Assessment of the Effectiveness of a Constructed Compound Channel River Restoration Project on an Incised Stream

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Abstract: Compound channels are often constructed in restoration projects on rivers and streams that have been channelized or are deeply incised. This design allows for flow over a wider cross-sectional area during high flows and is expected to reduce both flow velocities and bed-shear stresses in the channel during high flows. Using a compound channel restoration project on Tassajara Creek as a case study, the effectiveness of a constructed compound channel in reducing channel velocities and bed-shear stresses during high flow events was tested in two ways. First, since this is an a posteriori analysis, postproject surveys and assessments of the project are used to demonstrate the geomorphic and ecological benefits of the constructed compound channel for reducing further channel incision, improving channel stability, and enhancing native riparian vegetation, while still providing conveyance capacity for design flood flows. Second, the effectiveness of a constructed compound channel in reducing channel velocities and bed-shear stresses during high flow events is evaluated using both the one-dimensional (1D) model, HEC-RAS, and the three-dimensional (3D) numerical model, UnTRIM. This analysis demonstrates that the 1D analysis does not accurately portray the benefits of the compound channel, and is therefore not a suitable tool for evaluating the effectiveness of compound channel designs. These results demonstrate the advantages of using a 3D model and make a strong case for the implementation of more detailed hydrodynamic modeling in evaluating the suitability of restoration alternatives to improve the planning and design of river restoration projects.

Introduction

Incised channels are characterized by a lowering of the stream bed due to an increase in erosion, such that the stream is no longer hydraulically connected to its previous floodplain (Fischenich and Morrow 2000). Channel incision can result from

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steepening of the stream gradient through channelization, increased flood peaks, decreased sediment load, or from decreased erosional resistance (Schumm et al. 1984). Compound channels, which are often constructed in restoration projects on streams that are deeply incised, incorporate a constructed floodplain within the incised channel margin and thereby reconnect the channel to a new floodplain. This design allows for flow over a wider cross-sectional area during high flows and is intended to reduce flow velocities and bed-shear stresses in the channel during high flow events. This approach was used on a stream restoration project on Tassajara Creek, located in Alameda County, California.

Tassajara Creek flows from the southeastern slopes of Mount Diablo and drains approximately 60 km^2 at the compound channel project reach in northern Alameda County, just east of downtown Dublin, California. Climate in the Tassajara Creek watershed is Mediterranean, with mean annual precipitation of 43 cm at the project site. The project reach is in a moderately high energy transport zone, although local areas of deposition along the creek are not uncommon. Reviews of historical maps and aerial photography indicated that the project reach of Tassajara Creek has remained in essentially the same location and planform orientation for at least the past 150 years. As a result of historic channel straightening and grazing, the channel was deeply incised, and repeat surveys of the long profile demonstrated that it was still actively incising during periods of high flows, with 0.3 m
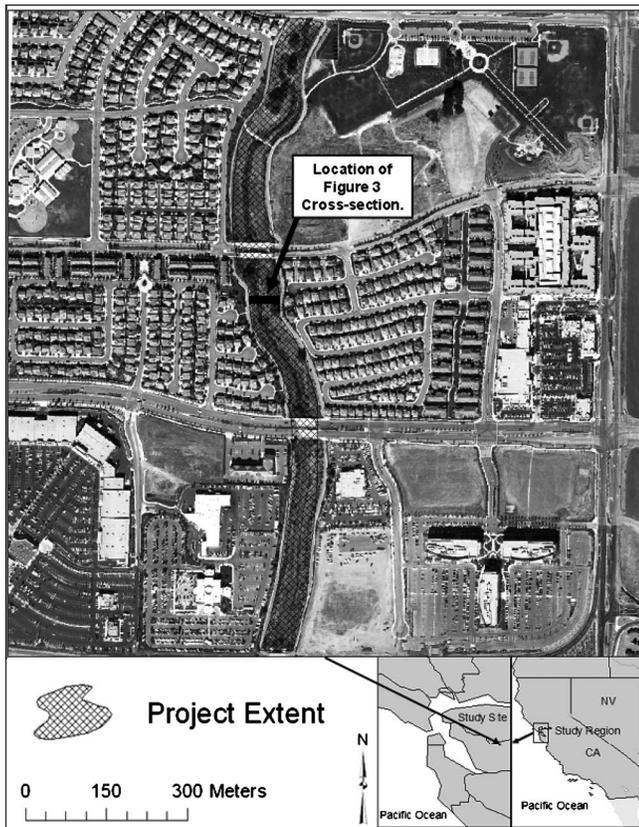
Fig. 1. General location, project extent (hatched area), and surrounding development for the Tassajara Creek restoration project. Flow is from north (top) to south (bottom). (Aerial image courtesy of U.S. Geological Survey)

Fig. 2. (a) Prerestoration incised channel; (b) postrestoration compound channel immediately following construction in Tassajara Creek restoration project

the same cross section from the restoration design after the banks were graded to create a compound channel, at the location indicated on Fig. 1. The objective of this approach is to create a two-stage compound channel in which low flows are contained within the main channel, and larger flows are spread onto the reconstructed floodplain. In the reach containing this representative cross section, the existing low-flow channel was left mostly intact (except where it was relocated to protect mature oak trees) and the floodplain surface was excavated to the 5-year flow (34 m^3/s) water-surface elevation in the low-flow channel (E. Boscacci, BKF Inc., Walnut Creek, California, personal communication, May 2006). In the downstream reach of the project, the entire channel was reconstructed with a low-flow channel designed to convey the 2-year flow ($14–18$ m^3/s) before overtopping onto the floodplain surface set within a leveed flood corridor designed to convey the 100-year flow with 1 ft of freeboard.

Many stream restoration projects, including compound channel projects, have failed because of channel instability or attempts to create habitat features which were not compatible with the prevailing channel processes (Kondolf 1995). Accurate calculation of the maximum bed-shear stress and the shear-stress distri-

of incision measured from 1996 to 1997 (Kondolf and Matthews 1997).

As part of the development plan for the surrounding area, a restoration project was implemented to restore about one mile of the channel upstream from Interstate-580. The broad objectives of this project included creation of a "natural" open channel capable of conveying expected 100-year storm flows and the natural sediment loads which are expected to change over time in response to natural processes of erosion and deposition. Project goals also included enhanced channel crossings for the public, maintenance access, protection of existing native riparian vegetation (especially mature oak trees), and enhancement of riparian vegetation by removing exotic species and replanting native species. The overarching project goals were channel stabilization to reduce further incision, improved flood control, and improved community access. Fig. 1 shows the location, project extent, and surrounding development for the Tassajara Creek restoration project. The restoration plan included the construction of a two-stage compound channel, restoring meanders in the upstream reach of the project, and extensive revegetation of the constructed floodplain (S. Cook, Alameda County, personal communication, 1999).

Fig. 2 shows the incised prerestoration condition in the upper reach and the postrestoration condition on the lower reach of the Tassajara Creek restoration project. As seen in this figure, the prerestoration channel was deeply incised and was largely disconnected from its historical floodplain even for 100-year flows, while the postrestoration channel consists of a low-flow channel connected to a constructed floodplain terrace at a lower elevation. Fig. 3 shows a typical cross section of the incised condition with
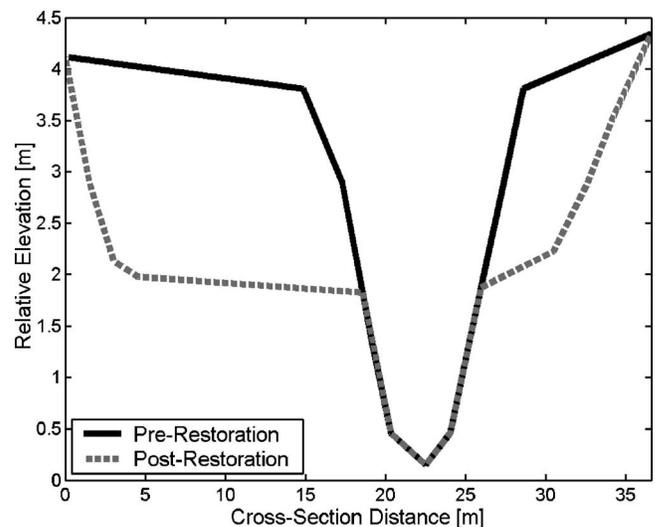

Fig. 3. Prerestoration and postrestoration cross-section geometry used in HEC-RAS and UnTRIM for prismatic channel. The location of this cross section in the restoration project reach is shown on Fig. 1.

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bution in the channel is essential to obtain a reliable estimation of channel stability for restoration design. However, rivers are typically modeled using one-dimensional (1D) numerical models, e.g., HEC-RAS (U.S. Army Corps of Engineers 2002), which provide only cross-sectional average estimates of velocity and shear stress. In order to understand the limitations of using average values computed using the modeling tools commonly used to design restoration projects, this study evaluates the effectiveness of the HEC-RAS model for design of a compound channel, based on the application of HEC-RAS to a restoration project on Tassajara Creek.

Postproject surveys of the Tassajara Creek restoration project were used to assess the geomorphic and ecological benefits of the constructed compound channel for reducing further channel incision, improving channel stability, and enhancing native aquatic, riparian, and floodplain vegetation and associated habitat. These surveys provide a quantitative measure of the effectiveness of the constructed compound channel at arresting further channel incision. HEC-RAS was then applied to model the prerestoration, restoration design, and postrestoration conditions to evaluate the predicted reductions in velocity and shear stress obtained through the use of a 1D model. Last, the ability of the 1D model to quantify flow and shear-stress modifications was assessed by comparing the HEC-RAS results to those of a three-dimensional (3D) hydrodynamic model, UnTRIM, for an idealized channel configuration. Through this approach, this study assesses the effectiveness of the restoration project at achieving its stated ecological, geomorphic, and flood conveyance objectives, evaluates the effectiveness of the compound channel design in terms of its ability to reduce flow velocities and bed-shear stresses in the channel under high flow conditions, and analyzes the suitability of a commonly used 1D model for the prediction of bed-shear stresses in a compound channel.

Methods

Postproject Surveys and Assessment

A series of postproject appraisals consisting of repeated longitudinal profile surveys and transect surveys at eight permanent monitoring sections were conducted as part of an informal monitoring program between 2001 and 2005 (Hudzik and Truitt 2001; Lave 2002; Krofta and Novotney 2003; Tompkins 2006). Through comparison of these surveys Tompkins (2006) documented channel change following construction of the project at each of these cross sections and provided a systematic evaluation of how well the project met the specific geomorphic, ecological, and flood conveyance objectives of the project. As one of the overarching goals of the Tassajara Creek project was to create a more natural, dynamic stream corridor, the systematic evaluation was focused on identifying and quantifying changes in key components of stream corridor habitat such as riparian vegetation, channel bed forms, and floodplain topography. For the current study, these postproject surveys provide an independent evaluation of the effectiveness of the constructed compound channel in arresting the channel incision, demonstrate the significance of floodplain vegetation for meeting the geomorphic and ecological goals of the project, and suggest lessons learned which can be applied to the design of future restoration projects.

Modeling Approach

1D models used to predict flow in channels are typically based on either the Manning formula or the Saint-Venant equations. These models represent flow in a channel by averaging the energy or momentum equations over a channel cross section, and solve for the cross-sectional average velocity and discharge at each cross section. In this study, 1D steady flow calculations were made using HEC-RAS (U.S. Army Corps of Engineers 2002). This program uses the step-backwater approach to compute water-surface elevations and hydraulic parameters (e.g., velocity, depth, and shear stress) based on the cross-sectional geometry of the channel. Water surface profiles are computed from one cross section to the next by solving the energy equation given by (U.S. Army Corps of Engineers 2002)

$$Y_2 + Z_2 + \frac{\alpha_2 V_2^2}{2g} = Y_1 + Z_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \tag{1}$$

where the subscripts refer to the cross section number; Y=depth of water at the cross section; Z=elevation of the main channel invert; V=average velocity; α=velocity weighting coefficient; g=gravitational acceleration; and h_e=energy head loss between Sections 1 and 2. The energy head loss is given by (U.S. Army Corps of Engineers 2002)

$$h_e = L\bar{S}_f + C \left| \frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g} \right| \tag{2}$$

where L=discharge-weighted reach length; $\bar{S}_f$=representative friction slope between two sections; and C=expansion or contraction loss coefficient. The unknown water surface at a cross section is determined by the iterative solution of Eqs. (1) and (2). HEC-RAS is capable of modeling subcritical, supercritical, and mixed flow regime water-surface profiles and includes capabilities to model the effects of various obstructions—such as bridges, culverts, weirs, and structures (U.S. Army Corps of Engineers 2002). Cross sections can be divided into channel and floodplain components, with separate roughness values and reach lengths applied to each subdivision.

The 3D simulations were made using the 3D nonhydrostatic hydrodynamic model for free-surface flows on unstructured grids, UnTRIM, described in Casulli and Zanolli (2002). The UnTRIM model solves the full 3D momentum equations for an incompressible fluid under a free surface. Formally, these are the *unsteady* Reynolds-averaged Navier-Stokes equations, where the time averaging is carried out over a time that is large compared to the time scale of the flow turbulence (see Sec. 1.4 of Sagaut 2002), leaving an unsteady "mean" flow equation set given by

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv = -\frac{\partial p}{\partial x} + \nu^h \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right)$$
$$+ \frac{\partial}{\partial z}\left(\nu^v \frac{\partial u}{\partial z} \right)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu = -\frac{\partial p}{\partial y} + \nu^h \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right)$$
$$+ \frac{\partial}{\partial z}\left(\nu^v \frac{\partial v}{\partial z} \right)$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{\partial p}{\partial z} + \nu^h\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right) + \frac{\partial}{\partial z}\left(\nu^v\frac{\partial w}{\partial z}\right)$$
$$- g \tag{3}$$

where x and y=spatial coordinates in the horizontal plan; z =spatial coordinate in the vertical direction; t=time; $u(x,y,z,t)$ and $v(x,y,z,t)$=velocity components in the horizontal x- and y-directions, respectively; $w(x,y,z,t)$=velocity component in the vertical z-direction; $p(x,y,z,t)$=normalized pressure defined as the pressure divided by a constant reference density; f=Coriolis parameter; g=gravitational acceleration; and ν^h and ν^v =coefficients of horizontal and vertical eddy viscosity, respectively (Casulli and Zanolli 2002). Conservation of mass is expressed by the continuity equation for incompressible fluids

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{4}$$

The free-surface equation is obtained by integrating the continuity equation over depth and using a kinematic condition at the free surface; this yields (Casulli and Zanolli 2002)

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}\left[\int_{-h}^{\eta} u\,dz\right] + \frac{\partial}{\partial y}\left[\int_{-h}^{\eta} v\,dz\right] = 0 \tag{5}$$

where $h(x,y)$=prescribed bathymetry measured downward from the reference elevation and $\eta(x,y,t)$=free-surface elevation measured upward from the reference elevation. Thus, the total water depth is given by $H(x,y,t)=h(x,y)+\eta(x,y,t)$. Discretization of the above equations and model boundary conditions are presented in detail by Casulli and Zanolli (2002) and is not reproduced here. All details and numerical properties of this 3D model are well documented (Casulli and Zanolli 2002, 2005). The UnTRIM model was modified to include an inflow boundary condition for volume and momentum, a radiation outflow boundary condition, and a modified formulation of bed drag and as described in MacWilliams (2004). It is well known that the vertical eddy viscosity has a nearly parabolic distribution with depth in an open channel flow, such as those simulated in this study, so parabolic vertical eddy viscosity model was applied following the approach of Celik and Rodi (1988). No horizontal eddy viscosity was specified. Additional sensitivity simulations using a two-equation vertical turbulence model comprised of a turbulent kinetic energy equation and a generic length-scale equation, produced nearly identical shear-stress predictions on the channel geometries modeled in this study to the simulations made using the parabolic eddy viscosity.

The UnTRIM model used in this study has been validated by MacWilliams (2004) using velocity measurements made in a laboratory flume by Nezu and Rodi (1986). In addition, the model has also been validated using near-bed and midwater column velocity measurements in a pool-riffle sequence by (MacWilliams et al. 2006). These results demonstrate that the UnTRIM model is suitable to be applied to rivers at a variety of scales ranging from the scale of individual pool-riffle units (MacWilliams et al. 2006) to large-scale floodplain flows (MacWilliams et al. 2004), and has also been applied extensively in large-scale estuarine systems. In this study, the UnTRIM simulations were run until they achieved statistical steady state so that they are comparable to those of HES-RAS.

Surveyed Channel

HEC-RAS was used to model three different channel configurations: prerestoration, restoration design, and postrestoration. Brian Kangas Foulk (BKF) developed the restoration design and their HEC-RAS models were obtained through the authorization of Alameda County, Calif. A survey was conducted on the upper reach following project construction (MacWilliams and Harrison 1999).

The prerestoration model is based on the prerestoration survey and HEC-RAS model developed by BKF. In the prerestoration model, the stream was deeply incised and the majority of the cross sections were not subdivided into channel and overbank areas; however, at a small number of cross sections, the channel was still connected to the floodplain for the 100-year flow event. We subdivided the cross sections in the prerestoration model to account for the natural floodplain that still existed for extremely high flows by adding bank stations at the edge of the channel for the cross sections in the study reach. This modification did not noticeably change the overall flow profile, but provided a more accurate comparison between channel parameters in the prerestoration and postrestoration models for the 100-year flow.

The restoration design HEC-RAS model used is essentially identical to the restoration design model obtained from BKF. The modeled reach in the restoration design extended above and below the restoration project. The postrestoration model was developed for our analysis based on the postconstruction survey (MacWilliams and Harrison 1999). For the postrestoration HEC-RAS model, the water-surface elevations for the downstream boundary conditions were obtained from a coinciding cross section in the restoration design model which extended further downstream to ensure similar flow characteristics between the postrestoration and restoration design models. In the restoration design and postrestoration HEC-RAS models, each cross section was subdivided into a main channel, a left overbank, and a right overbank.

The channel roughness was specified using Manning's n. Channel roughness was estimated by BKF to be 0.03 for the prerestoration channel and 0.04 for the restoration design channel. The higher channel roughness used in the channel for the restoration design relative to the prerestoration channel reflects the expected increase in roughness due to the establishment of riparian vegetation within the channel. In the restoration design model, a value of 0.06 was applied to the overbank areas to account for the effects of vegetation which will be established on the floodplain as a result of extensive planting of willows on the constructed floodplain. The same roughness values used in the restoration design model were applied in the postrestoration model in this study. Subsequent to the project design used in this study, the Manning's roughness coefficient was increased to 0.12 for both the left and right overbanks in the final project model used for permitting to demonstrate that the project would meet the freeboard requirements even with extensive floodplain vegetation.

Our analysis focuses only on the flow in the upper reach of the project, even though the prerestoration and restoration design models evaluated the entire project. Only model results from the cross sections within the reaches which coincide with the reach surveyed for the postrestoration model were extracted for comparison. For each of the three models, HEC-RAS was used to compute water-surface profiles for 2-, 25-, and 100-year recurrence-interval flows. The corresponding flow events were estimated by BKF to be 18.4, 58.0, and 121.8 m^3/s, respectively.

These flows were selected because they represent the range of potential flows that the reach will experience, and range from frequent return-interval flows to large floods.

Prismatic Channel

The performance HEC-RAS in assessing the expected reduction of channel shear stress as a result of the construction of the compound channel on the project reach identified some major shortcomings in the application of a 1D model to compound channels. In order to isolate these shortcomings, and to provide a best-case scenario for the application of a 1D model to compound channel flow calculations, straight-prismatic incised and compound channels were developed based on the prerestoration and postrestoration cross sections shown in Fig. 3. As seen in Fig. 1, the reach from which this cross section was selected is relatively straight, and a review of the upstream and downstream cross sections indicates consistently uniform geometry throughout this reach, in terms of floodplain and channel widths and depths. Thus, a prismatic channel is a reasonable representation of this reach of the restoration project, while providing some significant benefits in simplifying the analysis of the 1D model shortcomings. The use of straight-prismatic channels in this comparison eliminates any component of flow complexity resulting from channel curvature or irregular topography, as well as eliminating the flow expansion and contraction term from Eq. (2) such that all energy loss in the channel is associated with the bed drag. To further simplify the analysis, a uniform Manning's roughness of 0.03 is used in both the incised and compound channels in both the channel and overbank areas to remove any influence of spatially variable roughness on the assessment of the 1D model. Additional simulations were made using Manning's roughness values of 0.06 and 0.12 in the overbank areas to evaluate the effect of using higher roughness values on the floodplain. Through these simplifying assumptions, this approach presents the best-case scenario for the application of a 1D model to compound channel flow.

The modeled channel reach for the prismatic prerestoration incised and postrestoration compound channels is 61 m long, and both channels were designed to have a uniform slope of 0.003, based on the average slope of the reach from which the cross sections shown in Fig. 3 were selected. The HEC-RAS model consists of 20 cross sections at 3.05-m intervals. The prerestoration channel was modeled as a single channel, while the postrestoration case was subdivided into a main channel, right overbank, and left overbank. The 3D model grids used a uniform horizontal grid consisting of square grid cells with a side length of 0.61 m. The incised channel grid consists of 3,000 horizontal grid cells and 28 vertical layers with a vertical grid resolution of 0.15 m. The compound channel grid consists of 6,000 cells with 28 vertical layers with a vertical grid resolution of 0.15 m. The compound channel grid has twice as many horizontal grid cells as the incised channel grid because the compound channel grid is twice as wide as the incised channel grid.

In order to facilitate comparison between the models, a uniform flow was simulated on both channels by setting the downstream water-surface elevations to be the normal depths. The boundary conditions for both HEC-RAS and UnTRIM were identical, and consisted of a specified elevation at the downstream end of the domain and a specified inflow rate at the upstream end of the domain. On both the incised and compound prismatic channels the 58 m^3/s flow rate, corresponding to a 25-year recurrence-interval flow on Tassajara Creek, was simulated using the 1D HEC-RAS, and the 3D UnTRIM model. For the 1D
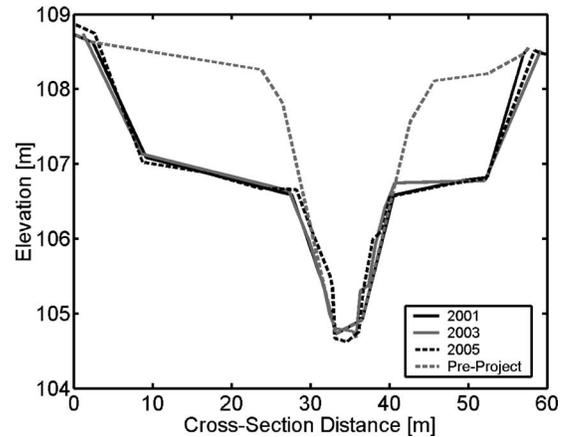

Fig. 4. Tassajara Creek cross section (F-F' in previous studies) looking downstream. Preproject topography is approximate. Data for 2005 from Tompkins (2006). Data prior to 2005 from Kondolf and Matthews (1997), Hudzik and Truitt (2001), and Krofta and Novotney (2003).

model, Manning's n was 0.03 for both the incised and compound channel simulations and was applied in both the channel and overbank areas. For the 3D model, the appropriate bed roughness was determined by calibrating the water surface in each of the channels to match the water-surface slope from the 1D model, with a uniform roughness applied over the domain. This ensured that identical flows were being compared between the 1D and 3D simulations and that the total energy losses due to bed friction for both the 1D and 3D simulations would be nearly identical.

Results

Postproject Surveys and Assessment

Tompkins (2006) surveyed a longitudinal profile of the low-flow channel bed and six permanent monitoring cross sections, mapped facies, vegetation, and aquatic habitats in the low-flow channel, and collected and reviewed historical aerial photography and relevant hydrology data for the site. He found that the most significant change to the low-flow channel profile was that the deep incision which was evident prior to the project had been arrested and had remained relatively stable through 2006. Based on annual surveys, the low-flow channel thalweg profile showed significant interannual variability above and below the average slope shown, suggesting that channel bed forms had become more dynamic, shifting and changing over time in response to changes in sediment supply, hydrology, and succession of vegetation.

The low-flow channel alternates between pools and narrow runs with silt and clay bed sediments. Aquatic habitat varies vertically between shallow riffles and deeper runs and pools, most with significant adjacent vegetative cover. However, aquatic habitat does not vary laterally within the channel in most locations. Cross section comparisons support the results of the long profile comparisons, with minor changes between 2001 and 2006. Fig. 4 shows an example cross section surveyed slightly downstream of the location of the cross section shown in Fig. 3. Over the period from 2001 to 2006, this cross section was extremely stable laterally and vertically, with less than 15 cm of incision in the channel. Subsequent monitoring surveys in 2006 and 2007 following a 20-year recurrence-interval discharge of 42.5 m^3/s (Chan and

Fig. 5. View of Tassajara Creek restoration project in May 2008, nine years after project construction

Heard 2006; Butler and Nolan 2007) found that the channel is still dynamic, with no long-term trend of continued channel incision. These postproject surveys demonstrate that the compound channel design used on Tassajara Creek was successful at arresting channel incision following project construction.

Channel cross section surveys also showed significant changes in floodplain topography from preproject (i.e., disconnected floodplain) to 2005 (i.e., connected floodplain with microtopography from local scour and deposition). Tompkins (2006) measured up to 24 cm of floodplain sedimentation from high flows in 2005, and documented new vegetation colonizing freshly deposited surfaces. Vegetation has interacted with sediment and other debris from high flows to create relatively complex conditions on floodplain surfaces between 2001 and 2006, as well as multiple alternate high flow paths across the floodplain.

A comparison of aerial photographs of Tassajara Creek from 1993 (preproject) and 2004 (postproject) by Tompkins (2006) identified approximately $16,600$ m^2 of new continuous stands of riparian and floodplain woody vegetation in 2004 (5 years after project completion) compared to preproject conditions, when the channel was incised and relatively barren of woody vegetation. A field reconnaissance in May 2008 (Fig. 5), approximately 9 years after project construction, found a significant increase in floodplain vegetation relative to the 2004 aerial photographs. Willows and other types of vegetation have established on the floodplain and within the low-flow channel, and evidence of wildlife utilization of the riparian zone is abundant. Systematic reoccupation of 2001 vegetation transects in fall 2008 showed some loss of species on transects, but overall successful establishment of vegetation, including volunteer plants of native species (Trinh and Percelay 2008).

Table 1 provides a summary of postproject appraisal findings for the Tassajara Creek restoration project relative to the specific geomorphic, ecological, and flood conveyance objectives of the project and identifies some lessons learned that can be applied to improve the design and modeling of future river restoration projects which employ a compound channel design on an incised stream. Tompkins' (2006) most significant finding with respect to compound channel restoration at Tassajara Creek was that the design of the elevation of the floodplain surface was important to the evolution of the restored stream, with lower floodplain elevations (e.g., 2-year water surface) more effective than higher floodplain elevations (e.g., 5-year water surface) in satisfying geomorphic and ecological objectives.

Table 1. Goals and Objectives, Postproject Assessment Relative to Goals and Objectives, and Lessons Learned from the Postproject Assessment of Tassajara Creek Restoration Project (Adapted from Tompkins 2006)

	Goals and objective category		
	Geomorphologic	Ecological	Flood conveyance
Specific goals and objectives	Create dynamic low-flow channel with natural geomorphic processes; arrest channel incision; and reconnect low-flow channel with floodplain.	Create open, natural channel; protect existing native riparian vegetation; enhance native riparian vegetation; vegetate new floodplain surfaces.	Convey 100-year flow; and convey sediment loads during peak flows.
Assessment relative to goals in category	Channel incision arrested; low flow channel dynamic in reaches with high Width:Depth ratios, more static in reaches with low Width:Depth; and floodplain regularly connected with low-flow channel.	Low flow channel "open" in most reaches; existing mature oak trees still alive; and native riparian vegetation enhancement extremely successful. Channel geometry not yet complex laterally.	100-year flow capacity exists in 2006; and relatively minor sediment deposition on floodplains.
Lessons learned	When excavating floodplain along existing incised channel, floodplain elevation may be better at 2-year water-surface elevation than at 5-year.	Design of low-flow channel geometry could include more complexity (e.g., excavated pools, installed wood or rock, etc.) to jump start aquatic habitat formation.	Floodplain surfaces should be designed with tolerance for sediment deposition. Typical floodplain roughness values used in hydraulic modeling of restoration design may be too high.

Table 2. Summary of HEC-RAS Results for Design Flows on Upper Reach of Tassajara Creek Restoration Project

Channel configuration	Flow rate (m^3/s)	Mean channel velocity (m/s)	Mean channel shear stress (N/m^2)
Prerestoration	18.4	2.17	49.8
	58.0	2.92	76.1
	121.8	3.40	84.7
Restoration design	18.4	1.80	61.8
	58.0	2.55	96.2
	121.8	3.26	135.5
Postrestoration	18.4	1.62	50.3
	58.0	2.39	85.2
	121.8	3.22	136.0

Fig. 6. Predicted bed-shear stress for prerestoration channel from HEC-RAS and UnTRIM

Surveyed Channel

The mean cross-sectional average values of channel velocity and channel shear stress for the upper reach of the project predicted using HEC-RAS are given in Table 2. The restoration design HEC-RAS model and postrestoration HEC-RAS model predict lower mean channel velocities than the prerestoration HEC-RAS model for all three flow rates. In general the results from the restoration design model produced similar results to the model based on the postrestoration channel survey. This verification demonstrates that the performance of the constructed channel closely matches the restoration design when evaluated in terms of predicted mean channel velocity and mean channel shear stress.

The predicted mean channel bed-shear stress in the restoration design and postrestoration simulations is greater than the predicted mean channel shear stress in the prerestoration incised channel for all three flow rates (Table 2). Thus, while HEC-RAS predicted a decrease in mean channel velocity from project construction, the HEC-RAS models exhibit an increase in bed-shear stress resulting from project construction relative to the prerestoration condition. The predicted increase in mean channel shear stress in the restoration design and postrestoration channels relative to the prerestoration incised channel suggests an increase in channel incision following project construction. This result is inconsistent with the postproject surveys which demonstrated that following project construction the channel has been stable with no long-term trend of continued channel incision, and that the active incision occurring prior to project construction (Kondolf and Matthews 1997) has been arrested.

Prismatic Channel

Average downstream velocity and bed-shear stress computed on the prismatic channels using UnTRIM and HEC-RAS are com-

pared in Table 3. For the prerestoration channel, the average channel velocity predicted using HEC-RAS differs from the average downstream velocity computed by UnTRIM by less than 4%. For the postrestoration channel, the difference is approximately 2.6%. The average values of the left and right overbank velocities differ by 6.2 and 3.4%, respectively. The discrepancy between the models in predicting the channel and overbank velocities is the result of a different routing of the flow through the channel and floodplain in the two models. UnTRIM predicts slightly more flow in the main channel and slightly less flow in the overbank areas than HEC-RAS.

The predicted bed-shear stresses for the prerestoration incised channel simulations are shown in Fig. 6. For the HEC-RAS simulation, a single average value of the bed-shear stress is predicted for the entire channel. In the UnTRIM simulation, the bed-shear stress is calculated for each horizontal grid cell using the near-bed velocities. The predicted bed-shear stresses for the postrestoration compound channel simulations are shown in Fig. 7. For the HEC-RAS simulation, separate values of the bed-shear stress are predicted for the channel and overbank areas based on the channel subdivisions specified in the model. In the UnTRIM simulation, no separate channel subdivisions are made. The mean bed-shear stress values for UnTRIM were obtained by averaging the shear stresses over the same regions that are used to subdivide the channel in HEC-RAS. As seen in Table 3, HEC-RAS predicts a 5% increase in mean channel shear stress in the compound channel
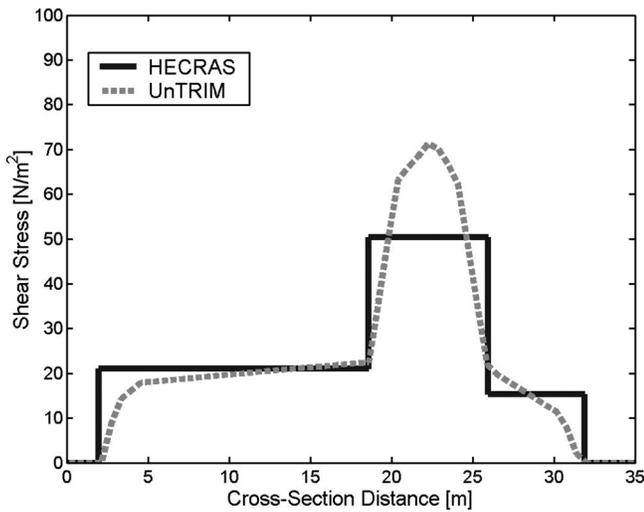
Table 3. Summary of Predicted Mean Velocity and Mean Bed-Shear Stress from HEC-RAS and UnTRIM Simulations of Prerestoration and Postrestoration Prismatic Channel for a Flow Rate of 58 m^3/s

Channel configuration	Model	Mean velocity (m/s)			Mean bed-shear stress (N/m^2)		
		Channel	Left overbank	Right overbank	Channel	Left overbank	Right overbank
Prerestoration	HEC-RAS	2.53	—	—	47.9		
	UnTRIM	2.44	—	—	56.0		
Postrestoration	HEC-RAS	2.61	1.46	1.18	50.3	21.1	15.3
	UnTRIM	2.67	1.37	1.14	52.7	19.2	13.4

Fig. 7. Predicted bed-shear stress for postrestoration channel from HEC-RAS and UnTRIM

Fig. 8. Prerestoration cross section of incised channel showing channel area, hydraulic radius, and wetted perimeter computed using HEC-RAS

relative to the incised channel, while UnTRIM predicts a 7% reduction in mean shear stress and a 24% reduction in maximum shear stress.

Discussion

One of the objectives of the Tassajara Creek restoration project was to mitigate further incision by reducing the velocities and shear stresses in the channel during high flows through reconfiguring the channel and floodplain into a two-stage compound channel. Repeated postproject surveys of the Tassajara Creek restoration project (Fig. 4) demonstrate that the project has been successful at stopping the incision which was evident prior to the construction of the project, and the channel has remained relatively stable since construction. The observed stability of the channel and cessation of further incision following the project construction corroborates the results of the UnTRIM model which show that the project results in a significant reduction in maximum channel shear stress at high flows, relative to the incised channel.

However, the results from HEC-RAS model shown in Table 2 indicate that the compound channel design successfully reduced mean channel velocity, but did not reduce mean channel shear stress for any of the modeled flow rates. This result is contrary to the design assumptions, namely, that the construction of a compound channel will lead to lower channel shear stresses during high flows.

An analysis of the method used in HEC-RAS to calculate the channel and overbank shear stresses in subdivided channels suggests that the increase in channel shear stress in the compound channel relative to the incised channel is an artifact of the computational method rather than a measure of the actual performance of the compound channel. In HEC-RAS, shear stress, τ, is computed using the relationship given by

$$\tau = \gamma R S_f \tag{6}$$

where γ=specific weight of water; R=hydraulic radius; and S_f =friction slope. The hydraulic radius is defined as the flow area, A, divided by the wetted perimeter, P. For the case where the channel is not subdivided, as in the incised channel simulation
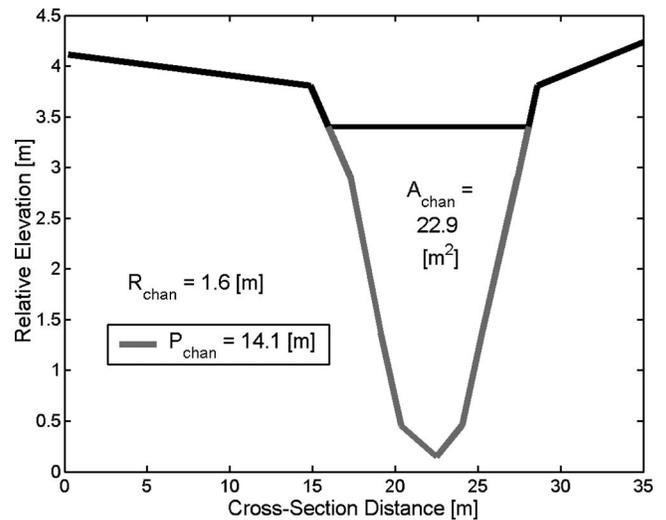
shown in Fig. 8, the wetted perimeter is the entire perimeter of the submerged area (excluding the water surface) and the flow area is the submerged cross-sectional area. When the channel is subdivided in the compound channel simulation, shown in Fig. 9, the wetted perimeter of the main channel is computed as the length of wetted channel bed between the two bank stations. In this case, the channel flow area is the submerged area of the channel between and below the bank stations plus the submerged area of the channel included in a rectangle with vertical sides drawn from the bank stations to the water surface, a bottom consisting of a horizontal line drawn between the bank stations and a top at the water surface. To illustrate how these subdivisions are drawn, these features are shown on Fig. 9. As a result of the method used to calculate the subdivision areas and wetted perimeters in HEC-RAS, the construction of the compound channel and the subdivision into channel and overbank areas causes a significant decrease in the channel wetted perimeter and a much smaller decrease in
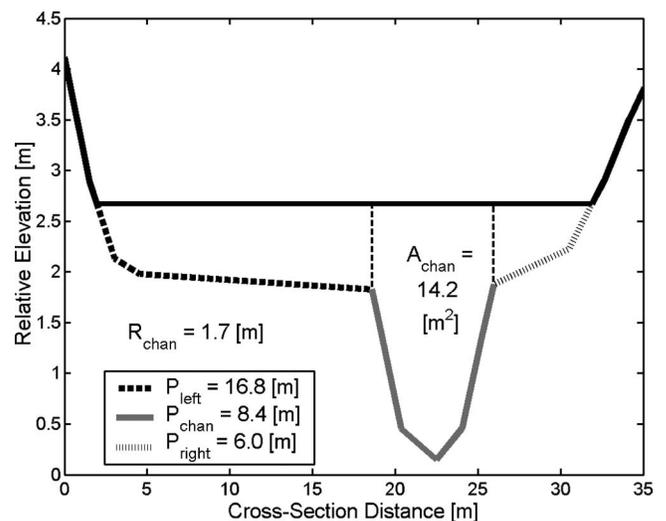

Fig. 9. Postrestoration cross section of compound channel showing channel area, hydraulic radius, and wetted perimeter for channel and overbank areas computed using HEC-RAS

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Table 4. Mean Bed-Shear Stress in the Postrestoration Prismatic Channel for Three Overbank Roughness Values Predicted Using HEC-RAS

Channel configuration	Model	Overbank Manning's n roughness value	Mean bed-shear stress (N/m^2)		
			Channel	Left overbank	Right overbank
Postrestoration	HEC-RAS	0.03	50.3	21.1	15.3
		0.06	54.6	25.4	18.7
		0.12	58.9	29.2	22.0

the flow area. The subdivision of the channel results in an elevated estimate of the hydraulic radius, which in turn results in a higher estimate of bed-shear stress. For the prerestoration example presented in Fig. 8, the calculated hydraulic radius and energy grade line slope were 1.63 m and 0.003, respectively. The corresponding values for the postrestoration example shown in Fig. 9 are 1.70 m and 0.003. The slope of the energy grade line is identical for both simulations because both were modeled as a uniform flow at the normal depth and therefore the slope of the energy grade line is identical to the bed slope. This example shows that the postrestoration hydraulic radius is 4% larger than the prerestoration value and that this results in a 4% increase in channel shear stress. However, in HEC-RAS the hydraulic radius is also used as the weighting factor for calculating the flow distribution between the channel subdivisions, so the difficulty associated with devising an accurate estimate of the hydraulic radius influences all aspects of the HEC-RAS results.

This analysis of the method used to calculate shear stress in HEC-RAS suggests that the higher mean channel shear-stress values for the postrestoration model results from this effect of subdividing the channel on calculating the hydraulic radius rather than an actual increase in bed-shear stresses within the channel resulting from project construction. Based on this analysis, the prediction of increased channel shear stress in the compound channel is not accurate.

The results shown in Table 2 are based on surveyed prerestoration and postrestoration conditions. These results include effects due to channel curvature or changes in cross section shape between sections. The shear-stress predictions obtained using HEC-RAS on these configurations demonstrate that the HEC-RAS model is not suitable for assessing the reduction in shear stress resulting from compound channel construction under complex natural conditions.

In order to provide a best-case scenario for the application of a 1D model to predict shear stress in a compound channel, straight-prismatic incised and compound channels were developed using a representative cross section from Tassajara Creek and modeled using HEC-RAS and UnTRIM. In the prismatic channel, a uniform roughness was applied to both the incised and compound channels to demonstrate that the variable roughness values used in the prerestoration and postrestoration HEC-RAS models was not the source of the higher shear stress in the postrestoration channel. The average shear stress results shown in Table 3 for the prismatic incised and compound channels show a similar trend to the results from HEC-RAS for the actual project topography. On the prismatic channels, HEC-RAS also predicted a slight increase in mean channel shear stress in the compound channel relative to the incised channel. In contrast, the UnTRIM mean shear stresses show a decrease in mean channel shear stress in the compound channel relative to the incised channel. This demonstrates that even in the absence of channel curvature, channel contraction or expansion, and using a uniform roughness in the channel and overbank regions that HEC-RAS still predicted an increase in

channel shear stress in the compound channel relative to the incised channel.

Two additional HEC-RAS simulations were made on the postrestoration prismatic channel to demonstrate the influence of floodplain roughness on shear-stress prediction in the channel. Table 4 shows the effect of floodplain roughness on the channel and overbank shear stresses predicted using HEC-RAS with a discharge of 58 m^3/s. In each simulation, a Manning's roughness of 0.03 was used in the channel, while Manning's roughness values of 0.03, 0.06, and 0.12 were applied in the overbank areas. These values are representative of the range of floodplain roughness values simulated as part of the restoration channel design. The case which applied a roughness of 0.03 in both the channel and overbank areas is identical to that shown in Table 3, which showed a predicted increase in channel shear stress of 5% over the prerestoration incised channel. In the incised channel, the overbank areas are not connected to the channel at a discharge of 58 m^3/s, so in the prerestoration channel, channel shear stress is not influenced by overbank roughness. Increasing the overbank Manning's roughness value in the postrestoration compound channel from 0.03 to 0.06 results in a predicted increase in the channel shear stress to 54.6 N/m^2, an increase of 14% above the prerestoration incised channel. Further increase of the overbank Manning's roughness to 0.12 (the value used in final project permitting), yields a predicted mean channel shear stress of 58.9 N/m^2, an increase of 23% above the prerestoration incised channel (Table 3). This analysis demonstrates that when a more typical roughness value is applied in overbank areas to reflect expected floodplain vegetation such as that evidence in the post-project assessments on Tassajara Creek, HEC-RAS predicts an even greater increase in channel shear stress in the compound channel relative to the incised channel.

In the evaluation of channel stability, the maximum shear stress is a much better indicator of the potential for erosion than the mean shear stress. In UnTRIM, the bed-shear stress is calculated from the near-bed velocity by

$$\tau_x = \rho_o C_d u_1 \sqrt{u_1^2 + v_1^2} \qquad (7)$$

where ρ_o=density of water and u_1 and v_1=near-bed velocities in the x- and y-direction, respectively. The coefficient of drag, C_d, is given by assuming a logarithmic velocity profile near the bed such that

$$C_d = \left[\frac{1}{\kappa} \ln\left(\frac{z_1}{z_0}\right) \right]^{-2} \qquad (8)$$

where κ=von Karman constant; z_0=bottom roughness height; and z_1=height (typically at the center of the first grid cell above the bed) at which the velocities u_1 and v_1 are calculated. By using this approach, the bed-shear stress is calculated at each flux face in the domain, and the distribution of shear stress across the cross section can be obtained. This method of calculating the bed-shear stress from the near-bed velocity yields a more accurate estimate

of the local bed-shear stress than can be obtained using a 1D model.

The UnTRIM results in Figs. 6 and 7 show that there is significant variability in the bed-shear stress across the channel that cannot be captured by a 1D model such as HEC-RAS. This variability occurs even in a straight-prismatic channel; the variability would be even more pronounced if there were significant bends or variations in geometry within the reach modeled. In the prerestoration channel, the maximum bed-shear stress in the channel predicted by UnTRIM exceeds the mean value predicted by HEC-RAS by 97%. In the postrestoration channel, the maximum bed-shear stress in the channel predicted by UnTRIM exceeds the mean value predicted by HEC-RAS by 42%. Because sediment transport is a nonlinear function of bed-shear stress, these large differences between the maximum and mean shear stress have significant implications on the potential for erosion and on channel stability. In contrast to the HEC-RAS results which show an increase in mean shear stress in the compound channel, the results from the UnTRIM simulations show a 24% reduction in maximum shear stress in the compound channel relative to the incised channel; these results are much more useful in predicting future channel stability than estimates of mean shear stress.

Although river systems are typically evaluated using 1D, steady, gradually varied flow models such as HEC-RAS, Fischenich and Abt (1995) note that more complicated analyzes are often warranted. Shields (1996) notes that in channels with bends, variations in shear stress across the channel can lead to scour and deposition even when average shear-stress values would not cause significant channel adjustment. The difference between the predicted mean and maximum shear stresses in both the incised and compound channels highlights the limited value of mean shear stress estimates in predicting channel stability.

Conclusions

Repeated postproject longitudinal and cross section surveys on Tassajara Creek demonstrate that the compound channel design used on Tassajara Creek was successful at arresting further channel incision, while achieving the specific geomorphic, ecological, and flood conveyance objectives of the restoration project. However, an analysis of the HEC-RAS model used in the design of the compound channel demonstrates significant shortcomings which limit the predictive ability of 1D models for evaluating bed-shear stresses in compound channels.

The simulation of uniform flow in a prismatic incised and compound channel offers a best-case scenario for the application of a 1D model to a compound channel flow. However, even under these ideal conditions, the 1D model is of very limited value in assessing changes in channel shear stress resulting from the construction of a compound channel on an incised stream. Contrary to underlying assumptions of compound channel design, the predicted mean channel shear stress from HEC-RAS show an increase in mean channel shear stress in the compound channel relative to the incised channel. This predicted increase in channel shear stress in the compound channel is shown to increase with increasing overbank roughness.

Although this study analyzed the change in shear stress for a single restoration project using a compound channel design, our analysis of the method used in HEC-RAS to compute channel shear stress in subdivided compound channels suggests that the artifact of the higher predicted shear stress in compound channels relative to the corresponding incised channel is likely to occur under almost all similar incised and compound channel geometries due to the method used in HEC-RAS to compute hydraulic radius in subdivided channels. This result suggests that HEC-RAS is not a suitable tool for evaluating the reduction in channel shear stress when designing compound channels for restoration projects.

Tompkins (2006) found that the design of the elevation of the floodplain surface was important to the evolution of the restored stream, with lower floodplain elevations more effective than higher floodplain elevations in satisfying geomorphic and ecological objectives. This study demonstrates that HEC-RAS has limited capacity to evaluate changes in channel bed-shear stress between different compound channel configurations with varying floodplain surface elevations channel configurations. The ability to detect and quantify differences in hydraulic performance between alternate compound channel designs is an important reason for designers to improve the formulation of HEC-RAS for the evaluation of bed-shear stresses in compound channels, or to consider using multidimensional models.

The UnTRIM results show a significant decrease in maximum shear stress, and demonstrate the capacity of 3D modeling to assess changes in flow velocity and bed-shear stress resulting from the construction of complex cross-section designs. Since the mean bed-shear stress is not as significant in predicting channel stability as the maximum bed-shear stress, the magnitude of the difference between the mean and maximum shear stress predicted by UnTRIM in both the incised and compound channels suggest that even an accurate measurement of mean shear stress is of limited value compared to an estimate of maximum channel shear stress and shear-stress distribution. The shear stresses and velocities predicted in the UnTRIM simulations indicate that the design and construction of the Tassajara Creek restoration project was successful at reducing the maximum bed-shear stresses in the channel.

The application of either two-dimensional (2D) or 3D models usually requires substantially higher resolution field surveys to develop representative model grids (e.g., Pasternack et al. 2004) than the cross section surveys that are typically collected for the development of 1D models. For many restoration projects, detailed design topography is readily available from the restoration design plans; however, more detailed preproject surveys may be necessary for 2D or 3D model applications. Additionally, 3D models require significantly more computational time than either 1D or 2D models, which can limit the number of design iterations that can be considered. However, 3D models can predict the variability of velocities and shear stresses across the channel, which provides a more accurate measure of channel stability than cross-sectional average shear stress estimates from 1D models, which are based on a calculation of average energy losses in the channel. The analysis presented in this study suggests that the application of 2D or 3D models may be necessary in order to accurately quantify the effectiveness of a compound channel design in reducing channel bed-shear stresses in an incised stream.

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