Flow Control Threshold Analysis
for the
San Diego Hydrograph Modification Management Plan

Prepared for

San Diego County and Copermittees

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December 23rd 2009

PWA REF. # 1915

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1. INTRODUCTION AND BACKGROUND

1.1 PURPOSE OF THE REPORT

San Diego County and its copermittees are required to develop a Hydromodification Management Plan (HMP) under their National Pollutant Discharge Elimination System (NPDES) MS4 permit. The purpose and requirements of the HMP are described in a 2007 Regional Water Quality Control Board (RWQCB) order renewing the NPDES permit (Order No. R9-2007-0001). The purpose of the HMP is to identify guidelines for managing 'geomorphically-significant' flows that, if not controlled, would cause increased erosion of receiving waters. Specifically, the HMP must identify a low and high flow threshold between which flows should be controlled so that the post-project flow rates and durations do not exceed pre-project levels between these two flow magnitudes. The lower flow threshold is required to correspond to critical flow producing critical shear stress in the channel. The flow control language in the Board Order is as follows:

> Utilize continuous simulation of the entire rainfall record to identify a range of runoff flows[8] for which Priority Development Project post-project runoff flow rates and durations shall not exceed pre-project runoff flow rates and durations, where the increased flow rates and durations will result in increased potential for erosion or other significant adverse impacts to beneficial uses, attributable to changes in the flow rates and durations. The lower boundary of the range of runoff flows identify shall correspond with the critical channel flow that produces the critical shear stress that initiates channel bed movement or that erodes the toe of channel banks. The identified range of runoff flows may be different for specific watersheds, channels or channel reaches.
>
> [8] The identified range of runoff flows to be controlled should be expressed in terms of peak flow rates of rainfall events, such as "10% of the pre-project 2-year peak flow up to the pre-project 10-year peak flow."

1.2 CONCEPTS BEHIND 'GEOMORPHICALLY-SIGNIFICANT FLOWS', CRITICAL FLOWS AND FLOW CONTROL

For the purposes of this project 'hydrograph modification' or 'hydromodification' is understood to mean changes to the frequency, duration and magnitude of surface runoff that, when untreated, cause an increase in erosion of the receiving water body. Hydromodification occurs when urbanization replaces areas of vegetated, uncompacted soil with impermeable surfaces such as buildings, roads and compacted fill. The reduction in permeability results in increased volumes of runoff, and faster and more concentrated delivery of this water to receiving waters. These changes have the potential to cause creeks to erode faster than before development.[1]

[1] Although the focus of hydromodification management plans has been on increased erosion it should be noted that in rivers that are depositional hydromodification can cause creeks to regain some transport equilibrium.

Stream flows are often expressed in terms of the frequency with which a particular flow occurs. For example, Q_2 refers to the flow rate that occurs once every two years, on average over the long term. Flow frequencies are a function of rainfall and watershed characteristics, and are unique to each stream channel (and location along the channel). The effects of urbanization tend to increase the magnitude of the flow associated with a given frequency (e.g. post-development Q_2 higher than pre-development Q_2). Similarly, urbanization tends to increase the frequency with which any given flow rate occurs. The purpose of the HMP is to control runoff from new developments so that flow magnitudes and frequencies match pre-development conditions within a critical range of flows.

Not all runoff causes erosion: runoff in receiving channels below a critical discharge (Q_{crit}) does not exert sufficient force to overcome the erosion resistance of the channel banks and bed materials. Flows greater than Q_{crit} cause erosion, with larger flows causing proportionally greater erosion. It has been determined by calculations and field measurements that most erosion in most natural creeks is caused by flows between some fraction of Q_2 and Q_{10} (see for example Leopold, 1964). Flows in this range are referred to as 'geomorphically-significant' because they cause the majority of erosion and sediment transport in a channel system.

Flows greater than Q_{10}, though highly erosive *per event*, occur too infrequently to do as much work as smaller but more frequent flows (see Figure 1). Hydromodification also has less impact on flows greater than Q_{10} since at such high rainfall intensities the soil becomes saturated and the infiltration capacity of undeveloped landscapes is rapidly exceeded. When the soil is saturated, runoff rates become more similar to those from impervious surfaces. For these reasons, HMPs have focused on identifying a low flow threshold that is close to Q_{crit} for most receiving channels, and controlling flows between that value and Q_{10} (see for example the HMPs completed in Santa Clara, Contra Costa, Alameda and San Mateo Counties). By requiring treatment (storage and either infiltration or detention) of excess runoff within the control range, and by limiting the release of excess water to Q_{crit} or less, HMPs seek to prevent additional erosion in receiving channels.

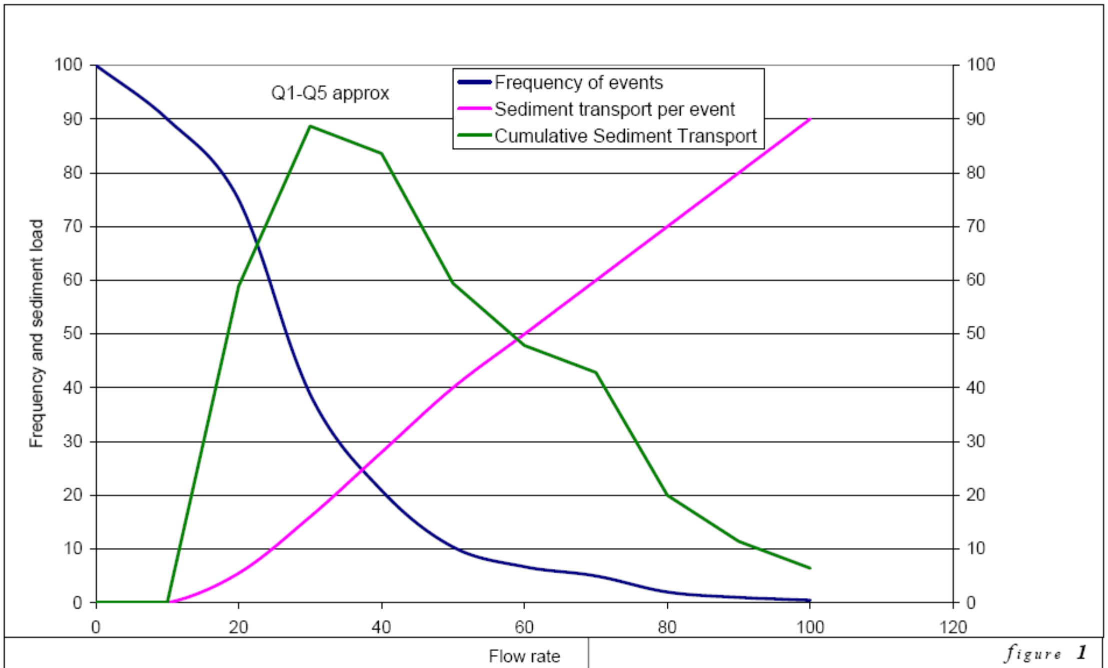

figure **1**

San Diego HMP

Hypothetical cumulative work curve

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2. IDENTIFYING A HIGH FLOW THRESHOLD

Previous HMPs have focused considerable attention on the low flow threshold, but little on the high flow threshold. The use of an upper flow threshold is based on two assumptions:

1. Flows above this level cause relatively little cumulative erosion in receiving waters due to their low recurrence
2. Flows above this level are relatively unaffected by hydromodification because at such high rainfall intensities and durations the pre-development ground cover become saturated and most rain runs off, similar to in a post development condition.

The five HMPs developed to date in California have all adopted a value of Q_{10} as the upper threshold. We propose adopting the same value for the San Diego HMP.

3. IDENTIFYING A LOW FLOW THRESHOLD

Erosion occurs when the shear stress exerted on the channel by flowing water (*boundary shear stress*) exceeds the resistance of the channel (*critical shear stress*). Critical shear stress varies by several orders of magnitude for different channel materials (Table 1). *Critical flow* (Q_{crit}) is the channel flow which produces boundary shear stress equal to the critical shear stress for a given channel. That is, the flow rate that can initiate erosion in a channel. Q_{crit} is a function not only of the critical shear stress of the channel materials, but also channel size, and channel geometry. A particular flow rate (expressed as a number of cubic feet per second) in a small, steep, confined channel will create more shear stress than the identical flow rate in a large, flat, wide open channel. Thus Q_{crit} can be extremely variable depending on channel and watershed characteristics and will be different in each channel, and in each watershed.

Boundary Category	Boundary Type	Permissible Shear Stress (lb/sq ft)
Soils	Fine colloidal sand	0.02 - 0.03
	Sandy loam (noncolloidal)	0.03 - 0.04
	Alluvial silt (noncolloidal)	0.045 - 0.05
	Silty loam (noncolloidal)	0.045 - 0.05
	Firm loam	0.075
	Fine gravels	0.075
	Stiff clay	0.26
	Alluvial silt (colloidal)	0.26
	Graded loam to cobbles	0.38
	Graded silts to cobbles	0.43
	Shales and hardpan	0.67
Gravel/Cobble	1-in.	0.33
	2-in.	0.67
	6-in.	2.0
	12-in.	4.0
Vegetation	Class A turf	3.7
	Class B turf	2.1
	Class C turf	1.0
	Long native grasses	1.2 – 1.7
	Short native and bunch grass	0.7 - 0.95
	Reed plantings	0.1-0.6
	Hardwood tree plantings	0.41-2.5
Temporary Degradable RECPs	Jute net	0.45
	Straw with net	1.5 – 1.65
	Coconut fiber with net	2.25
	Fiberglass roving	2.00
Non-Degradable RECPs	Unvegetated	3.00
	Partially established	4.0-6.0
	Fully vegetated	8.00
Riprap	6 – in. d_{50}	2.5
	9 – in. d_{50}	3.8
	12 – in. d_{50}	5.1
	18 – in. d_{50}	7.6
	24 – in. d_{50}	10.1
Soil Bioengineering	Wattles	0.2 – 1.0
	Reed fascine	0.6-1.25
	Coir roll	3 - 5
	Vegetated coir mat	4 - 8
	Live brush mattress (initial)	0.4 – 4.1
	Live brush mattress (grown)	3.90-8.2
	Brush layering (initial/grown)	0.4 – 6.25
	Live fascine	1.25-3.10
	Live willow stakes	2.10-3.10
Hard Surfacing	Gabions	10
	Concrete	12.5

[1] Ranges of values generally reflect multiple sources of data or different t

A. Chang, H.H. (1988).
B. Florineth. (1982)
C. Gerstgraser, C. (1998).
D. Goff, K. (1999).
E. Gray, D.H., and Sotir, R.B. (1996).
F. Julien, P.Y. (1995).
G. Kouwen, N.; Li, R. M.; and Simons, D.B., (1980).
H. Norman, J. N. (1975).
I. Schiechtl, H. M. and R. Stern. (1996).
J. Schoklitsch, A. (1937).

Table 1. Range of critical shear stresses (τ_{cr}) for different materials. From Fischenich, 2001.

It was the original intent of the HMP project team to identify a single low flow threshold for the entire county (per previous HMPs). However, an extensive assessment of channel and runoff conditions led the team to conclude that there was a very wide range in critical flows, based largely on channel material but also on channel dimensions, rainfall, and watershed area[2]. Adopting a single standard that is conservative for the most vulnerable channels would result in controls that were excessively conservative for more resilient channels, while adopting an 'average' value would leave some channels unprotected. As the ongoing SCCWRP Hydromod project is showing, individual creeks have different risk categories and respond in different ways to the same level of hydromodification. Because of this natural variability, we pursued an analytical approach for estimating Q_{crit} as a function of parameters such as channel materials, channel dimensions and watershed area. The following sections of this report describe an analysis of Q_{crit} as a fraction of Q_2 for the range of channel conditions in San Diego County. This is followed by a description of a calculator tool developed by PWA that may be used to calculate Q_{crit} for a specific channel based on parameters that may be readily measured in the field. The analyses described in this report provide background for the selection of low flow thresholds identified in the HMP.

[2] These early analyses are summarized in Appendix D of the Final Hydromodification Management Plan.

4. CRITICAL FLOW ANALYSIS

4.1 BACKGROUND

PWA conducted a sensitivity analysis in which a wide range of channel sizes and geometries, rainfalls, watershed areas and channel materials were modeled in a flow-erosion model to identify Q_{crit} as a function of Q_2. In all, 170 combinations of channel, rainfall and watershed conditions were assessed (described below). Based on the results of this sensitivity analysis, a range of Q_{crits} were identified for several categories of channel materials.

The steps used to conduct the sensitivity analysis:

1. Identify the typical range of rainfall conditions for the HMP area (west San Diego County)
2. Identify the range of typical watershed areas likely to be developed
3. Identify a range of typical receiving channel dimensions for each watershed area
4. Identify a range of typical channel materials for receiving channels
5. Simulate a range of flows and develop rating curves (relationships between discharge and boundary shear stress)
6. Identify the flow rate at which boundary shear stress exceeds critical shear stress for the channel and material
7. Express this flow rate as a function of Q_2
8. Group critical flow rates by channel materials.

Steps 1 through 4 were used to define the range of parameters to use in the sensitivity testing. The intent was to identify a typical range of conditions likely to occur in the HMP area (west San Diego County), rather than provide an exhaustive description of possible watershed and channel conditions. Sensitivity testing on many combinations of parameters within this typical range allows identification of the range of channel responses and critical flows.

Each step in the critical flow analysis is explained in detail in the following sections.

4.2 IDENTIFY THE TYPICAL RANGE OF RAINFALL CONDITIONS FOR THE HMP AREA (WEST SAN DIEGO COUNTY)

Mean annual rainfall was used to estimate receiving channel size, Q_2, Q_5 and Q_{10} (methods described in subsequent sections). Figure 2 shows mean annual rainfall for San Diego County. Based on the map, three mean annual rainfalls were selected to represent the range of rainfall conditions for the simulations: 10”, 20” and 30”.

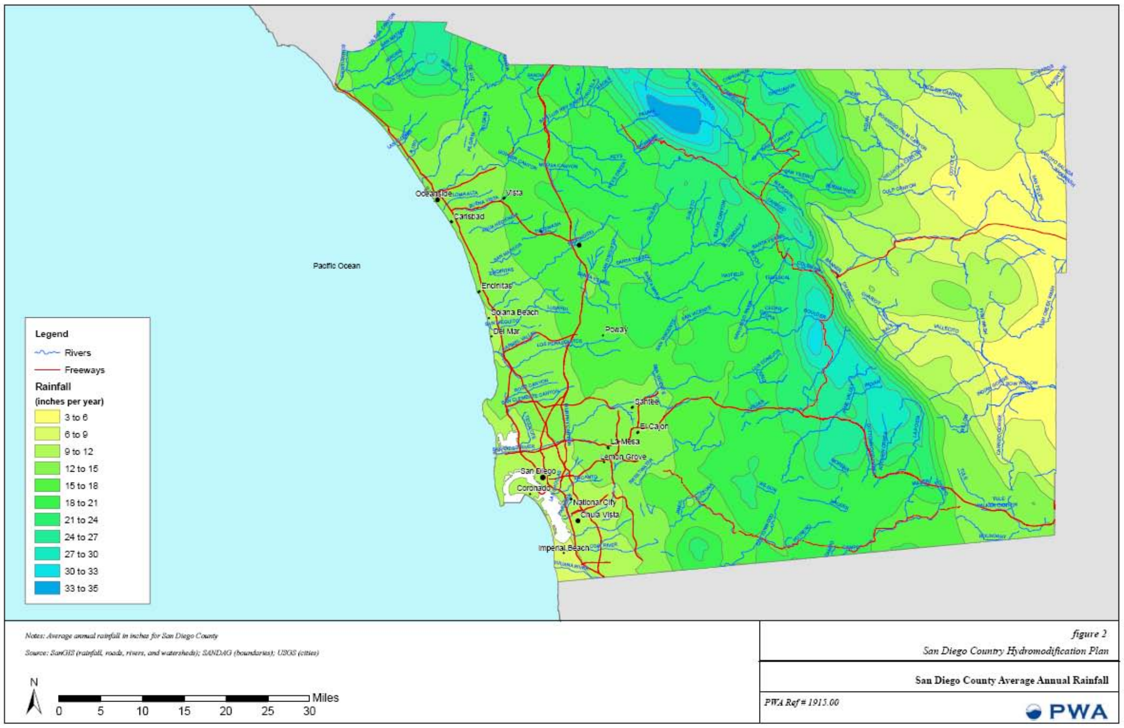


Figure 2. Rainfall distribution in San Diego County

4.3 IDENTIFY THE RANGE OF TYPICAL WATERSHED AREAS LIKELY TO BE DEVELOPED

Based on discussions with the Technical Advisory Committee, a range of representative watershed areas for development projects was identified. These were: 0.1 sq mi, 0.5 sq mi, 1 sq mi, 2 sq mi. We assumed that in project watersheds larger than 2 sq mi the development would either require site specific continuous simulation modeling, or be broken into multiple smaller sub watersheds with individual points of compliance.

4.4 IDENTIFY A RANGE OF TYPICAL RECEIVING CHANNEL DIMENSIONS FOR EACH WATERSHED AREA

Empirical relationships have been developed to express channel dimensions (width, depth and, to a lesser extent, gradient) as a function of dominant discharge. Dominant discharge for a creek channel is the flow rate that transports the majority of sediment and creates/maintains the characteristic size and shape of the channel over time. Dominant discharge may also be referred to as bankfull flow. For undeveloped channels in semi arid parts of the US, dominant discharge is approximately equivalent to Q_5. For example, Coleman et. al. (2005) found dominant discharge for streams in Southern California to average $Q_{3.5}$ (range = $Q_{2.1}$ – $Q_{6.7}$.) Goodwin (1998) found dominant discharge to vary from Q_2 to Q_{10} for semi arid regions.

To capture natural variability in channel geometry, we used three different empirical channel geometry relationships to estimate receiving channel dimensions for the range of watershed areas and rainfall characteristics used in this study. The relationships were:

Coleman et. al. 2005 (modified by Stein – personal communication) – derived from undeveloped channels in Southern California, tends to predict narrow, deep, steep dimensions.

$$\text{Width (ft)} = 0.6012 * Q_{bf}^{0.6875}$$

$$\text{Depth (ft)} = 0.3854 * Q_{bf}^{0.3652}$$

Where Q_{bf} is in cfs.

Parker et al. 2007 – suitable for gravel channels, tends to predict wide, shallow, flat braided dimensions.

$$\text{Width (m)} = 4.63 * (Q_{bf}^{2/5}) / (9.81^{1/5}) * (Q_{bf} / \text{Sqrt}\ (9.81 * d50) * d50^{2}))^{0.0667}$$

$$\text{Depth (m)} = 0.382*((Qbf^{2/5})/(9.81^{1/5})))$$

Where Q_{bf} is bankfull discharge in m^3/sec and d50 (diameter of median channel material) is in m.

The Parker equation was only used to assess gravel and cobble channel conditions.

Hey and Thorne 1986 tends to predict medium width, depth, and gradient channels.

$$\text{Width (m)} = 2.73*Q_{bf}^{0.5}$$

$$\text{Depth (m)} = 0.22 * \text{Width}^{0.37} * d50^{-0.11}$$

Where Q_{bf} is in m^3/sec and d50 is in m.

(Note that we have used the original combinations of English and metric units described in the source papers rather than standardized these equations in one set of measurements.)

The three equations cover a wide range of likely field conditions, from deeply incised channels (Coleman et al, 2005) to wide, braided conditions (Parker, 2007). Note that for the sensitivity analysis we set d50 in the Parker et al. equation to the d50 of the channel material being tested, and did not use the equation for channels where the material was sand or silt.

The equations produce estimations of width and depth. To estimate a slope for each combination of channel dimensions we calculated the velocity associated with each cross section (by dividing discharge by width multiplied by depth) and calculated the slope that corresponded with that velocity using Manning's equation.

$$\text{Velocity (ft/sec)} = 1.486 \frac{HR^{0.66} * s^{0.5}}{n}$$

Where HR is channel hydraulic radius, s is slope, and n is Manning's roughness coefficient (see definitions). For the purposes of the sensitivity analysis a value of n 0.035 was assumed, corresponding to a non vegetated, straight channel with no riffles and pools. This is a reflection of the small, ephemeral receiving channels which are most prevalent in Southern California developments. A relatively low value was used at the request of the San Diego RWQCB so that the values erred on the conservative side.

These equations all require a value for bankfull discharge. Bankfull discharge (assumed to be approximately Q_5) was estimated using the USGS regional regression for undeveloped watersheds in the South Coast region (Waananen and Crippen, 1977). This equation calculates Q_5 as a function of watershed area and mean annual precipitation, based on empirical observations of USGS gages. The relationship is:

$$Q_5 \text{ (cfs)} = 0.4 * \text{Watershed Area}^{0.77} * \text{Mean Annual Precipitation}^{1.69}$$

Where watershed area is in square miles and precipitation is in inches.

For each combination of typical watershed area (Section 2.2) and mean annual rainfall (Section 2.3) we calculated Q_5 using the USGS regression, then calculated three sets of channel dimensions based on the three channel equations. This provided the range of channel conditions to simulate for the critical flow analysis. The total number of channel conditions was as follows:

3 rainfalls (10, 20, 30 inches per year)
4 watershed areas (0.1, 0.5, 1, 2 square miles)
3 channel width, depth and slope combinations (narrow/deep, medium, wide/shallow)
= 36 combinations of receiving channel geometry

4.5 IDENTIFY A RANGE OF TYPICAL CHANNEL MATERIALS FOR RECEIVING CHANNELS

We identified a range of typical channel materials based on feedback from the TAC and experience gained working in San Diego County. The identified materials are not intended as a comprehensive list of possible channel materials, but to cover the range of critical shear stresses likely to be encountered in typical western San Diego County channels. The identified range is as follows:

Material	Critical shear stress (lb/sq ft)
Coarse unconsolidated sand	0.025
alluvial silt (non coloidal)	0.045
medium gravel	0.12
alluvial silt/clay	0.26
2.5 inch cobble	1.1

Combining the 5 channel material types with the 36 combinations of channel geometry produces 180 potential combinations of receiving channel characteristics. Ten sets of combinations were omitted from the analysis because they produced physically unrealistic conditions, such as slopes that were too steep to be developed. Exclusion of these results did not significantly affect the overall results.

4.6 DEVELOP SHEAR STRESS RATING CURVES

Rating curves for the 36 different combinations of receiving channel characteristics were developed using the same Excel worksheet that forms the basis for the Qcrit calculator developed for Track 2 (described in later sections). Using channel cross section, roughness and gradient input by the user, the tool calculates the average boundary shear stress associated with a range of different flow depths to construct a rating curve (discharge on the x axis versus shear stress on the y axis). It then identifies the flow rate where average boundary shear stress equals critical shear stress for the channel materials. This is the critical flow (Q_{crit}). By dividing this number by Q_2 we identify the critical flow for each simulation as a function of Q_2 (e.g. $0.1Q_2$ where the critical flow is one tenth of the Q_2 flow).

The tool calculates a shear stress rating curve for a range of flows between 1% and 100% of the bankfull flow depth. Bankfull flow depth is defined as the flow depth that corresponds to the dominant discharge for a given channel. The range 1% to 100% of bankfull is used because critical flow rarely falls outside these values. The tool then calculates an equation that allows for interpolation between the points. For each of the depths, the tool calculates discharge and average boundary shear stress exerted on the bed, as described below.

4.6.1 Calculating Average Boundary Shear Stress

Average boundary shear stress is the force that flowing water exerts on channel materials. For a given channel cross-section, it is calculated as follows:

$$\tau_b = \gamma * HR * s$$

where τ_b = average boundary shear stress (lb/ft^2)
γ = unit weight water (62.4 lb/ft^3)
HR = Hydraulic radius (cross section area / wetted perimeter)
S = channel slope (ft/ft)

For each depth increment between 1% and 100% of bankfull, cross section area, wetted perimeter, HR and τ_b are calculated. Slope is a constant for the cross section. These calculations produce a rating curve for boundary shear as a function of flow depth.

4.6.2 Calculating Flow Rate

This step converts flow depth to flow rate (Q) so that the rating curve may be expressed as a function of Q. For each depth increment between 1% and 100% of bankfull, the flow rate is calculated using Manning's equation:

$$\text{Velocity (ft/sec)} = 1.486 \frac{HR^{0.66} * s^{0.5}}{n}$$

where V = velocity (ft/sec)
n = Manning's roughness coefficient

For the sensitivity analysis Manning's n was assumed to be 0.035, which is typical for a non-vegetated ephemeral channel. We assumed that for most developments covered by the HMP the receiving channels would be relatively high in the watershed and would have received little summer flow. In interim sensitivity analysis found that relative to other factors such as critical shear stress, the range of roughness factors found in receiving channels had little effect on the estimated critical shear flow rate.

Discharge is calculated as velocity multiplied by cross section area (calculated for each cross section, above). The result of these calculations is a rating curve showing boundary shear stress for the receiving channel as a function of discharge, with the highest point representing bankfull depth (see Figure 3 below). Rating curves were created for each of the 36 combinations of channel characteristics.

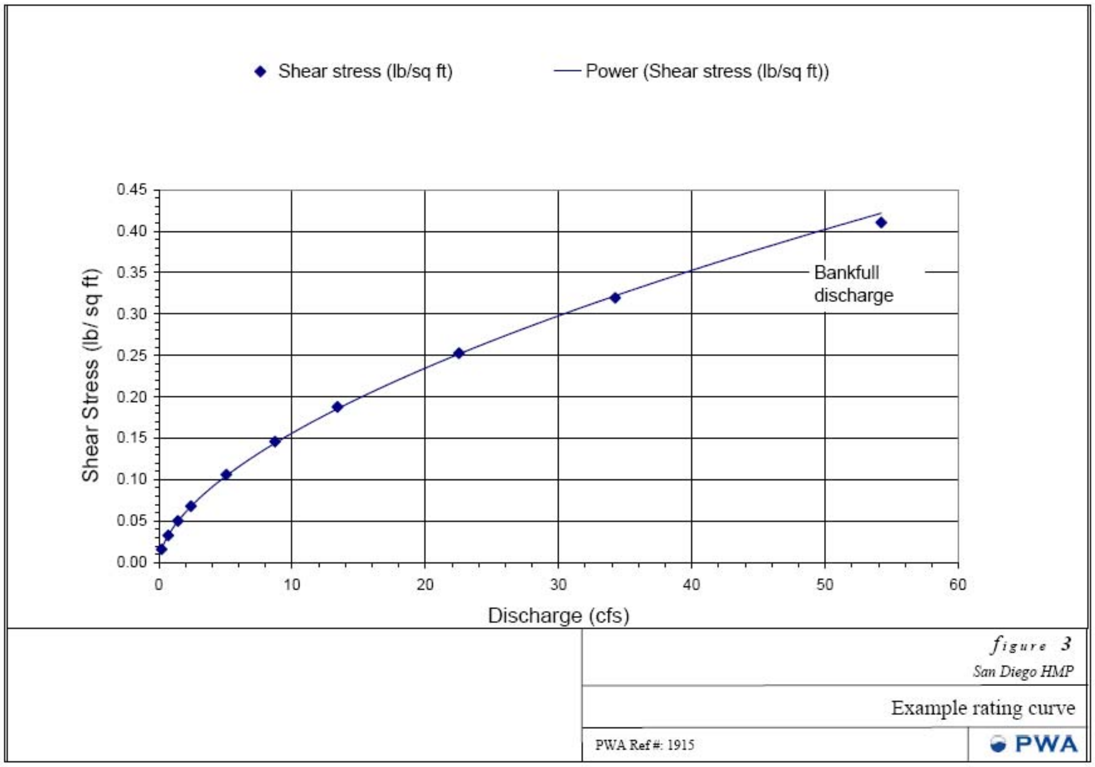


Figure 3. Shear stress rating curve for an example channel (0.5%, 10 feet wide, 2 feet deep). These curves were created for 36 different combinations of channel characteristics.

4.7 IDENTIFY CRITICAL FLOW FOR THE CHANNEL AND MATERIAL

Q_{crit} is the flow rate at which boundary shear stress equals critical shear stress. The tool uses a power function to interpolate the discharge versus boundary shear stress rating curve, to allow calculation of an intercept between the rating curve and critical shear stress. The critical shear stress for each channel material was plotted horizontally from the Y axis until it intercepted the rating curve. The intercept point was extended vertically to the X axis, showing the Q_{crit} (see Figure 4 below). In this way, Q_{crit} was calculated for each of the five channel materials using each of the 36 rating curves representing different channel dimensions. As mentioned above, 10 combinations unlikely to occur in nature were eliminated, resulting in a total of 170 Q_{crit} calculations.

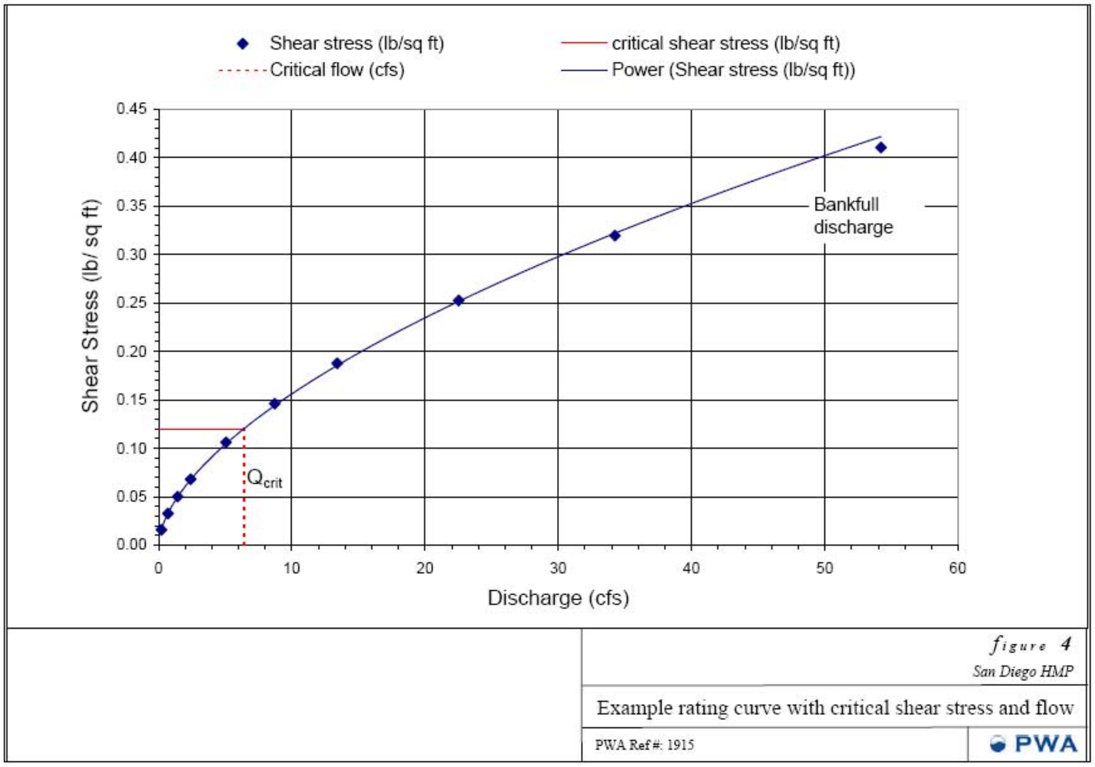


Figure 4. Example of a rating curve with critical shear stress for medium sized gravel. In this example critical shear stress = 0.12 lb/sq ft and critical flow Q_{crit} = 6.4 cfs.

4.8 EXPRESS CRITICAL FLOW AS A FUNCTION OF Q_2

As described above, each rating curve represents a particular combination of watershed area and channel dimensions. Q_2 was calculated for each combination using the USGS regional regression for Q_2 as described in section 4.4. By dividing the calculated Q_{crit} by the appropriate Q_2, Q_{crit} as a proportion of Q_2 was calculated for the 170 scenarios. These Q_{crits} were then plotted by material type, showing mean and one standard deviation either side of the mean. Note that although we assume that Q_5 is bankfull discharge, we express the critical flow as a function of Q_2 as has become standard for HMPs.

4.9 CRITICAL FLOW ANALYSIS RESULTS

The results show the high degree of variability in Q_{crit} based on different channel materials. It is important to note that in field conditions many of the most extreme cases shown in the figure (examples with very high or very low thresholds) would tend to evolve to conditions that yielded critical flows closer to the bankfull discharge because channels have a tendency to self equilibrate. For example, channels with materials that have very low critical flows such as unconsolidated sand tend to erode and either flatten (lowering shear stress, and so increasing critical flow rate) or armor (increasing flow resistance, and increasing critical flow rate). Likewise, channels with materials that have very high thresholds tend to either become steeper due to deposition (increasing shear stress and lowering critical flow rate) or fill in with finer material (reducing resistance and lowering critical flow rate).

4.10 DISCUSSION

As the results of this analysis demonstrate, critical flow is extremely variable among channel materials and, for a given channel material, can vary significantly with channel configuration (slope, width/depth ratio etc.). Unconsolidated fine sediments can be mobilized by extremely low flows in the absence of clays or other consolidating elements with the structure of the channel. This result is based on literature values for critical shear stress for unconsolidated materials and may not be realistic for natural channels. Therefore in setting flow thresholds this result should be balanced with the recognition that natural channels are likely to include some consolidating fraction within their structure, as well as practical considerations associated with controlling trickle flows that represent the smaller fractions of Q_2 analyzed in this study.

5. TOOL FOR CALCULATING SITE-SPECIFIC CRITICAL FLOW

5.1 BACKGROUND

PWA developed a tool for calculating a site-specific critical flow (Q_{crit}) based on local conditions. Q_{crit} for the receiving channel is calculated based on channel geometry (width, depth and gradient), channel materials, and watershed area.

The approach taken was to develop an Excel spreadsheet model to calculate the boundary shear stress associated with a range of flows up to Q_5 for a given channel width, depth and slope, then plot the critical shear stress for the channel material on this rating curve over to identify the flow where boundary shear stress equals critical shear stress (see example graph below).

The development steps were as follows:

1. Develop simplified channel cross section and gradient inputs
2. Calculate a shear stress rating curve
3. Characterize channel materials in terms of critical shear stress
4. Plot critical shear stress of the receiving channel on the rating curve to determine Q_{crit}
5. Divide the critical low flow by the project areas as a proportion of the receiving water watershed area to determine the allowable flow at the point of compliance

5.2 SIMPLIFIED CHANNEL CROSS SECTION AND GRADIENT INPUTS

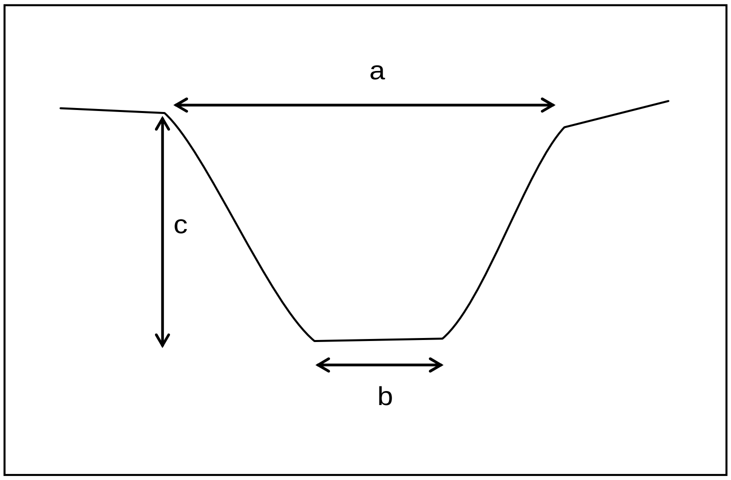
The tool generates a flow rating curve based on user inputs describing the receiving channel dimensions (cross section) and gradient. The first step in developing the tool was to create a template for inputting the required channel parameters. The template assumes a simple trapezoidal cross section, with the following elements:

1. Channel width at a well defined break point corresponding to top of bank (a)
2. Channel width at the toe of the bank (b)
3. Channel depth (elevation difference between bank top and channel bed) (c)

Assumptions:

1. Receiving channels can be reasonably represented by a simple trapezoidal cross section
2. The top of bank corresponds reasonably to the level inundated by the dominant discharge (approximately equal to Q_5)

If top of bank is much higher than the dominant discharge flow depth (e.g. in an incised channel) the applicant should adjust the cross section to represent the lower part of the channel so that depth (c) corresponds approximately to the Q_5 depth.



5.3 DEVELOP A SHEAR STRESS RATING CURVE

The tool creates a shear stress rating curve for a range of flows between 1% of the bankfull flow depth and bankfull depth (flow at depth (c).) The range 1% to 100% of bankfull is used because critical flow rarely lies outside these values. The tool then calculates a power function between the points to allow for interpolation. For each of the flows the tool calculates average boundary shear stress exerted on the bed, and discharge, as described below.

5.3.1 Calculating Average Boundary Shear Stress

Average boundary shear stress is the force that erodes channel materials. It is calculated as follows:

$$\tau_{crit} = \gamma * HR * s$$

where τ_{crit} = average boundary shear stress (lb/ft^2)
γ = unit weight water (62.4 lb/ft^3)
HR = Hydraulic radius (cross section area / wetted perimeter)
S = channel slope (ft/ft)

For each depth increment between 1% of bankfull and bankfull, cross section area, wetted perimeter, HR and τ_{crit} are calculated. Slope is assumed to be constant for the cross section; therefore multiple calculations may be required for variable slope conditions. These calculations produce a rating curve for boundary shear stress as a function of flow depth.

5.3.2 Calculating Discharge

For each depth increment between 1% of bankfull and bankfull discharge is calculated using Manning's equation:

$$V = 1.486 \, \frac{HR^{0.66} * S^{0.5}}{n}$$

where V = velocity (ft/sec)
n = Manning's roughness coefficient

Manning's n is entered by the user from a drop down dialogue box ranging from 0.03 (smooth, straight earth channel with no vegetation) to 0.12 (windy, rough bed channel with dense vegetation).

Discharge is calculated as velocity multiplied by cross section area. The product of these calculations is a rating curve showing boundary shear stress for the receiving channel as a function of discharge, with the highest point representing bankfull flow (see Figure 7 below).

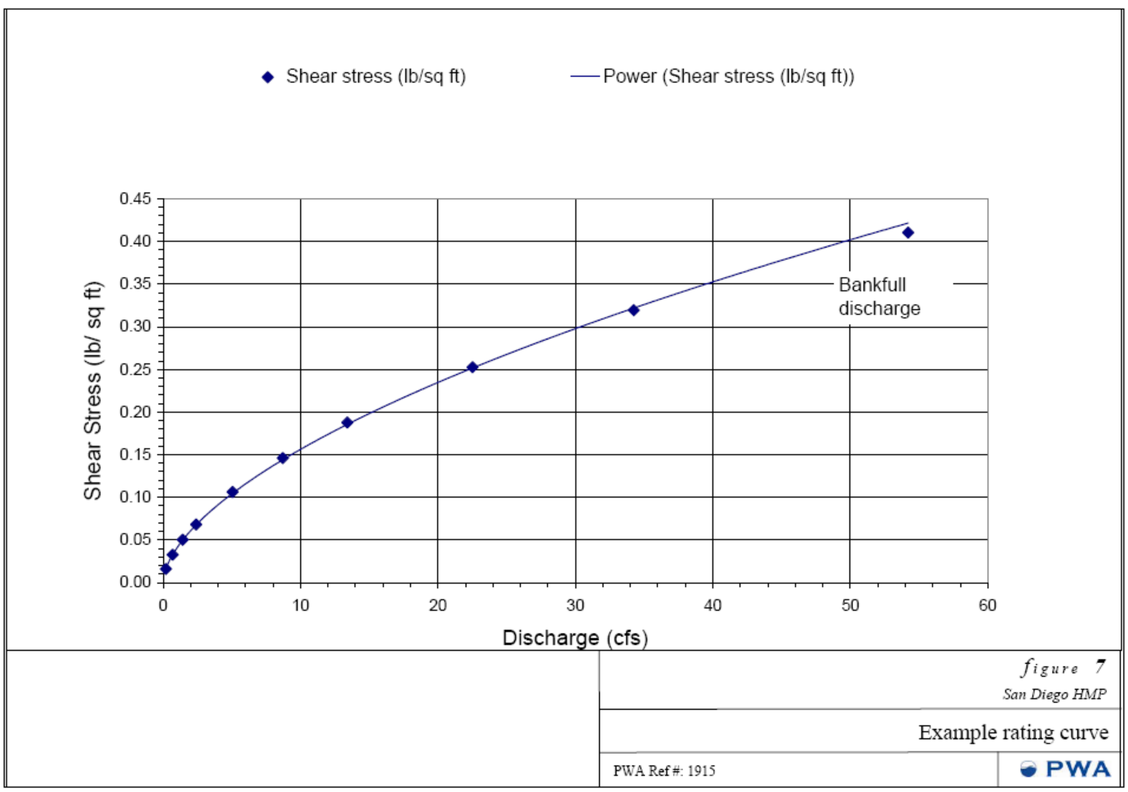


Figure 7. Shear stress rating curve for an example channel (0.5%, 10 feet wide, 2 feet deep)

5.4 CHARACTERIZE RECEIVING CHANNEL MATERIALS IN TERMS OF CRITICAL SHEAR STRESS

The critical shear stress of the channel materials is estimated using a look-up table based on values published by the USACE (Fischenich, 2001). The tool provides values of critical shear stress for a wide range of channel materials in a drop down box so the user can select from the list, or select a median particle size (d50). The values are shown in Table 1. The calculator also allows the user to input a vegetated channel material when this is appropriate (when the channel is completely lined in vegetation). The process for identifying representative materials is covered in the implementation chapter.

5.5 CALCULATING CRITICAL FLOW FOR THE RECEIVING WATER

Critical flow is the discharge at which boundary shear stress equals critical shear stress. The tool uses a power function to interpolate the discharge versus boundary shear stress rating curve. The critical shear stress for the weaker of the bed or banks is plotted horizontally from the Y axis until it intercepts the rating curve. The intercept point is extended vertically to the X axis, showing the critical flow (see Figure 8 below). This represents Q_{crit} for the receiving water. Note that the creation of a site-specific rating curve allows Q_{crit} to be expressed as a specific flow rate (Q) rather than a fraction of Q_2.

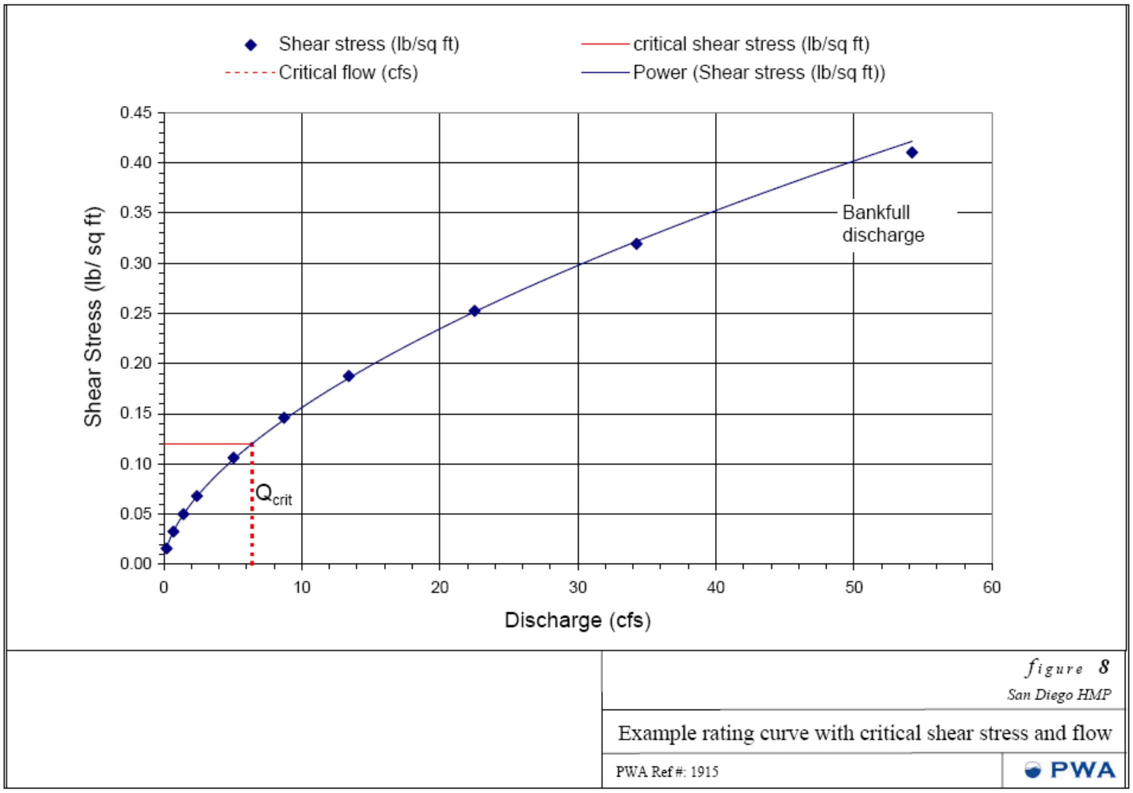


Figure 8. Example of a rating curve with critical shear stress for medium sized gravel. In this example critical shear stress = 0.12 lb/sq ft and critical flow Q_{crit} = 6.4 cfs.

5.6 CALCULATING CRITICAL FLOW AT THE POINT OF COMPLIANCE

The tool calculates critical flow based on the characteristics of the receiving water. Where the project watershed does not make up the entire watershed area for the receiving water, it is necessary to divide the estimated Qcrit based on the percentage of the watershed that is occupied by the project site[3]. For example, if a project occupies one tenth of the receiving water's watershed at the point of compliance and the critical flow level is 50 cfs, the project's 'share' of the non-erosive flow is 5 cfs (50 x 1/10). This prevents the cumulative impact of future developments from exceeding critical flow in the receiving water, since the critical flow is apportioned according to watershed area.

$$\text{Critical flow at Point of Compliance} = \text{Critical flow at receiving water} \times \frac{\text{project area}}{\text{watershed area}}$$

[3]. It is not necessary to adjust the "off-the-shelf" thresholds developed for Track 1 for point of compliance, since they are expressed as a fraction of Q2 for the relevant project area.

5.7 CONVERSION OF CRITICAL FLOW TO FLOW CLASS

To avoid having an infinite range of flow control standards the calculator assigns the discharge into one of three classes based on its value as a function of the estimated Q_2. These classes are: $0.1Q_2$, $0.3Q_2$, $0.5Q_2$. For example, a channel where the critical flow is $0.15Q_2$ would be assigned a flow threshold of $0.1Q_2$. Channels with critical flows less than $0.1Q_2$ are assigned to the $0.1Q_2$ class. The class flow rate is calculated (i.e. the critical flow corresponding to the assigned fraction of Q_2 and expressed as the final output of the tool.

6. GLOSSARY

Bankfull depth
The water depth between the deepest part of the channel and the water surface, during bankfull discharge. Also the vertical distance between the uppermost 'bankfull indicators' and the deepest part of the channel.

Bankfull discharge
The flow rate at which the actively scoured portion of the creek channel is filled with water. In southern California bankfull discharge has typically been found to be between Q2 and Q7, with an average of approximately Q5.

Bankfull indicators
Morphological evidence for the portion of a creek channel that is subject to active scour and sediment transport processes. Typical indicators include scour lines along a bank, the highest vertical level on point bars, base of undercut tree roots.

Bankfull width
The width of the channel at the water surface during bankfull discharge. Also the horizontal distance between 'bankfull indicators' across a channel.

Critical flow
The discharge corresponding to Critical Shear Stress. Varies with channel geometry and materials.

Critical shear stress
The shear stress at which a given channel material is eroded. In non cohesive sediments larger particles have higher critical shear stresses. In cohesive sediments (those smaller than 0.063 mm) sediment has higher critical shear stresses than fine, non cohesive materials

d50
The median sediment particle size in a sample of material taken from a creek bed (diameter of the 50^{th} percentile)

Geomorphically-significant flows
The range of flows that, over a period of several decades, erode and transport the majority of the sediment in a creek system. The mid range of this flow range tends to be similar to "bankfull" discharge, leading people to infer that these flows shape the channel as well as moving most sediment. Calculated by integrating the flow frequency curve with the sediment rating curve.

Point of Compliance

The point at which collected stormwater from a development is delivered from a constructed or modified drainage system into the natural creek receiving water. Note that the HMP applies only to discharge into a natural creek of receiving water, and does not apply to sheet flow or overland flow from a developed site.

Q2

The discharge that recurs on average every 2 years, and that has a 50% probability of occurring in any single year.

Q10

The discharge that recurs on average every 10 years, and that has a 10% probability of occurring in any single year.

Shear stress (also known as boundary shear stress or average boundary shear stress)

The average force exerted by flowing water on the channel boundary. Shear stress is the force responsible for eroding sediment from the channel boundary. It is a function of water surface gradient (related to channel gradient), water depth, and water density.

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