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CHAPTER 2. PROCEDURES FOR STABLE CHANNEL DESIGN AND ANALYSIS

2.1 INTRODUCTION

This chapter describes the procedures for analyzing and designing a stable channel reach. The procedures may be used to

- restore a hardscaped channel reach to its natural form,
- design a bypass channel along a new alignment, or
- observe noticeable degradation or aggradation in the existing channel, assess the situation and restore stability.

Although the procedures are used more often by capital projects to conduct systematic analysis of creek stability, they may be appropriate for maintenance projects as well. It is important for all of us to be aware that any change we apply to the creek will induce response, in terms of transformation in cross-section and/or channel slope. Stability will result only if the change is consistent with the creek's natural response. This chapter introduces some methods (in order of increasing complexity) for designing a stable channel.

The design of a stable reach of channel can generally be divided into 4 steps:

1. Establish the existing conditions. Determine if the channel is degrading, aggrading, or stable, and collect the necessary flow and sediment data for analysis.
2. Develop a cross section for the design reach that is prone to induce stability
3. Determine the equilibrium slope for the design reach. This is the slope which, when combined with the cross section determined above, will result in balanced sediment transport between the design reach and its neighboring upstream and downstream reaches. Calculating the equilibrium slope will also enable determining the need for grade control structures, following the procedure laid out in Chapter 3.
4. Design proper surface protection for channel bottom and banks to resist tractive force of the flow regime.

The procedures described below provide a framework for designing a stable channel reach. They include field observations and measurements, methods that are relatively simple and provide one-dimensional estimates of sediment transport capacity, and also a method to compute long-term sediment transport to verify stability.

2.2 PROCEDURES FOR STABLE CHANNEL DESIGN

1. Establish Existing Conditions

The first step in designing a stable channel is to understand in what state the channel is and how it has evolved in the past. This understanding requires a combination of data collection and data analysis, as described below in Steps 1A and 1B.

1A. Data Collection

The following data are necessary to establish the existing and past conditions and constraints on the design channel:

- Channel Invert and Cross-section Data
- Sediment Data
- Bed Armor Estimates
- Hydrologic Data
- Right of Way Data
- Maintenance Records
- Current or past HEC-RAS or HEC-2 models

Channel Invert and Cross-section data include topographic maps, as-built drawings, aerial photographic surveys, LIDAR surveys, ground surveys, and geometry data from previous HEC-2 or HEC-RAS models. These may be used to determine the channel invert profiles and cross-sectional shapes and how they have changed over time.

Sediment data include the sediment size distribution curves developed from sediment samples collected in the project reach, sediment load data developed from samples collected during rain storms, past sediment analysis reports for the project reach, and observations of sediment degradation or aggradation.

Bed armor estimates should be made from a combination of data collected from field visits and calculations for determining whether the bed is armored. The project team should look for signs of armoring in their creek. Usually, this involves observing whether the creek bed is covered with a layering of particles significantly larger than the subsurface layer.

Hydrologic data include flood-frequency data obtained for specific locations in the project reach from rainfall-runoff and flood–frequency analyses, design storm hydrographs, and historic flow records collected from gauge stations. The flood frequency data are used to evaluate channel flow conditions and sediment transport rates under various levels of flood flow rates. Storm hydrographs and historic flow records are used to estimate annual yield, or average annual sediment transport rates, which generally are useful in validation of the equilibrium slope calculations.

Right of Way data are needed to establish the boundaries of lands or easements available for siting the channel.

Maintenance records of sediment removal and channel modifications are useful in several respects. For one, maintenance records of removal rates provide a reference point for estimate of bed-load sediment yield. Sometimes they include sediment gradation information which can be used to calibrate the sediment transport calculation. The channel modification records also provide clues of channel morphology.

HEC-RAS or HEC-2 models of the design area allow for comparison of channel cross-sections to determine change over time. Care should be taken when examining old HEC-2 data. Survey practice in the past was typically less stringent than the present.

1B. Data Analysis

It is difficult to provide a step by step procedure for investigating the existing conditions based on collected data because the amount and type of data available for each creek and project is different. In the following, we outline some standard techniques for processing that data in a useful way.

- Examining HEC RAS results for sub-reaches where channel hydraulics (velocity, shear stress, stream power, etc.) are uniform (or relatively similar) and for locations where they change significantly (such as at breaks in the invert slope or mannings n value). Places where the hydraulics change will likely correspond with places where the sediment transport rates change. Since regions of uniform hydraulics may vary with flow rate, the engineer should examine their HEC-RAS results for a few different flow rates. Several may be considered- at a minimum, however, the low flow (if it exists for the creek), bankfull flow, and design flow rate cases should be examined, with conclusions more heavily weighted towards the smaller, more frequent flows.

- Collecting and plotting sediment data for establishing relationships between creek features and sediment bed composition. For example, it is useful to plot the sediment gradation curves for all locations together to see how they compare. It is also useful to map out the d_{50}, d_{10} and d_{90} values as they vary along-stream. Such mapping will help to identify whether control structures (e.g., bridges) or other features (e.g., a tributary) may affect the sediment size distribution. It will also allow the engineer to identify the bed composition, determine whether the bed is armored (See Chapters 8 and 10), and observe any significant changes in the bed composition with distance along-stream. In addition, it provides a check on the data collected, allowing for easy identification of outlier samples (which can then be discarded as bad data).

- Verifying armor characteristics. The team should visually assess the condition of the bed to determine first if the bed surface is composed of particles that are larger than the underlying materials, and if so, the average larger particle size and the percentage of bed which is covered by the larger particles. The team should collect sediment samples at each of these locations and process them via sieve analysis to determine their gradation curves; these samples should include both the surface layer sediments and some sub-surface layer sediments. The team should later assess whether the identified areas are actually armored by comparing the critical particle size for those areas with their best estimate of D90 for those areas; the bed is judged to be armored if the critical particle size is smaller than D90. Once this determination has been made, the engineer can be confident in their visual assessment of percent armoring. An example of this procedure is provided in the appendix attached to this chapter

- Conducting field visits to the project reach to identify sites of deposition, erosion, or stability. At stable sites, which would have a cross sectional shape with a bankfull channel and floodplain (see Chapter 9), the cross sectional parameters should be measured. These will be used in the initial design for the project reach, as they should exhibit stable invert slopes and cross section shapes existing near the project reach.

- Comparing cross sections and thalweg profiles for multiple different surveys to determine places of significant change, i.e., aggradation or degradation, which have occurred in the time between the surveys.

- Collecting sediment maintenance records. These may be used to estimate parameters, such as average annual sediment transport rates, which may be used for model validation.

- Comparing pictures from different time periods of the same locations.

The results of these investigations should yield a fairly complete picture of the sediment transport patterns in the existing creek. The engineer should try to synthesize this information to ensure that conclusions from each investigation are consistent and make sense. This part of the stable channel design is very important because it will help to determine later the hydraulic and sediment inputs used in the models for the quantitative calculations for determining equilibrium slope.

2. Stable Cross Section Design

2A. Stable Channel Characteristics

A stable channel cross section typically consists of:

- A channel for conveying the low flow (if it exists), which forms due to the year-round persistence of the low flow,

- Above the low flow channel, a secondary channel for conveying the bankfull flow, which forms in part because the bankfull flow is often responsible for carrying the largest percentage of sediment during a given year (if equivalent to the effective discharge), and

- Above the bankfull channel, a floodplain for carrying flows larger than the bankfull, which slows the flow down (through larger wetted perimeter), decreases the shear stress in the channel (see Chapter 9), and reduces the sediment transported by the section (for flows larger than the bankfull rate).

Thus, a stable channel cross section can be represented prototypically as a compound trapezoidal channel, as laid out in Figure 2-1.

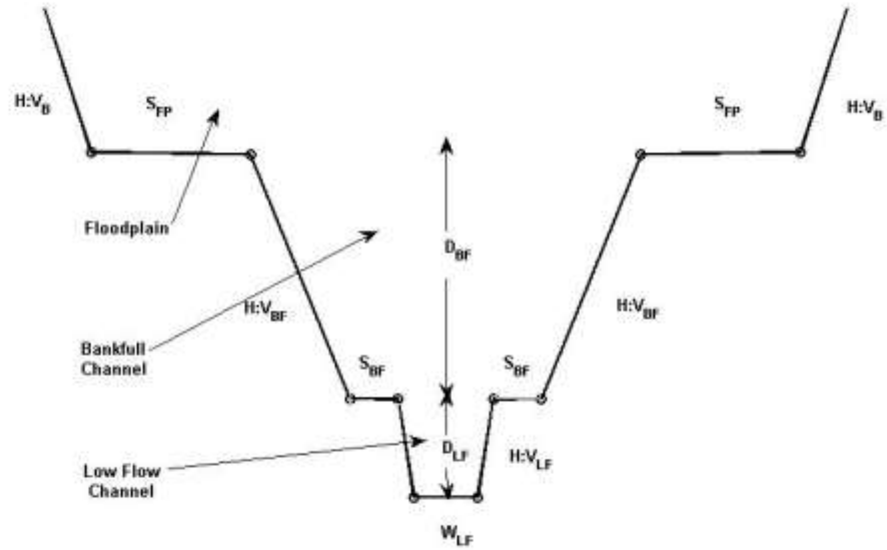

Figure 2-1. Definition Sketch of a Compound Trapezoidal Cross-Section

2B. Design Stable Channel

Estimates for the parameters to define a stable channel cross section can be collected in the field from a stable reach of creek channel, as follows:

1. Visiting the site and identifying areas around the project reach which are in a state of dynamic equilibrium (see Chapter 9 for a definition),

2. Measuring the parameters as laid out in Figure 1 above, which include low flow channel width (W_{LF}), low flow channel depth (D_{LF}), low flow channel side slopes ($H:V_{LF}$), bankfull channel width (W_{BF}), bankfull channel depth (D_{BF}), bankfull channel side slopes ($H:V_{BF}$), and the floodplain slope (S_{FP}). The bank slopes are generally set by a combination of geotechnical considerations (See Chapter 4).

3. Averaging each parameter over the number of cross sections measured, and using those values to develop a prototypical stable channel cross section shape, and

4. Comparing the prototypical cross section shape with surveyed cross sections in stable areas. Figure 3 shows the comparison between a prototypical design cross section and a surveyed cross section for the reach upstream of Comer Drive on Calabazas Creek.

With this data, a prototypical cross section shape can be conformed to the existing banks almost anywhere along the creek by adjusting the width of the floodplain (usually to fit within right of way boundaries). An example of the complete procedure is provided in Appendix 2.A.

3. Design Equilibrium Slope

The real equilibrium slope for a reach of creek is the result of months to many years of flow and its associated sediment transport, including lower flows to catastrophic floods. Whenever a channel modification is made to a creek, the area surrounding the creek is urbanized, a dam is built on the creek, the creek experiences a major flood, or the like, the channel profile will adjust itself towards a new equilibrium state in which the sediment transport coming into the reach balances that leaving it. The best estimates of equilibrium slope, then, are the result of models which take all of these factors into account: unsteady sediment transport models which are capable of tracking the movable bed profile and its effect back on the hydraulics. However, such models (e.g., HEC-6) are time-consuming and expensive. They also require a considerable amount of input data; for example, multi-year records of flow and of upstream sediment loading rates.

The methods presented below are simpler and are designed for lower-budget, smaller projects. The methods are explained below in order of increasing complexity. The first method is labeled 'Use Existing Slope Data' and is described in Section 3A; the second method is the 'Bankfull Method' and is described in Section 3B; the third method is the 'Annual Yield Method' and is described in Section 3C; the fourth method is the 'HEC-6 Method' and is described in Section 3D. Methods 3A – 3C can be viewed as simplifications of the more complex, moving bed models, which provide less information on the one hand, but are based on physical processes on the other. Once the equilibrium slope has been computed for the project reach or reaches, it is important to determine whether a surface protection layer is needed in the construction of the project reach. This is discussed in Section 2.3.

3A. Use Existing Slope Data

The simplest method for estimating the equilibrium slope for the project reach is simply to use the slope from a neighboring, stable reach of channel. This reach would probably be from the same area where cross sectional dimensions were collected in the field.

3B. Bankfull Method

The 'bankfull method' [3B] consists of finding the slope which results in balanced sediment transport rates at the bankfull flow rate between the design reach and its surrounding upstream and downstream reaches. The steps in this analysis are listed below as 3B.1 – 3B.4.

3B.1 Delineate Sub-Reaches

For the purposes of this chapter, a 'sub-reach' is defined to be a length of creek for which the channel cross section, slope, roughness, and sediment properties are relatively constant.

The first step in estimating the equilibrium slope is to break up your project reach into a few to several such sub-reaches. When doing so, it is important to consider the following factors:

- bridges
- drop structures
- areas of transition between different types of bank protection
- ramps
- invert slope breaks

- meander of the channel's path
- constrictions or expansions in channel width, and
- culverts or flap gates which may change the flow rates during storms.

At a minimum, there should be one sub-reach defined for the project reach, one for the area upstream of the project reach, and one for the area downstream of a project reach. There may be multiple sub-reaches delineated for the project reach if, for example, there is a significant width change to the existing banks (into which the geomorphic cross section will fit).

This delineation of a project reach into three or more sub-reaches simplifies the equilibrium slope analysis and also helps the engineer to decide whether a more complicated method may be necessary for computing the equilibrium slope.

3B.2 Choose Representative Cross Section for Each Reach

Once the creek is broken up into sub-reaches:

1. Choose a cross sectional shape representative of the geometry for each sub-reach. The cross section for the design reach is determined by field data collected from stable reaches of channel, as laid out in Section 2.2, Step 2A.

2. Assign roughness coefficients to the cross section, based on existing conditions [if the sub-reach is in the existing part of the channel] or proposed conditions [if the sub-reach is in the design reach].

3. Assign an invert slope to each sub-section which represents its average energy slope.

3B.3 Determine the Equilibrium Slope

Determination of the equilibrium slope is an iterative process, as follows:

- Step 3B.3.i: Select a sediment transport function.

- Step 3B.3.ii: Use SAM to compute the sediment transport rate for each sub-reach at the bankfull flow.

- Step 3B.3.iii: For each design reach, compare the sediment transport rate with those of their neighboring upstream and downstream reaches. If the sediment transport rates balance, then the slop(es) assigned to each of the design reach(es) is (are) the equilibrium slope(s). If not, then adjust the slope(s) in each design reach, and return to Step 3B.3.ii.

- Step 3B.3.iv: Once the sediment transport rates have been computed for each reach, multiply the sediment transport rate by the fraction of the channel bed which is not armored, i.e., (1-Pa), where Pa is the fraction of the bed which is armored. This factor was discussed above in the sections on Data Collection and Data Analysis (and Pa is set to 0 for reaches which are not armored).

3B.3.i Select a sediment transport function

Chapter 10 discusses sediment transport functions available in some detail. Some simple guidelines include:

- Compare characteristic values of the median particle size, velocity, depth, channel slope, and channel width with those for which each sediment transport function was developed. A list of these parameter ranges used to develop various sediment transport functions is available in the SAM User's manual (at X:\CPSD\Hydraulics Unit-345\software\SAMwin).

- Use a function which includes bedload at a minimum. If the sediment at your site includes a large percentage of suspended load, make sure that the formula computes suspended and bed load.

- The MPM and MPM-Toffaleti methods (available in the SAM package) have been used successfully for past sediment analyses in District Creeks (for the Adobe and Calabazas projects).

3.B.3.ii Compute Sediment Transport Rate in each sub-reach with SAM

First, launch SAMwin.

Run File → New Project. Save the project to a directory.

<u>For each sub-reach, compute the hydraulic inputs needed</u>:

- Navigate to Edit → Hydraulic Function Input → Normal Depth Calculations and Variations. A window for entering data will pop up

- In the "Calculation Options" frame, set the "Variable to Calculate" to "Normal Depth", the "Compositing Method" to "Equal Velocity" [the same method HEC-RAS uses], and "Geometry" to "Station Elevation"

- In the "Flow Data" table, enter the Bankfull Discharge, the "Energy Slope", and the water temperature.

- Push the "Enter Geometry Data" button, which launches a window for geometry data. Enter the x,y coordinates for the cross section representative of the reach. Enter the "river mile" (descriptive purposes only), the number of points included in your cross section, and the left and right bank stations [SET THE LEFT AND RIGHT BANK STATIONS TO THE EDGES OF THE BANKFULL CHANNEL.].

- Lastly, enter the "Roughness Characteristics…". There are quite a few choices; we recommend specifying the Manning's n values [set Equation = 0 and the Manning's n value as it varies across the cross section]. When doing so, recall that this cross section is representative of the entire reach, and try to ensure that the Manning's n values are set so they represent the average roughness in the reach. Press OK to close the window.

- In the “Normal Depth and Variations” window, Navigate to File → Save Current Data As, and elect a file name. This data will be saved to the current directly. You might name this file by its reach name, for example.

- Run “File→ Open Existing Input File” and open the file you just saved. This ensures that the output file will have the same name as the data you saved the information to.

- Now, push the Solve button. SAM.hyd will create two files with the same root name as was used to save your data: the *.ho contains the hydraulic outputs, the *.si contains an input file which is used to compute sediment data.

<u>**For each sub-reach, Compute the sediment transport**</u>:

- Launch SAMwin if you haven’t already (see instructions above)

- Open the appropriate project if it’s not already open.

- Navigate to “Edit → Sediment Transport Input.” This launches the “Sediment Transport Input” window

- Navigate to “File → Open Existing Input File” This will populate the “Flow Characteristics” table.

- Push the “Enter Bed Material” button, and enter the DMAX (maximum particle size—REQUIRED OR THE CODE WILL NOT RUN), Specific Gravity (if different from 2.65) and Particle Size/Percent Finer data. Note that it is not necessary to enter the particle size at 0% or 100%. Press OK and return to the “Sediment Transport Input” window.

- Select the sediment transport equations (one or more) in the “Transport Functions” frame.

- Navigate to “File → Save Current Data as…” and name the file (probably with the same root as used for the hydraulic input file—i.e., replace it.

- Navigate to “Open → Existing Input File” and open the file you just saved [this precaution may not be necessary, but it ensures that your output file will have the same name as your input file]

- Push the Solve button. The sediment transport rate in tons/day for each entered discharge (i.e., rating curve) will be stored at the very bottom (end) of the output file, and will also be displayed in an extension of the “Sediment Transport Input” window.

- Once the sediment transport rates have been computed for each reach, multiply the sediment transport rate by the fraction of the channel bed which is considered to be ‘active’ (i.e., not armored). This factor was discussed above in the sections on Data Collection and Data Analysis (and is set to 1 for reaches which are not armored).

3.B.3.iii Determine Equilibrium Slope

In the bankfull flow method, the equilibrium slope for the design reach is the slope for which the sediment transport rate(s) in the design reach(es) balance those of their neighboring upstream and downstream reaches.

Compare the sediment transport rate of the design reach(es) with their upstream and downstream reaches. If the sediment transport of the design reach balances to within about 20% of that upstream and downstream reaches, then the slope you have elected is a reasonable estimate for the equilibrium slope. If not, then adjust the slope input(s) for the design reach(es) and return to step 3.B.ii. Iterate until this criterion is met.

Important Considerations

- Sediment transport rates may be considered to be reasonably balanced if they agree to within about 20-30% percent.
- If sediment transport rates do not balance between the upstream and downstream reaches, try to figure out why this imbalance occurs. Maybe this is consistent with the existing conditions [e.g., if aggradation or degradation has been occurring in this area], or maybe this is merely due to chosen inputs [e.g., the channel cross section chosen is not really representative of one of the reaches, or the sediment gradation curve used for the calculations contains more fine particles than really exist in the creek]. In the former case, perhaps then the downstream or upstream reach should really be included in the project; in the latter case, then adjust the input parameters which are suspect according to physical reasoning and recalculate.
- Different formulae will compute different sediment transport rates, sometimes by an order of magnitude, given the same inputs — this is not an error, but rather a reflection of the type of sediment transport equation (e.g., combined load vs. bedload only), the flow regimes for which the equation was derived, and the way that the method handles particle sizes (e.g., does it treat multiple particle sizes, or represent the sediment as only one size?).

3C. Annual Yield Method

This method expands on the bankfull method [3B] in two ways: (1) it takes small variations in channel width over the channel into account, and (2) it takes into account the full range of flows experienced by a creek during an average year.

The basic procedure is still the same: compute the sediment transport (as annual yield, or average tons/year) for the design reach(es) and their surrounding reaches and iteratively adjust the bed slope in the design reach until a balance is achieved. However, the process is more involved, and requires more data, than Method 1. This procedure is outlined in Figure 2-2.

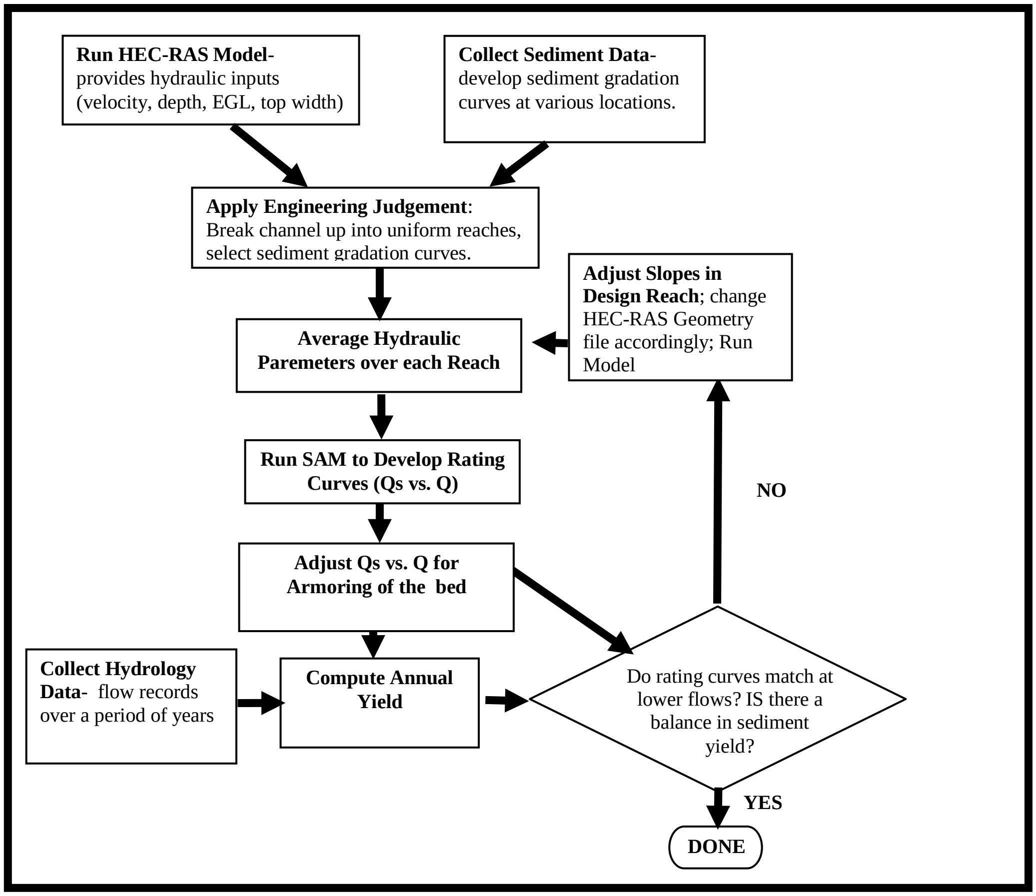

Figure 2-2. Steps of the 'Annual Yield' Method for Estimating Equilibrium Slope

3C.1 Collect Additional Data

The Annual yield method requires more input data than does the Bankfull method. In addition to data collected for the bankfull method, the following data inputs are required:

- A multi-year flow record from a gauge station on the creek (adjusted, if necessary, to accommodate its location relative to the project reach within the watershed).
- A HEC-RAS model for the proposed cross-sectional geometry. The design reach should consist of the prototype stable cross section developed for the creek (Step 2) and an estimate of the equilibrium slope (e.g., from existing data, see 3A). The model should extend reasonably far upstream and downstream of the design reach, so that the effects of the design reach on the existing channel are adequately modeled.

3C.2 Delineate Sub-Reaches

Similar to the 'bankfull' method [3B], the first step in the 'annual yield' method is to break the project reach into several sub-reaches. Follow the guidelines in Step 3B.1.

The only additional consideration to make in this method is whether the hydraulics are uniform within each sub-reach for flow rates ranging from small flows [i.e., smaller than the bankfull flow rate] up to the design flow [usually the 1% flow]. For example, a drop structure or ramp might trip supercritical flow at low flows, but not for high flows; if so, the ramp should probably be excluded from the project reach. Another example might be a change in roughness on the floodplain, which is non-existent in the bankfull channel- such a change would not affect the bankfull flow results, but would affect flows which expand onto the floodplain.

3C.3 Average Hydraulic Parameters over Each Reach

Step 3C.3.i: Setting up the HEC-RAS Model

This step assumes that the HEC-RAS model already has the design cross section and slope estimate coded into its geometry.

The HEC-RAS model should be set up so that bank stations are at the edges of the bankfull channel. If the channel is incised or if there isn't an identifiable bankfull channel, then bank stations should be set at the points where the 1.5 year interval water surface profile intersects with the cross section. NOTE: When setting the bank stations this way, do so independently of changing the roughness as it varies across the channel.

These settings are necessary because they ensure that computed channel velocities refer to the velocities, depths and widths which contribute to erosion of the channel invert. Including the floodplain in the channel definition would be misleading in this analysis. For most projects, this will involve creating a special geometry file for sediment transport. It should only change the definition of the channel limits, and not the overall hydraulics (since the roughness values as they vary across the channel are left in tact).

Step 3C.3.ii. Average the hydraulics inputs

Averaging the hydraulic parameters can be done in excel or MATLAB, and is done over the cross sections within each reach, at each flow rate. Several flow rates should be considered, spanning a flow maybe half of the bankfull flow rate at the lower end, to the design flow rate [usually the 100-year event flow]. The number of profiles will depend on this range of flows, but should be sufficiently many to form a sediment rating curve (Qs vs. Q) for each reach.

Velocity: Use the **channel velocity** from the HEC-RAS results, with the bank stations set as prescribed in step 3C.3.i.

Depth: If you have time to calculate it, use the **effective depth**, otherwise, use the **Hydraulic Depth C** (for the channel), which is more conveniently provided in HEC-RAS. MATLAB codes for computing the effective depth are available from the Hydraulics unit upon request; formulas are provided in the SAM manual.

Width: If time permits, compute the average **effective width**; otherwise, use the **Channel Area divided by the 'Hydraulic Depth C'** (an output computed by HEC-RAS). The effective width is essentially a depth-weighted width- so that, the effective width for a rectangular channel would simply be the top width, but the effective width for a trapezoidal channel would be smaller than its top width. This is because there is less water under the part of the width laying over the sloped sides as opposed to the horizontal bottom.

Energy Slope: Use the **energy slope** as provided in HEC-RAS.

When done with this process, you should have a table for each reach, giving the average velocity, depth, width and energy slope for each flow rate. An example is provided here:

Table 2-1
Hydraulic Input Data for Computing a Sediment Rating Curve

Reach-Averaged Hydraulic Inputs for Sub-Reach 1, Imaginary Creek

Discharge (cfs)	200	320	500	650	840	970	1100
Velocity (ft/s)	5	6	6.8	7.4	8	8.5	8.8
Depth (ft)	2	2.5	3	3.4	4.9	4.2	4.4
Width (ft)	19	21	22	22.6	23	23.2	23.4
Energy Grade Slope (ft/ft)	0.013	0.012917	0.012483	0.012405	0.012387	0.012428	0.012462
Temperature (deg F)	55	55	55	55	55	55	55

3C.4 Assign sediment gradation curves to each sub-reach

As the title suggests, in this step, examine the collected sediment gradation data for your project, and assign an appropriate sediment gradation curve to each sub-reach. In some cases, there may be sample data collected in each sub-reach (depending on how frequently samples were taken). If this is the case, apply engineering judgment to decide which one to use, or whether to combine the sample data to produce an averaged gradation curve.

3C.5 Compute the Rating Curve for Each Reach

A sediment transport rating curve is the relationship between the flow rate and its associated sediment transport rate, i.e., Qs (tons/day) vs. Q (cfs). Sediment transport rating curves vary along the channel, with changes in the channel geometry, roughness, and sediment properties. For the purposes of the 'annual yield' method, SAM is recommended for computing the rating curves, given the sub-reach-averaged hydraulic inputs developed in step 3C.3.

A rating curve must be computed for each sub-reach, as follows:

Begin By:

- Launch SAMwin (Start → Programs →SAMwin from the Windows start menu)
- Navigate to File → New Project and select the path, folder, and project filename.

For each reach:

- Navigate to Edit → Sediment Transport Input. This brings up the " Sediment Transport Input" window.
- Enter the data averaged in Step 3C.3 into the "Flow Characteristics" table (which looks just like Table 1).
- Push the "Enter Bed Material" button, and enter values for DMAX (the max particle size), Specific Gravity of Sediment, and Particle size/percent finer gradation curve.

- Select one or more sediment transport functions [See 3B.3.i for some guidance].

- Navigate to File → Save Current Data As, and select an appropriate file name (perhaps including the reach name). Open the file you just saved (as explained above, this step ensures that the output file generated when running the code is the same as that you just saved.

- Press the "Solve" button. An extension of the "Sediment Transport Input" window will appear; scroll down to the end to see the rating curves. Rating curves are also at the end of the sediment transport output file, which will have the same name as your data file with the *.so extension.

- Once a rating curve has been developed for each reach, its values should be adjusted for armoring. This is accomplished in the same way as for the "Bankfull Method" by multiplying the sediment transport capacity rate for discharges less than the critical discharge by the fraction of bed which is not armored, i.e., (1-Pa). Procedures for estimating this Pa were discussed in the Data Collection and Data Analysis sections above. This parameter ranges from 0 for a fully armored bed to 1 for a bed which is not armored.

3C.6 Compute Annual Yield for Each Reach

The annual yield is the amount of sediment transported in an average year. Because it takes a range of flows into account, as well as their percentage time of occurrence during a given year, it is a more robust metric for determining the equilibrium slope than the bankfull flow alone.

In order to compute sediment yield, you need the following data:

- A sediment rating curve, i.e., Qs. vs. Q [See Section 3C.5 above]

- A record of flows from a gauging station, adjusted (if necessary) to accommodate for the position of the project reach within the watershed and relative to the gauging location.

The formula for computing annual yield (from a raw flow record) is $\frac{1}{T_{years}} \int_{0}^{T_{end\_of\_record}} Q_S \, dt$

Where T_{years} is the number of years, $T_{end\_of\_record}$ is the total time in the flow record, Q_s is the sediment transport rate (obtained by interpolation of the flow rate into the rating curve), and dt is the incremental time between flows.

1. In excel or MATLAB, interpolate the multi-year flow record into the rating curve to convert it from a flow record into a sediment transport rate record.

2. Integrate the sediment transport record over the time of the period of record, and divide by the number of years- this is an estimate of the annual yield.

SAM is also capable of computing the sediment yield if the flow frequency data are available as discharge vs. percent exceedance information. This is another way to go. Check the SAM manual for more complete details.

3C.7 Determine Equilibrium Slope

As mentioned in the introduction to the Annual Yield Method, the determination of the equilibrium slope is an iterative process. In Method 2, the annual yield is computed for each sub-reach of creek. The annual yield values in the design reach(es) is(are) compared with annual yield values for their surrounding reaches. If there is a balance to within about 20%, then the procedure is complete. Otherwise, the slope(s) in the design reach(es) needs (need) to be adjusted. *In Method 2, this is some work, because it involves adjusting the HEC RAS geometry file in the design reach, running it again, then averaging the HEC-RAS hydraulic input values over each sub-reach.* However, the trade off to the work is that more processes are considered in this method: 1) the flows as they normally vary throughout the year, and 2) variations in channel width within each sub-reach are both taken into consideration (to some extent) with this method. It is also considerably less work than running HEC-6.

This method has one further advantage: at its end, the engineer has a HEC-RAS model which contains the design reach with its equilibrium slope, which can be used to ensure that the design flow is still contained in the channel.

3D. HEC-6: Another Approach

While true equilibrium slope is the result of long-term bed adjustment under the existing flow regime of a creek, the methods 3A-3C estimate the equilibrium slope by simplifying this complex process. These methods do not take into consideration a number of the processes at work in actually forming a channel flow, including (but not limited to):

- Unsteady effects, such as the response of the hydraulics to the changing bedform.
- Spatial variations which occur over length scales smaller than the sub-reach size.
- Formation of an armoring layer or sorting of bed sediments (e.g., for un-formed armoring layers).
- Three dimensional effects, such as the flow around a bend.

HEC-6 is a model which has been used successfully for several projects at SCVWD. HEC-6 is a significant improvement over the methods listed above for determining the equilibrium slope, especially for creeks with frequent changes to geometry and/or sediment properties, because it incorporates unsteady and spatial variations, as well as models the armoring/active bed layers. It is, however, a quasi- 2D model, which is not capable of modeling erosion around bends or other 3D effects.

The procedure for HEC-6 analysis is provided in Chapter 10, Section 10.2.

2.3 SAM Software

SAM is readily available at SCVWD for downloading onto personal computers.

SAMwin User's Manual

The SAMwin user's manual consists of two pdf files located at X:\CPSD\Hydraulics Unit-345\software\SAMwin.

Installation of SAMwin

1. Copy the directory X:\CPSD\Hydraulics Unit-345\software\SAMwin to your C:\ drive.
2. Run setup.exe from the SAMwin subdirectory.
3. Access the program from the Start→ Programs → SAMwin menu (or create an icon).

2.4 Model Validation

The methods presented above for estimating the equilibrium slope should be performed for the existing conditions first before they are used to predict the equilibrium slope for the design reach. Calculations for the existing condition entail evaluating the bankfull sediment transport capacity (or annual yield) for each reach as it exists currently- no iteration is needed. The results should reproduce sediment transport patterns established from historic data. Whether sediment removal data from maintenance records, creek profile comparisons from surveys in different years, or other data are available, the engineer should be able to judge whether the reach of interest is stable, degrading, or aggrading. The existing-condition calculations should be able to reproduce this state.

Modifications to the model are necessary if the existing-condition calculations do *not* match expectations based on past data. In this case, the engineer should re-evaluate the input parameters and sediment transport equations used in the analysis. This re-evaluation commonly occurs in the validation stage because so many of the input parameters are based on discrete data sets and engineering judgment. Re-evaluation of initial input data may include making modifications to the:

- sediment gradation curve assigned to each reach
- upstream and downstream limits of each reach
- armoring factor assigned to each reach
- sediment transport equation used
- energy grade line slope assigned to each reach (for the Bankfull Method)

The modifications made will depend on the particulars of each model and the judgment of the engineer doing the calculation.

It is important to note that these procedures for computing the equilibrium slope are still under development. As they are used in more projects and as more field data become available, these techniques will be updated accordingly.

2.5 Surface Protection Design

Part of the equilibrium slope analysis is to provide a surface protection design to facilitate channel stability. This design includes an examination of the surface armor condition in the existing project reach and determination of sediment and vegetation which should be used to cover the surface as part of the project construction. Whether the channel is being excavated or filled to create the proposed project reach, this is a necessary step of the design.

Design Procedure

1. Determine the design flow.

   Depending on the proposed cross-sectional geometry of the project reach, the design flow may vary. Follow guidelines provided in Section 4.2.2 to determine the design flow for channel surface protection.

2. Determine existing surface armor condition.

   Follow steps of Section 1.4.4 to determine if the surface is armored in the existing project reach, and if so, the armor particle size.

3. Design surface protection.

   If the proposed project does not change the flow or velocity in the project reach, and if the existing reach is armored, the best design is to duplicate what is present in the existing reach. This includes the same armor particle size and percent coverage area.

   If the flow, velocity or depth is changed in the project reach from the existing condition, and the existing channel is armored, determine the critical sediment size that is required to prevent motion under the design flow. Use the critical shear stress method to determine protection armor size.

   a. Compute channel velocity, hydraulic radius and energy slope using HEC-RAS.
   b. Calculate the bottom shear stress by Eq. (7-18).
   c. Determine critical particle size using Figure 8-11b or Eq. (8-20).

   If the existing channel is not armored, duplicate the sediment characteristics for the project reach.

   For all these scenarios, provide vegetation such as willows and/or grass for long term protection and habitat enhancement. Account for effect of vegetation in channel roughness (Figure 7-14) in the HEC-RAS model.

   The design procedures provided above follow the concept that the local flow regime will tend to sort the bed materials and armor the bed surface with a material that can adequately resist motion under the dominant flow condition. Through this sorting process finer bed materials will be transported downstream and the channel experiences degradation. After armor is installed, there will not be significant degradation or aggradation, and channel stability is achieved. If the bed surface material installed in construction matches that of the natural armor material and the overall sediment transport through the reach is balanced, channel stability should be attained.

   In addition to the critical shear stress, permissible velocity sometimes is used to determine initiation of motion. A classical set of permissible velocities reported by Fortier and Scobey [1926] is shown in Table 2-2 for information. Note that there is a difference in the permissible velocity, and shear stress, between clean and sediment-laden streams. This is consistent with what one would intuitively think from the conservation-of-energy point of view.

Note also that the data in Table 2-2 were obtained from experiments conducted in straight channels with water depth less than 3 ft. Since deeper water corresponds to higher bottom shear stress, the permissible velocity data must be corrected for depth effect.

Similar permissible velocity data were published in a Russian magazine in 1936, included in Chow [1959], and later recited in ASCE [1992]. These data are shown in Figures 2-3a for non-cohesive sediments, 2-3b for cohesive sediments, and 2-3c for correction factors to account for the effect of water depth. Note that in Figure 2-3c, at a depth of 3 ft, the correction factor is approximately 1.0, higher water depth corresponds to a correction factor greater than 1.0, and lower water depths less than 1.0. This suggests that the original data were obtained at close to 3 ft of water depth. For other permissible velocity data, different correction factors may apply depending on the original test condition. This is the main reason why critical shear stress, instead of permissible velocity, should be used in determining initiation of motion.

Table 2-2
Maximum Permissible Velocities Recommended by Fortier and Scobey [1926] and Corresponding Shear Stress Converted by USBR for Straight Channels of Small Slope and Water Depth Less Than 3 ft

	Clear Water		**Water Transporting Colloidal Silts**	
Material Type	**Velocity (fps)**	**Shear Stress (lb/ft^2)**	**Velocity (fps)**	**Shear Stress (lb/ft^2)**
Fine sand, colloidal	1.50	0.027	2.5	0.075
Sand loam, noncolloidal	1.75	0.037	2.5	0.075
Silt loam, noncolloidal	2.00	0.048	3.0	0.11
Alluvial silts, noncolloidal	2.00	0.048	3.5	0.15
Ordinary firm loam	2.5	0.075	3.5	0.15
Volcanic ash	2.5	0.075	3.5	0.15
Stiff clay, very colloidal	3.75	0.26	5.0	0.46
Alluvial silts, colloidal	3.75	0.26	5.0	0.46
Shales and harpans	6	0.67	6.0	0.67
Fine gravel	2.50	0.075	5.0	0.32
Graded loam to cobbles when noncolloidal	3.75	0.38	5.0	0.66
Graded silts to cobbles when noncolloidal	4	0.43	5.5	0.80
Coarse gravel, noncolloidal	4	0.30	6.0	0.67
Cobbles and shingles	5.00	0.91	5.5	1.10

Source: ASCE [1992]

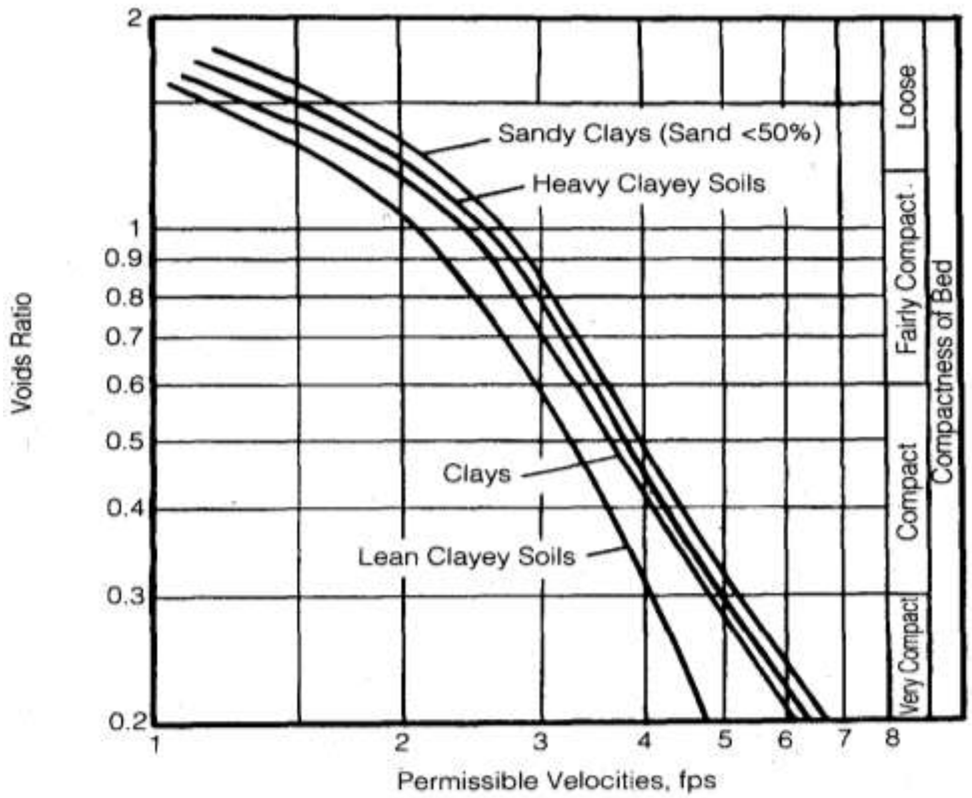

Figure 2-3a. Permissible Velocities for Cohesive Materials [ASCE 1992]

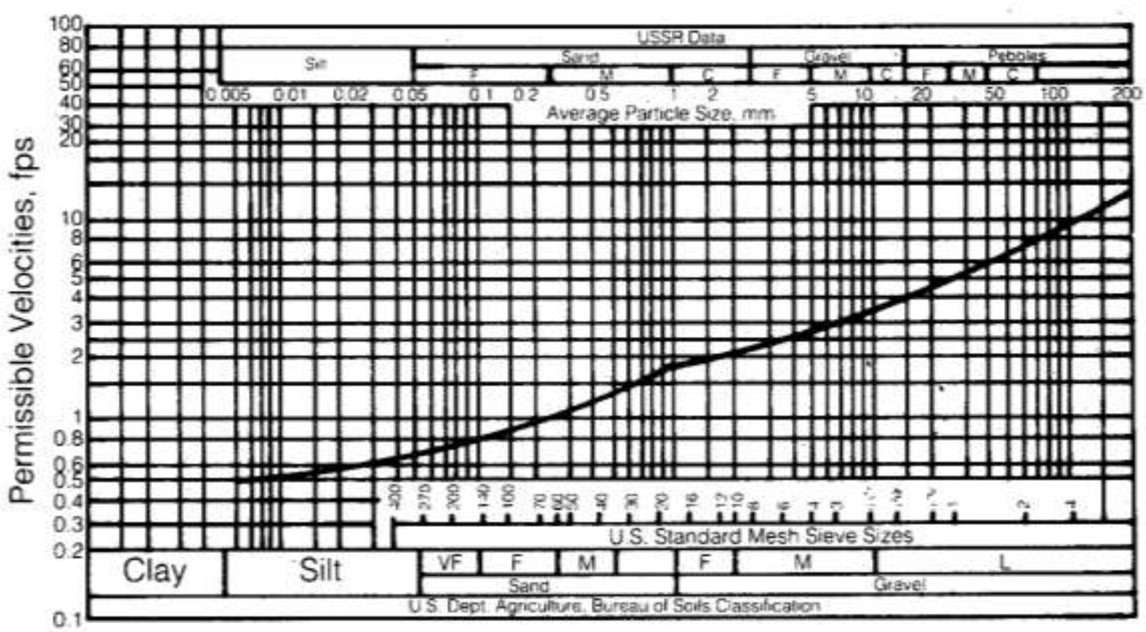

Figure 2-3b. Permissible Velocities for Non-Cohesive Materials [ASCE 1992]

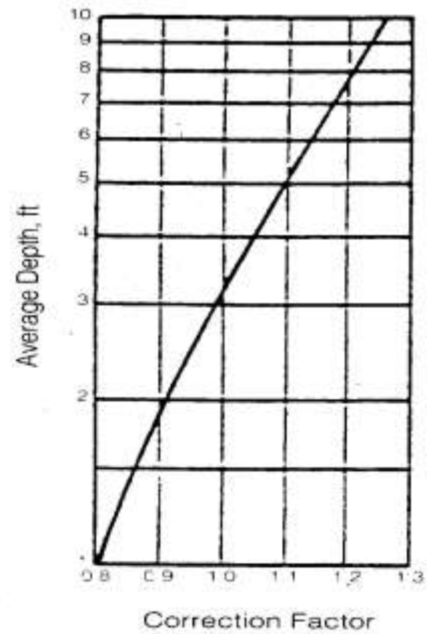

Figure 2-3c. Correction Factor for Depth Effect

REFERENCES

ASCE. 1992. *Design and Construction of Urban Stormwater Management Systems*, ASCE Pub., New York, New York.

Chow, V. T., Open-Channel Hydraulics, McGraw-Hill Book Company, Inc., reissued in 1988, original copyright 1959

Fortier, S. and Scobey, F. 1926. “Permissible Canal Velocities,” *Transactions, American Society of Civil Engineers*, Vol. 89, Paper No. 1588, pp 940-984.

APPENDIX 2A
An Example Application of Equilibrium Slope Procedure

2.A.1 Background Information

Located just downstream of Comer Drive Bridge on Calabazas Creek, Comer Debris Dam was constructed in 1973. The dam is about 13 feet deep and extends a distance of roughly 35 feet along-stream, inclined downstream at an angle of about 20 degrees to the horizontal. The bottom 7 feet of the dam (and more than half of its along-stream distance) was covered with a mixture of rocks and sediment to conform to the existing bed such that only part of the dam was exposed. Between 1973 and 1992, the reach immediately upstream of the dam and beneath Comer Drive Bridge was routinely excavated to serve as a sediment trap for the high sediment loads carried from upstream. During this time, significant erosion was occurring on the downstream face of the dam such that the invert dropped an additional 7 feet and the entire length of the dam became exposed. After 1992, when the District halted its maintenance program, the channel in the vicinity of Comer Debris Dam reached a state of quasi-equilibrium. Although stable, the reach of creek around Comer Drive Bridge has decreased the depth of the opening under the bridge from about 10 feet to about 4 feet (Kennedy/Jenks 2002), which has raised community concerns about bridge overtopping during large storm events. In addition, the Dam is not aesthetically pleasing, provides poor habitat for vegetation, and makes the creek less accessible to the public for recreation as there is a deep, steep drop at the dam face.

In response to these concerns and others, the District has identified three main conceptual alternatives for replacing the Dam. For the purposes of this example, we only list Alternative 3:

Alternative 3: The Dam is partially removed. A stable slope and cross section will be excavated upstream of the partially removed dam. The following analysis will describe the process used to design the cross section shape and slope which form the stable design for Alternative 3.

In the following pages, we will provide a walk through of the steps involved in designing Alternative 3 to be stable. We will follow the steps as they are laid out in the procedures in Chapter 2 for the Annual Yield Method as closely as possible.

2.A.2 Data Collection & Analysis

The first step in an equilibrium slope analysis project is data collection and analysis. For this particular study, the following data have been collected and are described in independent sections below:

Flow data were collected from Wilcox Gage Station on Calabazas Creek and are discussed below in Section 2.A.2.1. This gage station is located significantly far downstream of the project site, so the values had to be modified to better represent the lower flows experienced upstream.

Sediment samples were collected by the project team, and were processed with sieve analysis. The resulting gradation curves are plotted below in Section 2.A.2.2.

Sediment removal data were provided by maintenance and were used to validate the model results.

Bed armor data were collected in the field, including copious notes and pictures of the creek. Since Calabazas Creek contains a pool-riffle geomorphology, the notes included the start- and stop- locations of each pool and riffle. In addition, pictures of the bed showing both the field view and the zoomed-in view of the bed material (with a ruler laid down for scale) were taken along the creek. This data allowed for estimation of the percent cover of each reach by armoring material, presented below in Sections 2.A.2.3 and 2.A.2.4.

A HEC-RAS model for the existing conditions for the reach of creek extending about 200 feet downstream and upstream of the project area was provided by the project team. The model was developed recently (at the time of this writing) in about 2006. A complete description of this model is provided below in Section 2.A.3.1 discussing the division of the creek into sub-reaches.

Field measurements of the bankfull channel dimensions were collected in the reach upstream of Comer Debris Basin to define a geomorphic channel shape for the design reach. These data are presented in the section below on equilibrium slope.

2.A.2.1 Flow Data

Six years of recent historical flow data recorded at the Wilcox gauge station between 1999 and 2004 were used in this analysis. This data had been quality checked, reflects recent hydrology conditions, and was readily available at the time the equilibrium slope calculation was performed. Calabazas Creek is dry most of the year, and the flow records are flashy. Figure 2.A-1 plots the non-zero flows for each water year. The data are plotted as flow rate in cfs vs. time in days as recorded at Wilcox gauge station, where zero flow rates (occurring most of the time) have been removed from the record so that the data are treated as continuous hydrographs, even though the flow data are not contiguous. Since the project reach (i.e., surrounding Comer Debris Basin) is located far upstream of Wilcox gauge station, the flow rates have been reduced accordingly by a factor of about 0.28. This adjustment factor is the ratio between District hydrology predictions of the 10-year flow event magnitude near Comer Debris basin to the value near Wilcox.

As will be shown later in the calibration case, these six years of flow data yield reasonable estimates of the sediment transport capacity in the reach upstream of Comer Debris Basin relative to available sediment removal data there.

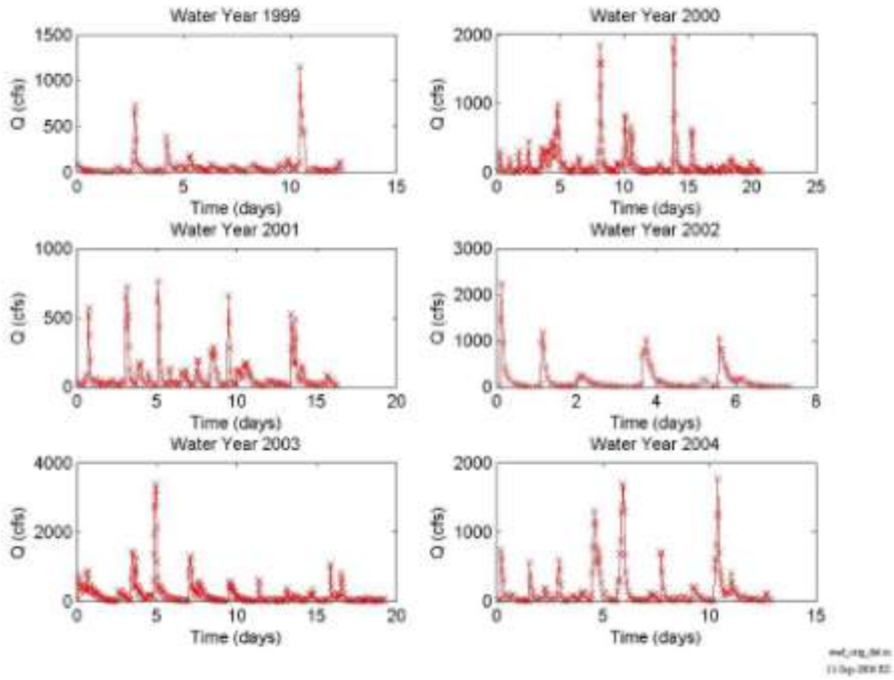

Figure 2.A-1. Flow Data at Wilcox Gauge Station for water years 1999 – 2004. Zero flows have been removed from the record, which is treated as a continuous flow record for the purposes of our sediment transport analysis.

2.A.2.2 Sediment Data

Sediment samples were collected in the vicinity of Comer Debris Dam in November of 2005. The sites were spaced anywhere from 200 to 1200 feet apart. At each sample site, three samples were collected- one from the armoring layer, one from the pond, and one from the subsurface layer beneath the point bar. Six samples between Wardell Road and Padero Road. Bridges were used in the sediment transport analysis. All of the sediment gradataion curves are shown in Figure 2.A-2.

After considerable deliberation, the sediment gradation curve used in the sediment transport calculations was computed as the average of the seventeen bags of sediment collected for the six samples used in the analysis (three samples at each of the six sites except for one, which lacked an armoring layer). Figure 2.A-2 shows the sediment gradation curves sampled for the six sites, plotted together with their curve average. Figure 2.A-3 shows the average for each of the six samples on the same figure along with their average. The sediment gradation curve used in this study – the average of all 17 samples – is the solid blue line with circle markers in Figure 2.A-3.

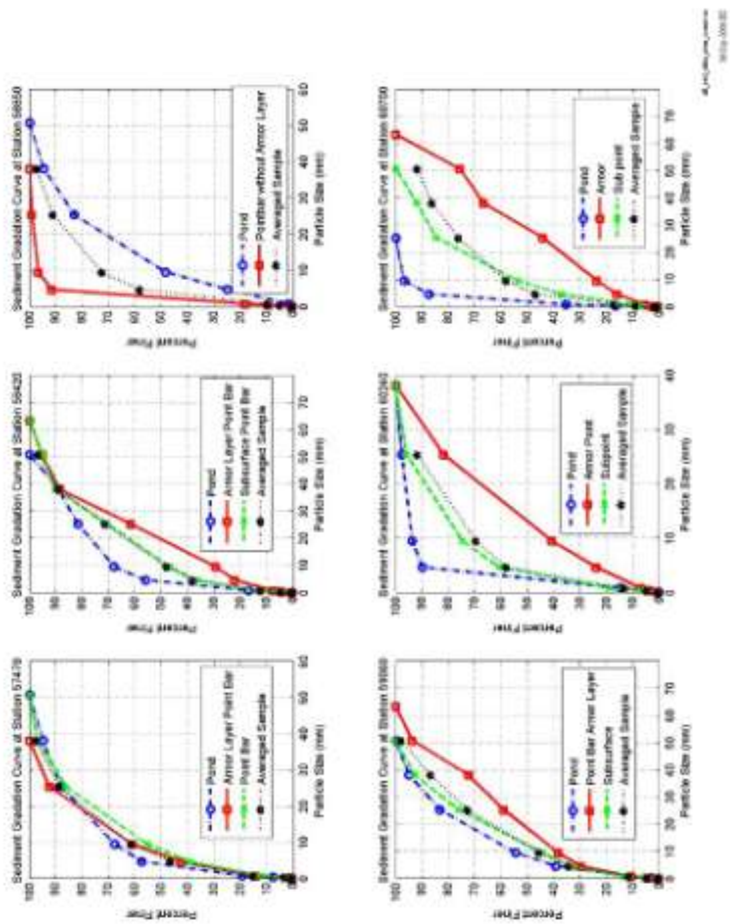

Figure 2.A-2. Sediment samples collected at various stations along Calabazas Creek, in the vicinity of Comer Debris Dam

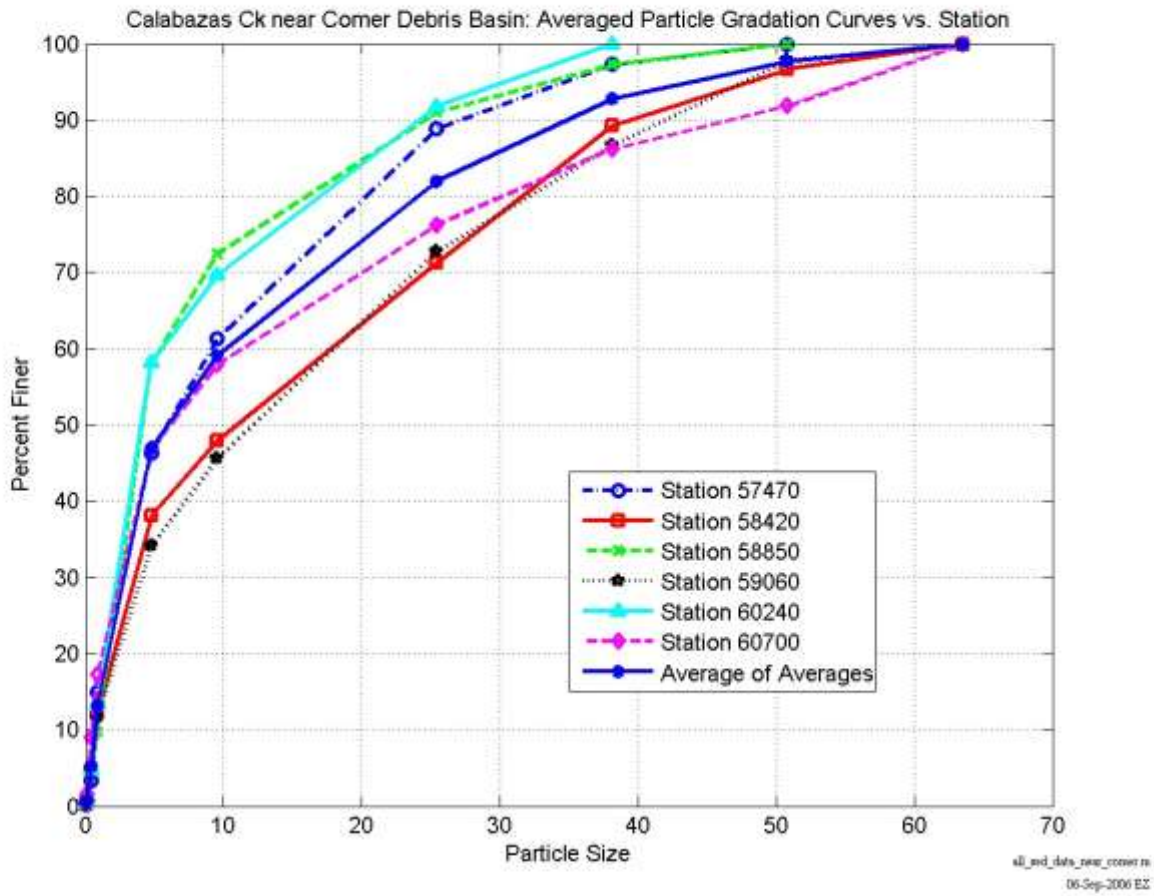

Figure 2.A-3. Averaged sediment profiles at 6 stations near Comer Debris Dam. The "average of averages" (i.e., the average of the 17 samples collected near the project site) profile was used in calculations of sediment transport capacity for each reach of channel

The decision criteria for selecting the sediment gradation curve formed by averaging the 17 samples between Wardell Road and Padero Road for the sediment transport analysis were:

1. There was no discernible pattern in the way that sediment size varied with distance downstream.

2. For each sample site, three samples were collected from regions with different particle characteristics (i.e., one each from the armoring layer, the pond, and the subsurface below the point bar). There is a reasonable chance that these samples were not statistically representative of the material at that site.

3. The sediment gradation curves are used to estimate the total sediment moved over a number of years. For this long time period, use of a mixture of sediment samples from the armoring layer, the pond, and the subsurface region below the point bar seems reasonable.

4. The selected sediment gradation curve, along with the choice of the Toffaleti-MPM method, produced sediment transport capacity values in the Reach upstream of Comer

Drive which matched well with sediment removal data. See the Section 8.1.4 for more information.

2.A.2.3 Bed Armor Estimates

Estimates of percent cover of the bed by an armoring layer have been made by a combination of field observations of percent cover (and percent of channel length covered by riffles) and calculations to determine whether the hydraulics in a given reach are strong enough to wash the surface materials away. The summary of results is presented here in Table 2.A-1. The next section provides details on how this judgment was made for Reach 2, located downstream of Comer Debris Basin.

Table 2.A-1
Bed Armoring Factors for Calabazas Creek, Near Comer Debris Basin

Reach	Fraction of bed covered by armor, via field observations
Reach 1	0.3
Reach 2	0.3
Project Reach	0.3
Reach 3	0.4
Reach 4	0.5

These estimates of percent cover by armor are probably a better predictor of the main patterns in armoring cover than they are of the exact percentages. Fortunately, for the equilibrium slope calculations, knowledge of how the armoring layer coverage varies from reach to reach is more important than knowledge of the true values of percent coverage by armor. This is due to the fact that the equilibrium slope estimate is determined by a comparison between reach-averaged sediment transport rates and not their absolute values.

These factors will be used in the following way- sediment transport rates computed for a reach are adjusted through multiplication by the fraction of the bed which is not armored, i.e., [1- (the armoring factor shown in Table 2.A-1)].

An important point to note here is that the estimation of the effects of armoring are difficult to make for the project reach, since it hasn't been constructed yet. In this case, we assume that the armoring layer in the project reach should be similar to that of the existing creek, since Alternative 3 preserves half of the drop of Comer Debris Dam. The armoring factor is deemed to be smaller than that of the reaches upstream (which is true for the existing conditions) and comparable to that for reaches downstream.

2.A.2.4 Bed Armor Estimate Procedure

Here, we provide details of how the bed armor estimates were made for reach 2. This is less of a procedure and more of a discussion of how one might go about making estimates of percent coverage.

Field Observations

First, we discuss the field observation data. Figures 2.A-4 and -5 below show field views of the creek bed for a pool and for a riffle in Reach 2, respectively. From these pictures we cannot discern details of percent coverage or determine whether the bed is armored, but can say that, if armoring is present, it does not cover the entire bed. The largest particle size class on the bed appears to be about 2 to 3 inches in diameter. Figure 2.A-6 shows a zoomed-in view of the bed on a riffle, where the bed appears to be armored. From looking at this picture, we judge that about 60 percent or so of the particles in it are 2 to 3 inches or larger [your judgment may be different]. However, from field notes and site visits, the coverage of the bed by larger particles isn't uniform over the entire bed. Field notes indicate that the surface sediment distribution shown in Figure 2 A.6 may only cover somewhere between 30 to 60 percent of the bed.

Calculations

In order to refine these visual estimates of percent coverage, it is necessary to determine whether it is possible for the bed to be armored (as we expect). As described in Chapters 8 and 2, the test for determining whether a section of creek is armored is to compute the critical particle size for that section and compare it to the d_{90} particle size of the bed sediments- the bed is armored or capable of becoming armored if $d_c < d_{90}$. A minor complication is that the d_c can vary with flow rate (at a given section). For now, we will confine our calculations to the bankfull flow rate- unless the creek you are working on is significantly incised along the entire reach of interest, this is probably the most significant flow rate for sediment transport purposes.

The next step is to determine whether the bed may be armored in reach 2 by applying this test to locations where sediment samples have been collected. There are two such locations in Reach 2, which spans stations 58500 to 59000 (yellow book standard).

The armored bed test is now applied to the location of Figure 2.A-6 Station 58670, where we have a picture of the bed sediments with a ruler for scale. What we note from the picture is that the bed is covered with some cobbles which are 2 to 3 inches in diameter, or about 50 to 75 mm in diameter. When compared with the d_{90} and d_{95} values (33 mm and 38 mm) from the shovel-collected sample of surface sediments taken 180 feet upstream, it seems that either that sample was missing a fraction of the surface sediments, or the bed is sporadically covered with larger sediments. So, based on this observation, it seems reasonable to use the picture in Figure 2.A-6 to make an estimate of what we think the d_{90} at station 58670 could be and compare it with the dc value for a station near by. Again, we compute dc with HEC-RAS results at the nearest stations to the location of Figure 2.A-6, and this calculation yields dc values of 50 mm, 92 mm and 147 mm at stations 58660 (the nearest station), 58737 and 58617, respectively. If we judge the d_{90} size to be about 2 inches or 50 mm, then we can conclude that the bed at the location of Figure 2.A-6 is armored, although the armoring does not seem to extend far upstream or downstream of this location. In addition to using pictures, the engineer should also perform the armor particle test for all locations where sediment samples were collected. For these calculations, the engineer should confirm that the sediment gradation curves are derived from samples which include the armoring layer sediments.

At this point, we have confirmed that part of the bed in Reach 2 is probably armored, but have already seen that part of it is also not armored. How do we estimate how much of the bed is armored? Well, one way to estimate a cap on the armoring in Reach 2 would be as follows. First, from field observations and pictures, estimate the largest particle size which covers a reasonably significant part of the bed. It is clear that there are larger rocks in Reach 2 than are pictured in Figure 2.A-6, however, from field notes and site visits, we know that they are quite sporadic and that Figure 2.A-6 is a good representative of the maximum armoring size [those large rocks are very sporadic in placement.]. Therefore, we could say that the largest estimate of d_{90} we can come up with for Reach 2 would be about 2 to 3 inches. Second, we calculate the dc value for all cross sections which fall within Reach 2- there are 11 such cross sections, and the dc results vary from 27 mm on the low end to 147 mm on the high end. Third, we ask: what percentage of the length of Reach 2 has dc particle sizes which are smaller than 3 inches? This will yield a cap on the possible armoring, given that 3 inches is a good estimate of the maximum value that d90 could achieve over the entire reach. The answer is about 65 percent. This falls close to our field estimate that between 30 and 60 percent of the bed looks to be covered with an armoring layer.

Lastly, we note the following: the bed in Figure 2.A-6 is not completely covered with sediment 3 inches in diameter or larger. From Figure 2 A.6, make a visual estimate of the percent cover by such particles. This could be done carefully, with a pebble count or probably by blowing up the picture and trying to count the area made up by particles 3 inches or larger. Or, as in this case, a visual estimate can be made- my judgment shows that about 50 percent of the particles in Figure 2.A-6 have 3-inch diameter or larger. Therefore, I will reduce my estimate of 65 percent coverage accordingly to about 30 percent coverage (=.65*.5*100%).

Figure 2.A-4. Picture taken at the beginning of a pool in Reach 2

Figure 2.A-5. Zoomed out picture of a riffle in Reach 2, just below Comer Debris Dam

Figure 2.A-6. Bed sediments in a riffle in Reach 2. Bed appears to have about 80 percent covered by armor (in the riffles) Station 58670

2.A.3 Existing Conditions: Model Validation Case

In this section, we describe one way for validating a sediment transport model. There are other ways, of course, and the validation method will depend largely on the data available for validation.

2.A.3.1 Divide Channel into Reaches

We begin with a description of the length of channel located between Wardell Road Bridge at its downstream end and Padero Road Bridge at its upstream end, which is the extent of the HEC-RAS model used in this analysis. This reach both extends between two control structures and is sufficiently large to characterize the areas downstream and upstream of each alternative. The length of this reach is about 4500 feet long, or about 0.85 miles. Comer Debris Dam is located about halfway through the reach. There are two bridges within this reach- Comer Drive Bridge, located about 200 feet upstream of Comer Debris Basin, and a foot bridge, located about 1100 feet upstream of Comer Drive Bridge.

The slope, channel roughness, and cross section shape vary considerably in the reach extending from Wardell Road Bridge at its downstream end to Padero Road Bridge at its upstream end. For the purposes of simplifying the sediment transport analysis, this reach has been broken up into five sub-reaches with relatively constant slopes, channel shape, and roughness characteristics- three downstream and two upstream of the dam. The reaches are outlined in Figure 2.A-7 and their major characteristics are summarized in Table 2.A-2 below. These sub-reaches, referred to herein as Reaches 0-4, were used in the existing conditions calibration case. The hydraulic inputs from each were averaged and input into SAM for computing the sediment rating curves.

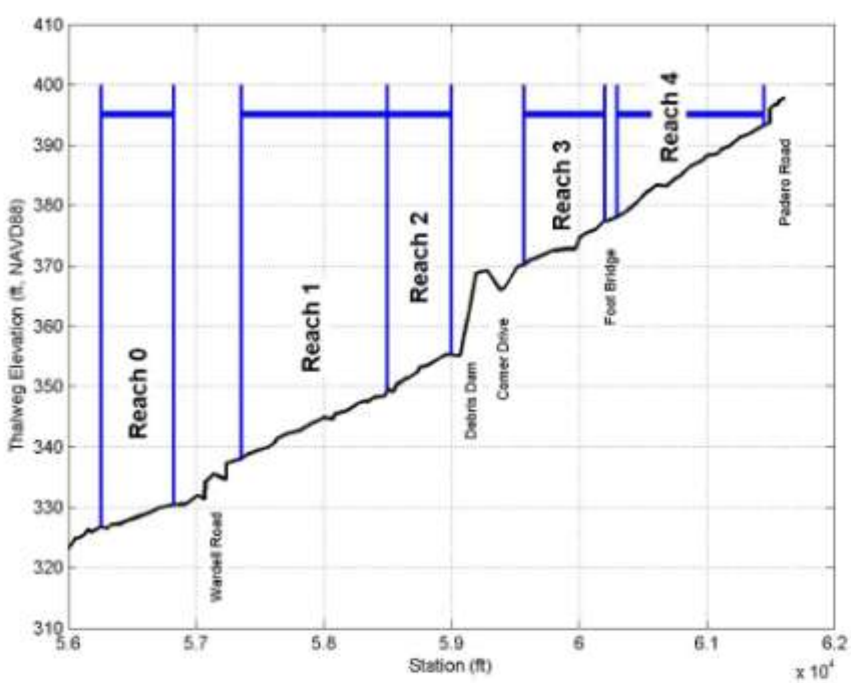

Figure 2.A-7. Definition of reaches 0- 4 relative to the thalweg profile for the existing conditions. Thalweg elevation data were obtained from the 2006 HEC-RAS model

Table 2.A-2
Characterization of Channel Geometry in Reaches 1-4

	Length of Reach (ft)	Average Percent Slope of Reach (ft/ft)*100 %	Description of Channel Cross Section Shape	Roughness of Low Flow Channel
Reach 0	560	0.7 %	Cross sections are uniform, narrower than Reach 1, and deep. 100-year flow is contained	n ~ 0.036
Reach 1	1140	0.9 %	Similar to Reach 2, but less incised	n ~ 0.03 – 0.047
Reach 2	500	1.3 %	Somewhat incised, well vegetated	n ~ 0.04 – 0.047
Reach 3	630	1.1 %	Wide flood plain (relative to Reach 4 upstream)	n ~ 0.034
Reach 4	1150	1.3 %	Deeper and narrower than Reach 3	n ~ 0.034

2.A.3.2 Sediment Transport Function Selection

The SAM package includes 20 different sediment transport equations. Although several were developed for computing sediment transport in gravel bed streams, we tested only the MPM (bedload only) and MPM-Toffaleti (combined bed- and suspended load) methods, because the MPM method produced reasonable results in previous calculations of the sediment transport rate in Calabazas Creek between Miller Avenue and Homestead.

The sediment transport capacity values averaged over the six years of flow data for each reach are given in Table 2.A-3 below. Not surprisingly, the two related methods produce different magnitudes, since the MPM method computes only the bedload whereas the MPM-Toffaleti computes the combined bed- and suspended load. However, they produce similar patterns from reach to reach, since they were given the same hydraulic inputs. Essentially, the transport capacity increases with distance upstream.

Table 2.A-3
Computed Values of Average Annual Sediment Transport Capacity (tons/year) using Different Sediment Transport Equations. Values are rounded to the nearest 5

Reach Identified	Sediment Transport Capacity MPM (1948), tons/year [values in parentheses modified for armoring]	Sediment Transport Capacity MPM-Toffaleti, tons/year (modified for armoring)
Reach 0	1580 (no est. of armor factor)	5055 (no est. of armor factor)
Reach 1	2010 (1410)	5850 (4095)
Reach 2	2540 (1780)	6610 (4630)
Reach 3	2140 (1280)	6115 (3670)
Reach 4	3415 (1710)	9225 (4610)

Apart from conceptual understanding of sediment transport patterns arising from observation of erosion and deposition over the years, the main data available for calibration of the sediment transport capacity model are found in maintenance records of sediment removal data for Comer Debris Basin. Sediment was removed from the basin in 1974, 1975, 1978, 1982, 2983, 1985, 1986, 1990, 1991 and 1992 before maintenance was halted. After each removal, the excavated area was filled back up with sediment from upstream. Thus, the amount of sediment removed annually (expressed as tons/year) at the Debris Basin represents a lower limit on the sediment *transported* annually by the reach upstream of Comer Debris Basin, which, in turn, is a lower limit to the annual sediment transport *capacity*.

Annual sediment removal rates at Comer Debris Basin range in value from about 2200 tons/year in a dry year to a maximum value of 13,700 tons/year in a wet year. The average value over the 10 years of data is about 5600 tons/year (Kennedy/Jenks 2002). The results presented in Table 2.A-3 are analyzed by comparing annual removal rates at Comer Debris Basin with the average annual capacity for Reach 3, located just upstream of Comer Debris Basin. The transport capacity of Reach 3 represents the upstream supply of sediment for the debris basin. Clearly, the average sediment transport capacity computed for Reach 3 with the MPM method of 2140 tons/year is too low, producing a number which is about 40 percent of the historical average sediment removal rate by the District of 5600 tons/year. The MPM-Toffaleti equation yields an average annual transport capacity of 6115 tons/year, which is only 10% larger than the annual removal rate. The results as modified for armoring show lower values; for now, we note that the trend is the same, with the values predicted by the MPM-Toffaleti method yielding results in better agreement with the data.

Kennedy/Jenks 2002 estimated that the sediment supply in Reach 3 should be about 8960 tons/year on average. This estimate is based on a combination of past field measurements of sediment load which showed that sand and gravel constituted about 40 percent of the total load and the assumption that only sand and gravel were deposited in the debris basin. Both assumptions are reasonable, and the value we show here seems to be about 30 percent low.

However, this is not the case. The smallest point on the sediment gradation curve entered into SAM was that 0.3 percent of the sample was finer than 0.07 mm. This resulted in an aggregate sample which, according to SAM, contained only particles which were larger than 0.0625 mm, the cut off for silt. [This has to do with the way SAM parses the entered gradation curve]. For now, we simply note that our estimates of sediment transport capacity include only transported sand and gravel and should, then, be on the order of the sediment removal data estimate of

5600 tons/year, rather than the 8960 tons/year estimated by Kennedy/Jenks. Thus, our calculation of 6115 tons/year of sand and gravel transport capacity, only about 10 percent larger than the removal rate of 5600 tons/year, is very reasonable.

More work could have been done to determine what percentage of silt and clay comes from upstream of the project reach. This is deemed unnecessary, since a reasonable estimate of the sand and gravel transport rate has been made, and silt and clay particles tend to remain suspended in the wash load. Furthermore, the remainder of the analysis attempts to balance the transport rates between the project reach and its neighboring upstream and downstream reaches- so that differences in this value between reaches are more important than magnitudes.

2.A.4 Equilibrium Slope Estimation

2.A.4.1 Geomorphic Cross Section Design

The shape of the channel cross section in the reach extending very roughly 400 feet downstream of Comer Debris basin differs significantly from the reach of channel extending upstream. Immediately downstream of the debris dam, the channel is well vegetated, somewhat incised, and has a relatively steep slope of about 1.3 percent. Immediately upstream of the dam, the channel is characterized by less vegetation, a wider floodplain and a milder slope of about 1 percent. Because of the channel incision downstream (and the locale of the alternatives), the design channel cross section shape was based on channel conditions upstream of Comer Debris Basin, where the channel is natural and stable.

The geomorphic design for the channel cross section shape to be used in the feasible alternatives was based on measurements made in the summer of 2006 of the existing channel dimensions upstream of Comer Dam. Measurements of the bankfull channel – (depth, bottom and top widths) and flood plain – (depth and width) dimensions were made at several locations where a geomorphic, stable channel was identified to have formed. Measurement locations spanned from a distance upstream of Comer Drive Bridge to locations upstream of the Footbridge. In addition, HEC-RAS was run for several flow rates to determine whether one of the flow rates consistently filled the bankfull channel identified in the field. It turned out that the 1.5 year flow event (about 200 cfs) satisfied this criterion reasonably well, which falls within normal range for the frequency of the effective flow rate. After these calculations were performed, District staff calculated the effective discharge for Calabazas Creek to have a recurrence interval of 1.1 years (based on data from the flow gauge far downstream at Wilcox.

The channel dimensions for the bankfull channel are summarized below in Table 2.A-4. The prototypical channel shape is also plotted together with a surveyed cross section located about 500 feet upstream of Comer Bridge to show that it is similar to the existing channel in shape.

Table 2.A-4
Recommended Stable Cross Section Dimensions for Calabazas Creek Near Comer Debris Basin

Bankfull Channel Width (Ft)	12
Bankfull Channel Cross-channel Slope, Horizontal:Vertical (Ft/ Ft)	2.5:1
Bankfull Channel Depth (Ft)	2.5
Flood Plain Slope, Vertical/Horizontal (Ft/Ft)	0.002
Bank Slope, Horizontal:Vertical (Ft/Ft)	2:1

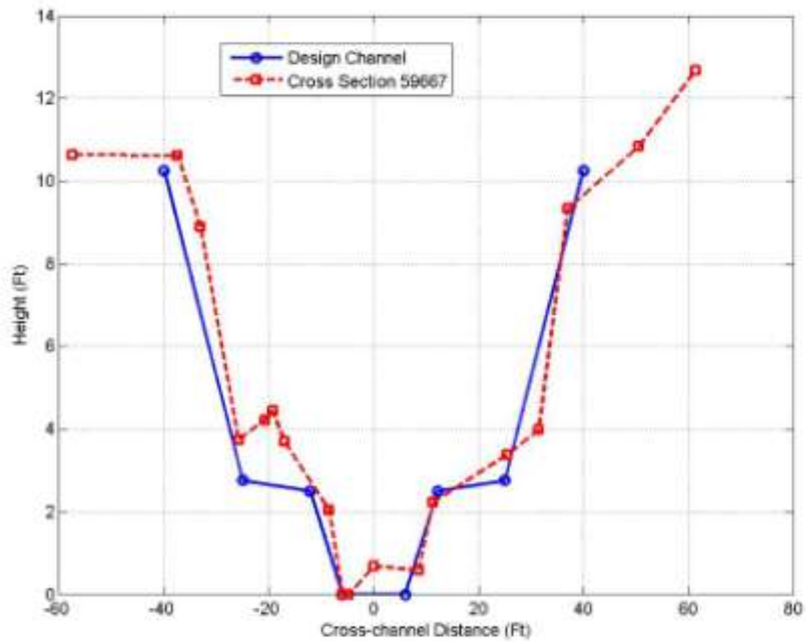

Figure 2.A-8. A channel cross section located about 500 feet upstream of Comer Dam superimposed on the design channel

2.A.4.2 HEC-RAS Model Development

Now that the model has been validated, the next task is to compute the equilibrium slope for Alternative 3. The first step in this process is to develop an initial HEC-RAS model with a geometry configuration which achieves the goals of Alternative 3 (partial dam removal and increased clearance beneath the bridge). Once developed, this geometry will be modified in successive iterations (through modification of the project reach bed slope) until balance of the annual yield is achieved between the project reach and its surrounding upstream and downstream reaches.

The initial HEC-RAS geometry configuration was developed as follows. First, the initial bed profile was developed to achieve partial removal of the dam and increased clearance beneath Comer Bridge. Second, the geomorphic cross section shape was developed to fit into the existing bank limits as well as to have the desired bed profile. This second step involved significant work. At the time, both a Matlab code and Autocad were used to develop the design geometry. However, the new HEC-RAS 4.0 beta version has significantly improved tools for channel modification of this sort (open the geometry editor, then select Tools -> Channel Modification/Design). This same procedure was followed for all successive iterations of the equilibrium slope procedure. Figure 2 A.9 plots the existing bed profile at Comer Dam together with this initial bed profile (labeled Alt 3a) and the two profiles developed for the iterations in the equilibrium slope procedure (labeled Alt 3b and Alt 3b1).

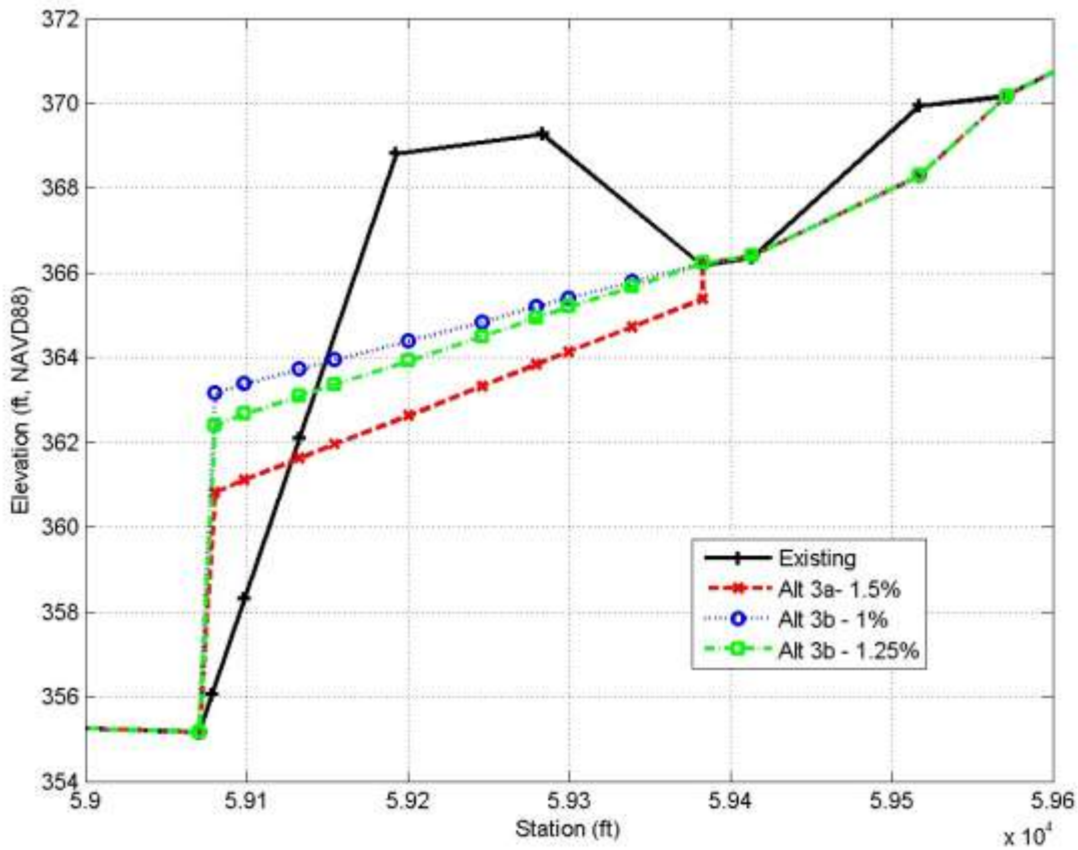

Figure 2.A-9. Bed profiles developed for Alternative 3. The profiles for Alternatives 3a, 3b and 3b1 show the profiles used in each successive iteration of the equilibrium slope procedure

Three geometry configurations were considered for Alternative 3. All versions of Alternative 3 extend from Comer Debris Dam about to a distance of about 225 feet upstream of Comer Drive Bridge, for a total impact distance of about 575 feet. The configurations tested for stability included three cases, called Alternative 3a, Alternative 3b and Alternative 3b1. Alternative 3a has a 1.5 percent slope case with removal of the top 8 feet of the dam (including a drop of 0.85 feet at the downstream end of Comer Drive Bridge). Alternative 3b has a 1 percent case with removal of the top 5.6 feet of the dam (with no drop). Alternative 3b1 has a 1.25 percent case with removal of the top 6.4 feet of the dam (with no drop). All versions of Alternative 3 conform to the existing channel a distance of about 225 feet upstream of Comer Dr. Bridge. The channel slope between the downstream face of the bridge and the conforming point is about 1.7 percent for all three cases.

Construction of alternatives 3a, 3b and 3b1 includes excavating sediment over the distance 225 feet upstream of the bridge to the downstream face of the bridge to form a uniform, 1.7 percent slope. This procedure would provide an additional three feet of clearance (for a total of seven feet of clearance) beneath the bridge. From the downstream face of the bridge, sediment would be further excavated with consistent slopes of 1 percent and 1.25 percent. The 1.5 percent case tested is different and would include an additional 0.85 ft drop at the downstream face of the bridge, downstream of which sediment would be excavated to form a uniform 1.5 percent slope.

2.A.4.3 Equilibrium Slope Calculations

The first step in the equilibrium slope calculations is to divide the channel up into reaches. Since we have already done this for the existing conditions case, we used almost the same reach delineations, modifying the design reach limits only slightly. The reach delineations are shown below as part of Figure 2.A-11.

The second step is to compute the annual yield for each of the reaches.

Step (A) — Run the HEC-RAS model for a variety of flows, and average the hydraulic inputs over each reach. In this case, HEC-RAS was run for flows in cfs of 200, 320, 500, 650 840, 970 and 1100, which represent our estimate of the bankfull, the 2.33-, 5-, 10-, 25-, 50-, and 100-year flow rates, respectively.

***Step (B)* —** Run SAM to compute the sediment transport rating curve (Qs vs. Q) for each reach. As discussed in the Model Validation section, the Toffaleti-MPM sediment transport equation was selected for use in these calculations. The sediment transport rating curves for the reaches are shown in Figure 2.A-10. As is evident, agreement for flows up to about the 5-year flow is excellent, and the sediment transport rates agree less well as the flow rate increases. It is important to get good agreement in sediment transport rates between reaches for the lower flows because they occur most frequently during any given year. Also, it is important to investigate both how sediment rating curves and how annual yield estimates vary from reach to reach because it is possible in some circumstances for the annual yield to balance even if the rating curves for lower flows don't. [Imagine two rating curves which cross each other at, say, the 10-year flow event.]

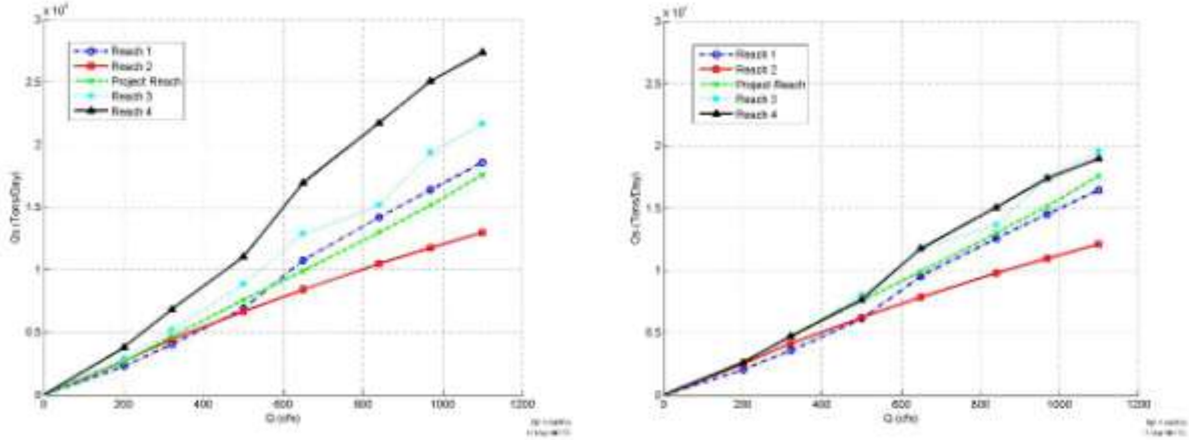

Figure 2.A-10. Sediment transport rating curves developed for each reach for Alternative 3. LEFT: The rating curves before they have been adjusted by the armoring factor. RIGHT: The rating curves for each reach after they have been adjusted for the armoring factors

***Step (C)* —** For each reach, interpolate the 6-year flow record into its rating curve to turn the flow record into a sediment transport record. Then, integrate the sediment transport flow record over the 6-year time period and divide by the total number of years (6). The results of this procedure are shown in Table 2.A-5 below and in Figure 2.A-5.

Table 2.A-5
Average Annual Sediment Transport Capacity for Different Versions of Alternative 3. Values are rounded to the nearest 5.

	Average Annual Sediment Transport Capacity (tons/year): Alternative 3a (1.5% Slope)	**Average Annual Sediment Transport Capacity (tons/year): Alternative 3b (1 % Slope)**	**Average Annual Sediment Transport Capacity (tons/year): Alternative 3b1 (1.25% slope)**
Reach 1	5850 (4095)	5845 (4090)	5845 (4090)
Reach 2	6550 (4655)	6515 (4560)	6515 (4560)
Project Reach for Alternative 3	14310 (10020)	5220 (3655)	6625 (4640)
Reach 3	7320 (4390)	7310	7310 (4385)
Reach 4	9185 (4590)	9565	9565 (4782)
Values in parentheses have been multiplied by the bed armor factor = 1- (the armor cover estimate for that reach, as provided in Table 2.A-1).			

The results presented in the table above and figure below show that the third iteration (Alternative 3b1) of the equilibrium slope process produces acceptable results. The project reach capacity for alternative 3b1 is only about 2 percent larger than that downstream and 9 percent smaller than that upstream. If the armor-adjusted values are used, agreement with the upstream sediment capacity improves to a difference of only 6 percent. By contrast, the project reach capacity for the 1 percent slope is about 20 percent lower than that downstream and 29 percent lower than that upstream. The transport capacity for Alternative 3a is significantly higher than upstream or downstream, because the steep slope induces supercritical flow in the project reach for most flow rates.

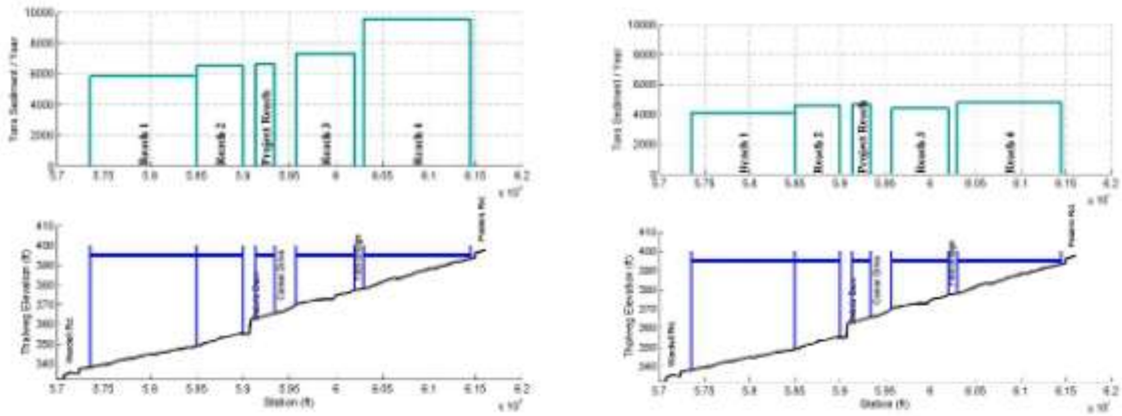

Figure 2.A-11. Average annual sediment transport capacity (computed with 6 years of flow data from 1999-2004) for Alternative 3 (version b1). LEFT: Results before adjustment for armoring. RIGHT: Results after armoring adjustment has been made.

The sediment transport of Reach 4 looks to be significantly higher than that of all reaches downstream before the armoring has been taken into account. After the bed armor estimates have been applied, however, the sediment transport in Reach 4 is reduced significantly relative to that downstream. This is consistent with field observations that more of the bed is covered with armoring in Reach 4 (i.e., unavailable to be moved by most of the flows experienced by Calabazas Creek within an average year).

2.A.4. Summary

This document was prepared with the intent of providing a complete example of how to perform a sediment transport analysis. Rather than summarize the whole procedure here, we make the following statement.

If ever a "garbage in, garbage out" argument is to be made, it applies to sediment transport calculations of this sort, which are based on simple, empirical formulas derived from experiments and field measurements which may or may not be similar to your situation in the field. Always collect and analyze your field data carefully. Always make sure that your field data are at least consistent with the results of your calculations. Do what you can to validate your 'model' of sediment transport in your creek. Lastly, run your results and analysis past another or multiple engineers. So many judgments are made in this process that everyone will come up with a different judgment, and those different judgments can be valuable in your final sediment transport analysis.

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