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Catena 61 (2005) 273–291

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Modeling scour and deposition in ephemeral channels after wildfire

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Abstract

The area burned by wildfire in the states of Arizona and New Mexico in the southwestern US has been increasing in recent years. In many cases, high severity burns have caused dramatic increases in runoff and sediment yield from burned watersheds. This paper describes the potential and limitations of the HEC6T sediment transport model to describe changes in channel scour and deposition following the Cerro Grande fire near Los Alamos, New Mexico. Following the fire, Pueblo Canyon, near Los Alamos, was subject to a peak flow two orders of magnitudes higher than any discharge in the 7-year period of record, and twice the initial post-fire estimate of the 100-year event. HEC6T requires that the limits of scour and deposition on a cross-section be specified prior to application. This was achieved by using geomorphologic principles, predicted post-burn hydrology and long-term estimates of channel change derived from air photos, to estimate post-fire channel widths. Because significant quantities of silt and clay were present in the runoff, erosion shear stress and erosion rate parameters for cohesive sediments had to be obtained experimentally. After a sensitivity analysis, an optimization routine was used to estimate the optimal model parameter values for sensitive parameters. HEC6T was able to accurately model the change in cumulative sediment volume change derived from Airborne Laser Swath Mapping (ALSM, often called Lidar) taken before and after the large post-fire event. One discrepancy between the HEC6T model prediction and the ALSM-estimated change was that the ALSM-estimated change showed the greatest amount of deposition in a portion of the canyon with increasing slope, which the HEC6T model did not predict.

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doi:10.1016/j.catena.2005.03.013

Any sediment transport model will predict increased sediment transport capacity with increasing energy slope, so that it was considered to be beyond the capability of any sediment transport model to predict this deposition. Therefore, HEC6T simulated the overall changes in scour and deposition within reasonable expectation of the capabilities of physically-based sediment transport modeling indicating that it is capable of modeling sediment transport in ephemeral channels following wildfire.

Keywords: Wildfire; Erosion; Sediment transport modeling; Scour; Deposition

1. Introduction

1.1. Background

Pulses of sediment destabilize channels and can have important long-term impacts on channel morphology and sediment transport. Even today, sediment introduced by mining during the 19th century gold rush in California continues to move through channel networks in the Bear and American Rivers near Sacramento California (James, 1999). As this sediment moves through the channel network, the estimates of the extent of return-period floods must be continually updated. While sluice gate mining introduced up to a billion cubic meters of sediment to these rivers, it did not dramatically change runoff. In contrast, landscape destabilization by wildfire has the potential to increase runoff delivered to channels, accelerate the delivery rate of sediment to the channel, accelerate delivery rate of sediment out of the channel, and to modify the channel-forming discharge.

In the wake of wildfire, runoff peaks have been observed to increase from one to two orders of magnitude in basins in Arizona, which is far greater than the impact of clear cutting (Robichaud et al., 2000). Studies in New Mexico and Arizona showed that erosion rates increase dramatically in the wake of wildfire, while erosion is extremely low in stable natural environments (White and Wells, 1979; Wilson et al., 2001; Miller et al., 2003; Robichaud et al., 2000). Sediment flux from hillslopes in the wake of wildfire is the greatest source of this increased erosion (Wondzell and King, 2003; Gonzalez-Bonorino and Osterkamp, 2004).

Both climate cycles and the current condition of forests have combined to increase incidence of stand-changing wildfire (i.e. a wildfire that kills off the tree stand) in Arizona and New Mexico. Studies have shown that wildfire and climate cycles are related in the desert southwest of the United States. Regional wildfires may be more frequent after dry years, but build-up of fuels following wet years may also contribute to wildfires (Westerling and Swetnam, 2003). Reconstruction of tree rings show that between 1700 and 1900 fires were more frequent in forests in New Mexico and Arizona than they are now, with widescale regional fires recognized across New Mexico and Arizona (Swetnam and Bentancourt, 1998). Following 1910, the largest fire season of the 20th century, the federal government adopted a policy of fire suppression, which has had tremendous consequences for fire frequency in the western United States. Since 1900, fire frequency has reduced substantially and regional fires have become nearly non-existent. However, the acreage burned in Arizona and New Mexico has been increasing since 1976, in part because of the increased density of fine and coarse fuels (Swetnam and Bentancourt, 1998). There have been six fire seasons since 1985, which burned five times more land than any year prior to 1970. Such fires have the potential to kill the entire stand of trees, and are very infrequent. A study in Colorado showed that over the past 2900 years stand-changing wildfire has occurred three times (Elliott and Parker, 2001).

In May 2000, the Cerro Grande Fire burned a total of 43,000 acres, including about 85% of the steep forested lands in the headwaters of streams that flow through Los Alamos County, the Los Alamos National Laboratory (LANL), and Pueblos located in the Jemez Mountains and on the Pajarito Plateau in Northern New Mexico. Much of this was high severity burn, which burned both trees and the underlying duff layer. The fire preceded the summer rainy season, which is characterized by intense convective rain events. Flood peaks following the fire increased by one or more orders of magnitude relative to pre-fire flood peaks. Roads, buildings, sewer lines and other infra-structure located in canyon bottoms were damaged by post-fire flooding and coincident sedimentation and scour. Of particular concern is the fact that sediment in some of the canyons downstream of LANL facilities contains low levels of residual contaminants from weapons related activities during and following the Manhattan Project (Lane et al., 1985; Graf, 1994; Reneau et al., 1998). Concern over the impact of post-fire hydrologic processes on human safety, facilities and infrastructure prompted the development and application of models to assess the likely magnitude of post-fire flooding and its impact on sediment and contaminant transport.

A suite of models was used to predict:

- magnitude and duration of post-fire hillslope runoff and floods,
- soil erosion and sediment yield from burned hillslopes,
- scour and deposition of contaminated floodplain and channel sediments, and
- routing of sediment and contaminants through stream networks.

In order complete these tasks, it was necessary to select a sediment transport model. The availability of relatively good quality baseline data allows the data from Los Alamos to be used to calibrate the HEC6T one dimensional sediment transport model (Thomas, 2003). LANL employed Airborne Laser Swath Mapping (ALSM, often called Lidar), field surveys, stream flow gauging and suspended sediment sampling to monitor the impact of the fire on runoff and erosion in the channels at Los Alamos.

Pueblo Canyon, one of the most important canyons in terms of residual plutonium, was highly impacted by changes in post fire runoff and erosion. Studies have been undertaken to map the residual plutonium in Pueblo Canyon and understand its movement and long-term changes (Reneau et al., 1998, 2003). These studies have shown that systematic agradation has occurred in some portions of the channel while degradation has occurred in others over the past 30 years.

Prior to the fire, the maximum discharge recorded at the Pueblo Canyon gauging station near the confluence with Los Alamos Canyon was 0.31 m^3/s (Schaull et al., 1999; installed in 1992 draining 21.7 km^2). Approximately one-quarter of the watershed above the gauging station was severely burned. After the fire there were numerous events that exceeded 0.31 m^3/s at this gauging station, including a 40 m^3/s event observed on July 2, 2001, which was twice the Burned Area Emergency Response (BAER) team estimate for the 100-year post-fire event (BAER, 2000). A significant consequence of these more frequent large events was increased scour in some portions of the channel and increased deposition in other parts of the channel.

1.2. Scope of this study

This study documents the application of a channel erosion model to a canyon at Los Alamos New Mexico that had been subjected to large post-fire flows. It describes the potential and limitations of applying a one-dimensional sediment transport model to assess the impact of post-fire flows.

2. Methods

2.1. Overview of methods

The HEC6T model was calibrated and used to model scour and deposition in Pueblo Canyon. A sensitivity analysis was performed on the HEC6T model for conditions in Pueblo Canyon. Then automatic calibration was performed by calibrating the most sensitive parameters against ALSM data.

ALSM surveys performed in July 2000 and November 2001 were used to prepare two 0.28 m × 0.28 m (1 ft × 1 ft) Digital Elevation Models (DEMs) of Pueblo Canyon. In general, these DEMs contained sufficient resolution to discern detail of the channel and floodplain geometry at a level consistent with field survey. The difference in the two ALSM surveys could be used to calculate scour and deposition as a result of the flows that occurred between July 2000 and November 2001, and these estimates could be used for calibration. However, rectifying the two surveys so that meaningful estimates of volumes of scour and deposition could be obtained was a significant task in itself, and is the subject of another study.

The initial conditions geometry for the HEC-6T model was developed from the July 2000 ALSM. A simulation hydrograph was formed from the measured runoff between the July 2000 ALSM survey and the November 2001 ALSM survey. The observed hydrograph series included all events larger than 1.7 m^3/s that occurred between August 2000 and July 2001, including the July 2, 2001 event that exceeded 40 m^3/s (Fig. 1). This hydrograph was used to simulate scour and deposition along 7500 m of Pueblo Canyon.

2.2. Pueblo Canyon

The channel reach included in this study extends from just above Acid Canyon to the confluence with Los Alamos Canyon (Fig. 2). Pueblo Canyon is located on the Pajarito Plateau near Los Alamos New Mexico, and drains much of the Los Alamos town site. The

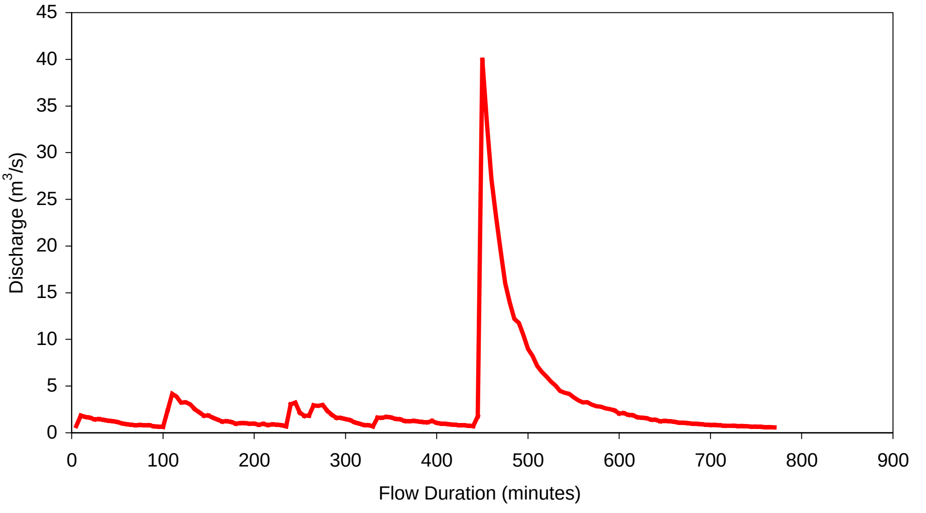

Fig. 1. The observed hydrograph in Pueblo Canyon for the period from August 2000 to July 2001. Events with peaks less than 1.7 m^3/s, and periods of no flow have been removed to create one continuous hydrograph for input into HEC6T.

drainage area at the gauging station near the confluence with Los Alamos Canyon is 21.7 km^2. More detail on the morphology of the Canyon can be found elsewhere (Reneau et al., 1998, 2003).

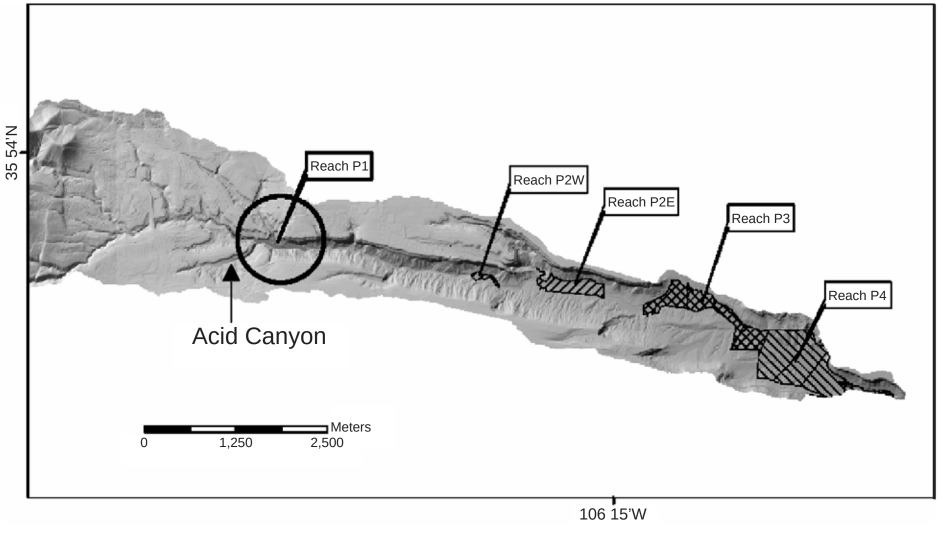

Fig. 2. Diagram of Pueblo Canyon. HEC6T was used to model scour and deposition in Pueblo Canyon from just above Acid Canyon to the confluence with Los Alamos Canyon. The reaches described in the Pueblo Canyon Reach Report (Reneau et al., 1998) are shown on this figure.

The basin is about 16 km long and is 2790 m in elevation at its upper end and 1915 m in elevation near the confluence with Los Alamos Canyon. Bedrock is composed of volcanic dacite and tuff in the upper reaches. Lower reaches are underlain by fanglomerates (Smith et al., 1970). Soils are typically sandy to silty loams with areas of outcropping bedrock (Nyhan et al., 1978; Benally, 1991).

Precipitation is about 650 mm/year in the headwaters and about 350 mm/year at the lower elevations (Bowen, 1996). About half of the annual precipitation occurs during summer thunderstorms, resulting in flash flooding which is responsible for most of the sediment transport on the Pajarito Plateau (Reid et al., 1999). Ponderosa Pine dominates the vegetation in the upper elevation with mixed conifer and pinon-juniper woodlands more prevalent lower in the basin.

In the wake of the Cerro Grande Fire, 23% of Pueblo Canyon were classified as high severity burn, which resulted in complete burning of all ground cover, including the pine needle duff layer, tree foliage and branches, and many trunks. After the fire, soils in high severity burn areas were determined to be hydrophobic using the water drop test by the BAER team (BAER, 2000).

2.3. Description of the HEC6T model

HEC6T (Thomas, 2003) is a one-dimensional sediment transport model that couples the solution of the gradually-varied form of the Saint Venant Equations with the five basic sedimentation processes: erosion, entrainment, transportation, deposition and the compaction of sediment. The HEC6T Model is an update of the widely-used United States Army Corps of Engineers HEC6 Model (USACE, 1995). HEC6 has been used to model scour and deposition in channels (Sinnakaudan et al., 2003; Zeng and Beck, 2003). HEC6T allows scour and deposition to be described at a cross-section, with a reach being characterized by the space between the two cross-sections. For each reach, the sediment available for scour can be envisioned as a control volume with a given width, depth and length.

Classical, non-cohesive sediment transport functions are used for sand and larger particles (>0.0625 mm), and cohesive sediment transport functions are used for silts and clays (<0.0625 mm). The empirical coefficients, that are required for the cohesive functions, can be prescribed in the input data. The basic processes employed in the HEC6T model are diagramed on Fig. 3.

HEC-RAS (USACE, 2001) is a flow routing and flood plain modeling software that was used to evaluate hydrologic and hydraulic response prior to passing cross-section geometry, bank stations and roughness values to HEC6T, and thus could be used to check hydraulic response prior to beginning sediment transport modeling. In order to validate the hydraulics of the HEC6T model, geometry and parameters that affect hydraulics were imported from the HEC RAS using the HEC GeoRAS (USACE, 2002) is an ArcView extension that allows cross-section geometry to be parameterized using a DEM and then input to HEC-RAS (Earles et al., 2004). Channel cross-section and profile geometry as well as channel hydraulic parameter values were written to HEC6T files using HEC6Tutilities and utilities developed for the LANL modeling effort. Therefore, HEC RAS can be used as a technology for data entry and modification, and a method for verifying HEC6T calculations.

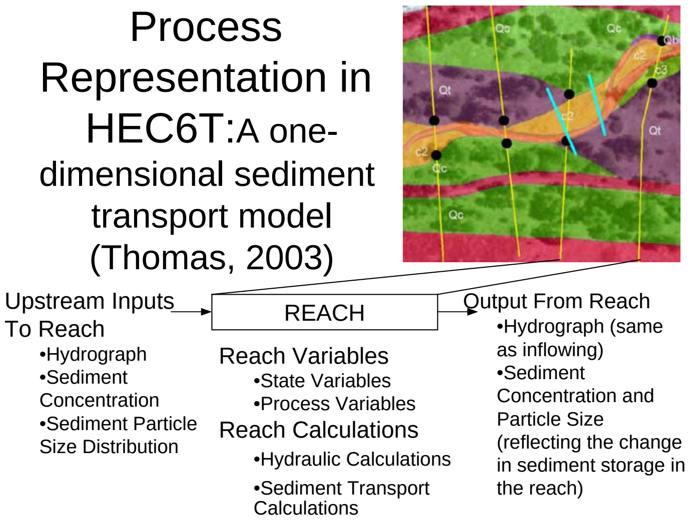

Fig. 3. Representation of processes simulated in HEC6T.

2.4. Parameterization of HEC6T

HEC6T can be used to describe sediment transport in large and small channels under a variety of different environmental conditions. As such, it contains numerous options for parameterizing the model.

Because of the variety of ways that HEC6T can be applied, there is a procedure by which the HEC6 and HEC6T models should be applied (USACE, 1992). Following this procedure helps to produce results that are repeatable and stable. This procedure involves reviewing historical stream behavior to understand the behavior of the so-called "prototype channel", parameterizing the model, verifying numerical stability, performing sensitivity analysis and calibrating the model. These were followed in this research.

2.5. Conceptual representation

Prior to modeling with HEC6T, the portions of a channel cross-section subject to scour or deposition must be specified explicitly. As a one-dimensional model, HEC6T can only raise or lower the bed in the portions of the cross-section that are wetted. Therefore, in HEC6T, the left and right limits of scour and deposition (i.e. the movable bed) must be specified. In post-fire conditions where peak discharges increase by orders of magnitude, defining the left and right limits of erosion and deposition is somewhat problematic. Furthermore, in calibrating a model against post fire scour and deposition, there is no way to know whether the events are likely to be superseded by much larger events that may scour out a much wider portion of the channel than were scoured in the events that were used to calibrate the model.

In this case, the conceptual representation must integrate the existing understanding on the erosion process in Pueblo Canyon including the channel morphologic mapping units (Reneau et al., 1998, 2003), which are shown in Fig. 4.

2.6. Estimating initial parameter values

In HEC6T, parameter values are needed to parameterize flow, sediment detachment, sediment entrainment, sediment transport and sediment deposition processes. In the following sections, the parameterization for (1) inflowing sediment concentration, (2) channel and overbank roughness, (3) sediment transport relationships, (4) shear stress entrainment parameters, (5) bed particle size and (6) bank erosion parameters are given.

2.6.1. Inflowing sediment concentration

A boundary condition for the HEC6T model is the inflowing sediment load concentration, and particle size distribution. If the transport capacity of the flow is not able to transport the particle sizes in the inflowing load, the sediment will deposit at the upstream end of the model. Likewise, if the transport capacity is greater than the transport capacity needed to transport the inflowing load, the flow will scour. Over the duration of a simulation a particle size discrepancy between the transport capacity of sediment entering the upstream boundary and transport capacity of the flow can make a difference of several meters of scour or deposition on the upstream boundary, which in turn, will affect the simulation downstream of this boundary.

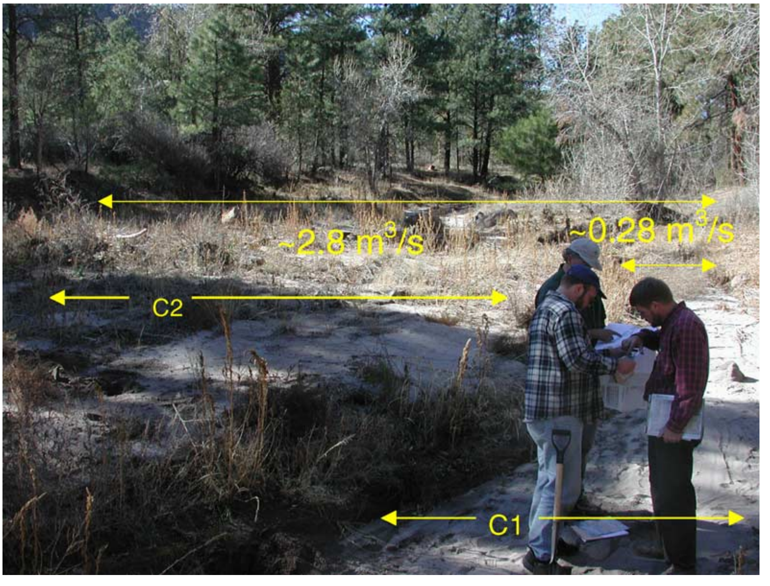

Fig. 4. Representation of geomorphic units.

The inflowing sediment load concentration was selected based on a review of post-fire suspended sediment data collected by LANL as well as data collected by the New Mexico Environment Department (NMED, 2002, 2003). These data show that the suspended sediment concentration varied from less than 10,000 mg/l to over 400,000 mg/l. The data do not appear to follow the trend of increasing concentration with discharge common in perennial streams. Instead, the concentration more reasonably followed the pattern of sediment rating curves observed in ephemeral streams, which indicate relatively constant concentration with discharge on the rising limb, and a drop off of concentration on the trailing limb (Renard, 1969).

2.6.2. Channel cross-section roughness

Manning's roughness values must be selected for the channel and the over bank. Values were selected using the methods of Arcement and Schneider (1992) by which separate roughness is applied for particle size, channel irregularity, obstructions and vegetation. Channel estimates of roughness included both the 0.28 m^3/s and 2.8 m^3/s channels (mapped as units C1 and C1+C2 by Reneau et al., 1998). The 0.28 m^3/s channel is the current active channel. The 2.8 m^3/s channel includes both the current active channel and portions of the channel that have been interpreted to be a post-1942 deposit formed by channel migration or incising of previous channel deposits (Reneau et al., 2003). The resulting estimated Manning's channel roughness was between 0.06 and 0.08, which reflected the effect of the additional vegetation and other roughness elements in the 2.8 m^3/s channel. These relationships are shown in Fig. 4.

An additional roughness factor was added in channel bends to account for the roughness brought about by the bend (Chow, 1959). Furthermore, the over bank had roughness values between 0.10 and 0.12. These over bank values were verified by reviewing the photographs in Arcement and Schneider (1992). For these estimates, the uncertainty is estimated to be on the order of 0.02, based on summing the uncertainties in each component of the roughness estimate.

2.6.3. Sediment transport relationship

Twenty-one different sediment transport relationships were evaluated in HEC6T, yielding highly variable results. Because the Yang (1973) relationship has been widely applied, is a total load relationship, behaved reasonably in this environment, and can be used in sandy alluvial streams (Yang, 1996) such as those in canyons at Los Alamos, it was used to simulate sediment transport in Pueblo Canyon.

2.6.4. Shear stress entrainment parameters

HEC6T requires separate parameters to describe detachment and entrainment of cohesive sediment such as silt and clay. Parameters for entrainment of silt and clay must be based on experimental data. Dr. Joe McNeil (UC-Santa Barbara) determined the entrainment characteristics of sediment from undisturbed soil samples from Los Alamos Canyon, which were subjected to shear stress in a flume (McNeil et al., 1996). By knowing the rate at which fines are entrained as a function of shear stress, it is possible to determine the value of entrainment parameters for modeling the entrainment and transport of cohesive sediment.

2.6.5. Particle size of bed

Particle size of the bed is an important parameter in the HEC6T because it describes the particles available for transport by the sediment transport relationship. A single particle size distribution is specified at each cross-section. Because HEC6T is a one-dimensional model, there is no mechanism for transporting sediment from the over bank into the channel and visa versa.

Pre-fire data published in 1998 are available on the particle size of the bed for different geomorphic units in different canyons (Reneau et al., 1998). In their sampling, they did sample sediment that could not fit into the sample jar. The results are presented for the <2 mm fraction and the percent gravel was also calculated, though the particle size distribution for the >2 mm fraction was not calculated. Therefore, for this study, the greater than 2 mm fraction was estimated using pebble counts. Since pebble counts reflect an estimate of particle size based on area rather than mass, a conversion of area to mass was accomplished using the methods of Leopold (1970). Fig. 5 shows the particle size distributions for the sediment at these cross-sections employed in the model.

2.6.6. Bank erosion

HEC6T allows for the possibility of bank erosion when scour in the channels result in banks that are steeper than a stable angle of repose. When the angle of repose is steeper than 39° (mean angle of repose for well graded sand with angular grains: Terzaghi and Peck, 1967), banks are allowed to collapse to 39°.

2.7. Sensitivity analysis of parameters in HEC6T

In evaluating the sensitivity of the HEC6T model, a baseline scenario was selected, and one parameter at a time was modified to determine that parameter's effect on

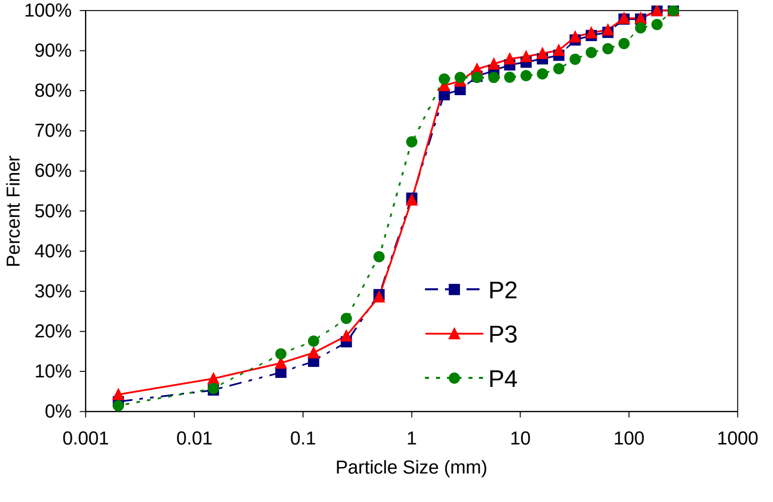

Fig. 5. Percent finer curves for three reaches based on the data of Reneau et al. (1998). The cross-sections where these particle sizes apply are listed next to the reach number.

Table 1
Parameters evaluated

Upstream boundary conditions	State variables	Process variables
• Inflowing sediment load concentration • Inflowing sediment load particle size distribution	• Sand, silt and clay density • Bed particle size distribution • Manning's roughness for channel and overbank • Erodible depth and width	• Shear stress deposition and entrainment thresholds • Shear stress mass entrainment rates and thresholds • Sediment transport relationship (21 different relationships)

model output. A list of parameters used in the sensitivity analysis is presented in Table 1. Because data are available (or could be collected on) several model outcomes, multiple outputs were monitored including scour and deposition at a cross-section, cumulative volume change, and sediment concentration. Ultimately, however, the calibration relied largely on the cumulative volume change, though predicted scour and deposition at a cross-section and sediment concentration were consistent with observations. Therefore, parameters sensitive to cumulative volume change were selected for calibration. Since this analysis, the model geometry has been updated and further field data were incorporated into the simulations. However, the results of the sensitivity analysis are helpful in understanding the effect that these parameters have on model performance.

2.8. Model calibration

The PEST model parameter estimation software (Doherty, 2003) was used to calibrate the model. The inflowing load, channel roughness, shear stress threshold for entrainment of sediment aggregates and mass at shear stress entrainment were calibrated. The square of the difference between the observed and calculated cumulative volume was used to calculate the error between observed and simulated cumulative volume change.

3. Results

3.1. Conceptual representation

As described in the methods section, the conceptual representation describes the way in which scour and deposition occurs across the cross-section in the prototype stream. Fig. 4 illustrates different channel bankfull. The conceptual models considered are as follows:

(1) Assume that most scour and deposition will occur in the inset (0.28 m^3/s) channel. This is consistent with the current observations in the ALSM differencing, which shows the most change in scour and deposition in the inset channel.

(2) Assume that most of the scour and deposition will occur in the C1 and C2 (2.8 m^3/s) channel.
(3) Assume that it is possible for an event to either scour or deposit across the wetted perimeter, regardless of whether this flow occurs in the over bank of the channel at high flow, or in the narrow inset channel.

When subjected to the hydrograph in Fig. 1, the three different conceptual representations yield different results as indicated in Fig. 6. All three conceptual representations may represent what is possible in Pueblo Canyon in an event depending on the event size. Subsequent evaluation of the scour and deposition data at cross-sections indicated that scour tended to be a vertical erosion process in the channel, so the inset channel representation was used in all simulations. Because of the dynamic nature of the erosion process, these characterizations reflect the channel morphology at the time of mapping. Since that time, in some locations the C1 and C2 have merged together, principally in locations of deposition, while the differences have become more apparent in locations of scour.

To select bank stations that included both the C1 and C2 units, a 2.8 m^3/s steady state discharge was run in HEC RAS to determine a discharge that would inundate all of the C1 and C2 units. Fig. 7 shows the location of the bank stations at 2.8 m^3/s discharge in relation to the mapped C1 and C2 units. Therefore, for the purposes of simulation, the C1 and C2 units together were considered to represent the channel in the HEC6T model.

3.2. Sensitivity of parameters on cumulative volume change

The effect of parameters on cumulative volume change at the downstream boundary was evaluated, in order to determine which parameters had the most impact on change

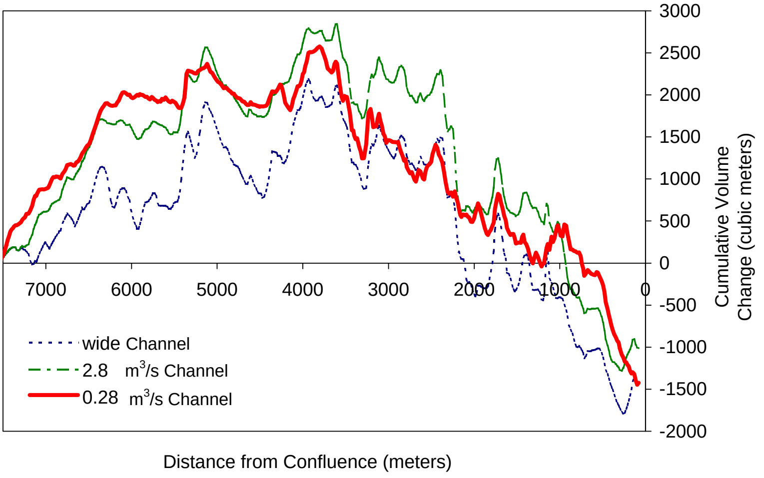

Fig. 6. Comparison of different conceptual representation on scour and deposition.

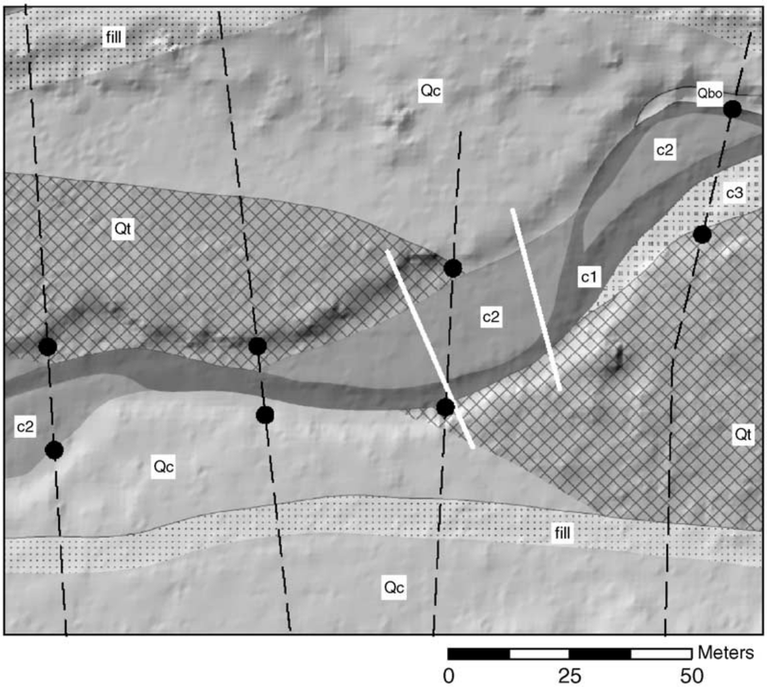

Fig. 7. The left and right bank stations in the HEC6T simulation correspond to the limits of the channel geomorphic units. The C1 and C2 units shown on the map correspond to the channel units mapped by Reneau et al. (1998). The left and right bank stations on a cross-section, which are selected based on the limits of a 2.8 m^3/s flow, are given by the ● symbol.

in cumulative volume. The relative change in parameter values was based on an estimate of the range of reasonable possible values. The results for parameters that resulted in at least a 10% change in cumulative volume change are summarized in Table 2.

Table 2
Sensitivity of cumulative volume change to parameter values

Variable	Base	High	Sensitivity, total volume change, %	Low	Sensitivity, total volume change, %
Channel roughness (n)*	0.042	0.080	17.0	0.02	38.6
Sand density (N/m^3)	11.8	13.0	− 11.7	9.4	5.3
Maximum inflowing load (mg/l)	25 000	100 000	112.7	10 000	− 11.3
Deposition threshold (N/m^2)	0.00166	0.01658	44.1	0.00017	− 0.8
Mass entrainment rate ($N/m^2/h$)	31.1	62.2	− 92.0	15.5	22.7
% Sediment < 2 mm					
Lower end	75.3	85.3	− 182.0	60.3	60.6
Middle section	77.2	87.2	62.2		
Upper end	70.2	80.2	55.2		

These results show that changes in parameters can increase cumulative volume change by almost a factor of two. On a percentage basis the changes in cumulative volume were much greater than scour or deposition. This is because the cumulative volume change measure has the effect of cumulative summing small differences to result in large differences. The sensitivity analysis showed that channel roughness, bed particle size and shear stress entrainment parameters are important parameters controlling sediment discharge. However, inflowing sediment load is also an important parameter in modeling cumulative volume change.

3.3. Results of model calibration

Based on this sensitivity analysis, the following selected model parameters were used for calibration:

- channel roughness,
- inflowing sediment load concentration,
- shear stress entrainment threshold,
- mass at shear stress entrainment threshold.

In addition, scenarios with both 10% more coarse material and 10% more fine material were considered. The initial and selected parameter values are shown in Table 3. This calibration resulted in the comparison between observed and simulated volume change shown in Fig. 8. High and low estimates are also included which are based on selecting the highest or lowest reasonable value for each of the four calibration parameters.

A positive Nash–Suttcliffe statistic (Nash and Sutcliffe, 1970) for the optimal fit indicates that the model is performing better than the mean measurement of cumulative scour or deposition. If there were no error between model-predicted cumulative volume change and observed cumulative volume change, the Nash–Sutcliffe statistic would be 1.0. The statistic of 0.79 indicates that the model was able to predict changes in cumulative scour and deposition. However, the large difference between the optimal estimate and the high and low estimate in Fig. 8 indicates that there is significant uncertainty in the prediction.

For the two scenarios with higher and lower >2 mm sediment, similar goodness of fit statistics were generated in the calibration exercise (0.75 and 0.77) with different calibrated parameter values. Too much significance cannot be placed on the calibrated

Table 3
Optimal parameter values

Variable	Base	Range of values		Optimal
Channel roughness (n)*	0.060	0.03	0.1	0.030
Maximum inflowing load (mg/l)	170 000	100 000	250 000	122 000
Entrainment threshold (N/m^2)	0.025	0.008	0.062	0.041
Mass entrainment rate (N/m^2/h)	22.8	6.22	82.9	32.3

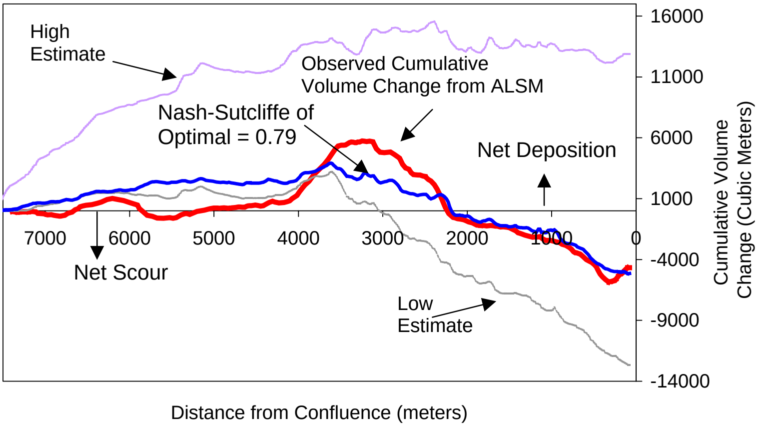

Fig. 8. Comparison of model cumulative scour for a high, low and optimal estimate in comparison with observed cumulative scour.

parameter set with the best goodness of fit statistics, because multiple parameter sets (non-unique parameter sets) can produce similarly good statistics.

4. Discussion

Since the movement of pulses of sediment may have a profound impact on the delivery of downstream sediment and the size of the floodplain, there are benefits to having a model that can predict the movement of these pulses of sediment. This study shows that HEC6T can be used to estimate the movement of this sediment and the changes in channel geometry. However, the exercise demonstrated that the model had limitations as well.

Both the observed and predicted cumulative sediment volume change shows an area of accumulation around 4000 m and scour from about 2500 m to the confluence of Pueblo Canyon with Los Alamos Canyon. The location of scour and deposition is related to channel slope. The modeled cumulative volume change tends to be inversely related to slope with deposition occurring as channel slope is decreasing and scour occurring where channel slope is increasing (Fig. 9). This indicates that modeled cumulative volume change is highly-dependent on slope; which it should be, because the Yang sediment transport relationship used in this simulation is a function of stream power (γQS). The observed cumulative volume change follows a similar trend, however the observed cumulative volume change shows the most deposition just where the slope begins to increase 4300 m upstream of the confluence.

The observation that cumulative volume change is not dependent on channel slope in the region of the most deposition, which peaks at river station 3350 m, indicates that some other factor is important in this region. One possible reason is the potential for transmission losses, which HEC6T does not describe, to increase in this portion of the

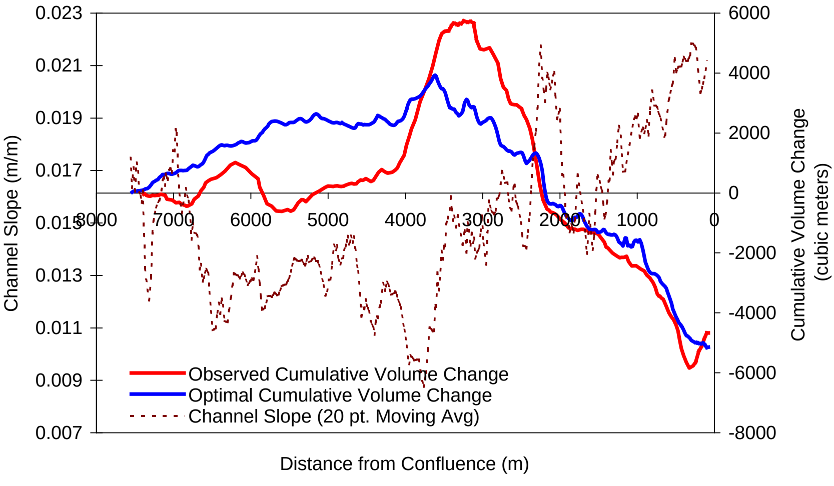

Fig. 9. Comparison of model cumulative scour, observed cumulative scour and channel slope.

channel. In ephemeral streams, the discharge from a reach is lower than the discharge entering a reach, which must therefore either increase the sediment concentration, or deposit sediment so that transport capacity of sediment leaving a reach is in balance with the sediment load just as it enters the reach.

Sediment supply to Pueblo Canyon in the wake of the Cerro Grande Fire has been estimated at about 35,000 tons from a 100-year runoff event (Wilson et al., 2001). The calibration simulation delivered 18,000 tons of sediment to the top of Pueblo Canyon and 12,000 tons out, resulting in net scour of about 6000 tons of sediment. Furthermore, this simulation included discharges an order of magnitude larger than previously observed, with concentrations that must be considered to be very high. These estimates indicate that considerable volumes of sediment are still available to be supplied to the channel, and the pulse of sediment released by the fire will continue to move into and through the channel network for years to come. Still, it is notable that while deposition is occurring between 3350 m and 4000 m, Pueblo Canyon is a net scour system. Therefore, the channel is scouring previously-deposited channel sediment even as sediment delivery to channels has increased, because runoff rates and amounts in the channel have also increased.

The peak runoff from the July 2, 2000 event is two orders of magnitude greater than any event in the previous seven years, and therefore must be considered to have been a low frequency event, based on pre-fire flow-frequency estimates. Sufficient data are not yet available to quantify its flood frequency in a post-fire environment.

While the HEC6T model performed well in this study, there are limitations. For example, the fact that modelers needed to understand the behavior of the prototype and represent this in the conceptual representation presents a limitation. In this case, the model could be calibrated against observed data of scour and deposition. A conceptual representation was formulated by studying the behavior of the prototype after the 40 m^3/s flow. Furthermore, initial values for the shear stress entrainment parameters must be obtained experimentally. In addition, while the model performed well, multiple parameter sets were shown to result in a similar goodness of fit with the observed data.

While the impact of scour and deposition may be important for contaminant transport in Pueblo Canyon, HEC6T may have a more general use in modeling the impact of fire on scour and deposition in channels in post fire-conditions. With the observed increase in burned areas over the past decade in Arizona and New Mexico, channel scour and deposition under post-fire conditions may be severely altered. Increased post-fire runoff rates and the post-fire infusion of sediment to channels from destabilized hillslopes have the potential to dramatically alter the pattern of flooding and flood-plain mapping. The smaller the affected drainage area, the greater the relative impact is likely to be.

5. Conclusions

Area burned by wildfire has increased in Arizona and New Mexico during the past decade. As a consequence, runoff and erosion has been observed to increase on hillslopes. This influx of sediment to channels can change the channel geometry. In Pueblo Canyon, near Los Alamos New Mexico, locations of increased scour and deposition have been identified using ALSM before and after a series of events including an event twice as large as the initial estimate of the 100-year runoff event. The HEC6T model could be used to model this post-fire change in scour and deposition. However, as a model that can predict general scour and deposition, the model could estimate increasing volume change in portions of the channel with decreasing slope, but could not predict increasing volume in a portion of the channel with increasing slope that experienced the highest cumulative volume increase. Virtually all the sediment transport equations available in HEC6T, including the unit stream power approach used in the Yang (1973) equation used in this simulation, are dependent on slope. As such, other conditions would need to become more important for deposition to occur in a location of increasing slope. Therefore, HEC6T proved to be an effective model for predicting changes in scour and deposition in the wake of wildfire, but cannot predict change (without the inclusion of knowledge of other processes and controls) if inputs to the sediment transport equations do not support the observed scour or deposition patterns.

Acknowledgements

The authors would like to thank the Cerro Grande Recovery Project at Los Alamos National Laboratory. We want to thank Tori George and Steve Mee of FWO-CGRP for their support. Steve Rae and Dr. Everett Springer provided modeling team leadership and supervision throughout the three-year effort. Dr. T. Andrew Earles and Tom Langan of Wright Water Engineers provided technical advice on application of the HEC-RAS model. Dr. Steve Reneau, Dr. Tom Dunn and Dr. Joseph McNeil provided helpful input to the sediment transport modeling effort. Dr. Mary Nichols provided editorial help in preparation of the manuscript.

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