APPENDIX C - State of the Hydromodification Science: A Literature Review

Pursuant to Permit Provision F.1.h(1)(g), this appendix provides the results of a literature review conducted as a basis for the development of the HMP.

Hydromodification in the context of this HMP refers to changes in the magnitude and frequency of stream flows due to urbanization and the resulting impacts on the receiving channels in terms of erosion, sedimentation, and degradation of in-stream habitat. The processes involved in aggradation and degradation are complex, but are caused by an alteration of the hydrologic regime of a watershed due to increases in impervious surfaces, more efficient storm drain networks, and a change in historic sediment supply sources, among other factors. The study of hydromodification is an evolving field, and regulations to manage the impacts of hydromodification must be grounded in the latest science available.

HMPs seek ways to mitigate erosion impacts by establishing requirements for controlling runoff from new development. In order to establish appropriate regulations, it is important to understand 1) how land use changes alter stormwater runoff; and 2) how these changes can impact stream channels. These and other issues central to HMPs adopted in California have been addressed in numerous journal articles, books, and reports. This literature review builds upon previous literature reviews developed for the South Orange County HMP and the San Diego County HMP, including recent studies or information relevant to Southern California.

C.1. Hydromodification Management Concepts

There are many different approaches to managing hydromodification impacts from urbanization, and most HMPs provide multiple options for achieving and documenting compliance with National Pollutant Discharge Elimination System (NPDES) permit requirements. In general, hydrograph management approaches focus on managing runoff from a developed area to not increase instability in a channel, and in-stream solutions focus on managing the receiving channel to accept an altered flow regime without becoming unstable. This section briefly summarizes various approaches for HMP compliance.

C.1.1. Stability of Alluvial Channels

Southern California streams typically combine steep slopes and erodible materials with a predominance of sand and gravel substrates, which may be assimilated to alluvial channels (SCCWRP, 2011). An exchange of material between the inflowing sediment load and the bed and banks of the stream is established, thus creating a constant adjustment of the channel's width, depth, slope, and planform in response to changes in water or sediment discharge (NEH, 2007). Stable natural alluvial channels typically form their geometry by moving boundary material. Lane's interrelationship (1955) conceptualizes this balance between hydrologic and geomorphic processes for alluvial channels:

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

Where:

Q_s = Sediment discharge

D_{50} = Median sediment size

Q_w = Flow

S = Channel Slope

As seen by Lane's interrelationship, if any of the four variables is altered, one or more of the remaining variables must change. In the case of urbanization, runoff usually is increased, causing a reduction in channel slope (S) through downcutting or increased channel meander. Urbanization may also result in a change in sediment discharge (Qs). Streambed material is derived from the channel bed and banks. If channels are altered by development in such a way as to reduce or increase sediment discharge, instability may occur.

Only a portion of the total sediment load in a channel is important for stream stability. Total channel sediment load may be classified by size or transport mechanism. The wash load commonly refers to the portion of the total sediment load that remains continuously in suspension (based on particle size). The wash load has a nominal impact on channel stability. Bed material load refers to the material that moves along the channel bed via saltation, and is continuously in contact or exchange with the channel bed. Bed material load is the critical portion of total sediment discharge for channel stability.

C.1.2.Hydrologic Management Measures

Facilities that detain or infiltrate runoff to mitigate development impacts are the focus of most HMP implementation guidance. They work by either reducing the volume of runoff (infiltration facilities) or holding water and releasing it below Qc (detention facilities). These facilities, also referred to as BMPs, can range from regional detention basins designed solely for flow control, to bioretention facilities that serve a number of functions. A number of BMPs, including swales, bioretention, flow-through planters, and extended detention basins have been developed to manage stormwater quality, and several resources describe the design of stormwater quality BMPs (CASQA 2003; Richman et al. 2004). In many cases, these facilities can be designed to also meet hydromodification management requirements.

Many HMPs also provide guidance for applying LID approaches to site design and land use planning to preserve the hydrologic cycle of a watershed and mitigate hydromodification impacts. These plans typically include decentralized stormwater management systems and protection of natural drainage features, such as wetlands and stream corridors. Runoff is typically directed toward infiltration-based stormwater BMPs that slow and treat runoff. Hydrologic management BMPs differ from those used to meet water quality objectives in that they focus more on generating a flow- uration curve that matches or reduces the undeveloped flow duration curve than on removing potential pollutants, although these two functions can be combined into one facility. Various methods exist for sizing hydrologic management BMPs.

- **Hydrograph Matching** uses an outflow hydrograph for a particular site that matches closely with the pre-project hydrograph for a design storm. This method is most traditionally used to design flood-detention facilities to mitigate for a particular storm recurrence interval (e.g., the 100-year storm). Although hydrograph matching can be employed for multiple storm recurrence intervals, this method generally does not take into account the smaller, more frequent storms that are identified by the actual state of the science as performing a majority of the erosive work in stream channel and is therefore not widely accepted for HMP compliance nor recommended for use as a part of this HMP.
- **Volume Control** matches the pre-project and post-construction runoff volume for a project site. Any increase in runoff volume is either infiltrated onsite, or discharged to another location where streams will not be impacted. The magnitude of peak flows and time of concentration is not controlled, so while this method ensures there is no increase in total volume of runoff, it can result in higher erosive forces during storms.
- **Flow Duration Control** matches or reduces both the duration and magnitude of a specified range of storms. The entire hydrologic record is taken into account, and pre-project and post-construction runoff magnitudes and volumes are matched as closely as possible. Excess runoff is either infiltrated onsite or discharged below Qcp (Geomorphically critical flow – 10% of the 2-year flow).

The Santa Clara Valley Urban Runoff Pollution Prevention Program (SCVUPPP) HMP reviewed each of these methods and concluded that a Flow Duration Control approach was the most effective in controlling erosive flows. Two examples were evaluated using this approach, one on the Thompson Creek subwatershed in Santa Clara Valley and one on the Gobernadora Creek watershed in Orange County. The evaluation approach used continuous simulation modeling to generate flow duration curves, and then designed a test hydromodification management facility to match pre-project durations and flows.

In addition to the SCVURPP HMP, the flow duration control approach has been applied by the Alameda Countywide Clean Water Program (ACCWP), San Mateo County Water Pollution Prevention Plan (SMCWPPP), the Fairfield-Suisun Urban Runoff Management Program (FSURMP), Contra Costa Clean Water Program (CCCWP), San Diego County, and South Orange County. Among these agencies, different approaches have emerged on how to demonstrate that proposed BMPs meet flow duration control guidelines. Both methods employ continuous simulation to match or reduce flow durations, but differences exist in how continuous simulation is used (site-specific simulation vs. unit area simulation). Differences also exist in the focus of the two approaches (regional detention facilities vs. onsite LID facilities). Both approaches were evaluated by the different RWQCBs and deemed valid (Butcher 2007).

Other existing HMPs have defined an approach to design and implement hydrologic management BMPs, including Counties of the Bay Area and Contra Costa County.

BAHM Approach

The Bay Area Hydrology Model (BAHM) is a continuous simulation rainfall runoff hydrology model developed for ACCWP, SMCWPPP, and SCVURPP. It was developed from the Western Washington Hydrology Model, which focuses primarily on meeting hydromodification management requirements using stormwater detention ponds alone or combined with LID facilities (Butcher 2007). The Western Washington Hydrology Model is based on the Hydrologic Simulation Program – FORTRAN (HSPF) modeling platform, developed by the U.S. EPA, and uses HSPF parameters in modeling watersheds.

Project proponents who want to size a hydromodification BMP select the location of their project site from a map of the Bay Area and BAHM correlates the project location to the nearest rainfall gauge and applies an adjustment factor to the hourly rainfall for the nearest gauge, to produce a weighted hourly rainfall at the project site. The user then enters parameters for the proposed project site describing soil types, slope, and land uses. BAHM then runs the continuous rainfall-runoff simulation for both the pre-project and the post-construction conditions of the project site. Output is provided in the form of flow duration curves that compare the magnitude and timing of storms between the pre-project and the post-construction modeling runs.

If an increase in flow durations is predicted, the user can select and size mitigation BMPs from a list of modeling elements. An automatic sizing subroutine is available for sizing detention basins and outlet orifices that matches the flow duration curves between the pre-project scenario and a post-construction mitigation scenario. Manual sizing is necessary for other BMPs included in the program, such as storage vaults, bioretention areas, and infiltration trenches.[7] The program is designed so that, once a BMP is selected and sized, the modeling run can be transferred to the local agency for approval. The model reviewer at the local agency can launch the program and verify modeling parameters and sizing techniques.

A HMP tool was also developed to support developers and applicants with the San Diego County HMP. The San Diego Hydrology Model (SDHM) derives from the BAHM, and integrates parameters that are specific to the San Diego Region. Similarly, the South Orange Hydrology Model (SOHM) was developed for the purposes of the South Orange County NPDES Permit.

A similar approach will be used for the SMR HMP. The Western Washington Continuous Simulation Hydrology Model (WWHM) has been modified to include local rainfall and loss rate information, in addition to preferred local BMP selection to provide project proponents a user-

[7] Hydrologic and Sediment Control BMPs shall have a minimum orifice diameter of 1-inch. to minimize clogging. (See **Section 3.2.iv)**. Any BMP shall have 100% drawdown within 72 hours to accommodate vector control requirements. (See **Section 3.2.ivi)**

friendly tool to develop a hydromodification mitigation strategy. The SMRHM allows the user to match or reduce the flow duration curve for the selected range of flows using locally preferred BMPs.

Contra Costa Clean Water Program (CCCWP) Approach

The CCCWP developed a protocol for selecting and sizing hydromodification BMPs, which are referred to as Integrated Management Practices (IMPs) in their guidebook. Instead of a project proponent running a site-specific continuous simulation to size hydromodification control facilities, the CCCWP provides sizing factors for designing site level IMPs. Sizing factors are based on the soil type of the project site and are adjusted for Mean Annual Precipitation. Sizing factors are provided for bioretention facilities, flow-through planters, dry wells and a combination cistern and bioretention facility.

Sizing factors were developed through continuous simulation HSPF modeling runs for a variety of development scenarios. Flow durations were developed for a range of soil types, vegetation and land use types, and rainfall patterns for development areas in Contra Costa County. Then, based on a unit area (one acre) of impervious surface, flow durations were modeled using several IMP designs. These IMPs were then sized to achieve flow control for the range of storms required, (from 10% of the 2-year storm up to the 10-year storm). These sizing factors were then transferred to a spreadsheet form for use by project proponents.

The primary difference between the CCCWP approach and the BAHM approach is the level of modeling required. The CCCWP approach is simplified for the project proponent in that both hydromodification and water quality mitigation is incorporated into the IMP sizing factors. The BAHM allows for more flexibility in that regional BMPs may be used for hydromodification, and if desired, water quality, in addition to site level approaches. The SMR NPDES Permit allows for offsite mitigation of hydromodification impacts, if the onsite infeasibility of hydrologic management measures has been demonstrated. Therefore, an approach that uses continuous simulation to assess regional or neighborhood level BMP implementation is preferred for this HMP.

C.1.3. Sediment Management Measures

Urbanization can reduce the mass of bed material transported through the elimination of alluvial channel sections. This occurs in site development when First-order and particularly larger streams are lined or placed into underground conduits. First-order streams are identified as the unbranched channels that drain from headwater areas and develop in the uppermost topographic depressions, where two or more contour crenulations (notches or indentations) align and point upslope (NEH, 2007). First-order streams may, in fact, be field ditches, gullies, or ephemeral gullies (NEH, 2007). There are two general approaches for managing the bed material load relative to urbanization and channel stability. The first approach attempts to correct for the change in bed material load by increasing or decreasing the discharge rate as appropriate to generally maintain the balance between hydrologic and geomorphic processes as conceptualized in Lane's interrelationship. While theoretically a sound approach, this option requires a significant amount of detailed information that is difficult to obtain and requires good calibration of sediment models. Sediment transport models are non-linear and relatively sensitive to the rate of sediment supply and particle size distribution. This HMP does not recommend any specific sediment transport equation or model as the selection of such a model should be based on stream and watershed specific information, and the amount and quality of available data. Examples of sediment transport equations the designer may consider include: Duboys Formula, Meyer-Peter Formula, Einstein Bed Load Function, Modified Einstein Procedure, Colby's Method, Engelund and Hansen Method, Ackers and White Method. There are several models that use these transport formulas to predict long-term sediment transport. General guidance for site-specific analysis is provided in **Appendix H**.

The second approach to maintaining sediment supply is physically based, relying on a field assessment of site locations that may supply bed material load to the receiving channel, and protecting those sources during the site planning and development process. With this approach, the project proponent will only provide engineered solutions for flow mitigation. Protection of site bed material sources is the preferred approach since it is physically based and potentially less prone to error. Guidelines for field assessment of bed material sources are provided with the sediment control management approach, which is described in **Section 2.3**.

C.1.4. In-Stream Stabilization Solutions

In-stream solutions focus on managing the stream corridor to provide stability, modifying the stream channel to accept an altered flow regime. In cases where development is proposed in a watershed with an impacted stream it may be beneficial to focus on rehabilitating the stream channel to match the new independent variables of channel cross section, sediment discharge, flow discharge and channel slope rather than retrofitting the watershed or only controlling a percentage of the runoff with onsite controls. This type of approach can restore stream functions, beneficial uses, and values at a much more rapid pace, especially in locations that cannot physically be returned to their natural state due to changes in stream channel alignment and restrictions on the channel cross section due to adjacent development. In addition, in some cases where a master planned watershed development plan is being implemented it may be more feasible to design a new channel to be stable under the proposed watershed land use rather than to construct distributed onsite facilities.

In-stream stabilization and restoration solutions are available as alternative compliance as a part of the SMR HMP. In-stream restoration projects are available if onsite controls are not feasible and it has been determined that the receiving water that the project discharges to has impacts due to hydromodification. Tiered benefits (benthic communities, morphology) of such in-stream restoration projects must offset the hydrologic and sediment changes induced by the associated PDP(s).

A number of methods exist for managing channels to accept altered flow regimes and higher shear forces. These have been covered in detail in a number of sources available to watershed groups and public agencies. A few helpful sources include Riley 1998, Watson and Annable 2003, and FISRWG 1998.

C.1.5. Stream Susceptibility – Domain of Analysis

Southern California Coastal Water Research Project (SCCWRP) has developed a series of screening tools that evaluate the susceptibility of a stream to hydromodification impacts (SCCWRP, 2010). These screening tools allow a project proponent to rate the susceptibility of the evaluated stream to erosion for a variety of geomorphic scenarios including alluvial fans, broad valley bottoms, incised headwaters, etc.

The development of HMPs in most Southern California counties is correlated to the ultimate findings of SCCWRP studies on hydromodification (SCCWRP, 2008 through 2011). It is generally acknowledged that SCCWRPs formulation of regional standards for hydromodification management may serve as a baseline for development of HMPs for specific regions in Southern California.

When evaluating the stream susceptibility though the SCCWRP screening tools, a domain of analysis is defined. This domain of analysis corresponds to the reach lengths upstream and downstream from a project from which hydromodification assessment is required. The domain of analysis determination includes an assessment of the incremental flow accumulations downstream of the site, identification of grade control points in the downstream conveyance system, and quantification of downstream tributary influences. The SMR program elected not to perform the extensive susceptibility mapping required to correlate channel reaches with variable low flow discharge thresholds, since the return on investment for this type of analysis appears to be very low.

The effects of hydromodification may propagate for significant distances downstream (and sometimes upstream) from a point of impact such as a stormwater outfall. Accordingly, the domain of analysis serves as a representative buffer domain across which the susceptibility of a stream should be evaluated. This representative domain spans multiple channel types/settings, and is defined as follows in this HMP (SCCWRP, 2010):

- Proceed downstream until reaching the closest of the following:
  - at least one reach downstream of the first grade-control point (but preferably the second downstream grade-control location)
  - tidal backwater/lentic waterbody
  - equal order tributary (Strahler 1952)
  - a 2-fold increase in drainage area

OR demonstrate sufficient flow attenuation through existing hydrologic modeling.

- Proceed upstream to extend the domain:
  - upstream for a distance equal to 20 channel widths or to grade control in good condition – whichever comes first. Within that reach, identify hard points that could check headward migration, evidence that head cutting is active or could propagate unchecked upstream

Within the analysis domain there may be several reaches that should be assessed independently based on either length or change in physical characteristics. In more urban settings, segments may be logically divided by road crossings (Chin and Gregory, 2005), which may offer grade control, cause discontinuities in the conveyance of water or sediment, etc.

The domain of analysis is discussed here since it may be relevant for use in site-specific analysis as discussed in **Appendix H**. It is not used in this HMP as a discriminator for HMP applicability to a specific project.

C.2. Flow Duration Control Approach

C.2.1. Effects of Urbanization and Critical Flow

The effects of urbanization on channel response have been the focus of many studies (see Paul and Meyer, 2001 for a review), and the widely accepted consensus is that increases in impervious surfaces associated with urbanizing land uses can cause channel degradation. Urbanization generally leads to a change in the amount and timing of runoff in a watershed, which increases erosive forces on channel bank and bed material and can cause large-scale channel enlargement, general scour, stream bank failure, loss of aquatic habitat, and degradation of water quality.

Channel erosion, like most physical processes, is a complex system based on a variety of influences. Channel erosion is non-linear (Philips 2003), meaning the response of streams is not directly proportional to changes in land use and flow regimes. Small changes or temporary disturbances in a watershed may lead to unrecoverable channel instability (Kirkby 1995). These disturbances may give rise to feedback systems whereby small instabilities can be propagated into larger and larger instabilities (Thomas 2001).

A number of studies have sought to correlate the amount of urbanization in a watershed and stream instability (Bledsoe 2001; Booth 1990, 1991; Both and Jackson 1997; MacRae 1992; 1993; 1996; Coleman et al. 2005). Evidence from these studies suggests that below a certain threshold of watershed imperviousness, streams maintain stability. This threshold or imperviousness transition zone appears to be around seven to 10% watershed urbanization for perennial streams (Schueler 1998 and Booth 1997), but may begin at a lower level for intermittent streams such as those found in Southern California. Studies done in Santa Fe, New Mexico (Leopold and Dunne 1978) suggest that changes occur at 4% impervious area of the watershed.

Initial studies by Coleman et al. (2005) suggest that a response in the stream channel may begin to occur at two to 3% watershed imperviousness for intermittent streams in Southern California. It is important to understand that use of impermeable cover alone is a poor predictor of channel erosion due to differences in stormwater detention and infiltration within regions.

In highly urbanized watersheds returning a stream to a natural condition is infeasible due to existing development in the watershed. In these scenarios the focus should be on in-stream restoration to restore the beneficial uses of the receiving water.

Though it is well established that watershed urbanization causes channel degradation, a detailed understanding of how development alters runoff and how this altered runoff in turn causes erosion is still being developed.

The ability of a stream to transport sediment is proportional to the amount of flow in the stream: as flow increases, the amount of sediment moved within a channel also increases. The ability of a stream channel to transport sediment is termed stream power, which integrated over time is work. Leopold (1964) introduced the concept of effective work, whereby the flow-frequency relationship of a channel is multiplied by sediment transport rate. This gives a mass-frequency relationship for erosion rates in a channel. Flows on the lower end of the relationship (e.g., two-year flows) may transport less material, but occur more frequently than higher flows, thereby having a greater overall effect on the work within the channel. Conversely, higher magnitude events, while transporting more material, occur infrequently causing less effective work. Leopold found that the maximum point on the effective work curve occurred around the 1-to 2-year frequency range. This maximum point is commonly referred to as the dominant discharge. It corresponds roughly to a bankfull event (a flow that fills the active portion of the channel up to a well-defined break in the bank slope).

Urbanization tends to have the greatest relative impact on flows that are frequent and small, and which tend to generate less-than-bankfull flows. Change is greatest in these events because prior to urbanization, infiltration would have absorbed much or all of the potential runoff, but following urbanization, a high percent of the rainfall runs off. Thus, events that might have generated little or no flow in a non-urbanized watershed can contribute flow in urban settings. These smaller less-than-bankfull events have been found to cause a significant proportion of the work in urban streams (MacRae 1993) due to their high frequency, and can lead to channel instability. Less frequent, larger magnitude flows (e.g., flows greater than Q10) are less strongly affected by urbanization because during such infrequent storm events, the ground rapidly becomes saturated, and acts (for purposes of runoff generation) in a similar manner as impervious surfaces.

Due to the increase in impervious surfaces and fewer opportunities for infiltration of stormwater, urbanization creates a higher runoff rate and more runoff volume than an un-urbanized watershed. Opportunities for infiltration of excess stormwater exist in urbanized areas, but many times are infeasible due to cost, technical barriers or land use constraints. Therefore, some of the excess stormwater must be discharged to a receiving stream. In order to achieve a comparable Ep to a predeveloped condition, this excess runoff volume must be discharged at a rate at which insignificant effective stream work is done.

Bed load sediment moves through transmission of shear stress from the flow of water on the channel bed. An increase in the hydraulic radius (measure of channel flow efficiency through a ratio of the channel's cross sectional area of the flow to its wetted perimeter) corresponds to an increase in shear stress. In order to initiate movement of bed material, however, a shear stress threshold must be exceeded. This is commonly referred to as critical shear stress, and is dependent on sediment and channel characteristics. For a given point on a channel where the bed composition and cross-section is known, the critical shear can be related to a stream flow. The flow that corresponds to the critical shear is known as the critical flow, or Qc. For a given cross-section, flows that are below the value for Qc do not initiate bed movement, while flows above this value do initiate bed movement.

C.2.2. Geomorphically-Significant Flows in Existing HMPs

SCVURPPP expressed Qc as a percentage of the two-year flow in order to develop a common metric across watersheds of different size, and allow for easy application of HMP requirements. For the two watersheds studied in detail in the SCVURPPP study, a similar relationship was found where Qc corresponded to 10% of the two-year flow. Several methodologies were used to determine both the two-year flows and the ten-year flows across the evaluated watersheds. The two-year flow was computed based on either the rational method, as described in the Santa Clara Valley Hydrology Procedures, or the Cunnane ranking schema applied to "all event frequency" curves. The ten-year flow was computed based on the Log Pearson type III distribution applied to annual flow frequency curves. This became the basis for the lower range of geomorphically significant flows under the SCVURPPP HMP and is referred to as Qcp to indicate that it is a percentage of flow. That program also adopted the 10-year flow as the upper end of the range of flows to control with the justification that increases in stream work above the 10-year flow were small for urbanized areas.

A similar study was conducted for the FSURMP on two watersheds in Fairfield, California following a geomorphic assessment. That study found Qcp to be 20%t of the pre-development two-year flow. The differences in the two values may be attributable to differences in watershed characteristics in Santa Clara County and Fairfield, the number of streams studied, the methodology used to compute the two-year flow, and the precision of the modeling tools. Channels in Fairfield were found to have a more densely vegetated riparian corridor and may have a higher resistance to increases in shear stresses (FSURMP). Values for Qcp appear to be similar among neighboring watersheds, but there appears to be a range of appropriate Qcp values. The characteristics of individual biomes (climatically and geographically defined areas of ecologically similar climatic conditions, such as communities of plants, animals, and soil organisms, often referred to as ecosystems) should be taken into account when developing a Qcp. For example, Western Washington State, which has more densely vegetated riparian zones than either Fairfield or Santa Clara County, has adopted a Qcp of 50% of the 2-year flow.

The Santa Clara HMP focused on using detention basins for hydromodification management and emphasized the lower flow control limit for site runoff. Extended detention flow control basins can be constructed with multi-stage outlets to mitigate both the duration and magnitude of flows within a prescribed range. To avoid the erosive effects of extended low flows, the maximum rate (depth) at which runoff is discharged is set below the erosive threshold. Per the Santa Clara HMP, the lower flow control limit was defined as the flow rate that generates critical shear stress on the channel bed and banks. Both Santa Clara and Alameda Counties correlated the lower flow control limit to a value equal to 10% of the 2-year runoff event.

The Contra Costa HMP emphasized the importance of using LID methods to meet hydromodification management criteria. LID approaches to hydromodification management rely on site design and distributed LID BMPs to control the frequency and duration of flows, and to mitigate hydrograph modification impacts. By minimizing directly connected impervious areas and promoting infiltration, LID approaches mimic natural hydrologic conditions to counteract the hydrologic impacts of development. LID systems are sized to achieve flow control for the range of storms required (from 10% of the 2-year storm up to the 10-year storm).

The County of San Diego HMP defined an adaptive lower flow threshold based on the channel susceptibility rating (high, medium, or low). Receiving streams in San Diego County were individually classified by their susceptibility to channel erosion impacts using a critical flow calculator and a channel screening tool developed by SCCWRP. This classification produced three lower flow thresholds which are 0.1Q2, 0.3Q2, and 0.5Q2. The upper range of the mitigation flow was considered the pre-project 10-year storm event.

To date, seven approved HMPs have been published. These include HMPs for SCVURPPP (2005), the CCCWP (2005), the Fairfield-Suisun Urban Runoff Management Program FSURMP (2005), the Alameda Countywide Clean Water Program (ACCCMP 2005), the San Mateo Countywide Stormwater Pollution Prevention Program (SMCWPPP [formerly STOPPP] 2005), the San Diego County Hydromodification Plan (2009), and the South Orange County Hydromodification Plan (2012). In addition, a number of HMPs were implemented while agencies developed their final plans. Interim HMPs are not detailed in this report because these plans have adopted findings from the above listed HMPs. A summary of flow control standards adopted in each of the approved HMPs in California and western Washington is given in **Table 7**.

Table 7 - Summary of Flow Control Standards – Approved HMPs

Permitting Agency	Q_{cp}	Largest Managed Flow
Alameda County	10% of the 2-year flow (0.1Q2)	10-year flow (Q10)
Contra Costa County	10% of the 2-year flow (0.1Q2)	10-year flow (Q10)
Fairfield-Suisun Urban Runoff Management Program	20% of the 2-year flow (0.2Q2)	10-year flow (Q10)
San Diego County	10, 30, or 50 % of the 2-year flow (0.1Q2, 0.3Q2, or 0.5Q2)	10-year flow (Q10)
San Mateo County	10% of the 2-year flow (0.1Q2)	10-year flow (Q10)
Santa Clara County	10% of the 2-year flow (0.1Q2)	10-year flow (Q10)
South Orange County	10% of the 2-year flow (0.1Q2)	10-year flow (Q10)
Western Washington State	50% of the 2-year flow (0.5Q2)	50-year flow (Q50)

C.2.3. Applicable Flow Thresholds for the Santa Margarita Region

HMPs that have been developed in the San Francisco Bay Area, Northern California (Contra Costa, Santa Clara, and Alameda Counties and the Sacramento area), in Southern California (San Diego, South Orange Counties) vary with regard to the emphasis placed on lower flow control thresholds as compared to other approaches, such as distributed LID methods. The SMR HMP was developed using the lower flow control threshold approach. There is consensus in that both the frequency and duration of flows must be controlled using continuous simulation hydrologic modeling (rather than the standard design storm approach used for flood control design) to mitigate for potential development impacts. At this point, it is generally accepted that events more frequent than the 10-year flow are the most critical for hydromodification management, since flows within this range of return period (up to the 10-year event) have been documented to perform the most work on the channel bed and banks. However, the range of analysis could potentially change in the future if new studies provide sufficient evidence warranting a modification.

Rates of sediment production from Southern California Rivers depend upon bedrock geology, rates of tectonic uplift, land use, and precipitation (Warrick et al., 2003). The California Geological Survey agency identifies 13 unique geomorphic zones based on geology, faults, topographic relief, and climate (California Department of Conservation, 2002). The SMR is located within the Peninsular Ranges geomorphic zone, whose geology is characterized by the granitic rocks intruding the older metamorphic rocks. South Orange County and San Diego County are also located within the same geomorphic zone, thus exhibits similar macro-scale geomorphic trends to those in the SMR.

The approaches developed for the San Diego County HMP and the South Orange County HMP were approved by the SDRWQCB and selected as the base approach for the SMR HMP. However, the South Orange County program elected not to perform the extensive susceptibility mapping required to correlate channel reaches with variable low flow discharge thresholds. The implementation of HMPs in Northern California, and in San Diego County has shown that numerically larger low flow thresholds generally have very limited applicability in practice. Accordingly, a base low flow threshold (0.1Q2) was selected for this HMP. The selection of the low flow threshold (0.1Q2) was based on other approved HMPs in California with similar hydrologic and geologic conditions. The low flow threshold (0.1Q2) is the most conservative of the potential range identified in the San Diego HMP. Nonetheless, the applicant may compute a site-specific low flow threshold at their option, following a methodology developed by the applicant. An example of such a procedure is described in the San Diego County HMP document.

If the applicant opts for developing a site-specific criterion, the selected lower flow threshold shall correspond to the critical channel flow that produces the critical shear stress that initiates channel bed movement or that erodes the toe of channel banks. For a channel segment that is lined but not exempt by this HMP, the low flow threshold must be computed assuming the lining has been removed.

C.3. Classification and Geomorphic Stability of Stream Channels

Numerous stream channel stability assessment methods have been proposed to help distinguish which channels are most at risk from hydrograph modification impacts and/or define where HMP requirements should apply. Assessment strategies range from purely empirical approaches to channel evolution models to energy-based models (see Simon et al., 2007 for a critical evaluation). Stream channel stability assessment methods are useful in assessing the impact of urbanization or control programs over time. Their value lies in showing trends as changes in a watershed occur, rather than classifying the reach of a discrete channel section at a given point in time.

C.3.1. Empirical approaches and Models

A recent study by Bledsoe et al. (2008) for SCCWRP describes nine types of classification and mapping systems with an emphasis on assessing stream channel susceptibility in Southern California. The summary below is taken from that study. Bledsoe also provides a summary of the implications of these classification and mapping systems to the development of hydromodification tools for Southern California. The article provides a detailed breakdown of guidelines for developing hydromodification tools given the advantages and disadvantages of each system previously assessed.

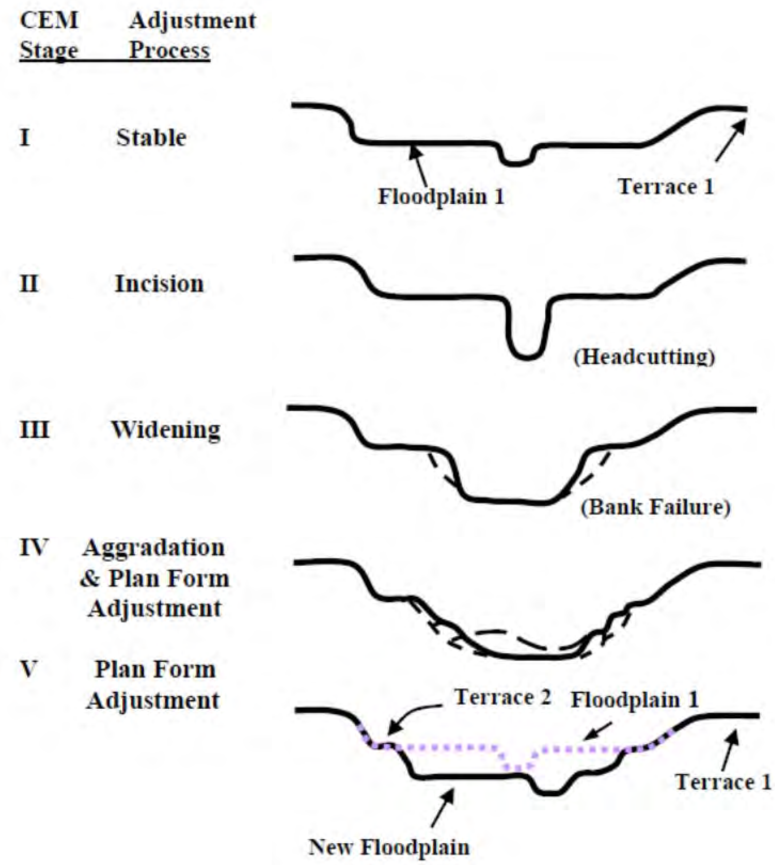
General Stability Assessment Procedures

By assessing an array of qualitative and quantitative parameters of stream channels and floodplains, several investigators have developed qualitative assessment systems for stream and river networks. These assessment methods have been incorporated into models used to analyze channel evolution and stability. Many parameters used to establish methodologies such as the Rosgen approach are extendable to a qualitative assessment of channel response in Californian river networks. Field investigations in Southern California have shown that grade control can be the most important factor in assessing the severity of channel response to hydromodification. Qualitative methodologies have proven extendable to many regions, and they use many parameters that may provide valuable information for similar assessments in California.

Channel Evolution Models of Incising Channels

The Channel Evolution Model (CEM) developed by Schumm et al. (1984) posits five stages of incised channel instability organized by increasing degrees of instability severity, followed by a final stage of quasi-equilibrium. Work has been done to quantify channel parameters, such as sediment load and specific stream power, through each phase of the CEM. A dimensionless stability diagram was developed by Watson et al. (2002) to represent thresholds in hydraulic and bank stability. This conceptual diagram can be useful for engineering planning and design purposes in stream restoration projects requiring an understanding of the potential for shifts in bank stability.

Figure 16 - Five Stages of the Channel Evolution Model (CEM)



Channel Evolution models Combining Vertical and Lateral Adjustment Trajectories (Schumm et al. 1984)

Originally, CEMs focused primarily on incised channels with geotechnically, rather than fluvially, driven bank failure. Several CEMs have been proposed that incorporate channel responses to erosion and sediment transport into the original framework for channel instability. In these new systems, an emphasis is placed on geomorphic adjustments and stability phases that consider both fluvial and geomorphic factors. The state of Vermont has developed a system of stability classification that suggests channel susceptibility is primarily a function of the existing Rosgen stream type and the current stream condition referenced to a range of variability. This system places more weight on entrenchment (vertical erosion of a channel that occurs faster than the channel can widen, resulting in a more confined channel) and slope than differentiation between bed types.

Equilibrium Models of Supply vs. Transport-capacity / Qualitative Response

The qualitative response model builds on an understanding of the dynamic relationship between the erosive forces of flow and slope relative to the resistive forces of grain size and sediment supply to describe channel responses to adjustments in these parameters. In this system, qualitative schematics provide predictions for channel response to positive or negative fluctuations in physical channel characteristics and bed material. Refinements to such frameworks have been made to account for channel susceptibility relative to existing capacity and riparian vegetation among other influential characteristics.

Hierarchical Approaches to Mapping Using Aerial Photographs / GIS

It has become an increasingly common practice to characterize stream networks as hierarchical systems. This practice has presented the value in collecting channel and floodplain attributes on a regional scale. Multiple studies have exploited geographical information systems (GIS) to assess hydrogeomorphic behavior at a basin scale. Important valley scale indices such as valley slope, confinement, entrenchment, riparian vegetation influences, and overbank deposits can provide information for river networks in California. Many agencies are developing protocols for geomorphic assessment using GIS and other database associated mapping methodologies. These tools may be useful as they are further developed in a monitoring program, but are not viable at a scale useful for reach-by-reach channel analysis.

The approach taken by this HMP to monitor its effectiveness is embedded in a derivative of the channel classification approach defined by Rosgen (1996). The author distinguishes three different levels of stream classification including: 1) Level I that generally describes stream relief, landform, and valley morphology; 2) Level II that describes the morphology of stream and associates the later to a stream type based on channel form and bed composition. Field measurements of entrenchment, width-to-depth ratio, sinuosity, slope, and representative sampling of channel material may be suitable; and 3) Level III that assesses stream condition and departure. A stream that is geomorphically stable per Rosgen's definition is characterized by two elements: 1) Dimension, pattern, and profile of a stream are maintained over time; and 2) the transport capacity of a watershed's flows and detritus is maintained. As such, physical and biological functions of a geomorphologically stable stream remain at an optimum.

C.3.2. Stream Classification System

Planform Classifications and Predictors

Alluvial channels form a continuum of channel types whose lateral variability is primarily governed by three factors: flow magnitude, bank erodibility, and relative sediment supply. Though many natural channels conform to a gradual continuum between straight and intermediate, meandering, and braided patterns, abrupt transitions in lateral variability imply the existence of geomorphic thresholds where sudden change can occur. The conceptual framework for geomorphic thresholds has proven integral to the study of the effects of disturbance on river and stream patterns. Many empirical and theoretical thresholds have been proposed relating stream power, sediment supply and channel gradient to the transition between braiding and meandering channels. Accounting for the effects of bed material size has been shown to provide a vital modification to the traditional approach of defining a discharge slope combination as the threshold between meandering and braided channel patterns. The many braided planforms in Southern California indicate the need to refine and calibrate established thresholds to river networks of interest. However, at this time there is not a well-accepted model to predict how hydromodification affects channel planform.

Energy-Based Classifications

The link between channel degradation and urbanization has been studied; however, impervious area is not the solitary factor influencing channel response. Studies have shown that the ratio between specific stream power and median bed material size D50b, where b is approximately 0.4 to 0.5 for both sand-and gravel-bed channels, can be used as a valuable predictor of channel form. Stream power, which is linearly related to the total discharge, is the most comprehensive descriptor of hydraulic conditions and sedimentation processes in stream channels. Several studies have been performed relating channel stability to a combination of parameters such as discharge, median bed-material size, and bed slope, as an analog for stream power.

A recent study by Bledsoe et al. (2008) for SCCWRP describes nine types of classification and mapping systems with an emphasis on assessing stream channel susceptibility in Southern California. The summary below is taken from that study. Bledsoe also provides a summary of the implications of these classification and mapping systems to the development of hydromodification tools for Southern California. The article provides a detailed breakdown of guidelines for developing hydromodification tools given the advantages and disadvantages of each system previously assessed.

Sand vs. Gravel Behavior / Threshold vs. Live-Bed Contrasts

It is well recognized that the fluvial-geomorphic behavior varies greatly between sand and gravel/cobble systems. Live bed channels (of which sand channels are good examples) are systems where sediment moves at low flows, and where sediment is frequently in motion. Threshold channels, such as gravel streams, by contrast, require considerable flow to initiate bedload movement. Live bed channels are more sensitive to increases in flow and decreases in sediment supply than threshold channels. Scientific consensus shows that sand bed streams lacking vertical control show greater sensitivity to changes in flow and sediment transport regimes than do their gravel/cobble counterparts. Factors such as slope, and sedimentation regimes are known to have greater impact on sand-bed streams. This can be an important issue for stormwater systems receiving runoff from watersheds composed primarily of streams with sandy substrate. The transition between sand and gravel bed behavior can be rapid, enabling the use of geographic mapping methods to prioritize channel segments according to their susceptibility to the effects of hydromodification.

Bank Instability Classifications

Early investigations provided the groundwork for bank instability classifications by analyzing shear, beam, and tensile failure mechanisms. The dimensionless stability approach developed by Watson characterized bank stability as a function of hydraulic and geotechnical stability. Rosgen (1996) proposed the widely applied Bank Erosion Hazard Index (BEHI) as a qualitative approach based on the general stability assessment procedures outlined above. Other classification systems, like the CEM, determine bank instability according to channel characteristics that control hydrogeomorphic behavior.

As required per Permit Provision F.1.h(1)(a), a Hydromodification Susceptibility Study has been performed as part of this HMP effort to identify and map stream channel segments that may be vulnerable to hydromodification and cause a Hydrologic Condition of Concern (HCOC). The study located in Appendix D helps project proponents determine whether or not a project will drain to a potentially susceptible stream channel segment.