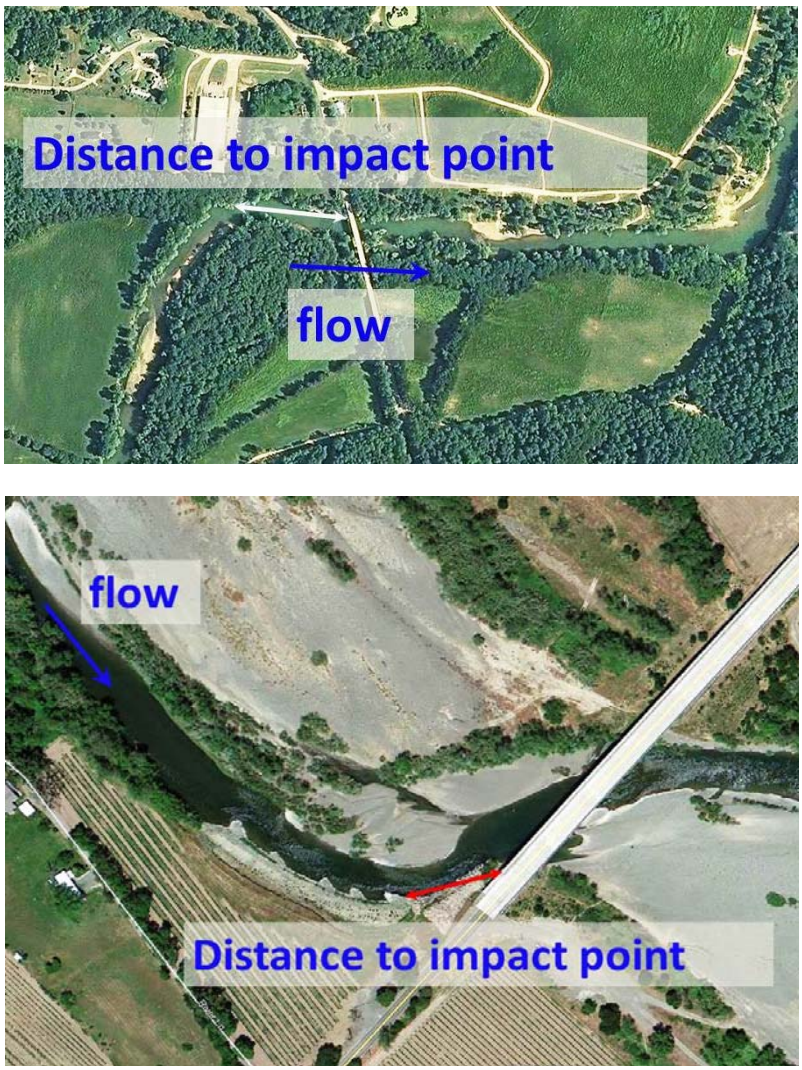

Figure 25. Stream Crossing Alignment with Flow Examples

Distance to impact point is measured starting at the upstream end of crossing and moving upstream to the point of greatest erosional stress on the bank of the first bend. ***Top:*** *This site would receive an excellent score for this indicator, because the impact point is more than 150 ft upstream of the bridge, and the approach channel is only slightly out of line with the bridge opening.* ***Bottom:*** *Poor score for alignment. Crossing is extremely skewed to flow and impact point is quite close to bridge (~100 ft from closest bridge opening). Score is reduced slightly by presence of countermeasures (rock vanes) intended to improve flow alignment.*

4.3.6 Scoring and Categorizing the Site

The total raw score for a given site is determined by summing the scores assigned to each of the 13 indicators. Therefore, the possible range of scores runs from a low of 13 for the least susceptible site to a high of 156 for the most sensitive site. In practice, the range is narrower. For example, Johnson (2006) reported that the scores of channels at 57 bridge sites located in 14 physiographic regions nationwide ranged from 40 to 132. For the most part, the assessment system described herein depends heavily on the assumption that the likelihood that a channel will be destabilized by future hydromodification can be

assessed based on its present condition. Because fluvial systems are highly nonlinear and display threshold types of response behavior, this assumption can be flawed. Accordingly, the engineer is cautioned against making the final assignment of a site to a susceptibility category merely an exercise in addition. The engineer should consider the possibility that a site should be scored as two reaches if conditions change markedly along the reach (e.g., at the crossing site). If one or two indicators are assigned scores that depart strongly from the others, these characteristics should be re-examined and their scores verified. Johnson (2006) provides the following example:

> *Occasionally, rating each of the 13 factors for a particular bridge will result in one factor which stands out as being much higher (worse) than the others. For example, Little Elk Creek received an excellent as the overall rating. All of the assessment factors received scores between 2 and 5, except for the alignment factor (#13). This factor was given a rating of 8 due to the fact that the right abutment of the bridge was located just downstream of the outside of a gentle meander bend. The meander bend appears to be migrating at a very slow rate; this is based on observations that there is undercutting of tree roots on the right bank, but all trees are oriented vertically.*

4.3.6.1 Consider the context and stream type

The presence of impending destabilizing factors, such as a headcut advancing from downstream, ongoing land use changes in the watershed, or failing control practices or structures, should be noted and considered in assigning a final category. Finally, additional sensitivity to the assessment scheme is provided by considering stream channel type when assigning categories (Table 8). The scheme in Table 8 is dependent on the information in Table 4 and Table 5, and considers the typical boundary mobility, lateral migration rate, and propensity for channel avulsion for the three stream types. The final total score should be obtained from Table 8.

Table 8. Overall Scoring of Hydromodification Susceptibility Based on Stream Channel Type

Category	Pool-riffle, plane-bed, dune-ripple, or engineered channels	Cascade or step-pool channels	Braided channels
Excellent	$R < 49$	$R < 41$	N/A
Good	$49 \leq R < 85$	$41 \leq R < 70$	$R < 94$
Fair	$85 \leq R < 120$	$70 \leq R < 98$	$94 \leq R < 129$
Poor	$120 \leq R$	$98 \leq R$	$129 \leq R$

R = final rating

4.3.6.2 Consider the crossing structure

Although the condition of existing bridges or culverts are not explicitly considered in the Johnson (2006) scoring scheme presented here, field inspectors charged with performing RSAs should consult previous inspection reports when preparing for the RSA, and take note of the condition of crossing structures while in the field. Notes regarding structural observations should be added to the bottom of the field form. Existing erosion countermeasures should also be inspected for damage, flanking and overall effectiveness. Unstable crossing structures or countermeasures that are prone to fail will trigger a low RSA score when failure of a crossing structure will trigger release of pollutants just as other forms of hydromodification. Elements of culvert crossings that should be noted are specified by Caltrans (2009), and include items listed in Table 9. Caltrans (2009) contains additional detail and illustrative photographs that are helpful.

Table 9. Factors to Consider in Condition Assessments of Highway Culverts

Component	Characteristic	Condition Rating			
		Excellent	Good	Fair	Poor
All types of material					
Channel	Streambed	Minor debris, scour, or erosion.	Significant debris, minor undermining of end treatment or minor gully embankment.	Channel alignment causing scour holes, ban erosion, and is threatening end treatment. Debris in streambed is causing flooding or diversions. Major erosion of slopes.	End treatment is significantly impacted by poor alignment of channel, bank erosion, scouring, or piping.
	Waterway adequacy	Minor debris and sediment	Significant debris and sediment, less than 25% blockage of design flow	Between 25% and 50% blockage of design flow. Flooding of roadway and/or adjacent properties	Over 50% of design flow. Flooding of roadway and/or adjacent properties.
Concrete					
Barrel	Alignment	Minor settlement and isolated misalignments	Settlement and misalignment throughout. Evidence of leaking joints, with straining at point of leakage. No evidence of infiltration of backfill.	Poor alignment and major settlement causing ponding of water. Dislocated joints allowing backfill to infiltrate culvert barrel. Evidence of piping in the surrounding area.	Severe separation of joints. Backfill into culvert barrel. Integrity of culvert is compromised due to misalignment.
Barrel	Joints	Tight, no openings. Minor cracking and spalling at joints	Joint separation. Significant cracking and spalling at joints	Dislocated joints allowing backfill to infiltrate culvert barrel	Significant separation at joints has compromised integrity of culvert
Barrel	Material	Minor cracking. Minor scaling of invert	Longitudinal cracks between 0.01 and 0.1 inches in width. Invert spalls to 0.25 in. Minor spalling	Longitudinal cracks larger than 0.1 inches in width. Invert scaling larger than 0.6-inches. Major spalling and slabbing with exposed reinforcing steel. Major corrosion of reinforcing steel.	Complete to minor collapse of barrel
Headwall	Material	Minor spalling and cracking. Minor spalling of invert.	Significant spalling with some exposed reinforcing steel.	Major spalling and/or slabbing. Major corrosion of reinforcing steel.	Headwall has failed, is endanger of tipping over, and/or separation from culvert barrel.

Table 9. Factors to Consider in Condition Assessments of Highway Culverts					
Headwall	Shape	Minor settlement of headwall and/or wingwalls (if present).	Major settlement of headwall and/or wingwalls (if present). Still mostly vertical plumb;	Headwall and/or wingwall (if present) out of plumb. Separations of joints between headwall and wingwall.	Headwall and/or wingwalls (if present) out of plumb and is endanger of collapse.
Plastic or Polymer					
Barrel	Material	Minor abrasions.	Heavy abrasions. Some perforations present.	Significant perforations and tears, but no evidence of backfill infiltration	Significant perforations and/or tears allowing backfill to infiltrate culvert barrel.
Barrel	Seams and Joints	Tight, openings. Minor cracking.	Minor separation of joints.	Significant joint separation with piping or infiltration of material.	Significant separation at joints/seams has compromised the integrity of culvert.
Barrel	Shape	Minor isolated distortions in top half. Minor flattening of invert and/or crown. Horizontal diameter is 0% to 10% of design.	Significant distortions throughout crown and/ or invert, Some kinds present. Horizontal diameter 10% to 20% of design.	Major distortions and flattening of crown and/or invert through pipe. Horizontal diameter between 20% and 35% of design.	Complete collapse of crown.
Steel or Aluminum					
Barrel	Material	Superficial rust or corrosion. Minor pitting.	Scattered heavy rusting or corrosion and deep pitting.	Extreme rusting or corrosion and deep pitting. Perforations present.	Significant perforations. Integrity of invert is compromised.
Barrel	Seams and Joints	Tight, no openings. Minor cracking at bolt holes.	Minor separation of joints/seams.	Significant joint separation with piping or infiltration of backfill material into culvert.	Failed
Barrel	Shape	Minor isolated distortions on top half. Minor flattening of invert and/or crown. Horizontal diameter is 0 to 10% of design.	Significant distortion at isolated locations on top half. Significant flattening of invert. Some kinks present. Horizontal diameter 10% to 20% of design.	Major distortions within pipe. Major kinks and deflections. Flattening of crown and/or invert. Horizontal diameter between 20% and 35% of design.	Complete collapse of crown.
Flared end section	Shape	Minor dents and kinks.	Major kinds and dents in flared section and/or apron.	Flared section and/or apron is severely dented and/or kinked, but water flow is not restricted.	Flared end section has separated from culvert barrel. Flared ends and/or apron are bent such that water flow is restricted.

Source: *Adapted from Caltrans 2009*

Bridges should also be assessed when performing an RSA. Many of the indicators described above have direct implications for bridge performance. An excellent brief field guide is provided by FHWA (2009). Evidence of accelerated or unusually large amounts of erosion or deposition adjacent to bridge piers, abutments, or approaches should be noted.

If a score of final rating of “excellent” or “good” is achieved, then the Engineer should implement Design Pollution Prevention and Post Construction Treatment BMPs as planned for the project and described defined in the Storm Water Quality Handbook, Project Planning and Design Guide (PPDG, Caltrans 2010). However, if a rating of “fair” or “poor” is identified, then the Engineer will need to consult with the District Design Storm Water Coordinator and the District Hydraulics Engineer before engaging in further analyses, as described in the following section.

Section 5

Beyond the Rapid Stability Assessment

5.1 Three-level Approach

Unless the initial, rapid assessment indicates very low risk of channel destabilization by the proposed hydromodification (Excellent or Good rating), the rapid assessment should be followed by quantitative analyses using basic hydrologic, hydraulic, and sediment transport engineering concepts. In general, the solution procedure for analyzing stream stability should involve the following three levels of analysis:

Level 1: Application of simple geomorphic concepts and other qualitative analyses to identify potential problems

Level 2: Application of basic hydrologic, hydraulic, and sediment transport engineering concepts

Level 3: Application of mathematical or physical modeling studies

FHWA guidance for evaluating channel stability at stream crossings provides guidance for this three-level approach (Lagasse et al. 2012). The rapid assessment channel stability is a subset of the Level 1 analyses (pp. 5.23-5.33 of Lagasse et al. 2012). A complete Level 1 includes six major steps:

1. Define stream geomorphic characteristics
2. Evaluate historical land use changes
3. Assess overall stream stability. Channel response to several factors is rated as stable, unstable, degrading or aggrading.
4. Evaluate lateral stability using field inspections, aerial photographs, maps and surveys.
5. Evaluate vertical stability using historic surveys, gaging records and other types of data.
6. Evaluate channel response to change using a composite of information developed in the five previous steps and simple predictive geomorphic relationships.

If the results of the rapid assessment indicate that the representative reach is laterally and vertically stable (i.e., a rating of excellent or good) the Department does not have to conduct further analyses and must implement the Design Pollution Prevention Best Management Practices and the Post-Construction Storm Water Treatment Controls in Section E.2.d.

If the results of the rapid assessment indicate that the representative reach will not be laterally and vertically stable (i.e., a rating of excellent or good), the Department must determine whether the instability, in conjunction with the proposed project, poses a risk to existing or proposed highway structures by conducting appropriate Level 2 (and, if necessary, Level 3) analyses. The Department shall follow the Level 2 and 3 analysis guidelines contained in HEC-20 (FHWA,2001) or a suitable equivalent within an accessible portion of the reach. If the results of the appropriate Level 2 (and, if necessary Level 3) analyses indicate that there is no risk to existing or proposed highway structures, the Department must implement the Design Pollution Prevention Best Management Practices and the Post-Construction Storm Water Treatment Controls in Section E.2.d. and document the methodologies used, the results, and the mitigation measures suggested as part of the appropriate Level 2 and, if necessary, Level 3 analyses.

Figure 26. Language from NPDES Permit Explaining when Level 2 and Level 3 Analyses are Required.

A list of specific topics included in the RSA as well as each of the analytical Levels is provided in Table 10 below.

Table 10. Comparison of topics and tools applicable to the rapid stability assessment and Level 1, 2 and 3 analyses

Rapid stability assessment indicators	Level 1	Level 2	Level 3
Watershed and floodplain activity and impacts	Stream reconnaissance	Flood history and rainfall-runoff relations	1D mathematical models
Flow characteristics	Drift accumulation potential	Hydraulic conditions (e.g., velocity, flow depth, top width) for given flow events from previous studies or HEC-RAS	2D mathematical models
Channel pattern	Stream channel classification	Bed and bank material size	physical models
Entrenchment/channel confinement	RSA	Watershed sediment yield and changes due to recent and predicted disturbances	
Bed material	Lane relation	Incipient motion analysis	
Bar development	Planform predictor	Armoring potential	
Obstructions	Regime equations	Evaluation of rating curve shifts	
Bank soil texture and coherence		Evaluate scour conditions	
Average bank slope angle		Predict meander migration rates using map and photo overlays and planform classifications	
Vegetative or engineered bank protection		Equilibrium slope and base level control	
Bank erosion		Sediment continuity (spreadsheet computations)	
Mass wasting or bank failure		1D mathematical models	
Stream crossing alignment with flow			

(Lagasse et al. 2012)

It is important to note that the guidance for rapid assessment provided herein is more prescriptive and specific than the Level 1 approach described by Lagasse et al. (2012), so strict comparison is difficult. The guidance provided by Lagasse et al. (2012) is a “cafeteria” of concepts and methodologies; the user is left to make appropriate selections of approaches for a given situation. In addition to items prescribed herein for rapid stability assessment, the Level 1 analysis may include more work in the office using maps, surveys, gage data and aerial photos to assess lateral and vertical channel stability. Level 1 resources in Lagasse et al. (2012) include two types of field data sheets; an extensive discussion on assessing large wood and drift production, transport and accumulation potential; and instruction on use of the Lane relation, channel planform predictors, and regime equations.

It should be noted that the NPDES permit text (Figure 26) calls for “appropriate” Level 2 analyses. If the Rapid Assessment yields a rating of Poor or Fair, the engineer may take the potential threat channel instability poses to the highway structure into account when selecting the types of Level 2 analyses to conduct. Often highways placed in dynamic fluvial environments (for example, braided channels on alluvial fans in arid or semiarid regions) are designed to be robust in the face of bank erosion, bed degradation or aggradation. An example of a stable structure crossing an unstable channel and appropriate Level 2 analysis is provided as Example 2 in Appendix B below.

5.2 Level 2 Analysis

Level 2 analyses are quantitative treatments of issues or hypotheses raised by the RSA. Expertise in hydraulic engineering (specifically movable bed hydraulics), sediment transport, and fluvial geomorphology is required. A suite of analytical tools is available, and the engineer must select suitable analyses for a given site (Table 10). As noted above, the engineer may take the potential threat channel instability poses to the highway structure into account when selecting the types of Level 2 analyses to conduct. Data requirements vary based on the analyses selected. Lagasse et al. (2012) offer detailed guidance for Level 2 analyses; basic steps include examining the flood history of the site and changes in rainfall-runoff relations with time. Arroyos and other ephemeral streams may be stable for long periods but unstable when subjected to rare high flows, so the history of channel response to previous floods is especially important. An example of Level 2 analysis is provided in Example 2 in Appendix B below. The web resource at http://onramp.dot.ca.gov/hq/design/drainage/training.php[12] may be useful for Level 2 analyses of culverts.

Constructing a disturbance history of the site is an initial step. Time series of aerial photos should be consulted for information regarding the history of disturbances in the TDA, particularly watershed development, land use changes (particularly changes in riparian vegetation), and channel modifications (straightening, widening, placement of bank protection, bridges, dams, weirs, etc.). Time series that span recent decades (ca. 1990–present) are available on Google Earth. Additional information regarding disturbance history may be available from Caltrans files, news accounts of fires, floods and other events and from local informants.

In many cases, it may be useful to assess hydrologic (stream discharge and stage) data available for the stream crossing sites of interest. If gages are present in or adjacent to the reach of interest, the record should be scanned for significant floods and droughts. If stage data are available, the elevation of annual floods should be noted. The California Department of Water Resources (DWR) provides data, graphs, and statistics for gages it maintains, at cdec.water.ca.gov. Local governments and water agencies also have hydrologic data for some sites.

These stream flow data are needed to compute dominant discharge (or bankfull flow), flow duration curves, and flow frequency curves. An online tool (Streamstats) provided by USGS may be used to delineate watersheds, describe watersheds, and generate flow-frequency curves for gauged and ungaged sites. Flow frequency curves are simply tables of flood peak discharge for flows of selected frequency (e.g., 2-, 10-, 25-, and 100-year events). Additional statistics are available for many gaged sites on Streamstats, including flow duration curves that may be helpful in assessing how flashy the hydrograph tends to be. Flow duration curves are tables of discharge values and the corresponding percentage of time a given discharge is equaled or exceeded. If a flow of 10 cubic feet per second (cfs) is matched with a value of 50%, then the stream flow equals or exceeds 10 cfs half of the time.

Following these hydrologic analyses, Level 2 proceeds to hydraulic analyses (computation of flow widths, depths, and velocities for specific return-interval events), which usually involve a one-dimensional model such as HEC-RAS (USACE 2010). Hydraulic data needed include cross section and thalweg profile surveys, channel and bank roughness estimates, channel alignment data, and other data for computing channel hydraulics, including water surface profile calculations. In some cases, hydraulic information may be available from previous studies, such as flood insurance studies.

With outputs from the hydraulic analysis and information about the bed sediment size, sediment transport computations can examine the frequency of bed movement (incipient motion analysis), armoring potential, and local and general scour potential. Analysis of basic sediment transport

[12] This is a Caltrans Intranet site, only Caltrans staff will be able to access it.

conditions requires information on land use, soils, geologic conditions, sediment sizes in the watershed and channel, and measured sediment transport rates, if available.

Additional Level 2 work involves estimating changes in watershed sediment yield under assumed future land use and climatic conditions, as well as examining rating curves, specific gage plots, and thalweg profiles for evidence of reach-scale trends in bed aggradation or degradation. Two-dimensional bank stability analysis tools, such as the BSTEM model (based on an Excel spreadsheet); can be quite powerful and efficient when mass wasting or bank failure is a potential problem. The BSTEM model is available for free download at http://ars.usda.gov/Research/docs.htm?docid=5044&page=1.

5.3 Level 3 Analysis

Level 3 analyses are typically much more costly than Level 2 analyses, so benefits (reduction of uncertainty, impact avoidance) must be weighed against costs. Application of mathematical (computer) and physical model studies requires the same basic data as in Level 2 analysis, but typically in much greater detail. For example, water and sediment routing by mathematical models, or construction of a physical model, requires more detailed channel cross sectional data. Specialized expertise is needed for Level 3, and suitable laboratory facilities are needed for physical model studies. Mathematical models can provide reasonable simulations of flow patterns and sediment transport, including bed scour and deposition at the reach scale. Few models accurately simulate bank erosion, thus lateral channel migration is poorly predicted. Zevenbergen et al. (2012) provide a survey of 1- and 2-dimensional mathematical models available for alluvial river analyses. Physical model studies can sometimes provide better information on complex flow conditions than mathematical models, due to the complexity of the process and the limitations of mathematical models. However, erosion and sedimentation processes are less well represented in physical models. Often the use of both physical and mathematical models can provide complementary information.

Appendix A: Worksheets for Field Assessments of Hydromodification Susceptibility

Field Form for Caltrans Rapid Assessment of Stream Channel Stability and Susceptibilty to Hydromodification Induced Instability

Step 1. Provide Basic Information	Step 2. Check California Physiographic Province		Step 3. Check Stream Type(s)
Date(s):	☐ Modoc Plateau	☐ Coast Ranges	☐ Bedrock
Persons:	☐ Cascade Range	☐ Transverse Ranges	☐ Cascade
Site/Location	☐ Sierra Nevada	☐ Peninsular Ranges	☐ Step-Pool
Conditions:	☐ Klamath Mountains	☐ Mojave Desert	☐ Engineered/channelized
Identify Associated File Locations	☐ Great Valley	☐ Colorado Desert	☐ Plane-Bed
GPS/*.kml	☐ Basin and Range		☐ Pool-Riffle
Photos			☐ Dune-Ripple
Other			☐ Braided

Step 5. Review Resulting Score of Hydromodification Susceptibility (Below) Based on Stream Channel Type

Category	Pool-riffle, Plane-bed, Dune-ripple, Engineered Channels	Cascade or Step-pool Channels	Braided Channels
Excellent	R < 49	R < 41	N/A
Good	49 < R < 85	41 < R < 70	R < 94
Fair	85 ≤ R < 120	70 ≤ R < 98	94 ≤ R < 129
Poor	120 ≤ R	98 ≤ R	129 ≤ R

R = Raw Score

Step 6. Summarize Site Score and Rating

Raw Score ____

Rating _____

Step 4. Enter Stability Indicator Ratings at 10 Equally-Spaced Cross Sections

	Stability Indicators (Below) and Cross Section (XS) Numbers (Right)	1	2	3	4	5	6	7	8	9	10	Overview Entire Reach: Upstream	Overview Entire Reach: Downstream	Score for Reach		Notes by Cross Section
	GPS shot? (check boxes for XS where GPS coordinates recorded) >>	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐				2	
1	Watershed and floodplain activity and impacts	Evaluate at watershed-scale for upstream and downstream reaches >													3	
2	Flow characteristics	Evaluate at watershed-scale for upstream and downstream reaches >													4	
3	Channel pattern														5	
4	Entrenchment/channel confinement														6	
5	Bed material														7	
	Fs = approximate percentage of sand in bed sediments, 0 to 100.														8	
6	Bar development														9	
7	Obstructions, including bedrock outcrops, armor layer, LWD jams, grade controls, bridge bed paving, revetments, dikes, vanes, or riprap.														10	
8	Bank soil texture and coherence														11	
9	Average bank slope angle														12	
10	Vegetative or engineered bank protection														13	
11	Bank erosion														14	
12	Mass wasting or bank failure														U/S	
13	Stream crossing alignment with flow and distance from stream crossing to upstream meander impact point.	Evaluate only for upstream approach >													D/S	

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Stability indicators, descriptions, and ratings (Table 6 repeated here for field use)				
Stability Indicators	Excellent (1–3)	Good (4–6)	Fair (7–9)	Poor (10–12)
1. Watershed and floodplain activity and impacts	Stable, forested, undisturbed watershed	Occasional minor disturbances in the watershed, including cattle activity (grazing and/or access to stream), construction, logging, or other minor deforestation; limited agricultural activities	Frequent disturbances in the watershed, including cattle activity, landslides, channel sand or gravel mining, logging, farming, or construction of buildings, roads, or other infrastructure; urbanization over significant portion of watershed	Continual disturbances in the watershed; significant cattle activity, landslides, channel sand or gravel mining, logging, farming, or construction of building, roads, or other infrastructure; highly urbanized or rapidly urbanizing watershed
2. Flow characteristics	Perennial steam with no flashy behavior	Perennial stream or ephemeral first-order stream with slightly increased rate of flooding	Perennial or intermittent stream with flashy behavior	Extremely flashy; flash floods are prevalent mode of discharge; ephemeral stream other than first-order stream
3. Channel pattern	Straight to meandering with low radius or curvature; primarily suspended load	Meandering, moderate radius of curvature; mix of suspended and bed loads; well-maintained engineered (channelized) channel	Meandering with some braiding; tortuous meandering; primarily bed load; poorly maintained engineered channel	Braided; primarily bed load; engineered channel that is not maintained
4. Entrenchment/channel confinement	Active floodplain exists at top of bank; no sign of undercutting infrastructure; no levees	Active floodplain abandoned, but is currently rebuilding; minimal channel confinement; infrastructure not exposed; levees, if present, are low and set well back from the river	Moderate confinement in valley or channel walls; some exposure of infrastructure; terraces exist; floodplain abandoned; levees, if present, are moderate in size and have minimal setback from the river	Knickpoints visible downstream; exposed water lines or other infrastructure; channel-width-to-top-of-banks ratio small; deeply confined; no active floodplain; levees, if present, are high and along the channel edge
5. Bed material Fs = approximate fraction of sand in bed sediments	Assorted sizes tightly packed, overlapping, and possibly imbricated; most material >4 mm (0.16 in.). Fs<20%	Moderately packed with some overlapping; very small amounts of material <4 mm (.16 in); 20<Fs<50%	Loose assortment with no apparent overlap; small to medium amounts of material <4 mm (0.16 in.); 50<Fs<70%	Very loose assortment with no packing; large amounts of material <4 mm (0.16 in.); Fs>70%

Stability indicators, descriptions, and ratings (Table 6 repeated here for field use)				
Stability Indicators	Excellent (1–3)	Good (4–6)	Fair (7–9)	Poor (10–12)
6. Bar development. Note slope (S) units are ft/ft.	For S<0.02 and W/D>12, bars are mature, narrow relative to stream width at low flow, well vegetated, and composed of coarse gravel to cobbles; for S>0.02 and W/D<12, no bars are evident	For S<0.02 and W/D>12, bars may have vegetation and/or be composed of coarse gravel to cobbles, but minimal recent growth of bar is evidenced by lack of vegetation on portions of the bar; for S>0.02 and W/D<12, no bars are evident	For S<0.02 and W/D>12, bar widths tend to be wide and composed of newly deposited coarse sand to small cobbles and/or may be sparsely vegetated; bars forming for S>0.02 and W/D<12	Bar widths are generally greater than half the stream width at low flow; bars are composed of extensive deposits of fine particles up to coarse gravel with little no vegetation; no bars for S<0.02 and W/D>12
7. Obstructions, including bedrock outcrops, armor layer, LWD jams, grade controls, bridge bed paving, revetments, dikes, vanes, or riprap	Rare or not present	Occasional obstructions, causing cross currents and minor bank and bottom erosion	Moderately frequent and occasionally unstable obstructions, causing noticeable erosion of the channel; considerable sediment accumulation behind obstructions	Frequent and often unstable obstructions, causing a continual shift of sediment and flow; traps are easily filled, causing channel to migrate and/or widen
8. Bank soil texture and coherence	Clay and silty clay; cohesive material	Clay loam to sand clay loam; minor amounts of noncohesive or unconsolidated mixtures; layers may exist, but are cohesive materials	Sandy clay to sandy loam; unconsolidated mixtures of glacial or other materials; small layers and lenses of noncohesive or unconsolidated mixtures	Loamy sand to sand; noncohesive material; unconsolidated mixtures of glacial or other materials; layers or lenses that include noncohesive sand and gravels
9. Average bank slope angle (where 90° is a vertical bank)	Bank slopes <3H:1V (18°) in noncohesive unconsolidated materials, to <1:1 (45°) in clays, on both sides	Bank slopes up to 2H:1V (27°) in noncohesive or unconsolidated materials, to 0.8:1 (50°) in clays, on one or occasionally both banks	Bank slopes to 1H:1V (45°) in noncohesive or unconsolidated materials, to 0.6:1 (60°) in clays, common on one or both banks	Bank slopes over 45° in noncohesive or unconsolidated materials, or over 60° in clays, common on one or both banks
10. Vegetative or engineered bank protection	Wide band or woody vegetation with at least 90% density and cover; primarily hardwood, leafy, deciduous trees with mature, healthy, and diverse vegetation located on the bank; woody vegetation oriented vertically; in absence of vegetation, both banks are lined or heavily armored	Medium band of woody vegetation with 70–90% plant density and cover. A majority of hardwood, leafy, deciduous trees with maturing, diverse vegetation located on the blank. Woody vegetation oriented 80–90° from horizontal with minimal root exposure. Partial lining or armoring of one or both banks	Small band of woody vegetation with 50–70% plant density and cover; a majority of softwood, piney, coniferous trees with young or old vegetation lacking in diversity located on or near the top of bank; woody vegetation oriented at 70–80° from horizontal, often with evident root exposure; no lining of banks, but some armoring may be in place on one bank	Woody vegetation band may vary depending on age and health, with less than 50% plant density and cover; primarily softwood, piney, coniferous trees with very young, old, and dying vegetation and/or monostand vegetation located off of the bank; woody vegetation oriented at less than 70° from horizontal with extensive root exposure; no lining or armoring of banks

Stability indicators, descriptions, and ratings (Table 6 repeated here for field use)				
Stability Indicators	Excellent (1–3)	Good (4–6)	Fair (7–9)	Poor (10–12)
11. Bank erosion	Little or none evident; infrequent raw banks, insignificant percentage of total bank	Some intermittently along channel bends and at prominent constrictions; raw banks are minor portion of bank in vertical direction	Significant and frequent on both banks; raw banks are large portion of bank in vertical direction; root mat overhangs	Almost continuous cuts on both banks, some extending over most of the banks; undercutting and sod-root overhangs
12. Mass wasting or bank failure	Little or no evidence of potential or very small amounts of mass wasting; uniform channel width over the entire reach	Evidence of infrequent and/or minor mass wasting; mostly healed over with vegetation; relatively constant channel width and minimal scalloping of banks	Evidence of frequent and/or significant occurrences of mass wasting that can be aggravated by higher flows, which may cause undercutting and mass wasting of unstable banks; channel width quite irregular, and scalloping of banks evident	Frequent and extensive mass wasting; considerable potential for bank failure, as evidenced by tension cracks, massive undercutting, and bank slumping; channel width is highly irregular, and banks are scalloped
13. Stream crossing alignment with flow and distance from stream crossing to upstream meander impact point.	>150 ft; crossing is well aligned with river flow	75-150 ft; crossing is aligned with flow	50-75 ft; crossing is skewed to flow, or flow alignment is otherwise not centered beneath crossing	<50 ft; crossing is poorly aligned with flow

H = horizontal, V = vertical, Fs = fraction of sand,

S = slope, W/D = width-to depth-ratio

Appendix B: Examples

Example 1: North Fork American River near Auburn B-3
Example 2: Route 66 Wash near Ludlow B-13
Example 3: Murietta Creek at Main Street, Temecula B-27
Example 4: Arcade Creek in Citrus Heights B-41
Example 5: Placer County Road 193 Simple Culvert B-53

Example 1: North Fork American River near Auburn

This example is only loosely based on reality, the reader should be aware that some aspects of the example data are fictional and have been created for instructional purposes only. Placer County Road 49 (also known as State Route 193, The Golden Chain Highway) crosses the North Fork American River via a bridge at Post Mile 0.2, 38°54'55.74"N, 121° 2'25.89"W, about 2.3 miles northeast from Auburn, California (Figure B1.1). This location is in the Sierra Nevada physiographic subregion. The confluence of the North and Middle Forks of the American River is just 1,000 ft upstream from the bridge, and North Fork flows are regulated by North Fork Dam, which is about 5,000 ft upstream from the bridge (Figure B1.2). The project in question includes pavement of a 0.9-mile-long segment of access road located on the right bank of the Middle Fork starting about 0.5 mile upstream from the bridge. The net new impervious surface for the project is about 3 acres, including a small parking lot. Although not reflected in the narrative below, actual effort for an RSA for a situation such as this one where the stream crossing is a bridge may be reduced by using information obtained through the biannual federal bridge inspection program.

Preparing for field work

Initial steps in the stability assessment were performed in the office using maps, aerial photographs and file data.

Determining average channel width

Since the new road will drain into the river upstream from the bridge, the threshold drainage area (TDA) associated with this project was defined by locating a point 20 channel widths (20W) downstream from the bridge. Channel width was defined by computing the average of the widths of 10 cross sections measured on aerial photographs using visual cues such as tree lines and colors of soil and rock to define top of banks. An initial estimate of W was 350 ft. The 10 cross sections were located at roughly equal intervals between a point about 20W (7,000 ft) downstream from the bridge and 20W (7,000 ft) upstream. The average top width of the 10 cross sections was 357 ft, so a top width of 360 ft was adopted for analysis, and 20W = 7,200 ft. The 20W distance was measured along the centerline of the river channel on aerial photographs, resulting in an endpoint of 38°53'59.91"N, 121° 3'11.31"W (Figure B1.3).

Defining the threshold drainage area

The TDA was then defined as the watershed draining to this point using Arc Hydro software and the sub-basin data from the National Hydrography Dataset (http://nhd.usgs.gov/), confirmed using the Streamstats online tool (http://streamstats.usgs.gov/california.html). A map of the TDA is shown in Figure B1.4, and output from Streamstats is provided in Figure B1.5. Following definition of the TDA, the location of the project relative to the TDA was confirmed: in this case, the entire project area is within the TDA. A rapid assessment is required if any impervious portion of the project is located within a TDA. It is apparent that the small size of the area of new impervious surface (~3 acres) relative to the size of the TDA (967 square miles or 619,000 acres) means that hydromodification impacts of this project will be undetectable.

Setting endpoints for the representative reach

The NPDES permit states, “The assessment will be conducted within a representative channel reach to assess lateral and vertical stability. A representative reach is a length of stream channel that extends at least 20 channel widths upstream and downstream of a stream crossing.” For purposes of this manual, we interpret this wording to mean that a total channel length of 40W is to be evaluated—roughly 20W upstream and 20W downstream of the crossing.

However, channel nonuniformity may require adding additional distance to extend the inspected representative reach. In the case of this site, there is a major confluence (tributary junction) about 900 ft or 2.5W upstream from the bridge, and there is another bridge located about 3W downstream. The permit states, "If sections of the channel within the 20 channel width distance are immediately upstream or downstream of steps, culverts, grade controls, tributary junctions, or other features and structures that significantly affect the shape and behavior of the channel, more than 20 channel widths should be analyzed." For purposes of this manual, we interpret this to mean that the representative reach should extend at least 5 to 7W past the feature(s) in question. If we designate a representative reach that starts 20W downstream from the bridge and extends 20W upstream from the bridge (on the Middle Fork, since that is where the project is located), the upstream end of the representative reach will be about 17.5W upstream from the tributary junction, and the downstream end of the reach will be 17W downstream from the second bridge. This should be adequate. Therefore the representative reach will be 20W = 7,200 ft long, centered on the bridge. For field work, the locations of five equally-spaced cross sections downstream from the bridge and an equal number of cross sections upstream from the bridge were marked on a map and saved as waypoints in a GPS. Since W = 360 ft, these stations were located about 7,200 ft, 5,760 ft, 4,320 ft, 2,880 ft, and 1,440 ft from the bridge, measured along the channel centerline.

Stream classification

The channel is tightly confined by steep valley walls and flows on a bed of angular boulders and cobble. Large wood is absent. The channel has a single-thread, meandering planform with low sinuosity. Referring to Table 2, the US Army Corps of Engineers classification system, this channel has some of the characteristics of a mountain torrent (large boulders, debris, relatively steep slope) and some characteristics of a meandering alluvial river (meandering planform). Upstream dams regulate flow, so the type "Regulated Streams," also applies. By comparing the appearance of the stream with Table 3, the stream was classified as step-pool (Table B.1), meeting all of the criteria for that classification except for the average bed slope. This classification places the reach in the second of the three categories (bedrock, cascade and step-pool reaches) that are used to interpret the assessment score.

Table B1.1. Application of Table 3[a] to Example Site 1

	Cascade	Step-pool	Plane-Bed	Pool-Riffle	Dune-Ripple	Braided	Bedrock
Typical bed material	Boulder	Cobble, boulder	Gravel, cobble	Gravel	Sand	Variable	N/A
Bedform pattern	None	Vertically oscillatory	None	Laterally oscillatory	Multilayered	Laterally oscillatory	N/A
Reach type	Transport	Transport	Response	Response	Response	Response	Transport
Dominant roughness elements	Grains, banks	Bedforms, grains, large woody debris (LWD), banks	Grains, banks	Bedforms, grains, LWD, sinuosity, banks	Sinuosity, bedforms	Bedforms	Boundaries
Dominant sediment sources	Fluvial, hill slope, debris flow	Fluvial, hill slope, debris flow	Fluvial, bank failure, debris flows	Fluvial, bank failure, inactive channel, debris flows	Fluvial, bank failure, inactive channel	Fluvial, bank failure, debris flow	Fluvial, hill slope, debris flow
Sediment storage elements	Lee and stoss sides of flow obstructions	Bedforms	Overbank, inactive channel	Overbank, bedforms, inactive channel	Overbank, bedforms, inactive channel	Overbank, bedforms	N/A
Typical slope, ft/ft	0.08 < S < 0.30	0.03 < S < 0.08	0.01 < S < 0.03	0.001 < S < 0.02	S < 0.001	S < 0.03	Variable

Table B1.1. Application of Table 3[a] to Example Site 1							
	Cascade	Step-pool	Plane-Bed	Pool-Riffle	Dune-Ripple	Braided	Bedrock
Typical confinement by valley walls	Confined	Confined	Variable	Unconfined	Unconfined	Unconfined	Confined
Pool spacing (channel widths)	< 1	1 to 4	None	5 to 7	5 to 7	Variable	Variable

Note: *Highlighted entries show characteristics for Example 1.*

[a] *Montgomery-Buffington Stream Classification System, from Johnson (2006)*

Watershed and floodplain activity and impacts

The watershed is stable, 68% forested and largely undeveloped. Only 0.3% of the area was under impervious cover as of 2001. However, there is virtually no floodplain since the channel is tightly confined in a narrow valley, and some slope failures or mass wasting of slopes into the channel likely occur. Accordingly, a value of 2 was assigned to the "Watershed and floodplain activity and impacts" indicator (Figure B1.6).

Flow characteristics

The size of the watershed indicates that the flow characteristics are best described as "Perennial stream with no flashy behavior," and the presence of upstream flow regulation dictates a value of 2 for that indicator.

Field evaluations

The remainder of the rapid assessment was conducted in the field. Upon arriving at the site, the stream classification and other evaluations determined in the office were verified. The RSA team then proceeded to the downstream end of the representative reach (20W downstream from the bridge) and walked the channel. Notations regarding stability indicators 3-12 were made at each of five equally-spaced locations downstream and upstream from the bridge. For example, downstream from the bridge, the team stopped and filled in the check form at cross sections located 7,200 ft, 5,760 ft, 4,320 ft, 2,880 ft, and 1,440 ft from the bridge. Although no sections were adjacent or close to the bridge, special attention was paid to entrance and exit conditions at the bridge and the field team looked for evidence of bed degradation and flow obstruction at both bridges in the reach.

Channel pattern

Channel pattern throughout the reach was straight to meandering with a high radius of curvature (Figure B1.3). Sinuosity for the entire reach was measured on aerial photography to be only 1.1. No braiding was noted. However, the Johnson scheme calls for "primarily suspended load" for an "Excellent" rating for this indicator, and the bed and bank material in the reach is so coarse that it is unlikely that transport in this channel is primarily suspended. Nevertheless, all other aspects of the channel pattern merit a score of 2, so all cross sections were assigned a score of 2 for this indicator (Figure B1.6).

Entrenchment/channel confinement

As noted above, the representative reach is confined by steep valley walls with essentially no floodplain (Figure B1.7). The valley is slightly wider in the vicinity of the North Fork/Middle Fork confluence. There were no knickpoints were noted anywhere along the representative reach. All cross sections were assigned a score of 9 for this indicator except for the first one upstream from the bridge which was assigned a score of 7 (Figure B1.6).

Bed material

Bed material for this reach is comprised of boulders, cobble and some gravel with almost no sand or finer material (Figures B1.1 and B1.8). Bedrock controls were evident at several cross sections. Although it was large, the granular material (gravel and cobble) was not tightly packed or overlapped. Bed material at each cross section received scores between 1 and 4 (Figure B1.6).

Bar development

Straight sections of the representative reach have very little in the way of bar deposits, but there are sparsely vegetated point bars in bends, particularly upstream from the bridge. Scores for bar development depend upon the average channel slope and the ratio of channel width to channel depth. As noted above, the average bed slope for the representative reach is about 0.002, which is less than the 0.02 criteria used in the scoring scheme (Table 6). The average channel width was estimated to be 360 ft, but it is difficult to estimate an alluvial channel depth due to the confinement of the channel in a narrow gorge. It seems safe to say that W/D < 12 due to the depth of the valley, however. An Excellent score for this indicator requires bars be, "mature, narrow relative to stream width at low flow, well vegetated....," while the Good description states that bars, "may have vegetation and/or be composed of coarse gravel to cobbles, but [show evidence of] minimal recent growth...". Using some judgment, cross sections with no bars (Figure B1.1) were assigned scores of 2 because the lack of bar deposits coupled with the immobile boundary (bedrock and large boulders) indicated that these sections were extremely stable. Sections crossing or very close to bars (Figure B1.8) were assigned scores of 5. This yielded an average score of 3.8 for the reach (Figure B1.6).

Obstructions

The criteria for this indicator result in higher scores for sections that have any type of flow obstruction, including bedrock outcrops, armor layer, LWD jams, grade controls, bridge bed paving, revetments, dikes, vanes, or riprap. The RSA team noted bedrock outcrops, large boulders and a second bridge in the representative reach. The large, partially vegetated bar in the bend about 2,800 ft upstream from the bridge produced a score of 4; a similar score was assigned for the cross section just upstream from the bridge that crosses the channel downstream from the Placer 49 bridge. Banks downstream from the bridge were frequently comprised of boulders or bedrock outcrops, but these offered little obstruction to flow; scores for these sections were 2. The average score for this indicator was 2.7 (Figure B1.6).

Bank soil texture and coherence

With few exceptions, bank soils in the representative reach were judged to be highly resistant to erosion and quite stable. Bank toes and lower banks were often comprised of bedrock or large boulders, and soils above the mid bank elevation were often cohesive materials. Excellent ratings (1 or 2) were assigned to such cross sections (Figure B1.1). Banks fronted by large bars cobbles and gravel such as those just upstream from the bridge were assigned Excellent to Good ratings (3 or 4). The average score for this indicator was 2.2 (Figure B1.6).

Average bank slope angle in degrees

The scoring scheme for the bank slope indicator requires that the bank soils and bank slopes be considered. Banks comprised of cohesive soils, armor or bedrock may be as steep as 1H:1V and still receive Excellent scores. Bank slopes within the representative reach tend to be quite steep due to the confinement of the channel in a narrow valley. Exceptions occur where bars have formed, but most of the banks are steeper than 1H:1V and thus were scored only Good (4-6). The average score for this indicator was 4.4 (Figure B1.6).

Vegetative or engineered bank protection

No engineered bank protection was found within the representative reach. However, banks for several cross sections were comprised of bedrock or large boulders or were heavily vegetated with trees. Bank vegetation and presence of natural armor varied a good bit from cross section to cross section. Scores ranged from 2 to 7 and averaged 3.2 for the reach (Figure B1.6).

Bank erosion

No significant bank erosion was observed at any cross section. All cross sections received a score of 2 for this indicator.

Mass wasting or bank failure

Although it is likely that the steep slopes comprising the valley walls fail into the channel from time to time, no evidence of such failures was noted within the representative reach. Scores of 1 for this indicator were assigned to each cross section.

Stream crossing alignment

The stability indicator referred as, “Stream crossing alignment with flow and distance from stream crossing to upstream meander impact point” was evaluated by locating the impact point for the concave bank of the bend immediately upstream from the bridge on aerial photoimagery. The impact point corresponds to the intersection of a line drawn at the channel centerline at the upstream bend entrance and the outside of the bend. In the case of this site, there is a prominent boulder or bedrock outcrop at this point and the turbulence associated with flow around this obstruction is easy to see on recent aerial photos (Figure B1.9). The distance from this point to the upstream center of the bridge was measured on aerial photos and was found to be 250 ft, which calls for an Excellent rating. Due to the fact that the bend upstream from the bridge is very sharp, a score of 2 rather than 1 was assigned.

Scoring and Categorizing the Site

The total raw score for a given site is determined by summing the scores assigned to each of the 13 indicators, so the raw score for this site is 38. This score is less than any of those published by Johnson (2006), who reported that the scores of channels at 57 bridge sites located in 14 physiographic regions nationwide ranged from 40 to 132. As noted above, the likelihood that the addition of 3 acres of new impervious area to such a large watershed would modify the site hydrology or impact channel or structural stability is remote. Furthermore, the RSA has shown that the site is currently stable due to the presence of erosion-resistant boundary materials such as boulders, cobbles and bedrock even though the channel is tightly confined within its valley.

Application of the stream classification (step-pool channel) for interpretation of the raw score (Table 8) yields an RSA overall rating of Excellent since the raw score < 41.

Figure B1.1. Placer-49, PM 0.2. Bridge over North Fork American River.

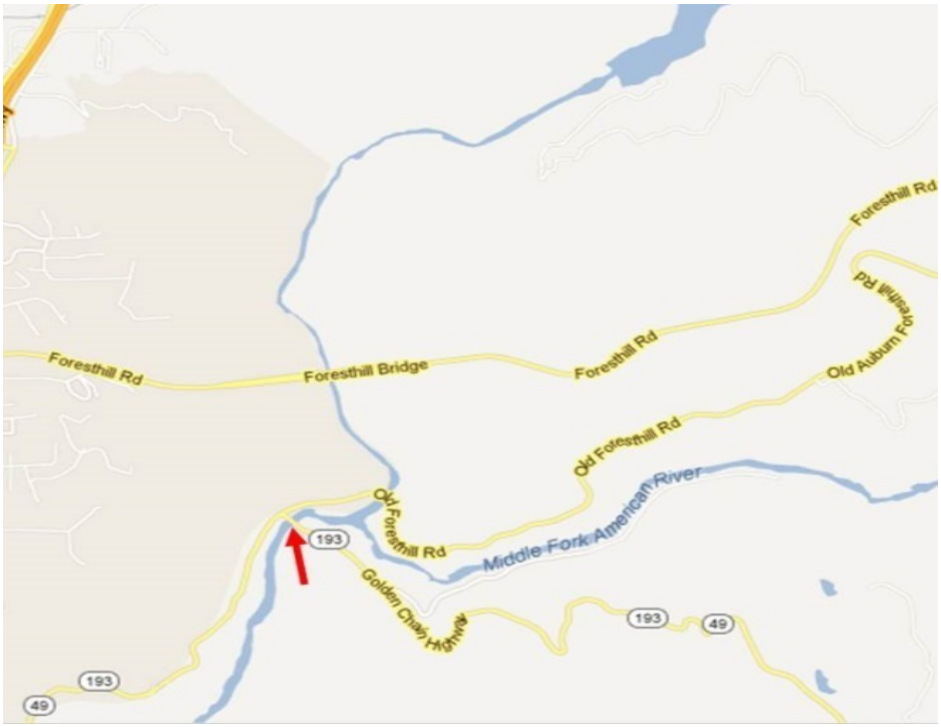

Figure B1.2. Example 1 site map. Red arrow shows bridge location. Gray curve above label for "Middle Fork American River" shows approximate location of new impervious area.

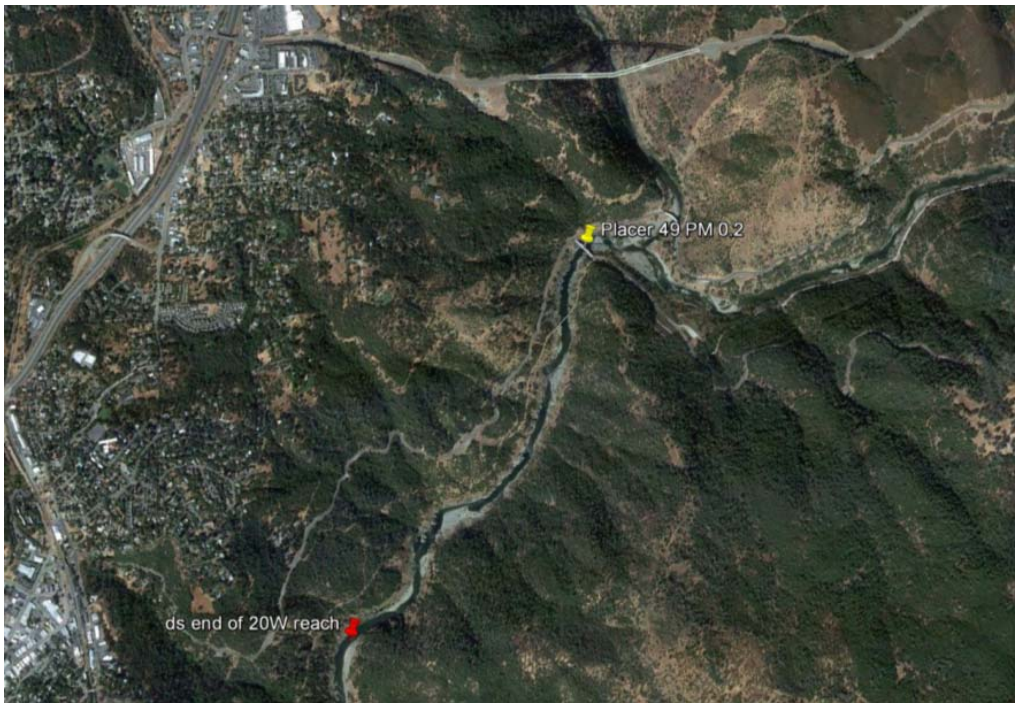

Figure B1.3. Location of point for delineation of threshold drainage area.

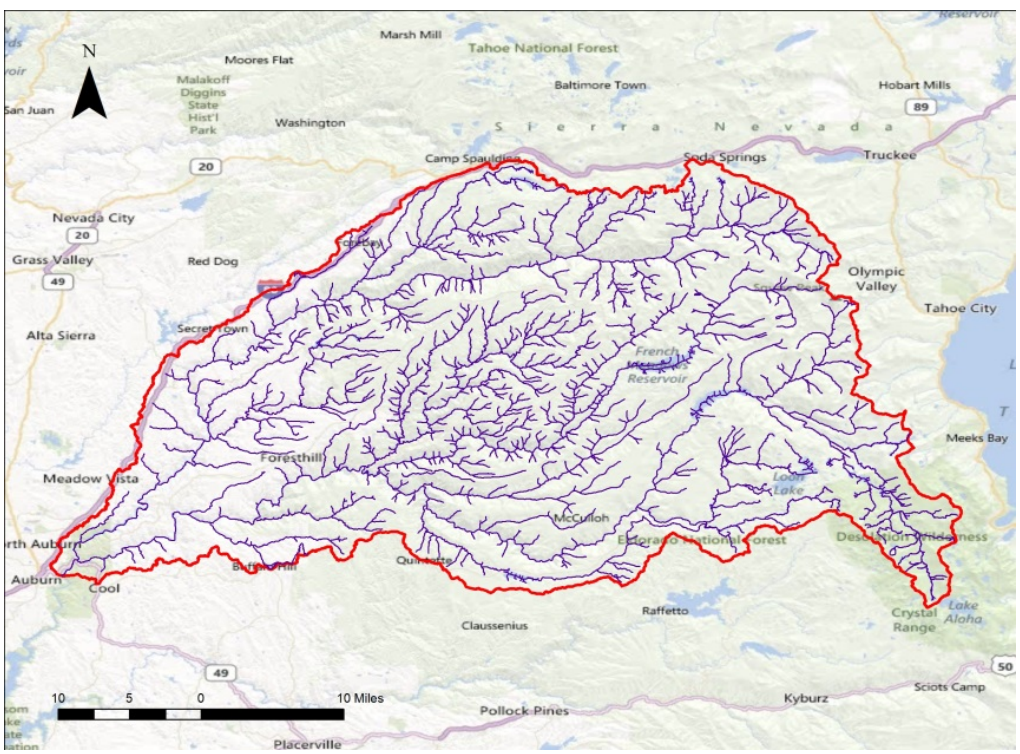

Figure B1.4. Threshold drainage area, Example 1.

USGS
California StreamStats

Basin Characteristics Report

Date: Wed Apr 17 2013 10:12:35 Mountain Daylight Time
NAD27 Latitude: 38.8997 (38 53 59)
NAD27 Longitude: -121.0524 (-121 03 09)
NAD83 Latitude: 38.8996 (38 53 59)
NAD83 Longitude: -121.0534 (-121 03 12)

Parameter	Value
Area, in square miles	966.9
Mean annual precipitation, in inches	59.8
Average maximum January temperature, in degrees Fahrenheit	46.4
Average minimum January temperature, in degrees Fahrenheit	28
Maximum elevation, in feet	9944
Minimum elevation, in feet	512
Relief, in feet	9432
Elevation at outlet, in feet	522
Average basin elevation, in feet	4696
Relative relief - Basin relief divided by basin perimeter, in feet per mile	39.6
High Elevation Index - Percent of area above 6000 feet	27.2
Altitude Index, in thousands of feet. Estimated as 0.00083 times mean basin elevation.	3.9
Mean basin slope computed from 30 m DEM, in percent	33.7
Percentage of basin covered by forest	65.2
Percent of area covered by lakes and ponds	0.81
Percentage of impervious area determined from NLCD 2001 imperviousness dataset	0.3
X coordinate of the centroid, in map coordinates	-2083411.6
Y coordinate of the centroid, in map coordinates	2054952.4
Latitude of the outlet, NAD83	38.89960
X coordinate of the outlet, in map coordinates	-2127750.0
Y coordinate of the outlet, in map coordinates	2045760.0
Basin perimeter, in miles	238
Distance in miles from basin centroid to the coast	136
Length of the longest flow path in meters	141843
Elevation relief in meters	2875

Figure B1.5. Characteristics of the threshold drainage area for Example 1 from USGS Streamstats (http://streamstats.usgs.gov/california.html).

Caltrans Rapid Assessment of Stream Channel Stability and Susceptibilty to Hydromodification Induced Instabili

Date(s): 03.12.2013
Persons: Elvis Presley, Jimi Hendrix, John Lennon
Site: Placer 49 PM 0.2, NF American R
Location: 38°54'55.74"N, 121° 2'25.89"W
Conditions:

Associated file locations
GPS/*.kml
Photos
Other

Stream type

	Bedrock
	Cascade
x	Step-Pool
	Engineered/channelized
	Plane-Bed
	Pool-Riffle
	Dune-Ripple
	Braided

Physiographic region

- [ ] Modoc Plateau
- [ ] Southern Cascade Range
- [x] Sierra Nevada
- [ ] Klamath Mountains
- [ ] Great Valley
- [ ] Basin and Range
- [ ] California Coast Ranges
- [ ] Transverse Ranges
- [ ] Peninsular Ranges
- [ ] Mojave Desert
- [ ] Colorado Desert

Assign scores to indicators 1-13 using the scheme on the following worksheet (Table 6 in report)

	Observations at equally-spaced cross sections										OR	Overview entire reach		
Cross section number	1	2	3	4	5	6	7	8	9	10		Upstream	Downstream	Value for reach
GPS shot (check boxes for XS where GPS coordinates were recorded)	✖	✖	✖	✖	✖	✖	✖	✖	✖	✖				
1. Watershed and floodplain activity and impacts	n/a											2	2	2.0
2. Flow characteristics	n/a											2	2	2.0
3. Channel pattern	2	2	2	2	2	2	2	2	2	2				2.0
4. Entrenchment/channel confinement	9	9	9	9	9	7	9	9	9	9				8.8
5. Bed material	1	1	1	2	1	3	4	4	4	1				2.2
Fs = approximate percentage of sand in bed sediments, 0 to 100.	5	5	5	5	5	10	20	20	15	5				
6. Bar development	5	5	2	2	2	5	5	5	5	2				3.8
7. Obstructions, including bedrock outcrops, armor layer, LWD jams, grade controls, bridge bed paving, revetments, dikes, vanes, or riprap.	2	2	3	2	4	3	4	3	2	2				2.7
8. Bank soil texture and coherence	1	1	1	2	1	4	4	3	3	2				2.2
9. Average bank slope angle in degrees (where 90° is a vertical bank)	5	5	4	5	5	3	3	5	4	5				4.4
10. Vegetative or engineered bank protection	2	2	1	1	1	7	4	6	7	1				3.2
11. Bank erosion	2	2	2	2	2	2	2	2	2	2				2.0
12. Mass wasting or bank failure	1	1	1	1	1	1	1	1	1	1				1.0
13. Stream crossing alignment with flow and distance from stream crossing to upstream meander impact point.	n/a													2
												Raw total score		38

Figure B1.6. Rapid stability assessment form, Example 1.

Figure B1.7. View upstream from Placer 49, PM 0.2 bridge showing channel confinement by narrow valley and downstream bridge.

Figure B1.8. View upstream from the bridge showing typical bed material. Also see Figure B1.1.

Figure B1.9. Measurement of distance from stream crossing to upstream impact point.

Example 2: Route 66 Wash near Ludlow

This example is only loosely based on reality, the reader should be aware that some aspects of the example data are fictional and have been created for instructional purposes only. Most details are drawn from Johnson (2006), who inspected the channel ca. 2003. US Route 66, also referred to as the National Trails Highway crosses an unnamed ephemeral wash via a small bridge with timber clad abutments about 3.5 mi east of Ludlow, California, 34°42'57.84"N, 116° 6'18.98"W (Figure B2.1). This location is in the Mohave Desert subregion and drains a desert watershed. A railroad and Interstate 40 cross the wash about 0.4 and 0.8 miles, respectively, downstream from the Route 66 bridge (Figure B2.2). The project in question is a rest area that will involve about 2.3 acres of new impervious surfaces immediately southeast of the crossing. Although not reflected in the narrative below, actual effort for an RSA for a situation such as this one where the stream crossing is a bridge may be reduced by using information obtained through the biannual federal bridge inspection program (http://smi.dot.ca.gov/[14]). Hypothetical knowledge from biannual bridge inspections is taken into account in the Level 2 analysis below.

Preparing for field work

Initial steps in the stability assessment were performed in the office using maps, aerial photographs and file data.

Determining average channel width

Since the new road will drain into the river upstream from the bridge, the threshold drainage area (TDA) associated with this project was defined by locating a point 20 channel widths (20W) downstream from the bridge. Channel width was defined by computing the average of the widths of 14 cross sections measured on aerial photographs using visual cues such as tree lines and colors of soil and rock to define top of banks. Since our initial rough estimate of W was 25 ft, the 14 sections were spaced at more or less uniform intervals along a reach centered on the bridge that was about 40W = 1,000 ft long. The average of measured top widths for the 14 sections was 28 ft, so 20W = 560 ft. The 20W distance was measured along the centerline of the wash on aerial photographs, resulting in an endpoint of 34°43'2.81"N, 116° 6'15.59"W for TDA determination (Figure B2.3).

Defining the threshold drainage area

The TDA was then defined as the watershed draining to this point using Arc Hydro software and the sub-basin data from the National Hydrography Dataset (http://nhd.usgs.gov/), confirmed using the Streamstats online tool (http://streamstats.usgs.gov/california.html). A map of the TDA is shown in Figure B2.4, and output from Streamstats is provided in Figure B2.5. Following definition of the TDA, the location of the project relative to the TDA was confirmed: in this case, about half of the new impervious surface area will be within the TDA. A rapid assessment is required if any impervious portion of the project is located within a TDA.

Setting endpoints for the representative reach

The NPDES permit states, “The assessment will be conducted within a representative channel reach to assess lateral and vertical stability. A representative reach is a length of stream channel that extends at

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[13] Follow this link, and then select BIRIS (Bridge Inspection Reporting Information System). This is a Caltrans Intranet site, only Caltrans staff will be able to access it.

[14] Follow this link, and then select BIRIS (Bridge Inspection Reporting Information System). This is a Caltrans Intranet site, only Caltrans staff will be able to access it.

least 20 channel widths upstream and downstream of a stream crossing." For purposes of this manual, we interpret this wording to mean that a total channel length of 40W is to be evaluated—roughly 20W upstream and 20W downstream of the crossing.

No major channel nonuniformities were found that would require adding additional distance to extend the inspected representative reach. For field inspection, we designated a representative reach that was 40W = 40 x 28 = 1,120 ft long, centered on the bridge. The locations of five equally-spaced cross sections downstream from the bridge and an equal number of cross sections upstream from the bridge were marked on a map and saved as waypoints in a GPS. Since W = 28 ft, these stations were located 112 ft, 224 ft, 336 ft, 448 ft, and 560 ft from the bridge, measured along the channel centerline.

Stream classification

The channel is a braided, sand bed arroyo with occasional deposits of gravel and cobble. Large wood is absent. The overall channel has low sinuosity. Referring to Table 2, the US Army Corps of Engineers classification system, this channel is typical of the arroyo type: *Present in arid and semiarid lands, these are streams that remain dry most of the time and carry flow only during flood events. Discharge and sediment transport can be substantial during flow episodes.* By comparing the appearance of the stream with Table 3, the Montgomery-Buffington classification system, the stream was classified as braided (Table B2.1), meeting all of the criteria for that classification. This classification places the reach in the third of the three categories (Braided Channels) that are used to interpret the assessment score.

Table B2.1. Application of Table 3[a] to Example Site 2

	Cascade	Step-pool	Plane-Bed	Pool-Riffle	Dune-Ripple	Braided	Bedrock
Typical bed material	Boulder	Cobble, boulder	Gravel, cobble	Gravel	Sand	Variable	N/A
Bedform pattern	None	Vertically oscillatory	None	Laterally oscillatory	Multilayered	Laterally oscillatory	N/A
Reach type	Transport	Transport	Response	Response	Response	Response	Transport
Dominant roughness elements	Grains, banks	Bedforms, grains, large woody debris (LWD), banks	Grains, banks	Bedforms, grains, LWD, sinuosity, banks	Sinuosity, bedforms	Bedforms	Boundaries
Dominant sediment sources	Fluvial, hill slope, debris flow	Fluvial, hill slope, debris flow	Fluvial, bank failure, debris flows	Fluvial, bank failure, inactive channel, debris flows	Fluvial, bank failure, inactive channel	Fluvial, bank failure, debris flow	Fluvial, hill slope, debris flow
Sediment storage elements	Lee and stoss sides of flow obstructions	Bedforms	Overbank, inactive channel	Overbank, bedforms, inactive channel	Overbank, bedforms, inactive channel	Overbank, bedforms	N/A
Typical slope, ft/ft	0.08 < S < 0.30	0.03 < S < 0.08	0.01 < S < 0.03	0.001 < S < 0.02	S < 0.001	S < 0.03	Variable
Typical confinement by valley walls	Confined	Confined	Variable	Unconfined	Unconfined	Unconfined	Confined
Pool spacing (channel widths)	< 1	1 to 4	None	5 to 7	5 to 7	Variable	Variable

Note: *Highlighted entries show characteristics for Example 2.*

[a] *Montgomery-Buffington Stream Classification System, from Johnson (2006)*

Watershed and floodplain activity and impacts

The watershed is undeveloped desert. Only 0.3% of the area was under impervious cover as of 2001. Although the watershed receives only about 4-5 inches of precipitation annually, the denuded nature of the landscape means that rare events can produce episodes of very high sediment yield. The Corps of Engineers Classification system notes, "*Incising channels, width enlargement, and deposition are typical problems associated with arroyos*." Accordingly, a value of 10 was assigned to the "Watershed and floodplain activity and impacts" indicator (Figure B2.6).

Flow characteristics

Flow characteristics are best described as an ephemeral stream with flash floods as the prevalent mode of discharge. Based on Table 6, a value of 12 was assigned to that indicator.

Field evaluations

The remainder of the rapid assessment was conducted in the field. Upon arriving at the site, the stream classification and other evaluations (such as the absence of major channel discontinuities within 20W of the crossing) determined in the office were verified. The RSA team then proceeded to the downstream end of the representative reach (20W downstream from the bridge) and walked the channel. Notations regarding stability indicators 3-12 were made at each of five equally-spaced locations downstream and upstream from the bridge.

Channel pattern

Channel pattern throughout the reach is braided (Figure B2.3). Bed material in the reach indicates that this is a primarily bed load channel. All cross sections were assigned a score of 10 for this indicator (Figure B2.6).

Entrenchment/channel confinement

The representative reach is not confined or incised. There are zones of local scour, but no general entrenchment. No infrastructure such as pipeline crossings or bridge foundations were exposed. This indicator was assigned a score 6 for all cross sections (Figure B2.6).

Bed material

Bed material for this reach is comprised of sand and gravel with a few boulders (Figures B2.1 and B2.8). Fs, the estimated percentage of sand in surficial bed sediments, averaged 70. Bed material scores ranged from 6 to 12, with an average value of 10.2 (Figure B2.6).

Bar development

Both mid-channel bars and those attached to banks were present, but bends were so gradual and braiding was so prevalent that the bars could not be called point bars. There was no significant bar vegetation. Scores for bar development depend upon the average channel slope and the ratio of channel width to channel depth. The average bed slope for the representative reach is about 0.02 ft/ft, which is right on the 0.02 ft/ft criteria used in the scoring scheme (Table 6), and the channel W/D ratio was about 10, which is less than the 12 criteria used in the scoring scheme. Bar sizes and the types of sediments found on bars were very irregular throughout the reach. The phrase in the rightmost column of Table 6 seemed to best describe the bars in the reach: " ....bars are composed of extensive deposits of fine particles up to coarse gravel with little to no vegetation...", and therefore scores of 9-12 were assigned to this indicator at each cross section, yielding a reach average of 10.4.

Obstructions

The criteria for this indicator result in higher scores for sections that have any type of flow obstruction, including bedrock outcrops, armor layer, large wood jams, grade controls, bridge bed paving, revetments,

dikes, vanes, or riprap. The RSA team noted little obstruction to flow; primary obstruction was due to the irregular bars, random deposits of coarse sediment, and the bridge itself (Figures B2.1, B2.7, B2.8, and B2.9). The average score for this indicator was 4.8 (Figure B2.6).

Bank soil texture and coherence

Bank soils in the representative reach were clay, unconsolidated silt and sand, and were highly erodible. Cross section scores ranged from 10 to 12, with lower scores assigned to cross sections where bank toes were protected by large gravel or boulders. The reach average score for this indicator was 11.1 (Figure B2.6).

Average bank slope angle in degrees

Banks slopes were steeper than the angles of repose for the component materials, with values between 70 and 90 degrees (2.75V:1H to infinity V:1H). The scoring scheme for the bank slope indicator requires that the bank soils and bank slopes be considered. Banks comprised of noncohesive or unconsolidated materials should be no steeper than 3H:1V in order to receive Excellent scores. Bank slope is not important for very low banks (say < 2 ft), and bank heights in the representative reach ranged from 2 to 6 ft. Cross section scores ranged from 8 (very low banks) to 12 (high, sandy banks). Where bank slopes differed strongly for the left and right banks of a given cross section, the higher score was used. The average score for this indicator was 10.7 (Figure B2.6).

Vegetative or engineered bank protection

No engineered bank protection was found within the representative reach, and vegetation was limited to dormant grasses and widely separated shrubby plants (Figures B2.7 and B2.8). The cross section scores for this indicator were all 12.

Bank erosion

Although there was no flow at the time of the inspection, patterns of bank scour and deposition along with the noncohesive nature of the unvegetated bank soils suggested that banks were subject to fluvial erosion during flow events. All banks within the reach were exposed and bare, so all cross sections were assigned a score of 12 for this indicator.

Mass wasting or bank failure

Mass wasting is generally associated with cohesive bank soils which slide or tumble into the channel as large masses or blocks of material rather than individual grains. However, noncohesive banks may also exhibit mass wasting in the form of shallow, planar slides, particularly as toes are undercut by flow, creating even steeper bank angles. Frequent bank slides were noted along the reach. Cross section scores ranged from 9 to 12 for this indicator with an average score of 11.4 (Figure B2.6).

Stream crossing alignment

The stability indicator referred as, “Stream crossing alignment with flow and distance from stream crossing to upstream meander impact point” was difficult to evaluate for this site because the stream has a braided rather than meandering planform. The overall top bank alignment upstream from the bridge is very well aligned with the bridge (yellow arrow, Figure B2.10) but there is a small gully that joins the main channel immediately upstream from the bridge that makes a sharp angle with the main channel and thus strikes the bridge opening at an oblique angle (blue arrow, Figure B2.10). There is a large bar at the confluence of the two channels. Accordingly, the score for this indicator was set at 9.

Scoring and Categorizing the Site

The total raw score for a given site is determined by summing the scores assigned to each of the 13 indicators, so the raw score for this site is 130. Application of the stream classification (Braided Channel)

for interpretation of the raw score (Table 8) yields an RSA overall rating of Poor since the raw score is ≥ 129. Johnson (2006) computed a score of 132 for this site, but assigned much higher scores to the flow obstruction than our team did. Since the site score is not Excellent or Good, according to the NPDES permit,

> *If the results of the rapid assessment indicate that the representative reach will not be laterally and vertically stable (i.e., a rating of excellent or good), the Department must determine whether the instability, in conjunction with the proposed project, poses a risk to existing or proposed highway structures by conducting appropriate Level 2 (and, if necessary, Level 3) analyses. The Department shall follow the Level 2 and 3 analysis guidelines contained in HEC-20 (FHWA, 2001) or a suitable equivalent within an accessible portion of the reach.*

Beyond the RSA

The overall objective of the procedure required following an RSA rating of Poor or Fair is to assess how the proposed project will impact the stability of the site and crossing structure. The engineer must use judgment to determine what Level 2 analyses are "appropriate" to determine if there is a threat to existing or proposed highway structures. The full suite of Level 2 analyses includes eight steps (Lagassse et al. 2012):

1. **Evaluate Flood History and Rainfall-Runoff Relations:** Compute or estimate the magnitude of recent and historical peak flows. Using sequential surveys, bridge inspection reports, or aerial photographs, determine the magnitude of morphological changes produced by these events. Compute or estimate the magnitude of future events and estimate how the project is likely to affect these events.
2. **Evaluate Hydraulic Conditions:** For the flows identified in step 1, compute or estimate the average flow depths, velocities and shear stresses likely to occur at the site. Some information may be available from flood insurance studies, stream crossing design work, stream gaging records, or projects on similar adjacent reaches. In other cases it may be necessary to obtain thalweg and cross section surveys, channel and bank roughness estimates, and high stage elevations for simple spreadsheet computations or for running a one-dimensional backwater model such as HEC-RAS.
3. **Bed and Bank Material Analysis:** Sample and analyze bed and bank sediments to characterize their resistance to erosion. Alternatively, sediment size may be estimated. Appropriate allowances must be made for formation and breakup of armor layers. High, steep banks subject to mass wasting types of failure require more detailed description of soil strength and soil moisture. Consider major tributary channels also.
4. **Evaluate Watershed Sediment Yield:** Qualitatively assess the prevalent sources of sediment in the watershed and important processes that affect sediment yield: development, mining, fires, impoundments, etc. Sediment yield models such as USLE or RUSLE may be used to project impacts of land use changes associated with the project. Is the sediment yield changing in a way that will affect channel stability?
5. **Incipient Motion Analysis:** For gravel- and cobble-bed channels, assess the incipient motion size for the hydraulic conditions from step 2 above and compare with the bed material sizes derived from step 3 above. What size event mobilizes the bed sediments? How frequently does this event occur?
6. **Evaluate Armoring Potential:** If the channel bed sediment is a mixture of fine (sand, silt, clay) and coarser sediments, and if the sediment load entering the reach is not too large, there is a possibility that bed degradation may be limited by formation or an armor layer as the finer sediments are selectively transported away. Detailed analyses are described by Lagasse et al.

(2012). A good rule of thumb is that armoring is probable if the computed incipient motion size is equal to or smaller than the D_{95} size in the bed material.

7. **Evaluation of Rating Curve Shifts:** If there are gaging sites on the stream of interest, examine records of rating curves for shifts indicating channel instabilities (i.e., changes in bed elevation, channel cross-sectional area, channel roughness). Note that some rating curve shifts are due to issues not related to channel stability such as ice, vegetation changes, beaver activity, etc. With sites with >25 years of record, plots of specific gage height (i.e., the gage height associated with a given discharge or a narrow range of discharges) against time can be most illuminating.
8. **Evaluate Scour Conditions:** Lagasse et al. (2012) direct the reader to guidance provided by Arneson et al. (2012), also known as HEC-18, for computing the three major components of scour at stream crossings: local scour, contraction scour and aggradation/degradation.

These eight steps are loosely related in the ways shown in the flow chart extracted from Lagasse et al. (2012), Figure B2.11.

Appropriate level of analysis

Although the braided, ephemeral wash is quite unstable, and although it apparently moves its bed and banks during rare flow events, the bridge structure appears sound. No evidence of exposure of foundations, approach erosion or excessive local channel scour was noted at the bridge, and these observations are consistent with the last three biannual bridge reports. It is hypothesized that the addition of 2.3 acres of new impervious area to the 0.4-square-mile (256 acres) is unlikely to have measureable effects on site stability. A low level of analysis was implemented, primarily to test this hypothesis.

Evaluate flood history and rainfall-runoff relations

Channel forming flow events in desert watersheds are quite episodic. Long periods with little evident erosion or deposition do not imply channel stability; they may simply correspond to dry periods. Wet periods may produce uncommon, large flows that trigger rapid channel changes. Since there are no gages at the site or within the watershed containing the site, a search for gages in the area nearby was conducted. Annual peak flow records are available for a USGS gaging station about 5 miles southeast of the site that has a similar sized watershed (0.34 square miles). This station is a crest-stage gage which only records the peak stage occurring between inspections of the gage. Discharge values for recorded stages are derived by the USGS from indirect measurements and computation, so discharge values are likely of unknown accuracy. Annual peaks are available for 50 years during the period 1959- 2012. Of the 50 years of record, no flow was recorded for 23 years. Only 10 flow peaks > 50 cfs were recorded, and the record peak was 125 cfs. Regional regression formulas developed by Thomas et al. (1997) and Gotvald et al. (2012) indicate that this flow magnitude has a return interval between 10 and 25 years. The confidence intervals on these regression-based estimates are quite broad, however.

Available Google Earth air photo coverage include five dates between 5/21/1994 and 5/27/2012. Channel location appears to be stable during this time frame. The aforementioned USGS gage recorded peaks of 110 cfs on 7/7/2001 and 83 cfs on 10/18/2005. Channels depicted on the aerial imagery appear to scour and fill during this period, and a straight ditch running parallel and just south of the highway appears and then fades, perhaps due to filling by blowing sand.

Evaluate hydraulic conditions

No survey information is available for this site, so a uniform channel was assumed with a trapezoidal cross section with geometry similar to that observed during the site inspection. Accordingly, top width = 28 ft, bank slopes = 60°, and channel slope = 0.02 ft/ft. Assuming uniform flow (and therefore neglecting backwater effects due to the bridge), the average boundary shear stress during a bankfull event may be estimated as follows:

$$\tau_o = \gamma R S$$

Where τ_o is the average boundary shear stress in lb/ft^2, γ is the specific weight of water in lb/ft^3, *R* is the hydraulic radius in feet, and *S* is the average bed slope.

The average velocity during such an event may be estimated using the Manning formula

$$V = \frac{1.486}{n} R^{2/3} S^{1/2}$$

where *V* is the mean velocity in ft/s, *n* is the Manning coefficient, and *R* is the hydraulic radius in ft. For purposes of this analysis, the Manning n value was estimated using the Strickler formula and a median grain size of 50 mm (2 inches) with consideration of the effects of flow depth. Manning n values ranged from 0.055 for flow depths < 2 ft to 0.044 for flow depths $\geq$ 2 ft. The discharge, *Q*, in cfs, is given by the continuity formula:

$$Q = AV$$

where *A* is the cross-sectional area of the flow in ft^2. For purposes of this analysis, hydraulic characteristics for flows ranging from 135 to 1062 cfs were computed within an Excel spreadsheet with results shown in Figure B2.12.

Bed and bank material analysis

Information about bed and bank material was limited to visual observations during the site inspection. Bed material is a mixture of coarse sand, gravel and some coarser material with the overall surficial fraction of sand estimated to be 70%. Banks are comprised of finer materials, but are often protected by large bars.

Evaluate watershed sediment yield

Typical of desert watersheds, sediment yield appeared to be relatively high and limited only by precipitation. Slopes are steep and vegetative cover is minimal. Addition of 2.3 acres of impervious cover will have negligible effects on sediment yield to the channel downstream.

Incipient motion analysis and armoring potential

Incipient motion size was computed using the hydraulic information derived above in an Excel spreadsheet. Since the channel bed is estimated to be comprised of 70% sand, the entire bed is probably mobilized by flows $\geq$ 100 cfs (Figure B2.13), and incipient motion analysis is not relevant. Armoring potential is also low due to the abundant supply of bed material from upstream and the lack of particles in the bed large enough to resist movement.

Evaluation of rating curve shifts

No rating curve information is available for this site or for the nearby gage, as it is only a crest-stage gage.

Evaluate scour conditions

As-built construction drawings and bridge construction reports indicate that the channel bed elevation in the vicinity of the bridge fluctuates about 3 ft from year to year but exhibits no systematic trend. This

magnitude of scour is to be expected as bars, dunes and other bedforms pass and are not large enough to pose a threat to channel or structural stability.

Conclusion of Level 2 Analysis

Level 2 analysis confirms that this dry wash or arroyo is a typical braided channel draining a desert watershed. High flows are rare, with sharp hydrographs that mobilize much of the bed. However, due to abundant sediment supply from upstream, the reach containing the crossing that will receive runoff from the proposed project is not subject to excessive bed scour. Furthermore, although banks are eroding, channel lateral stability appears to pose no threat to the highway structures. Sediment yield is sporadic and relatively high, but no change in sediment yield or water quality is likely to occur due to this project.

Figure B2.1. Route 66 crossing over unnamed Wash 3.5 miles east of Ludlow, California. Looking downstream. From Johnson (2006).

Figure B2.2. Example 2 site map. Red arrow shows bridge location.

Figure B2.3. Location of point for delineation of threshold drainage area.

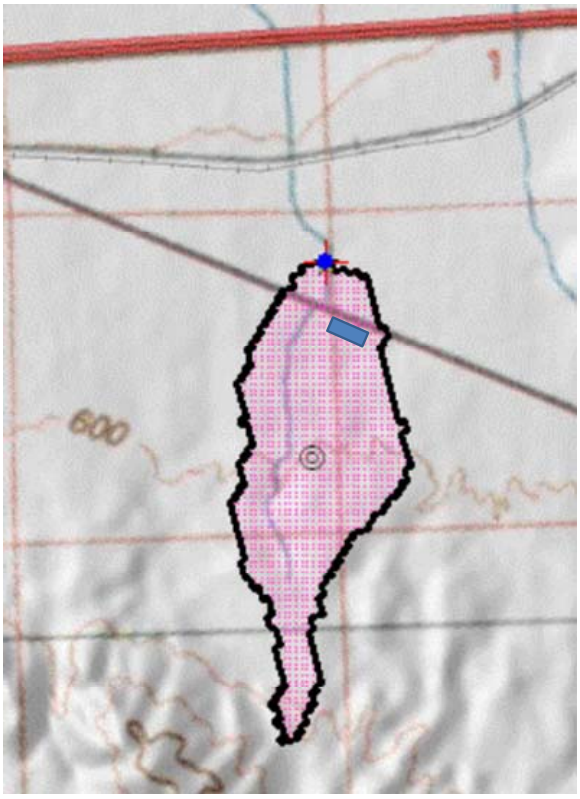

Figure B2.4. Threshold drainage area, Example 2. Gray rectangle indicates new impervious area.

USGS California StreamStats

Basin Characteristics Report

Date: Mon Apr 22 2013 13:17:34 Mountain Daylight Time
NAD27 Latitude: 34.7171 (34 43 02)
NAD27 Longitude: -116.1009 (-116 06 03)
NAD83 Latitude: 34.7171 (34 43 02)
NAD83 Longitude: -116.1017 (-116 06 06)

Parameter	Value
Area, in square miles	0.4
Mean annual precipitation, in inches	4.47
Average maximum January temperature, in degrees Fahrenheit	61.5
Average minimum January temperature, in degrees Fahrenheit	34.5
Maximum elevation, in feet	2165
Minimum elevation, in feet	1846
Relief, in feet	319
Elevation at outlet, in feet	1848
Average basin elevation, in feet	1958
Relative relief - Basin relief divided by basin perimeter, in feet per mile	72.4
High Elevation Index - Percent of area above 6000 feet	0
Altitude Index, in thousands of feet. Estimated as 0.00083 times mean basin elevation.	1.62
Mean basin slope computed from 30 m DEM, in percent	4.47
Percentage of basin covered by forest	0
Percent of area covered by lakes and ponds	0
Percentage of impervious area determined from NLCD 2001 imperviousness dataset	0.3
X coordinate of the centroid, in map coordinates	-1812975.4
Y coordinate of the centroid, in map coordinates	1486654.8
Latitude of the outlet, NAD83	34.71709
X coordinate of the outlet, in map coordinates	-1812660.0
Y coordinate of the outlet, in map coordinates	1487580.0
Basin perimeter, in miles	4.4
Distance in miles from basin centroid to the coast	124
Length of the longest flow path in meters	2698
Elevation relief in meters	97

Figure B2.5. Characteristics of the threshold drainage area for Example 1 from USGS Streamstats (http://streamstats.usgs.gov/california.html).

Caltrans Rapid Assessment of Stream Channel Stability and Susceptibilty to Hydromodification Induced Instability

Date(s): **5/21/2005**
Persons: **Johnson & Johnson**
Site: **Rt 66 Wash**
Location: **0.9 mi E Ludlow, CA**
Conditions:

Associated file locations
GPS/*.kml
Photos
Other

Stream type
- [ ] Bedrock
- [ ] Cascade
- [ ] Step-Pool
- [ ] Engineered/channelized
- [ ] Plane-Bed
- [ ] Pool-Riffle
- [ ] Dune-Ripple
- [x] Braided

Physiographic region
- [ ] Modoc Plateau
- [ ] Southern Cascade Range
- [ ] Sierra Nevada
- [ ] Klamath Mountains
- [ ] Great Valley
- [x] Basin and Range
- [ ] California Coast Ranges
- [ ] Transverse Ranges
- [ ] Peninsular Ranges
- [ ] Mojave Desert
- [ ] Colorado Desert

Assign scores to indicators 1-13 using the scheme on the following worksheet (Table 6 in report)

	Observations at equally-spaced cross sections										OR	Overview entire reach		
Cross section number	1	2	3	4	5	6	7	8	9	10		Upstream	Downstream	Value for reach
GPS shot (check boxes for XS where GPS coordinates were recorded)	✖	✖	✖	✖	✖	✖	✖	✖	✖	✖				
1. Watershed and floodplain activity and impacts	n/a											10	10	10.0
2. Flow characteristics	n/a											12	12	12.0
3. Channel pattern	10	10	10	10	10	10	10	10	10	10				10.0
4. Entrenchment/channel confinement	6	6	6	6	6	6	6	6	6	6				6.0
5. Bed material	12	9	9	9	12	6	9	12	12	12				10.2
Fs = approximate percentage of sand in bed sediments, 0 to 100.	90	70	60	60	80	50	70	80	80	90				
6. Bar development	12	9	10	11	10	12	10	9	10	11				10.4
7. Obstructions, including bedrock outcrops, armor layer, LWD jams, grade controls, bridge bed paving, revetments, dikes, vanes, or riprap.	2	3	6	4	6	10	5	6	4	2				4.8
8. Bank soil texture and coherence	10	11	11	12	10	12	11	12	10	12				11.1
9. Average bank slope angle in degrees (where 90° is a vertical bank)	10	8	12	11	12	9	11	12	12	10				10.7
10. Vegetative or engineered bank protection	12	12	12	12	12	12	12	12	12	12				12.0
11. Bank erosion	12	12	12	12	12	12	12	12	12	12				12.0
12. Mass wasting or bank failure	12	9	12	12	12	12	12	10	11	12				11.4
13. Stream crossing alignment with flow and distance from stream crossing to upstream meander impact point.	n/a													9
												Raw total score		130

Figure B2.6. Rapid stability assessment form, Example 2.

Figure B2.7. View downstream from Route 66 bridge showing lack of channel confinement and broad, flat floodplains. From Johnson (2006).

Figure B2.8. View upstream from the bridge showing typical bed material. Also see Figure B2.1. From Johnson (2006).

Figure B2.9. Route 66 crossing over unnamed wash 3.5 miles east of Ludlow, California. Looking upstream. From Johnson (2006).

Figure B2.10. Stream crossing alignment with upstream flow in main channel (yellow arrow) complicated by tributary gully (blue arrow), unnamed wash 3.5 miles east of Ludlow, California. Looking upstream.

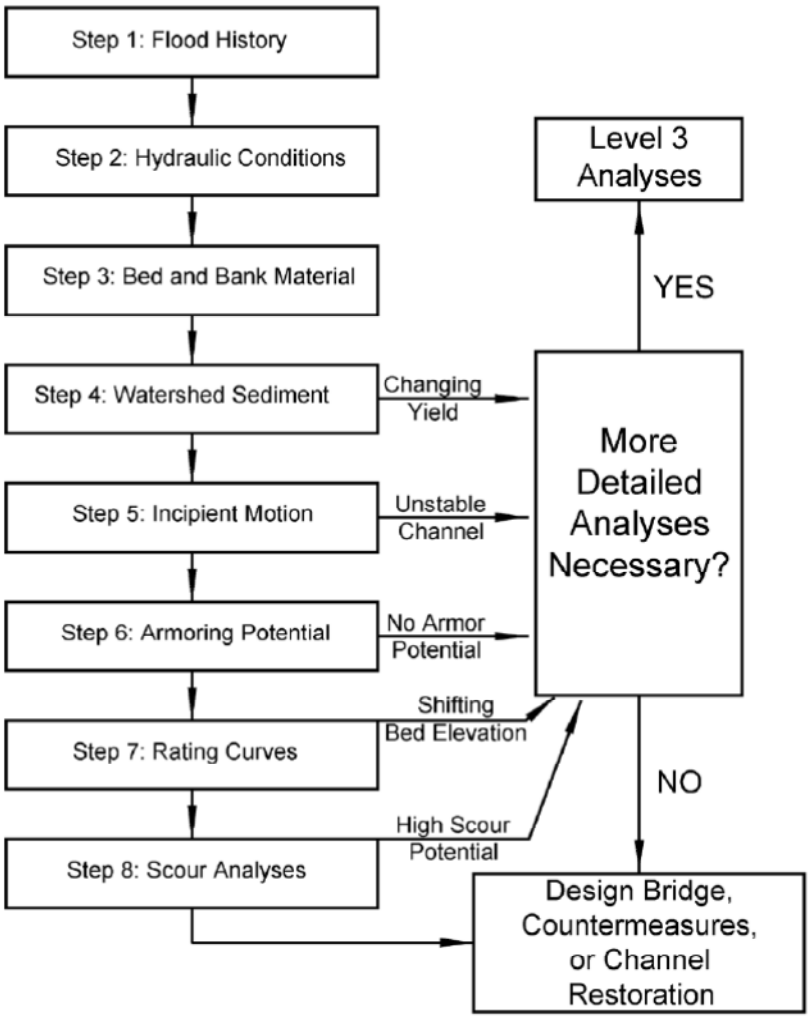

Figure B2.11. Flow chart for Level 2: Basic Engineering Analysis. From Lagasse et al. (2012)

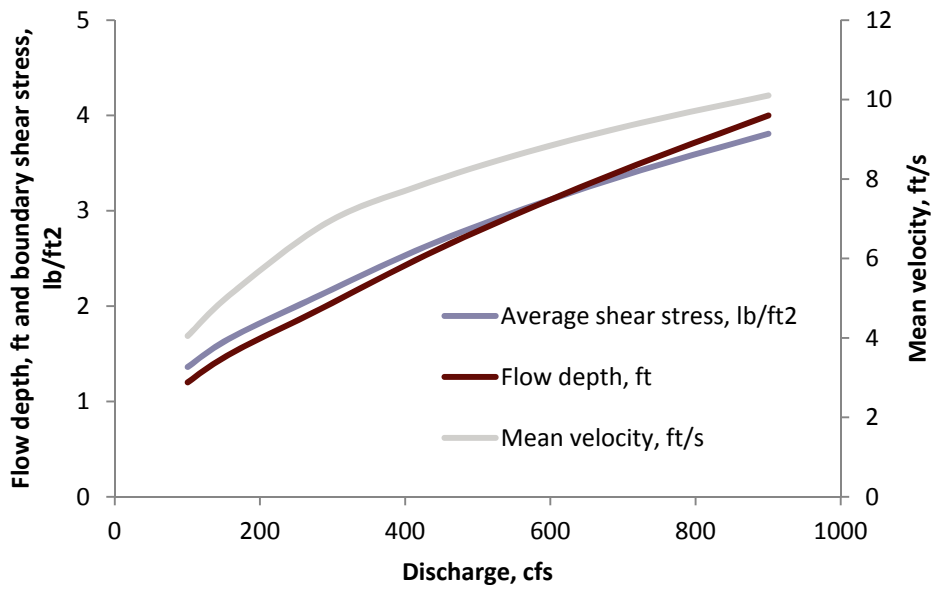

Figure B2.12. Hydraulic characteristics of representative reach, Route 66 Wash near Ludlow, based on assumption of uniform flow.

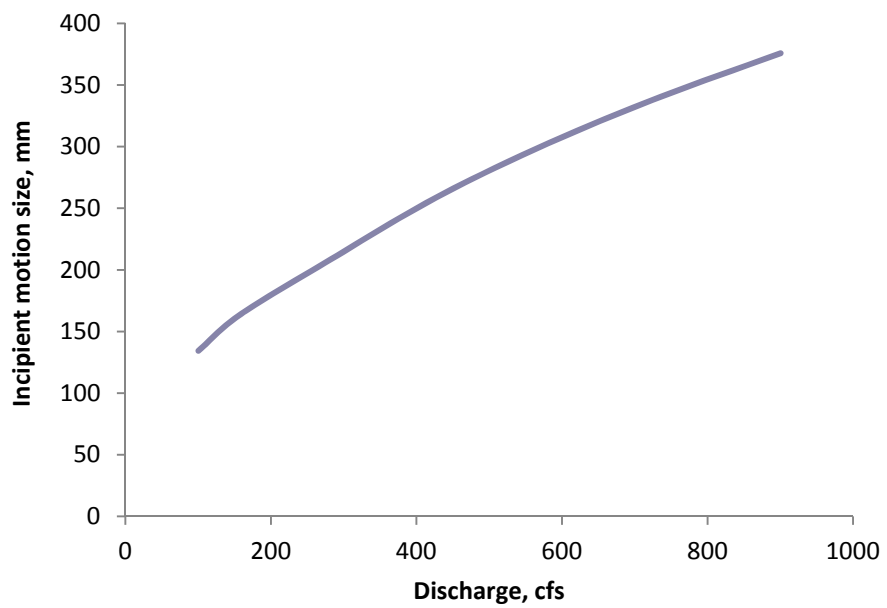

Figure B2.13. Incipient motion size for representative reach, Route 66 Wash near Ludlow.

Example 3: Murietta Creek at Main Street, Temecula

This example is only loosely based on reality, the reader should be aware that some aspects of the example data are fictional and have been created for instructional purposes only. Most details are drawn from Johnson (2006), who inspected the channel ca. 2003. Main Street in Temecula, California, crosses Murietta Creek via a bridge at 33°32.51"N, 117° 8'59.84"W (Figure B3.1). This location is in the Peninsular Ranges physiographic subregion. The project in question includes construction of a 2.1 acre "park and ride" lot on the right descending side of the channel about 300 ft upstream from the bridge (Figure B3.2). Although the bridge is not a State bridge, the project is a Caltrans project. Although not reflected in the narrative below, actual effort for an RSA for a situation such as this one where the stream crossing is a bridge may be reduced by using information obtained through the biannual federal bridge inspection program, available at http://smi.dot.ca.gov/[15].

Preparing for field work

Initial steps in the stability assessment were performed in the office using maps, aerial photographs and file data.

Determining average channel width

Since the new road will drain into the river upstream from the bridge, the threshold drainage area (TDA) associated with this project was defined by locating a point 20 channel widths (20W) downstream from the bridge. Channel width was defined by computing the average of the widths of 10 cross sections measured on aerial photographs using visual cues such as tree lines and colors of soil and rock to define top of banks. These 10 cross sections were spaced at roughly equal intervals within a reach 40W long centered on the bridge, where W was an initial rough estimate of channel width. Since W = 150 ft, the reach was 6,000 ft long. The average of the ten measured top widths was 172 ft, so a top width of 170 ft was adopted for analysis, and 20W = 3,400 ft. The 20W distance was measured from the bridge downstream along the centerline of the river channel on aerial photographs, resulting in an endpoint of 33°29'3.59"N, 117° 8'41.57"W (Figure B3.3) for TDA definition.

Defining the threshold drainage area

The TDA was then defined as the watershed draining to this point using Arc Hydro software and the sub-basin data from the National Hydrography Dataset (http://nhd.usgs.gov/), confirmed using the Streamstats online tool (http://streamstats.usgs.gov/california.html). A map of the TDA is shown in Figure B3.4, and output from Streamstats is provided in Figure B3.5. Following definition of the TDA, the location of the project relative to the TDA was confirmed: in this case, the entire project area is within the TDA. A rapid assessment is required if any new impervious portion of the project is located within a TDA. It is apparent that the small size of the area of new impervious surface (2.1 acres) relative to the size of the TDA (220 square miles or 140,800 acres) means that hydromodification impacts of this project will be undetectable.

Setting endpoints for the representative reach

Next, the NPDES permit states, "The assessment will be conducted within a representative channel reach to assess lateral and vertical stability. A representative reach is a length of stream channel that extends at least 20 channel widths upstream and downstream of a stream crossing." For purposes of

[15] Follow this link, and then select BIRIS (Bridge Inspection Reporting Information System). This is a Caltrans Intranet site, only Caltrans staff will be able to access it.

this manual, we interpret this wording to mean that a total channel length of 40W is to be evaluated—roughly 20W upstream and 20W downstream of the crossing.

However, channel nonuniformity may require adding additional distance to extend the inspected representative reach. The permit states, "If sections of the channel within the 20 channel width distance are immediately upstream or downstream of steps, culverts, grade controls, tributary junctions, or other features and structures that significantly affect the shape and behavior of the channel, more than 20 channel widths should be analyzed." In the case of this site, there is another bridge crossing (Rancho California Road) located about 16W upstream from the Main Street bridge (Figure B3.2). To satisfy the above requirement, the representative reach should extend to about 6W upstream from the Rancho California Road bridge (22W upstream of the crossing in question) Therefore the representative reach will be about 42W = 7,140 ft long. For field work, the locations of ten cross sections, spaced at intervals of about 790 ft with the first cross section located about 3,400 ft (20W) downstream from the bridge, were marked on a map and saved as waypoints in a GPS. One cross section location was shifted slightly downstream to avoid locating the section underneath an existing bridge.

Stream classification

Murietta Creek flows through the urban/suburban, relatively flat Temecula Valley which is flanked on both sides by steep terrain. The channel is only slightly sinuous, with some braiding in the reach segments closest to the Main Street bridge (Figure B3.3). It becomes a much narrower, single-thread channel with very low sinuosity further downstream. Several banks appear to have been hardened or protected, and the fact that lands bordering both sides of the channel are developed suggests that it has been at least partially channelized. The bed is all sand and covered with dunes and bars. Flow is ephemeral, and vehicle tire tracks appearing on the bed in one of the historical aerial photos suggest that the bed of the channel is used for recreational all-terrain vehicle traffic during dry periods. Referring to Table 2, the US Army Corps of Engineers classification system, this channel has some of the characteristics of a meandering alluvial river (meandering planform, lower portion of watershed), some characteristics of a braided channel (shifting, braided channel, sand), and some characteristics of a modified channel (straightened, enlarged, floodplain encroachment). By comparing the appearance of the stream with Table 3, the stream was classified as dune-ripple (Table B3.1), meeting all of the criteria for that classification except for the pool spacing. This classification places the reach in the first of the three categories (Pool-riffle, Plane-bed, Dune-ripple, or Engineered Channel reaches) that are used to interpret the assessment score.

Table B3.1. Application of Table 3[a] to Example Site 3

	Cascade	Step-pool	Plane-Bed	Pool-Riffle	Dune-Ripple	Braided	Bedrock
Typical bed material	Boulder	Cobble, boulder	Gravel, cobble	Gravel	Sand	Variable	N/A
Bedform pattern	None	Vertically oscillatory	None	Laterally oscillatory	Multilayered	Laterally oscillatory	N/A
Reach type	Transport	Transport	Response	Response	Response	Response	Transport
Dominant roughness elements	Grains, banks	Bedforms, grains, large woody debris (LWD), banks	Grains, banks	Bedforms, grains, LWD, sinuosity, banks	Sinuosity, bedforms	Bedforms	Boundaries
Dominant sediment sources	Fluvial, hill slope, debris flow	Fluvial, hill slope, debris flow	Fluvial, bank failure, debris flows	Fluvial, bank failure, inactive channel, debris flows	Fluvial, bank failure, inactive channel	Fluvial, bank failure, debris flow	Fluvial, hill slope, debris flow
Sediment storage elements	Lee and stoss sides of flow obstructions	Bedforms	Overbank, inactive channel	Overbank, bedforms, inactive channel	Overbank, bedforms, inactive channel	Overbank, bedforms	N/A
Typical slope in ft/ft	0.08 < S < 0.30	0.03 < S < 0.08	0.01 < S < 0.03	0.001 < S < 0.02	S < 0.001	S < 0.03	Variable
Typical confinement by valley walls	Confined	Confined	Variable	Unconfined	Unconfined	Unconfined	Confined
Pool spacing (channel widths)	< 1	1 to 4	None	5 to 7	5 to 7	Variable	Variable

Note: *Highlighted entries show characteristics for Example 3.*

[a] *Montgomery-Buffington Stream Classification System, from Johnson (2006)*

Watershed and floodplain activity and impacts

The watershed is suburban/urban with only 2.7% forest cover, and 6.1% impervious cover (as of 2001). Development is concentrated in the flatter regions in valley bottoms along channels. Accordingly, a value of 12 was assigned to the "Watershed and floodplain activity and impacts" indicator (Figure B3.6).

Flow characteristics

Sequential air photos confirm the ephemeral nature of the stream, and the dense development in the stream corridor and presence of stormwater outfalls along the representative reach suggest that it is quite flashy. Flow records from a USGS gage 1,100 ft downstream from the TDA control point contain annual peaks for the period 1931-2011, and these range from 1.3 cfs to 25,000 cfs. A value of 12 was assigned to this indicator.

Field evaluations

The remainder of the rapid assessment was conducted in the field. Upon arriving at the site, the stream classification and other evaluations determined in the office were verified. The RSA team then proceeded to the downstream end of the representative reach (about 3,400 ft downstream from the Main Street bridge) and walked the channel. Notations regarding stability indicators 3-12 were made at each of the ten predetermined cross-section locations.

Channel pattern

Channel pattern throughout the reach was straight to meandering with a high radius of curvature (Figure B3.3). Sinuosity for the entire reach was measured on aerial photography to be only 1.03. Braiding occurred in the lower end of the representative reach. It appears that the channel through the representative reach has been enlarged (widened) and straightened, and the braiding may be a response to those perturbations. Accordingly, scores of 7 to 9 were assigned to five of the cross sections for this indicator which corresponds to "meandering with some braiding…poorly maintained engineered channel, primarily bed load." (Figure B3.6). Lower scores (3 or 4) were given to sections where the stream was constricted into a single channel and showed no braiding or multiple channel development. The average score was 5.8 (Figure B3.6).

Entrenchment/channel confinement

The channel was not deeply incised, as banks were 5 to 8 ft high and large, well-vegetated alternate sandbars that were up to W/2 wide were present (Figure B3.7). There were no headcuts or knickpoints, but the channel slope became noticeably steeper in the downstream portion of the representative reach. On the other hand, development of the riparian zone and floodplains indicates that the stream no longer has periodic access to the floodplain. Exposure of bridge pier foundations suggests that the thalweg has degraded 4 to 6 ft since the bridge was constructed (Figure B3.1 and Figure B3.8). Similar exposure was noted for the 1st Street bridge, and the base flow channel just downstream was deep and narrow, suggesting a knickzone. Considering all factors in light of the stability indicator criteria (Table 6), scores were assigned to nine of the ten cross sections that ranged from 6 to 9. The cross section nearest the exposed piers and just upstream from the constricted base flow channel at the 1st Street bridge was assigned a score of 11, resulting in a reach average of 7.8 (Figure B3.6).

It should be noted at this point that the exposure of pier footings is the key finding of the RSA. Erosion of the sand bed has jeopardized the stability of the stream crossing structure. Additional findings of the RSA may shed light on the question as to whether the erosion is local scour or general bed degradation, but the structure is in jeopardy in either case. The fact that the 1st Street bridge foundations are also exposed points to general bed lowering rather than local scour, as does the steepening of the profile in the downstream direction. The channel may be undergoing progressive downcutting consistent with the Channel Evolution Model (Figure 7), except for the fact that the sandy bed material precludes formation of a discrete, vertical headcut (knickpoints). The implication of this finding is that the threat to the crossing structure may increase in the future unless countermeasures are implemented.

Bed material

Bed material for this reach is comprised of almost entirely of medium sand (Figure B3.9 and Figure 3B.10). In some places the higher surfaces along the channel such as the crowns of bars are heavily vegetated, but sequential aerial photos showed that this vegetation periodically disappears and regrows. Bed material scores were 12 for all cross sections, consistent with the RSA scoring criteria (Table 6), which assigns highest scores to easily eroded materials.

Bar development

Scores for bar development depend upon the average channel slope and the ratio of channel width to channel depth. Using the channel flow path profile tool in Streamstats, the average bed slope for the representative reach was estimated to be only 0.0003 ft/ft except for the most downstream segment, which had a slope of about 0.01 ft/ft. Both slopes are less than the 0.02 ft/ft criteria used in the Johnson (2006) scoring scheme (Table 6). The average channel width was estimated to be 170 ft, and the average depth is about 6 ft, giving W/D = 28 > 12. Bars were generally about half the channel width wide and were located on alternate banks, although spacing was irregular (Figure 3B.7). Aerial photo coverage from 1996 to present were viewed in Google Earth, and bar vegetation appeared and

disappeared intermittently. The ephemeral nature of bar vegetation dictated scores between 10 and 12. The average score for this indicator was 10.7 (Figure B3.6).

Obstructions

The criteria for this indicator result in higher scores for sections that have any type of flow obstruction, including bedrock outcrops, armor layer, LWD jams, grade controls, bridge bed paving, revetments, dikes, vanes, or riprap. The RSA team noted a second bridge in the representative reach, but no other obstructions except for small amounts of debris and rubble which had been dumped on some banks and vegetation growing in the channel, which periodically disappears. All sections received a score of 1 with the exception of section 4, which had a score of 10 due to the 1st Street (Santiago Road) bridge crossing and section 9, which had a score of 10 due to the Rancho California Road bridge. The average score for this indicator was 2.8 (Figure B3.6).

Bank soil texture and coherence

Bank soils were sandy, silty clay. In some cases debris or rubble had been dumped on banks. Cross section scores varied from 10 to 12, with higher scores assigned to sandier banks (Figure B3.6). The average score for this indicator was 11.1.

Average bank slope angle in degrees

Except when fronted by bars, bank slopes varied from 60 to 80 degrees, which exceeds the criteria for a Poor score (Table 6). Scores for this indicator varied from 8 to 12 and averaged 9.9 (Figure B3.6).

Vegetative or engineered bank protection

Bank vegetation was comprised of a relatively thin band of reeds and sparse deciduous trees (Figure 3B.9 and Figure 3B.10). Trees were generally vertical and located well back from the top bank on the flood plain. Engineered bank protection was limited to small segments adjacent to the bridge abutments or fronting a parking lot. Some dumped rubble and other construction debris was noted at a few locations. Cross section scores ranged from 8 to 11 and averaged 10.3 for the reach.

Bank erosion

Frequent erosion of the sandy banks was noted all along the reach. However, bank erosion did not appear severed enough to cause bank line scalloping or lateral migration of the channel. Furthermore, bank erosion had not prompted riparian landowners or managers to institute more than casual countermeasures. Scores ranged from 1 for stable banks to 7 for sliding or bare and eroding banks and averaged 3.7 (Figure B3.6).

Mass wasting or bank failure

Although the sandy banks may fail by sliding when they are undermined during high flows, no mass wasting was evident except for a slight area of distress at cross section 7. Scores of 1 were assigned to all cross sections except for this one, which received a score of 5. The average score for this indicator was 1.4 (Figure B3.6).

Stream crossing alignment

The stability indicator referred as, “Stream crossing alignment with flow and distance from stream crossing to upstream meander impact point” was evaluated by locating the impact point for the concave bank of the bend immediately upstream from the bridge on aerial photoimagery. The impact point corresponds to the intersection of a line drawn at the channel centerline at the upstream bend entrance and the outside of the bend. The reach containing the bridge is almost straight and the upstream bend is very gradual (Figure 3B.3). The distance from the impact point to the upstream center of the bridge was measured on aerial photos and was found to be 870 ft, which calls for an Excellent rating of 2.

Scoring and Categorizing the Site

The total raw score for a given site is determined by summing the scores assigned to each of the 13 indicators, so the raw score for this site is 101, which is within the "Fair" range for streams classified as Pool-riffle, Plane-bed, Dune-ripple, or Engineered Channels. As noted above, the likelihood that the addition of 3 acres of new impervious area to such a large watershed would modify the site hydrology or impact channel is remote. However, the potential instability of the stream crossing structure calls for prompt action. Countermeasures should be installed that will protect the stream bed in the representative reach from future bed erosion and degradation even if channel evolution trends (incision) continue and if watershed development (of which the proposed project is a small part) continue to increase peak flows.

In the case of this site, a riprap grade control structure was installed downstream from the 1st Street bridge ca. 2004 (Figure B3.11). Presentation of design criteria for grade controls is beyond the scope of this document. However, properly designed grade controls placed downstream from bridges can be effective countermeasures against failure due to undermining by erosion. Evidently the Murietta Creek grade control structure crest elevation was set high enough to protect both the 1st Street and the Main Street bridges, prompting sediment deposition at both locations that filled the areas around the exposed pier footings. Long term evolution of the channel of Murietta Creek will continue to be influenced by development and changes in watershed land cover, and a major flood control project is planned for this reach, also.

Figure B3.1. Ground level (top) and aerial (bottom) views of Main Street Bridge over Murietta Creek at Temecula, CA.

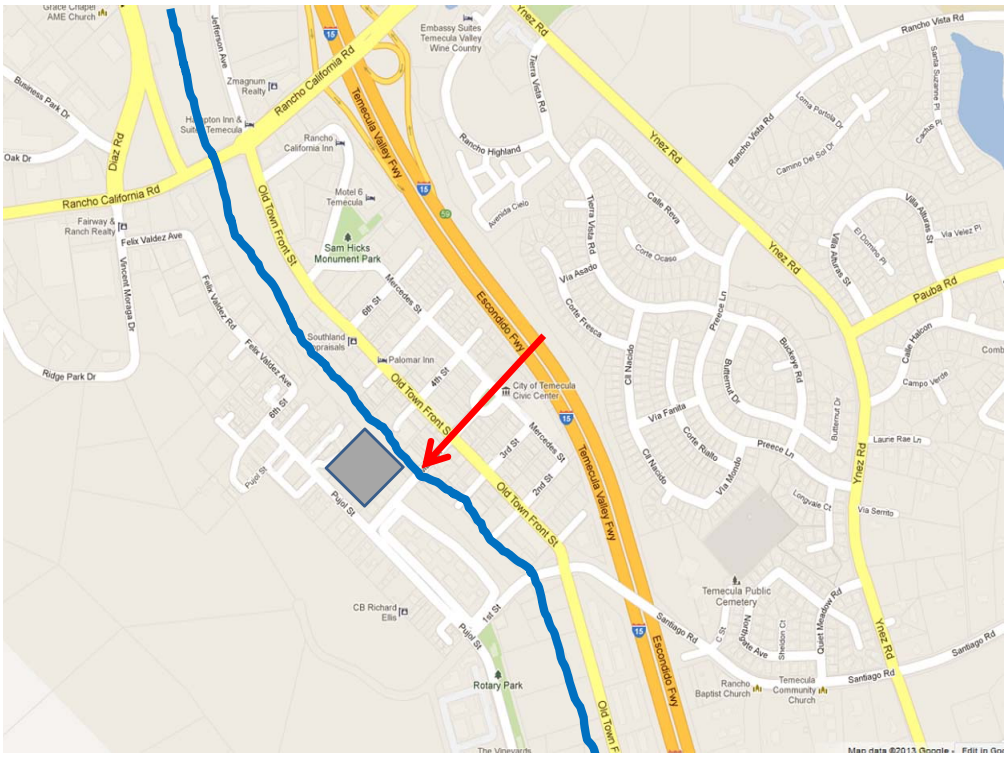

Figure B3.2. Example 3 site map. Red arrow shows bridge location. Gray rectangle shows approximate location of new impervious area.

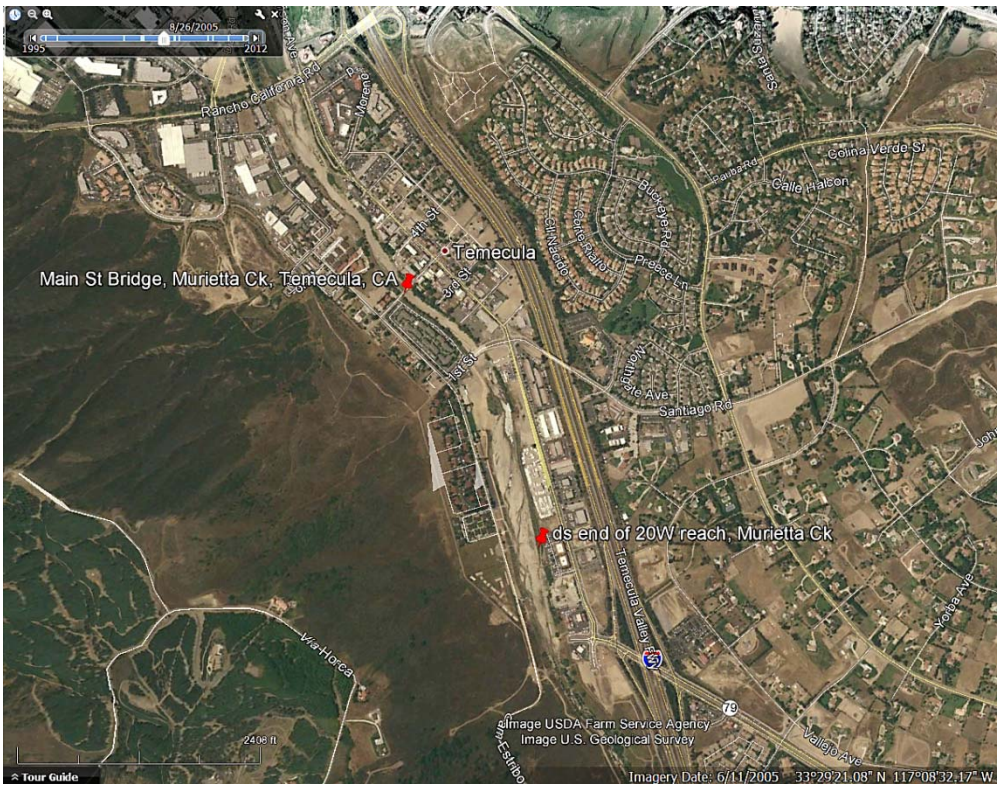

Figure B3.3. Location of point for delineation of threshold drainage area.

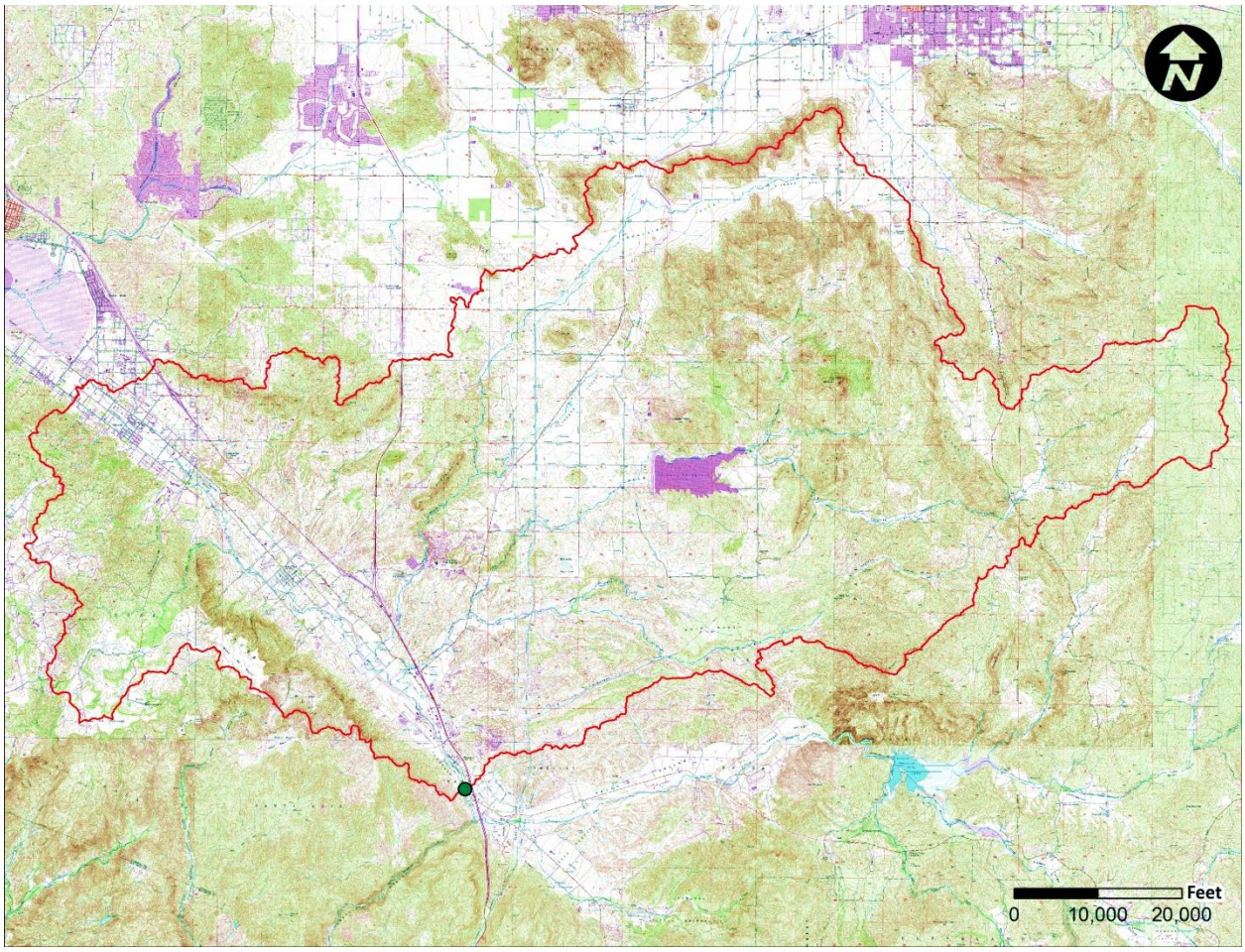

Figure B3.4. Threshold drainage area, Example 3.

California StreamStats

Basin Characteristics Report

Date: Mon Apr 29 2013 13:42:10 Mountain Daylight Time
NAD27 Latitude: 33.4829 (33 28 58)
NAD27 Longitude: -117.1435 (-117 08 37)
NAD83 Latitude: 33.4829 (33 28 58)
NAD83 Longitude: -117.1444 (-117 08 40)

Parameter	Value
Area, in square miles	219.7
Mean annual precipitation, in inches	14.7
Average maximum January temperature, in degrees Fahrenheit	65
Average minimum January temperature, in degrees Fahrenheit	38.6
Maximum elevation, in feet	4566
Minimum elevation, in feet	984
Relief, in feet	3582
Elevation at outlet, in feet	984
Average basin elevation, in feet	1714
Relative relief - Basin relief divided by basin perimeter, in feet per mile	28.7
High Elevation Index - Percent of area above 6000 feet	0
Altitude Index, in thousands of feet. Estimated as 0.00083 times mean basin elevation.	1.42
Mean basin slope computed from 30 m DEM, in percent	12.6
Percentage of basin covered by forest	2.74
Percent of area covered by lakes and ponds	3.54
Percentage of impervious area determined from NLCD 2001 imperviousness dataset	6.1
X coordinate of the centroid, in map coordinates	-1928642.4
Y coordinate of the centroid, in map coordinates	1383893.1
Latitude of the outlet, NAD83	33.48291
X coordinate of the outlet, in map coordinates	-1935600.0
Y coordinate of the outlet, in map coordinates	1373430.0
Basin perimeter, in miles	125
Distance in miles from basin centroid to the coast	29.4
Length of the longest flow path in meters	49943
Elevation relief in meters	1092

Figure B3.5. Characteristics of the threshold drainage area for Example 3 from USGS Streamstats (http://streamstats.usgs.gov/california.html).

Caltrans Rapid Assessment of Stream Channel Stability and Susceptibilty to Hydromodification Induced Instability

Date(s): **5/22/2003**
Persons: **Johnson & Johnson**
Site: **Murietta Creek**
Location: **Main St., Temecula, CA**
Conditions:

Associated file locations
GPS/*.kml
Photos
Other

Stream type
- Bedrock
- Cascade
- Step-Pool
- Engineered/channelized
- Plane-Bed
- Pool-Riffle
- x Dune-Ripple
- Braided

Physiographic region
- ☐ Modoc Plateau
- ☐ Southern Cascade Range
- ☐ Sierra Nevada
- ☐ Klamath Mountains
- ☐ Great Valley
- ☐ Basin and Range
- ☐ California Coast Ranges
- ☐ Transverse Ranges
- ☒ Peninsular Ranges
- ☐ Mojave Desert
- ☐ Colorado Desert

Assign scores to indicators 1-13 using the scheme on the following worksheet (Table 6 in report)

	Observations at equally-spaced cross sections										OR	Overview entire reach		
Cross section number	1	2	3	4	5	6	7	8	9	10		Upstream	Downstream	Value for reach
GPS shot (check boxes for XS where GPS coordinates were recorded)	✖	✖	✖	✖	✖	✖	✖	✖	✖	✖				
1. Watershed and floodplain activity and impacts	n/a											12	12	12.0
2. Flow characteristics	n/a											12	12	12.0
3. Channel pattern	9	8	9	3	3	3	3	9	7	4				5.8
4. Entrenchment/channel confinement	6	6	8	11	9	8	8	7	6	9				7.8
5. Bed material	12	12	12	12	12	12	12	12	12	12				12.0
Fs = approximate percentage of sand in bed sediments, 0 to 100.	100	100	100	100	100	100	100	100	100	100				
6. Bar development	10	11	11	10	10	10	11	12	12	10				10.7
7. Obstructions, including bedrock outcrops, armor layer, LWD jams, grade controls, bridge bed paving, revetments, dikes, vanes, or riprap.	1	1	1	10	1	1	1	1	10	1				2.8
8. Bank soil texture and coherence	12	11	11	11	10	11	12	12	11	10				11.1
9. Average bank slope angle in degrees (where 90° is a vertical bank)	12	12	10	12	10	10	9	8	8	8				9.9
10. Vegetative or engineered bank protection	11	11	11	11	8	10	11	11	11	8				10.3
11. Bank erosion	2	2	1	9	2	5	4	7	4	1				3.7
12. Mass wasting or bank failure	1	1	1	1	1	1	5	1	1	1				1.4
13. Stream crossing alignment with flow and distance from stream crossing to upstream meander impact point.	n/a													2
												Raw total score		102

Figure B3.6. Rapid stability assessment form, Example 3.

Figure B3.7. View from Main Street bridge facing downstream showing heavily vegetated alternate bars.

Figure B3.8. Main Street bridge showing exposure of bridge pier foundation due to bed lowering.

Figure B3.9. View upstream from the Main Street bridge showing typical bed material. Also see Figure B3.1.

Figure B3.10. View downstream from Main Street bridge.

Figure B3.11. Aerial view (2011) of grade control structure constructed downstream from 1st Street Bridge.

Example 4: Arcade Creek in Citrus Heights

This example is only loosely based on reality, the reader should be aware that some aspects of the example data are fictional and have been created for instructional purposes only. Arcade Creek flows southeast through a highly developed suburban corridor that roughly parallels Interstate 80 in Citrus Heights, a suburb just northeast of Sacramento (Figure B4.1). Bridge replacements and improvements are planned for three crossings along the route (Figure B4.2) which involve widening traffic lanes, addition of pedestrian walkways, bike lanes, and in two cases, additional vehicular traffic lanes. Although none of the sites will result in more than 1 acre of net new impervious area, the sum of net new impervious surface area will be 1.35 acres. Although not reflected in the narrative below, actual effort for an RSA for a situation such as this one where the stream crossing is a bridge may be reduced by using information obtained through the biannual federal bridge inspection program, available at http://smi.dot.ca.gov/[16].

This example differs from those previously presented in that the new impervious area is comprised of multiple subareas that are not contiguous and are not hydraulically connected along a single highway route. However, since all of the subareas are along the same stream, it stands to reason that the most downstream site will have a TDA that encompasses the others which is the case for this example (Figure B4.4). Accordingly, TDA delineation focuses on the most downstream site. RSAs are completed for each crossing site, however. RSAs are presented in summary form, as they are somewhat redundant with Examples 1-3.

Preparing for field work

Initial steps in the stability assessment were performed in the office using maps, aerial photographs and file data.

Determining average channel width

The threshold drainage area (TDA) associated with this project was defined by locating a point 20 channel widths (20W) downstream from the existing bridge at the most downstream site. Since the channel is almost fully canopied by trees, width could not be determined from aerial photographs, and a rough estimate of 40 ft was derived from existing bridge sections. For TDA delineation, 20W = 800 ft. The 20W distance was measured from the bridge downstream along the centerline of the river channel on aerial photographs, resulting in an endpoint of 38°39'14.81"N, 121°20'27.93"W (Figure B4.3).

Defining the threshold drainage area

The TDA was then defined as the watershed draining to this point using the Streamstats online tool (http://streamstats.usgs.gov/california.html). A map of the TDA is shown in Figure B4.4, and output from Streamstats is provided in Figure B4.5. Following definition of the TDA, the location of the project components relative to the TDA was confirmed: all new impervious areas are within the TDA. A rapid assessment is required if any impervious portion of the project is located within a TDA. The TDA for the downstream crossing is 26.4 square miles and includes both of the other sites and their TDAs. The watershed is relatively flat and highly developed with 42% impervious cover as of 2001 (Figure B4.5).

[16] Follow this link, and then select BIRIS (Bridge Inspection Reporting Information System). This is a Caltrans Intranet site, only Caltrans staff will be able to access it.

Setting endpoints for the representative reach

In a fashion similar to that presented for Examples 1-3, representative reaches were identified for each of the three stream crossings in the project. In all three cases, the total reach length was 40W, with somewhat smaller values for W for the upstream sites. Representative reaches were centered on the stream crossings.

Stream classification

Arcade Creek is in the Great Valley physiographic subregion. The gravel-bed channel is deeply incised and meanders through a highly developed urban corridor with primarily residential and commercial uses (Figure B4.3). Referring to Table 2, the US Army Corps of Engineers classification system, this channel has some of the characteristics of a meandering alluvial river (meandering planform, lower portion of watershed), and some characteristics of a modified channel (straightened, floodplain encroachment). By comparing the appearance of the stream with Table 3, the stream was classified as a modified/Pool-riffle/Plane-bed channel (Table B4.1). This classification places the reach in the first of the three categories (Pool-riffle, Plane-bed, Dune-ripple, or Engineered Channel reaches) that are used to interpret the assessment score.

Table B4.1. Application of Table 3[a] to Example Sites 4

	Cascade	Step-pool	Plane-Bed	Pool-Riffle	Dune-Ripple	Braided	Bedrock
Typical bed material	Boulder	Cobble, boulder	Gravel, cobble	Gravel	Sand	Variable	N/A
Bedform pattern	None	Vertically oscillatory	None	Laterally oscillatory	Multilayered	Laterally oscillatory	N/A
Reach type	Transport	Transport	Response	Response	Response	Response	Transport
Dominant roughness elements	Grains, banks	Bedforms, grains, large woody debris (LWD), banks	Grains, banks	Bedforms, grains, LWD, sinuosity, banks	Sinuosity, bedforms	Bedforms	Boundaries
Dominant sediment sources	Fluvial, hill slope, debris flow	Fluvial, hill slope, debris flow	Fluvial, bank failure, debris flows	Fluvial, bank failure, inactive channel, debris flows	Fluvial, bank failure, inactive channel	Fluvial, bank failure, debris flow	Fluvial, hill slope, debris flow
Sediment storage elements	Lee and stoss sides of flow obstructions	Bedforms	Overbank, inactive channel	Overbank, bedforms, inactive channel	Overbank, bedforms, inactive channel	Overbank, bedforms	N/A
Typical slope	0.08 < S < 0.30	0.03 < S < 0.08	0.01 < S < 0.03	0.001 < S < 0.02	S < 0.001	S < 0.03	Variable
Typical confinement by valley walls	Confined	Confined	Variable	Unconfined	Unconfined	Unconfined	Confined
Pool spacing (channel widths)	< 1	1 to 4	None	5 to 7	5 to 7	Variable	Variable

Note: Highlighted entries show characteristics for Example 4.

[a] *Montgomery-Buffington Stream Classification System, from Johnson (2006)*

Watershed and floodplain activity and impacts

The watershed is suburban/urban with 9.6% forest cover, and 41.9% impervious cover (as of 2001). Accordingly, a value of 11 was assigned to the "Watershed and floodplain activity and impacts" indicator for all three reaches (Table B4.2).

Flow characteristics

The stream appears to be perennial at all of the sites. However, the dense development in the stream corridor and presence of stormwater outfalls suggest moderately flashy behavior. This was confirmed by viewing hydrographs for a USGS gage on Arcade Creek 2.5 miles downstream from the TDA (Figure B4.6). A value of 8 was assigned to this indicator for all three reaches.

Field evaluations

The remainder of the rapid assessments were conducted in the field. Upon arriving at the site, the stream classification, average channel width, and other evaluations determined in the office were verified. The RSA team then proceeded to the downstream end of the representative reach at each site and walked the channel. Notations regarding stability indicators 3-12 were made at each of the ten predetermined cross-section locations at each site.

Channel pattern

Channel pattern throughout the reach was straight to meandering. Some straightening of the channel appears likely due to floodplain development. Accordingly, scores of 8 were assigned to this indicator for all three sites. (Table B4.2).

Entrenchment/channel confinement

The channel was deeply incised, as banks were 8 to 12 ft high on both sides (Figure B4.7). Infrastructure and tree roots were exposed. Consistent with the Channel Evolution Model, incision appears to be proceeding from downstream to upstream (Figure 7), as it becomes less severe in the upstream direction. Such incision is common in urban and suburban watersheds. Scores were assigned accordingly, with the downstream site 22 receiving a score of 11 and the upstream sites 8.

Bed material

Bed material for this reach is comprised of mostly of gravel with limited amounts of sand, silt and clay (Figure B4.8). In some places small amounts of riprap have been added to the channel bed. Reach-average bed material scores were 5 for all locations.

Bar development

Bars were absent or very small in all reaches. Even though slopes were estimated to be less than 0.02, the description, "bars forming for S > 0.02 and W/D < 12," most closely approached the conditions observed, and scores were assigned accordingly (Table B4.2).

Obstructions

Flows in the inspected reaches were obstructed by exposed pipes, riprap, trash and debris, rootwads, and general channel sinuosity. Reach average scores ranged from 8 to 10 (Figure B4.7 and Figure B4.8).

Bank soil texture and coherence

Bank soils were sandy, silty clay. A good bit of variation occurred from one cross section to the next, but cohesive soils were dominant, and average scores were 5 or 6 (Table B4.2).

Average bank slope angle in degrees

In the downstream reach where channels were most incised, bank slopes varied from 60 to 80 degrees, and scores for this indicator averaged 11, with progressively lower scores for the upstream sites. (Figure B4.9).

Vegetative or engineered bank protection

Scores for this indicator were 7-8. Bank vegetation was comprised of a thin but fairly dense band of trees growing at the top of both banks. Several banks featured exposed roots and leaning trees (Figure B4.7, Figure B4.8 and Figure B4.9). Seasonal grasses covered bank slopes, but these are temporary and not flow-resistant. No significant engineered bank protection was found.

Bank erosion

Bank erosion scores averaged 7 or 8 due to the frequency of raw soil exposures and root mat overhangs.

Mass wasting or bank failure

Mass wasting was found at a few of the cross sections, particularly along higher banks. Mean scores were 8 for all reaches.

Stream crossing alignment

Channel alignments were generally favorable relative to the stream crossings (Figure 4B.1), and scores of 2-7 were assigned. However, this indicator is not very important in this case as the crossings are to be replaced as part of the proposed project.

Scoring and Categorizing the Sites

Raw score totals for the three inspected reaches ranged from 95 to 105, increasing in the downstream direction. In all three cases, these scores lead to a rating of “Fair” for the assigned stream type (Table 8). Since the rating was not Excellent or Good, according to the NPDES permit the project must be referred for higher level analysis.

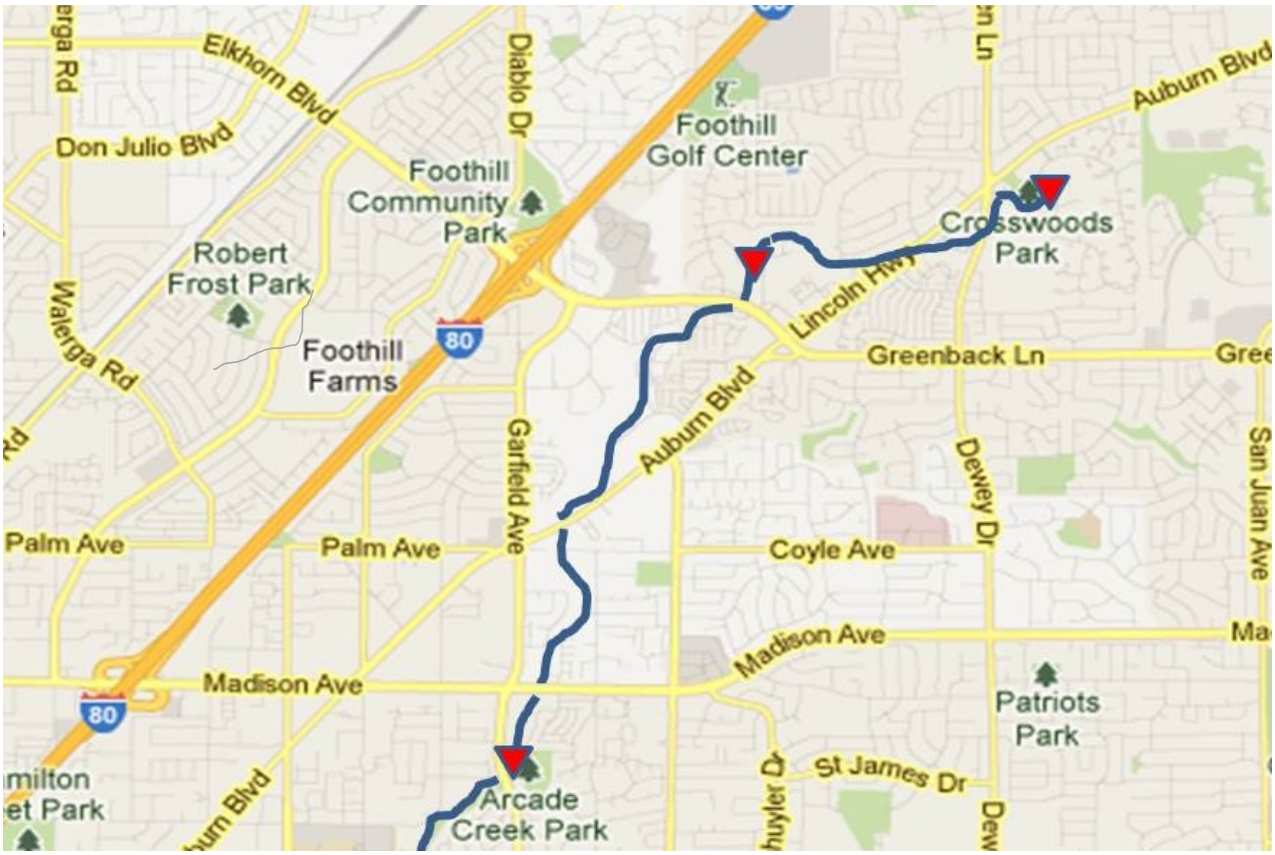

Figure B4.1. Example 4 site map. Red triangles show locations of crossings slated for replacement.

Figure B4.2. Ground level views of existing crossings of Arcade Creek, Citrus Heights, CA, at the three sites included in the project for Example 4.

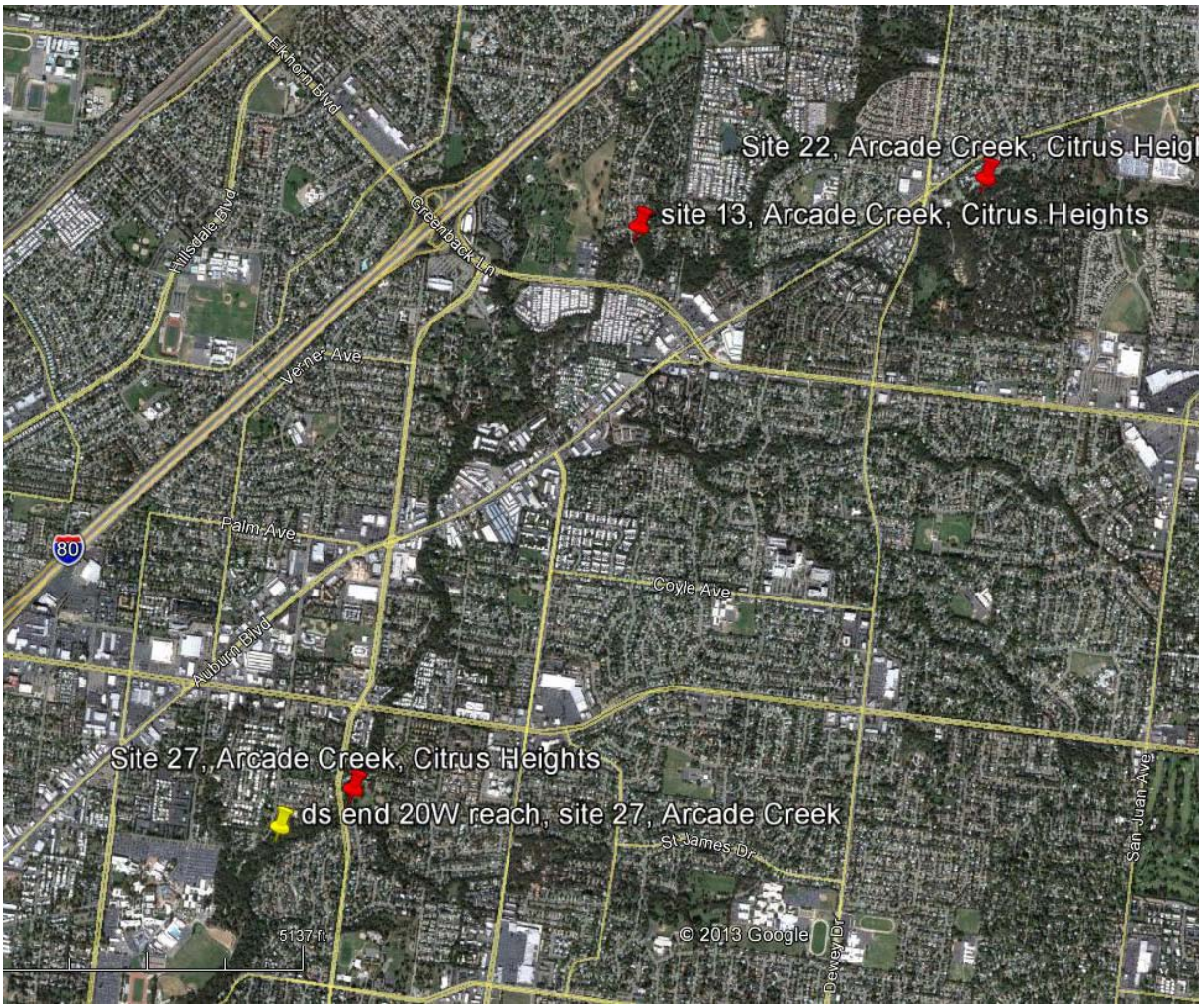

Figure B4.3. Yellow icon shows location of point for delineation of threshold drainage area at 20 channel widths (20W) downstream from site 27. Arcade Creek is shown by the forested corridor that runs from northeast to southwest.

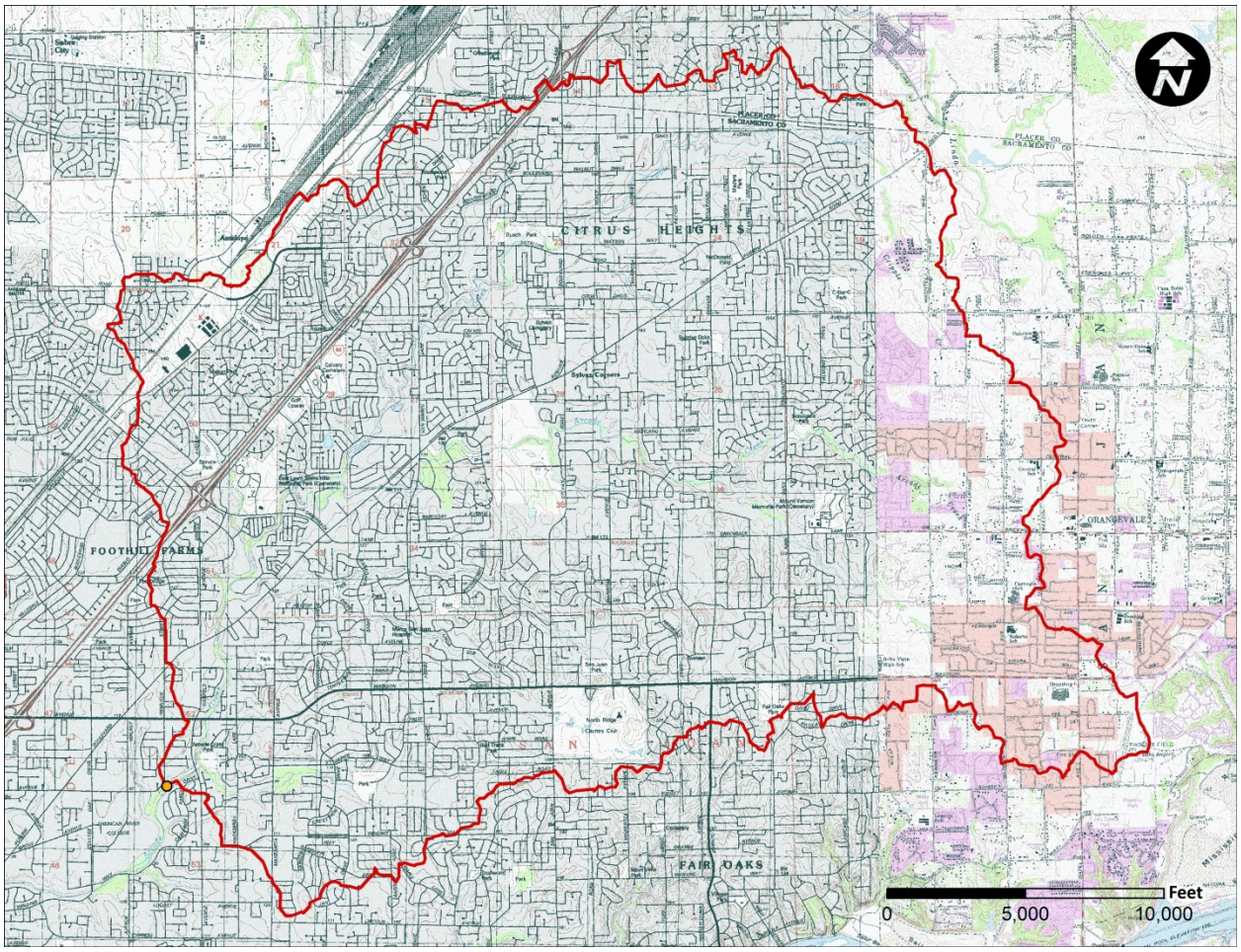

Figure B4.4. Threshold drainage area, Example 4.

USGS California StreamStats

Basin Characteristics Report

Date: Tue Apr 30 2013 14:38:53 Mountain Daylight Time
NAD27 Latitude: 38.6543 (38 39 15)
NAD27 Longitude: -121.3394 (-121 20 22)
NAD83 Latitude: 38.6542 (38 39 15)
NAD83 Longitude: -121.3405 (-121 20 26)

Parameter	Value
Area, in square miles	26.4
Mean annual precipitation, in inches	24
Average maximum January temperature, in degrees Fahrenheit	53.1
Average minimum January temperature, in degrees Fahrenheit	38
Maximum elevation, in feet	283
Minimum elevation, in feet	78
Relief, in feet	204
Elevation at outlet, in feet	82
Average basin elevation, in feet	169
Relative relief - Basin relief divided by basin perimeter, in feet per mile	5.95
High Elevation Index - Percent of area above 6000 feet	0
Altitude Index, in thousands of feet. Estimated as 0.00083 times mean basin elevation.	0.14
Mean basin slope computed from 30 m DEM, in percent	2.49
Percentage of basin covered by forest	9.62
Percent of area covered by lakes and ponds	0
Percentage of impervious area determined from NLCD 2001 imperviousness dataset	41.9
X coordinate of the centroid, in map coordinates	-2153498.7
Y coordinate of the centroid, in map coordinates	2027851.3
Latitude of the outlet, NAD83	38.65420
X coordinate of the outlet, in map coordinates	-2158800.0
Y coordinate of the outlet, in map coordinates	2025690.0
Basin perimeter, in miles	34.3
Distance in miles from basin centroid to the coast	89.8
Length of the longest flow path in meters	19178
Elevation relief in meters	62

Figure B4.5. Characteristics of the threshold drainage area for Example 4 from USGS Streamstats (http://streamstats.usgs.gov/california.html).

Table B4.2. Mean Values for RSA Indicators for Each Representative Reach.			
Stability Indicator	Site 27	Site 13	Site 22
Watershed and floodplain activity and impacts	11	11	11
Flow characteristics	8	8	8
Channel pattern	8	8	8
Entrenchment/channel confinement	11	8	8
Bed material	5	5	5
Bar development	9	8	8
Obstructions, including bedrock outcrops, armor layer, LWD jams, grade controls, bridge bed paving, revetments, dikes, vanes, or riprap	10	10	8
Bank soil texture and coherence	6	5	5
Average bank slope angle	11	9	4
Vegetative or engineered bank protection	8	7	8
Bank erosion	8	7	7
Mass wasting or bank failure	8	8	8
Stream crossing alignment with flow and distance from stream crossing to upstream meander impact point	2	5	7
Total raw score	105	99	95
Rating	Fair	Fair	Fair

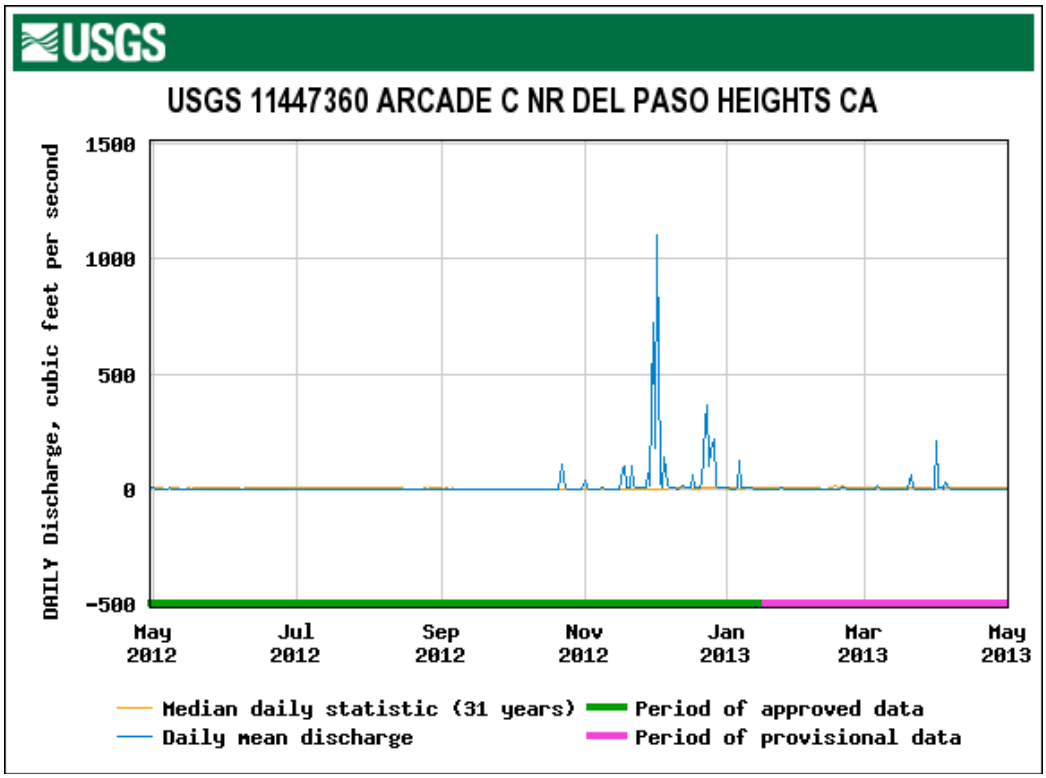

Figure B4.6. Daily mean discharge for USGS gaging station downstream from TDA. From http://nwis.waterdata.usgs.gov/nwis/inventory/?site_no=11447360.

Figure B4.7. Arcade Creek site 13. Exposed tree roots in banks, leaning tree trunks, small width to depth ratio, and vertical drop at concrete apron in foreground are collectively diagnostic for channel incision.

Figure B4.8. Typical Bed Material Size, Arcade Creek site 13. Note exposed pipeline, which is diagnostic of channel incision.

Figure B4.9. Typical Bank Conditions, Arcade Creek site 27.

Example 5: Placer County Road 193 Simple Culvert

This example is only loosely based on reality, the reader should be aware that some aspects of the example data are fictional and have been created for instructional purposes only. Lane addition is proposed for a 3.2-mile segment of highway, and there are 32 culverts within the project area. Since net new impervious area will total about 5 acres, RSAs are required for each culvert. The example shown is for a typical, 24-inch diameter corrugated metal pipe that is 10 years old (Figure B5.1).

Preparing for field work

Initial steps in the stability assessment were performed in the office using maps, aerial photographs and file data. Soil survey information was accessed at websoilsurvey.nrcs.usda.gov. Records from the Caltrans culvert inspection program were retrieved for all structures of interest from http://10.112.5.74/MaintGISApps/culverts/.

Determining average channel width

Many of the culverts do not drain well-defined channels, but simply convey ephemeral flow from grassy swales or discharge into similar features (Figure B5.2). In order to be conservative, a channel width equal to 1.5 times the culvert diameter was assumed. Similar assumptions were made for each of the culverts.

Defining the threshold drainage area

Drainage area for a point located 20W (20 x 3 ft = 60 ft) below the existing culvert outlet was estimated from a detailed contour map developed for project design. This exercise confirmed that part of the new impervious area was within the TDA.

Setting endpoints for the representative reach

Since channels upstream and downstream from the culvert were poorly defined grassy areas, representative reach delineation was done in the field.

Stream classification

The grassy swales do not fit the Johnson stream classification. To be conservative, the reach was assigned to the most stable of the three: Cascade or Step-Pool.

Watershed and floodplain activity and impacts

The watershed that contributes runoff to the TDA control point is rural/suburban with an estimated 60% pasture, 30% shrub and brush and 10% pavement/roof cover. Grazing is the dominant disturbance. Accordingly, a value of 5 was assigned to the “Watershed and floodplain activity and impacts” indicator for reaches upstream and downstream from the crossing (Figure B5.3).

Flow characteristics

Flow is obviously ephemeral, but since this is a first order (or lower) stream, a value of 5 was assigned consistent with criteria in Table 6.

Field evaluations

The remainder of the rapid assessment was conducted in the field. Upon arriving at the site, initial impressions of the site were verified. The RSA team inspected areas tributary to the culvert 60 ft upstream from the inlet and the area 60 ft downstream from the inlet. Since these areas were relatively uniform, indicators 3-12 were assigned a single score for the regions above and below the crossing (Figure B5.3).

Channel pattern

Channel pattern was straight to slightly meandering for both upstream and downstream reaches, and no evidence of bedload transport was noted. A score of 2 was assigned (Figure B5.3).

Entrenchment/channel confinement

The grassy swales were completely unconfined, so a score of 3 was assigned (Figure B5.3).

Bed material

Bed material for this reach is loamy soil protected by healthy turf grass (Figure B5.2). This type of bed surface is not covered in the scheme of Table 6. However, since this material is quite stable for the current and likely future flow conditions, bed material scores were 2 for both reaches.

Bar development

Bars were absent. Estimated width to depth ratios for the grassy swales were <12 and their bed slopes were likely > 0.02 ft/ft. Therefore a score of 3 was assigned for this indicator.

Obstructions

Obstructions consisted of very minor surface irregularities and trees. A small amount of riprap protected the scour hole at the culvert outlet (Figure B5.1). A score of 3 was assigned for both reaches (Figure B5.3).

Bank soil texture and coherence

Bank soils were sandy, silty clay. A good bit of variation occurred from one cross section to the next, but cohesive soils were dominant, and scores of 2 were assigned.

Average bank slope angle in degrees

Banks were extremely low, and slopes were most gradual with the exception of the small scour hole at the culvert outlet. Scores of 1 were assigned to both reaches (Figure B5.3)).

Vegetative or engineered bank protection

The pasture grasses, shrubs and trees in the representative reach provide adequate protection against bank erosion (Figure B5.2). However, the scoring scheme presented in Table 6 showed a score of 7-9 should be assigned to sites with a “small band of woody vegetation with 50-70% plant cover…”. To be conservative, scores of 7 were assigned.

Bank erosion

Bank erosion was virtually absent in the representative reach. A score of 2 was assigned (Figure B5.3).

Mass wasting or bank failure

Mass wasting was limited to the scour hole below the outlet. A score of 2 was assigned.

Stream crossing alignment

The channels entering the culvert from upstream included roadside swales or ditches that ran at an angle to the culvert centerline, but alignments were otherwise ideal. A score of 3 was assigned.

Scoring and Categorizing the Sites

The total raw score for the site was 40. The stability of the crossing structure was considered in assigning a rating using criteria provided by Caltrans 2009 and in Table 9. The corrugated metal pipe is in good condition, with only minor abrasion and corrosion noted in this inspection, which is consistent

with previous reports. The likely responses of the reach and crossing structure to higher peak flows likely to follow the project were also considered and judged to be minor and acceptable. These scores and observations led to a rating of “Excellent” for the assigned stream type (Table 8). .

Figure B5.1. Flared outlet for Example 5 culvert.

Figure B5.2. Area upstream of culvert inlet for Example 5.

Caltrans Rapid Assessment of Stream Channel Stability and Susceptibilty to Hydromodification Induced Instability

Date(s): **02.07.13**
Persons: **Sean Penders**
Site: **Placer 193 PM 1.97**
Location:
Conditions:

Associated file locations
GPS/*.kml
Photos
Other

Stream type

	Bedrock
	Cascade
	Step-Pool
	Engineered/channelized
x	Plane-Bed
	Pool-Riffle
	Dune-Ripple
	Braided

Physiographic region

- ☐ Modoc Plateau
- ☐ Southern Cascade Range
- ☐ Sierra Nevada
- ☐ Klamath Mountains
- ☐ Great Valley
- ☐ Basin and Range
- ☐ California Coast Ranges
- ☐ Transverse Ranges
- ☐ Peninsular Ranges
- ☐ Mojave Desert
- ☐ Colorado Desert

Assign scores to indicators 1-13 using the scheme on the following worksheet (Table 6 in report)

	Observations at equally-spaced cross sections										OR	Overview entire reach		
Cross section number	1	2	3	4	5	6	7	8	9	10		Upstream	Downstream	Value for reach
GPS shot (check boxes for XS where GPS coordinates were recorded)														
1. Watershed and floodplain activity and impacts	n/a											5	5	5.0
2. Flow characteristics	n/a											5	5	5.0
3. Channel pattern												2	2	2.0
4. Entrenchment/channel confinement												3	3	3.0
5. Bed material												2	2	2.0
Fs = approximate percentage of sand in bed sediments, 0 to 100.											Warning--input value out of 0-100 range!			
6. Bar development												3	3	3.0
7. Obstructions, including bedrock outcrops, armor layer, LWD jams, grade controls, bridge bed paving, revetments, dikes, vanes, or riprap.												3	3	3.0
8. Bank soil texture and coherence												2	2	2.0
9. Average bank slope angle in degrees (where 90° is a vertical bank)												1	1	1.0
10. Vegetative or engineered bank protection												7	7	7.0
11. Bank erosion												2	2	2.0
12. Mass wasting or bank failure												2	2	2.0
13. Stream crossing alignment with flow and distance from stream crossing to upstream meander impact point.	n/a													3
													Raw total score	40

Figure B5.3. Rapid stability assessment form, Example 5.

Appendix C: Abbreviations and Acronyms

Caltrans	California Department of Transportation
CEM	channel evolution model
CEQA	California Environmental Quality Act
CFR	Code of Federal Regulations
cfs	cubic feet per second
CWA	Clean Water Act
DHIPP	Digital Highway Inventory Photography Program
DWR	California Department of Water Resources
EPA	U.S. Environmental Protection Agency
FHWA	Federal Highway Administration
FISRWG	Federal Interagency Stream Restoration Working Group
Fs	fraction of sand
ft	feet
ft/sec	feet per second
ft2	square feet
H	horizontal
HEC-RAS	a one-dimensional hydraulic model developed by USACE
LWD	large woody debris
m	meters
m/s	meters per second
mm	millimeters
NEPA	National Environmental Policy Act
NPDES	National Pollutant Discharge Elimination System
RSA	rapid stability assessment
S	slope
SWRCB	State Water Resources Control Board
TDA	Threshold Drainage Area
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
V	vertical
W/D	width-to-depth ratio

Appendix D: References

Arneson, L.A., L.W. Zevenbergen, P.F. Lagasse, and P.E. Clopper. 2012. Federal Highway Administration, 2012b, "Evaluating Scour at Bridges," Fifth Edition, Report FHWA-HIF-12-003, Hydraulic Engineering Circular No. 18, U.S. Department of Transportation, Washington, DC: Federal Highway Administration.

Boyer, K. L., and F. D. Shields, Jr. 2007. "Ecological and Physical Considerations for Stream Projects." Chapter 1 in Stream Restoration Design, National Engineering Handbook Part 654, USDA-NRCS. Washington, DC. CD-ROM.

Brice, J. C. 1982. Stream Channel Stability Assessment. Washington, DC: U.S. Geological Survey and Federal Highway Administration.

Caltrans. 2009. Caltrans Culvert Inspection Program, Culvert Inspection Manual. State of California, Department of Transportation, Sacramento, California.

Caltrans. 2010. Storm Water Quality Handbook, Project Planning and Design Guide. State of California, Department of Transportation, Sacramento, California.

California Geological Survey. 2002. California Geomorphic Provinces. California Department of Conservation, California Geological Survey, Sacramento.

Castro, J. 2003. Geomorphologic Impacts of Culvert Replacement and Removal: Avoiding Channel Incision. Portland, OR: Oregon Fish and Wildlife Office.

Cluer, B., and C. Thorne. 2013. A Stream Evolution Model Integrating Habitat and Ecosystem Benefits. River Research and Applications. DOI: 10.1002/rra.2631 Published online.

Copeland, R. R. 1994. Application of Channel Stability Methods—Case Studies. Technical Report HL-94-11. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Dellinger, D. A. 1989. California's Unique Geologic History and Its Role in Mineral Formation, with Emphasis on the Mineral Resources of the California Desert Region. U.S. Geological Survey.

FHWA (Federal Highway Administration). 2009. Stream Instability, Bridge Scour, and Countermeasures: A Field Guide for Bridge Inspectors. FHWA Publication No. FHWA-NHI-08-106, US Department of Transportation Federal Highway Administration and National Highway Institute, Washington, DC.

FISRWG (Federal Interagency Stream Restoration Working Group). 1998. Stream Corridor Restoration: Principles, Processes and Practices. Springfield, VA: National Technical Information Service, U.S. Department of Commerce. Also published as NRCS, U.S. Department of Agriculture (1998) National Engineering Handbook (NEH), Part 653. Washington, DC.

Harrelson, C. C., C. L. Rawlins, and J. P. Potyondy. 1994. Stream Channel Reference Sites: An Illustrated Guide to Field Technique. General Technical Report RM-245. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.

Hawley, R. J., B. P. Bledsoe, E. D. Stein, and B. E. Haines. 2012. "Channel Evolution Model of Semiarid Stream Response to Urban-Induced Hydromodification." Journal of the American Water Resources Association, 48(4):722-744.

Johnson, P. A. 2005. "Preliminary Assessment and Rating of Stream Channel Stability near Bridges." Journal of Hydraulic Engineering, 131(10), 845-852.

Johnson, P. A. 2006. Assessing Stream Channel Stability at Bridges in Physiographic Regions (No. FHWA-HRT-05-072).

Johnson, P. A., G. L. Gleason, and R. D. Hey. 1999. Rapid assessment of channel stability in vicinity of road crossing. Journal of Hydraulic Engineering, 125(6), 645-651.

Lagasse, P. F., J. D. Schall, and E. V. Richardson. 2001. Stream Stability at Highway Structures. Hydraulic Engineering Circular No. 20. Washington, DC: Federal Highway Administration.

Lagasse, P. F., L. W. Zevenbergen, W. J. Spitz, and L. A. Arneson. 2012. Stream Stability at Highway Structures. Fourth Edition, Publication No. FHWA-HIF-12-004, Hydraulic Engineering Circular No. 20. Washington, DC: Federal Highway Administration.

Lane, E.W. 1955. The Importance of Fluvial Morphology in Hydraulic Engineering. Proceedings: American Society of Civil Engineers 81(745), 1-17.

McNab, W. H., and P. E. Avers. 1994. Ecological Subregions of the United States: Section Descriptions. WO-WSA-5. Washington, DC: U.S. Department of Agriculture, Forest Service, Ecosystem Management.

McNab, W.H., D.T. Cleland, J. A. Freeouf, J. E. Keys, Jr., G. J. Nowacki, C. A. Carpenter, C.A., comps. 2005. Description of ecological subregions: sections of the conterminous United States [CD-ROM]. Washington, DC: U.S. Department of Agriculture, Forest Service.

Montgomery, D. R., and J. M., Buffington .1997. "Channel-reach morphology in mountain drainage basins." Geological Society of America Bulletin, 109(5), 596-611.

Montgomery, D. R., and L. H. MacDonald. 2002. "Diagnostic Approach to Stream Channel Assessment and Monitoring."Journal of the American Water Resources Association, 38(1), 1-16.

Niezgoda, S. L., and P. A. Johnson. 2005. "Improving the Urban Stream Restoration Effort: Identifying Critical Form and Processes Relationships." Environmental Management, 35(5), 579-592.

Schumm, S.A., M.D. Harvey, and C.C. Watson, 1984. Incised channels: Morphology, dynamics and control. Water Resources Publications, Littleton, CO.Simon, A. 1989. A Model of Channel Response in Disturbed Alluvial Channels. Earth Surface Processes and Landforms, 14(1), 11-26.

Simon, A., and P. W. Downs. 1995. "An Interdisciplinary Approach to Evaluation of Potential Instability in Alluvial Channels." Geomorphology, 12(3), 215-232.

SWRCB (State Water Resources Control Board). 2012. Order No. 2012-DWQ, NPDES No. CAS0000003, National Pollutant Discharge Elimination System (NPDES) Statewide Stormwater Permit, Waste Discharge Requirements (WDRS) for State of California, Department of Transportation, Sacramento.

Thomas, B.E., H.W. Hjalmarson, and S. D. Waltemeyer. 1997, Methods for Estimating Magnitude and Frequency of Floods in the Southwestern United States: U.S. Geological Survey Water-Supply Paper 2433. Washington, DC: US Geological Survey.

Thorne, C. R. 1998. Stream Reconnaissance Handbook: Geomorphological Investigation and Analysis of River Channels. Chichester, UK: John Wiley & Sons Ltd.

Thorne, C. R., R. G. Allen, and A. Simon. 1996a. "Geomorphological River Channel Reconnaissance for River Analysis, Engineering and Management." Transactions of the Institute of British Geographers, 469-483.

Thorne, C. R., S. Reed, and J. C. Doornkamp. 1996b. A Procedure for Assessing River Bank Erosion Problems and Solutions. Almondsbury, Bristol, UK: National Rivers Authority.

USACE (U.S. Army Corps of Engineers). 1994. Channel Stability Assessment for Flood Control Projects. Engineer Manual EM 1110-2-1418. Washington, DC: Headquarters, U.S. Army Corps of Engineers.

USACE. 2010. River Analysis System, HEC-RAS, User's Manual, Version 4.1. Davis, CA: U.S. Army Corps of Engineers, Hydrologic Engineering Center.

Zevenbergen, L. W., L. A. Arneson, J. H. Hunt, and A. C. Miller. 2012. Hydraulic Design of Safe Bridges. Report FHWA-HIF-12-018, Hydraulic Design Series No. 7. Washington, DC: Federal Highway Administration.

Appendix E: Glossary

Aggradation: General and progressive buildup of the longitudinal profile of a channel bed due to sediment deposition.

Alluvial channel: A channel that is wholly in alluvium (sediment); no bedrock is exposed in channel at low flow or likely to be exposed by erosion.

Alluvial fan: A fan-shaped deposit of material at the place where a stream issues from a narrow valley of high slope onto a plain or broad valley of low slope. An alluvial cone is made up of the finer materials suspended in flow while a debris cone is a mixture of all sizes and kinds of materials.

Alluvial stream: A stream that has formed its channel in sediments that have been, and can be, transported by the stream.

Anastomosing stream: An anabranched stream.

Anabranched stream: A stream whose flow is divided at normal and lower stages by large islands or, more rarely, by large bars; individual islands or bars are wider than about three times water width; channels are more widely and distinctly separated than in a braided stream.

Armor (armoring): Surfacing a channel bed, banks, or embankment slope to resist erosion and scour. (a) Natural process whereby an erosion-resistant layer of relatively large particles is formed on a streambed because fine particles have been removed by stream flow. (b) Placement of a covering to resist erosion.

Bank: The sides of a channel between which the flow is normally confined.

Bank height: The vertical distance from the top of the bank to its toe.

Bank, left/right: The side of a channel, viewed looking downstream.

Bar: An elongated deposit of alluvium within a channel, not permanently vegetated.

Baseflow: Typical level of streamflow during periods between storm events.

Bed: The bottom of a channel bounded by banks.

Bed load: Sediment moving along the bed of a stream by sliding, bouncing or rolling. Also the rate of such sediment movement in dimensions of mass per unit time.

Bed material: Material found in and on the bed of a stream. These materials may be transported as bed load or in suspension.

Bedrock: The solid rock exposed at the surface of the earth or overlain by soils and unconsolidated material.

Bed material size: The size of sediments found on the bed of a stream channel. Sediment size may be loosely classified as boulders, cobble, gravel, sand, silt, or clay. More quantitative measurements may be used to produce a grain size distribution, and various percentiles of the distribution (such as the median, D50) are often used to describe the bed material size.

Best Management Practices (BMPs): Schedules of activities, prohibitions of practices, maintenance procedures, and other management practices to prevent or reduce the pollution of waters of the United States. BMPs include structural and nonstructural controls, treatment requirements, operation and maintenance procedures, and practices to control runoff, spillage and leaks, sludge and waste disposal, and drainage from raw material storage.

Braided stream: A stream whose flow is divided at normal stage by small mid-channel bars or small islands; the individual width of bars and islands is less than about three times water width. A braided stream has the aspect of a single large channel, within which are subordinate channels.

Channel: The bed and banks that confine the surface flow of a stream.

Channel classification: Classification of a stream according to a set of observations or typical characteristics. For example, channels are classified as straight, meandering, or braided based on their planform.

Channel diversion: The removal of flows, by natural or artificial means, from a natural length of channel.

Channel evolution models: Ideas or schemes that explain the way that alluvial channels typically respond to disturbance, particularly base-level lowering or straightening. These models typically suggest that channels evolve through a definite set of phases or stages to regain a state of dynamic equilibrium.

Channel-forming discharge: See dominant discharge.

Channelization: Straightening or deepening of a natural channel through the use of artificial cutoffs, grading, flow-control measures.

Clay (mineral): A particle with a diameter in the range of 0.00024 to 0.004 mm (10-5 to 0.00016 in.).

Climax vegetation: Floral community which establishes itself on a given site for given climatic conditions in the absence of major disturbance after a long time (it is the asymptotic or quasi-equilibrium state of the local ecosystem).

Cobble: A fragment of rock with a diameter in the range of 64 to 250 mm (2.5 to 9.8 in.).

Confluence: The junction of two or more streams.

Cohesive streambed: Streambed with cohesive bed material, which can include caliche, hardpan, loess, highly compact and dense clays, and, in a broader sense, erodible rock.

Constriction: A natural or artificial control section, such as a bridge crossing, channel reach, or dam, with limited flow capacity, upstream of which the water surface elevation is related to discharge.

Contraction: The effect of channel or bridge constriction on flow.

Degradation (bed): A general and progressive (long-term) lowering of the channel bed due to erosion, over a relatively long channel segment.

Depth: The depth a stream channel—the vertical distance from the floodplain surface to the channel bed. Since depth varies over a cross section, average and maximum depths are sometimes specified.

Deposition: The settling of sediments to the bottom of a water body due to gravity. When deposition exceeds erosion, sediment bars or deposits will form.

Design Pollution Prevention Best Management Practices:

a) Conserve natural areas, to the extent feasible, including existing trees, stream buffer areas, vegetation, and soils.

b) Minimize the impervious footprint of the project.

c) Minimize disturbances to natural drainages.

d) Design and construct pervious areas to effectively receive runoff from impervious areas, taking into consideration the pervious areas' soil conditions, slope, and other pertinent factors.

e) Implement landscape and soil-based BMPs, such as compost-amended soils and vegetated strips and swales.

f) Use climate-appropriate landscaping that minimizes irrigation and runoff, promotes surface infiltration, and minimizes the use of pesticides and fertilizers.

g) Design all landscapes to comply with the California Department of Water Resources Water Efficient Landscape Ordinance: http://www.water.ca.gov/wateruseefficiency/landscape ordinance/technical.cfm

Where the California Department of Water Resources Water Efficient Landscape Ordinance conflicts with a local water conservation ordinance, Caltrans shall comply with the local ordinance.

Discharge: The volume of water passing through a channel during a given time.

Dominant discharge: a) The discharge of water that is of sufficient magnitude and frequency to have a dominating effect in determining the characteristics and size of the stream course, channel, and bed. (b) The discharge that determines the principle dimensions and characteristics of a natural channel. The dominant formative discharge depends on the maximum and mean discharge, duration of flow, and flood frequency. For hydraulic geometry relationships, it is taken to be the bankfull discharge, which has a return period of approximately 1.5 years in many natural channels.

Drainage basin: An area confined by drainage divides, often having only one outlet for discharge (catchment, watershed).

Dynamic equilibrium: A state or condition of a fluvial system in which channels may exhibit local changes in width, depth, slope, or bed material size, or may experience small fluctuations in reach-average properties, but tend to fluctuate about an unchanging mean condition.

Entrenched stream: A stream cut into bedrock or consolidated deposits.

Erosion: Displacement of soil particles by water or wind.

Fine sediment load: The part of total sediment load that is composed of particles finer than those represented in the bed. Also called wash load. Normally, fine sediment load is finer than 0.062 mm (0.0024 in) for sand-bed channels. Silts, clays, and sand could be considered wash load in coarse gravel-bed and cobble-bed channels.

Floodplain: A nearly flat, alluvial lowland bordering a stream, subject to frequent inundation by floods.

Fluvial geomorphology: The science dealing with the morphology (form) and dynamics of streams and rivers.

Fluvial system: The natural river system consisting of (1) the drainage basin and watershed, or sediment source area; (2) tributary and mainstream river channels, or sediment transfer zone; and (3) alluvial fans, valley fills, and deltas, or the sediment deposition zone.

Geomorphology/morphology: The science dealing with the form of the Earth, the general configuration of its surface, and the changes caused by erosion and deposition.

Graben: A depressed block of land bordered by parallel faults. Graben is German for ditch or trench. A graben is the result of a block of land being downthrown producing a valley with a distinct scarp on each side.

Grade-control structure (sill, check dam): Structure placed bank to bank across a stream channel (usually with its central axis perpendicular to flow) to control bed slope and prevent scour or headcutting.

Headcutting: Channel degradation associated with an abrupt change or step in the bed elevation (headcut); headcutting generally migrates in an upstream direction.

Highway facility: Linear facility designed to carry vehicular and pedestrian traffic. These include freeways, highways, and expressways, as designated by the California Streets and Highway Code and the California legislature. These facilities also include all associated support infrastructure, including bridges, toll plazas, inspection and weigh stations, soundwalls, retaining walls, culverts, vegetated slopes, shoulders, intersections, offramps, onramps, overpasses, lights, signal lights, gutters, guard rails, and other support facilities. The support infrastructure is considered a highway facility only when accompanied by an increase in highway impervious surface. Otherwise, it is considered a non-highway facility.

Horst: The raised fault block bounded by normal faults or graben. A horst is formed from extension of the Earth's crust. The raised block is a portion of the crust that generally remains stationary or is uplifted while the land has dropped on either side.

Hydrograph modification (hydromodification): Alteration of the hydrologic characteristics of surface waters through watershed development. Under past practices, new and redevelopment construction activities resulted in urbanization, which in turn modified natural watershed and stream processes. The impacts of hydromodification include, but are not limited to, increased bed and bank erosion, loss of habitat, increased sediment transport and deposition, and increased flooding. Urbanization causes these effects by altering the terrain, modifying the vegetation and soil characteristics, introducing impervious surfaces (such as pavement and buildings), and altering the condition of stream channels through straightening, deepening, and armoring them. These changes affect hydrologic characteristics in the watershed and affect the supply and transport of sediment in the stream system.

Hydromodification Management Plan: A plan to control and reduce the impacts of hydrograph modification caused by development activities in a watershed.

Hydrographs: A graph showing water stage or discharge over time.

Imbrication: Preferential orientation of sediment particles (gravel or cobble) such that they overlap each other like shingles and interlock, thereby increasing their resistance to erosion.

Impervious area: The area of land covered with impervious surface.

Impervious surface: Any surface in the landscape that cannot effectively absorb or infiltrate rainfall; for example, sidewalks, rooftops, roads, and parking lots.

Incised reach: A stretch of stream with an incised channel that only very rarely overflows its banks, if ever.

Incised stream: A stream that has deepened its channel through the bed of the valley floor, so that the floodplain is a terrace.

Infiltration: The process by which water on the ground surface enters the soil. The infiltration rate is a measure of the rate at which soil is able to absorb rainfall or irrigation. It is usually measured in inches per hour or millimeters per hour. The rate decreases as the soil becomes saturated. If the precipitation rate exceeds the infiltration rate, runoff will usually occur unless there is some physical barrier.

Knickpoint: A headcut in noncohesive alluvial material. Also“nickpoint.”

Lateral erosion: Erosion in which the removal of material extends horizontally, as contrasted with degradation and scour in a vertical direction.

Load (or sediment load): Amount of sediment being moved by a stream.

Longitudinal profile: The profile of a stream or channel drawn along the length of its centerline. In drawing the profile, elevations of the water surface, or thalweg, are plotted against distance, as measured from the mouth or from an arbitrary initial point.

Low impact development (LID): An approach to land development with the goal of mimicking or replicating the preproject hydrologic regime. LID employs design techniques to create a functionally equivalent hydrologic site design. Hydrologic functions of storage, infiltration, and groundwater recharge, as well as the volume and frequency of discharges, are maintained through the use of integrated and distributed microscale stormwater retention and detention areas, reduction of impervious surfaces, and lengthening of runoff flow paths and flow time. Other strategies include preservation/protection of environmentally sensitive site features such as riparian buffers, wetlands, steep slopes, mature trees, floodplains, woodlands, and highly permeable soils.

Lower bank: That portion of a streambank having an elevation lower than the mean water level of the stream.

Meander or full meander: Two consecutive loops in a river, one flowing clockwise and the other counter-clockwise.

Migration: Change in the position of a channel through lateral erosion of one bank and simultaneous accretion of the opposite bank.

Moribund: A stream unable to erode its bed or banks because of naturally resistant materials or human modifications.

New development: Any newly constructed facility, street, road, highway, or contiguous road surface installed as part of a street, road, or highway project within Caltrans right-of-way.

Non-highway facility: For purposes of the NPDES permit, a non-highway facility is any facility not meeting the definition of a highway facility, including, but not limited to, rest stops, park-and-ride facilities, maintenance stations, vista points, warehouses, laboratories, and office buildings.

Peneplain: A low-relief plain, usually the result of a long period of fluvial erosion during times of extended tectonic stability.

Perennial stream: Sometimes referred to as a "blue-line stream"—any stream shown as a solid blue line on the latest version of the USGS 7.5-minute series quadrangle map. Where 7.5-minute series maps have not been prepared by USGS, 15-minute series maps are used.

Planform: The pattern a channel exhibits when viewed from above. Channels are classified as straight, meandering, or braided based on their planform.

Point bar: An alluvial deposit of sand or gravel, lacking permanent vegetal cover, occurring in a channel at the inside of a meander loop, usually somewhat downstream of the apex of the loop.

Project: A project includes all work associated with a capital improvement to the highway system or other highway support facilities that is contained in one contract and set of plans. This definition is in accordance with CFR 49 Chapter 53 definitions section 5302.

Project limits: For the determination the threshold drainage area and the applicability of the rapid assessment, the project limits encompass the area extending from the begin-construction to end-construction highway signs and from right-of-way fence to right-of-way fence. In some cases a project will have multiple locations, and in these cases the project limits begin and end in multiple locations. For projects that have multiple locations, the net new impervious area shall be additive for each subwatershed. For example, a project with multiple locations along a right of way that parallels a stream may have several locations that all drain to the parallel stream. In such a case, the impervious areas of locations are additive. If the total area > 1 acre, an RSA is required. If a project has multiple locations in separate watersheds, (for example, guard rail in multiple counties), then they are not additive.

Post-Construction Stormwater Treatment Controls: Permanent structures, landscape features, and activities (such as BMPs and LID) intended to reduce pollutant loads associated with stormwater runoff.

Rapid stability assessment (RSA): Assessment of the susceptibility of a channel reach to accelerated erosion or deposition in response to planned hydromodification. RSAs generally require no more than a few hours of effort by trained professionals working in the office and conducting a visual field inspection of the reach in question.

Receiving waters: Distinct bodies of water, such as channels, ponds, lakes, bays, estuaries, or oceans, that receive pollutants from an area of interest.

Redevelopment: The creation, addition, and/or replacement of impervious surface on an already developed site. Examples include the expansion of a building footprint, road widening, and the addition

or replacement of a structure. Replacement of impervious surfaces includes any activity that removes impervious materials and exposes the underlying soil or pervious subgrade temporarily or permanently. Redevelopment does not include trenching and resurfacing associated with utility work; pavement grinding and resurfacing of existing roadways; construction of new sidewalks, pedestrian ramps, or bike lanes on existing roadways; or routine replacement of damaged pavement such as pothole repair or replacement of short, noncontiguous sections of roadway. Redevelopment does include replacement of existing roadway surfaces where the underlying soil or pervious subgrade is exposed during construction. Replaced impervious surfaces of this type shall be considered "new impervious surfaces" for the purpose of determining whether post-construction stormwater treatment controls apply.

Representative reach: A representative reach is a length of stream channel that extends at least 20 channel widths upstream and downstream of a stream crossing. For example, a 20-ft-wide channel would require analyzing a total of 400 ft of the channel extending roughly equal distances (~200 ft) upstream and downstream of the discharge point or bridge. If sections of the channel within the 20-channel-width distance are immediately upstream or downstream of steps, culverts, grade controls, tributary junctions, or other features and structures that significantly affect the shape and behavior of the channel, more than 20 channel widths should be analyzed.

Runoff: The part of precipitation that appears in surface streams of perennial or intermittent form.

Sand: Soil or sediment with particle diameters in the range of 0.062 to 2.0 mm (0.0024 to 0.08 in).

Scour: Erosion of streambed or bank material by flowing water; often considered to be localized.

Sediment discharge: The quantity of sediment that is carried past any cross section of a stream in a unit of time. Discharge may be limited to certain sizes of sediment or to a specific part of the cross section.

Sediment load: Amount of sediment being moved by a stream.

Silt: Soil or sediment with particle diameters in the range of 0.004 to 0.062 mm (0.00016 to 0.0024 in)

Slope (of channel or stream): Elevational gradient or fall per unit length along the channel centerline, or thalweg.

Soil erosion: Removal or soil from the land surface by the action of water or wind. In general, natural background erosion removes soil at roughly the same rate that soil is formed. Accelerated erosion often occurs in association with human activities.

Stability: The condition of a channel when, although it may change slightly at different times of the year under varying conditions of flow and sediment discharge, there is no appreciable change from year to year; that is, accretion balances erosion over the years.

Stable channel: A stream channel with a bed slope and cross section that allows it to transport water and sediment delivered from the upstream watershed without aggradation, degradation, or bank erosion (a graded stream).

Stream: A body of water flowing in a channel that may range in size from a large river to a small rill. By extension, the term is sometimes applied to a natural channel or drainage course formed by flowing water, whether or not it is occupied by water.

Stream crossing: Infrastructure such as a bridge, culvert, or pipe that is placed where a highway right-of-way crosses a stream channel. A stream crossing requiring an RSA is only those highway drainage crossings that are considered "Waters of the US" as defined by the Army Corps of Engineers guidance.

Streambank erosion: Removal of soil particles from a bank surface, due primarily to water action. Other agents, such as weathering, ice and debris abrasion, chemical reactions, and land use changes may also directly or indirectly lead to bank erosion.

Streambank failure: Sudden collapse of a bank due to an unstable condition, such as removal of material at the toe of the bank by scour.

Stormwater: Stormwater runoff, snowmelt runoff, and surface runoff and drainage, as defined in Title 40, Code of Federal Regulations (CFR), Section 122.26 (b)(13).

Stormwater runoff: The portion of precipitation that does not naturally percolate into the ground or evaporate, but moves via overland flow, interflow, channels, or pipes.

Stoss: The side of a flow obstruction that faces the flow.

Thalweg: A line connecting the lowest points of successive cross sections along the course of a channel.

Threshold drainage area (TDA): The watershed or drainage area that contributes flows to a point on a channel located at the lower end of a representative reach downstream of a stream crossing.

Unstable channel: A channel reach that, over a period of several years, either discharges more sediment than it receives (due to bed or bank erosion) or discharges less sediment than it receives (due to deposition). Unstable channels tend to change their dimensions and locations much more rapidly than stable channels.

Velocity: The speed of water movement, expressed in meters per second (m/s) or feet per second (ft/sec). The average velocity at a given cross section is determined by dividing discharge by cross sectional area.

Wash load: Suspended material of very small size (generally clays and colloids), originating primarily from erosion on the land slopes of the drainage area and present to a negligible degree in the bed itself.

Watershed disturbance: Events or activities acting on a watershed that change the amount or timing of water and sediment flow out of the watershed. Natural disturbances include floods, fires, droughts, earthquakes, landslides, and logjams. Human-caused disturbances include channel enlargement and straightening, land use changes, and construction of dams, levees, and diversions.

Watershed: See drainage basin.

Width: The width of a stream channel—the horizontal distance between the tops of opposite banks at a given cross section. Top banks are local maxima in elevation. When water surface elevation exceeds top bank elevation, overflow onto the adjacent floodplain occurs. When one top bank elevation is higher than the other, the channel width is the horizontal distance from the lower top bank to the opposite bank.