EVALUATING SEDIMENT SOURCES, EROSION, AND TRANSPORT PROCESSES IN THE UPPER YUBA RIVER WATERSHED, CALIFORNIA

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Abstract: In this study a conceptual model of sediment sources, erosion, and transport processes was developed and sediment-transport studies were conducted in the upper Yuba River watershed located in northern California. Field observations of sediment production due to mass wasting, channel storage volumes, and the relative importance of sediment sources, erosion, and transport processes were used to develop the conceptual model. A geographic information system (GIS) was used to spatially distribute hillslope erosion potential and channel storage throughout the study area. The GIS-based hillslope erosion-potential model illustrates that landscapes with low potential evapotranspiration, sparse vegetation, steep slopes, erodible geology and soils, and high road densities display the greatest hillslope erosion potential. Although mass wasting was observed to be the dominant hillslope erosion process, fluvial erosion of stored sediment is the primary contributor to the annual sediment yield based on model assumptions and field observations.

Sediment-transport studies included development of suspended-sediment and bed-load rating relations and estimates of annual sediment discharge at two gaging stations, from October 1 to September 30 of water years (WY) 2001, 2002, and 2003. Seasonal suspended-sediment rating curves were developed using a group-average method and non-linear least-squares regression of measured data; whereas bed-load rating curves were estimated using an empirical bed-load transport model. Due to its larger drainage area, higher streamflow, and absence of man-made structures that restrict sediment movement in the lower basin, the South Yuba River (5 tonnes/km^2/yr) transports a greater and coarser sediment load than the Middle Yuba River (2 tonnes/km^2/yr). In both rivers, bed-load represented 1 percent or less of the total annual load throughout the three-year project period. Relatively dry conditions prevailed during the project period; therefore, the calculated average annual sediment transport may not represent longer-term conditions.

INTRODUCTION

This study is part of the California Bay-Delta Authority (CBDA) Upper Yuba River Studies Program (UYRSP), which is currently evaluating options for introducing spring-run Chinook salmon and steelhead trout upstream of Englebright Lake located in the foothills of the northwestern Sierra Nevada, CA (Figure 1). During the initial phase of the UYRSP, conceptual and GIS models (Curtis et al., 2005a) provided a means of identifying potentially important sediment sources and evaluating erosion and transport processes, and were further utilized to develop a deterministic watershed-scale sediment-transport model (Flint et al., 2004). Sediment rating curves (Curtis et al., 2005b) were used to assess the magnitude and duration of sediment loads that may impact the viability of long-term fish-introduction strategies (Curtis et al., 2004) and were further utilized to calibrate the watershed model.

Study Area: The Yuba River, a tributary to the Feather River in northern California, drains approximately 3,480 km^2 along the western slope of the Sierra Nevada (Figure 1). The study area is located within the upper Yuba River watershed, a heavily managed basin recovering from hydraulic gold mining (Gilbert, 1917), and includes two tributaries: the Middle Yuba River and the South Yuba River. The climate is Mediterranean with hot/dry summers and cool/wet winters. Runoff is typically generated by warm, winter Pacific storms, spring snowmelt, or occasionally by convective storms generated in the late summer or early autumn by subtropical air masses from the Gulf of Mexico. Beginning in November, Pacific frontal systems bring winter precipitation into northern California, resulting in about 85% of precipitation falling between November and April.

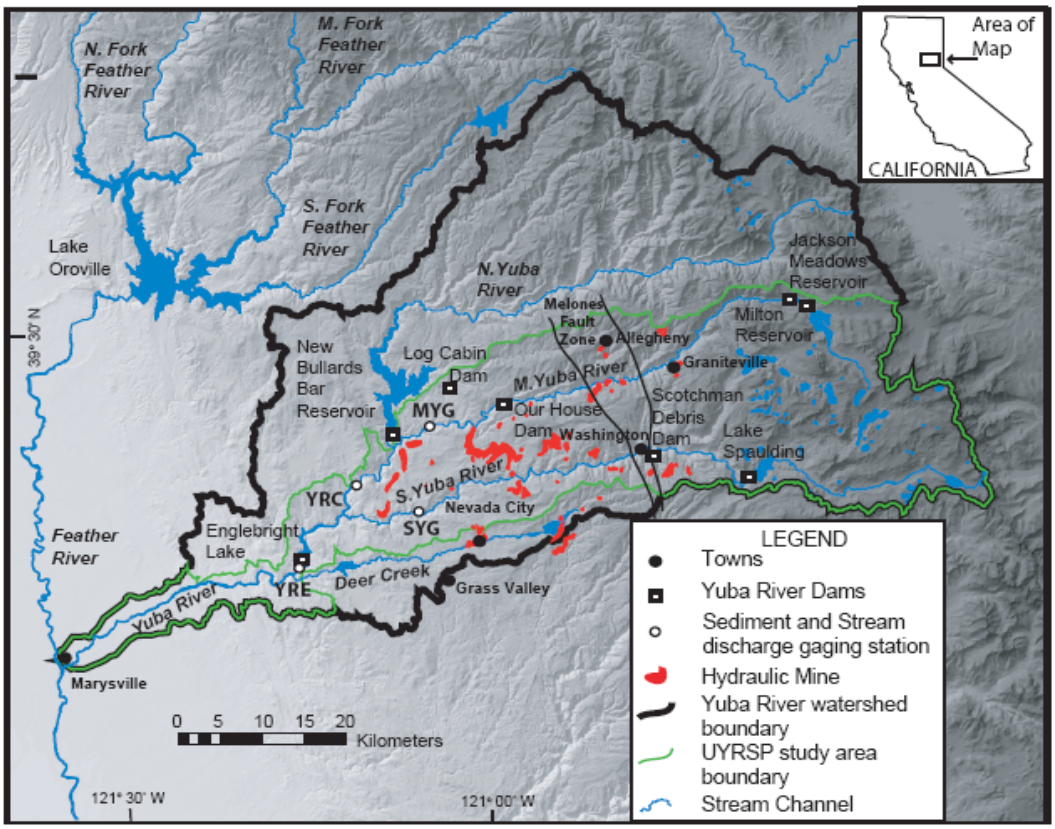

Figure 1 Study area map. MYG = Middle Yuba River gage; SYG = South Yuba River gage.

METHODS

Verifying, Refining, and Spatially Distributing Components of a Conceptual Model: An initial hypothesis of a conceptual model of upper Yuba River sediment dynamics was verified, refined, spatially distributed and used to discretize hillslopes units in the deterministic watershed model developed for this site (Flint et al., 2004). Subsequent aerial-photo and field observations clarified the relative importance of model components and identified sediment-source locations where key transport processes occur, thereby enabling verification and refinement of the model. As important sediment sources and transport processes were illuminated, components and linkages in the initial conceptual model were removed or moved, and line thicknesses indicating the relative magnitude of transport processes were defined (Figure 2).

Field measurements at mass-wasting sites (n=22) included scarp areas, mean evacuated depth, and sediment delivery (Figure 3). Surface erosion rates were not quantified; however the relative importance of surface and mass-wasting processes were evaluated at an additional 39-hillslope sites where the type and relative severity of hillslope erosion were documented. Field measurements at channel storage sites included length, width, and height of discrete channel storage elements (debris jams, channel bars, floodplains, and terraces).

The channel-storage and hillslope erosion-potential components of the conceptual model were spatially distributed using GIS. Development of the spatially distributed channel-storage component was a three-step process: 1) cumulative channel lengths for zero- through fifth-order stream channels were defined using a digital elevation model, 2) the arithmetic mean of storage volumes for individual storage elements (debris jams, bars, floodplains, and terraces) was calculated for each stream-order class, and 3) the arithmetic mean of storage volumes for each stream-order class were multiplied by channel lengths to provide basin-wide estimates. The spatially distributed hillslope erosion-potential component was developed using a raster-based map of hillslope erosion-potential generated at a 30-meter grid resolution. The first step in developing the hillslope erosion potential map was to

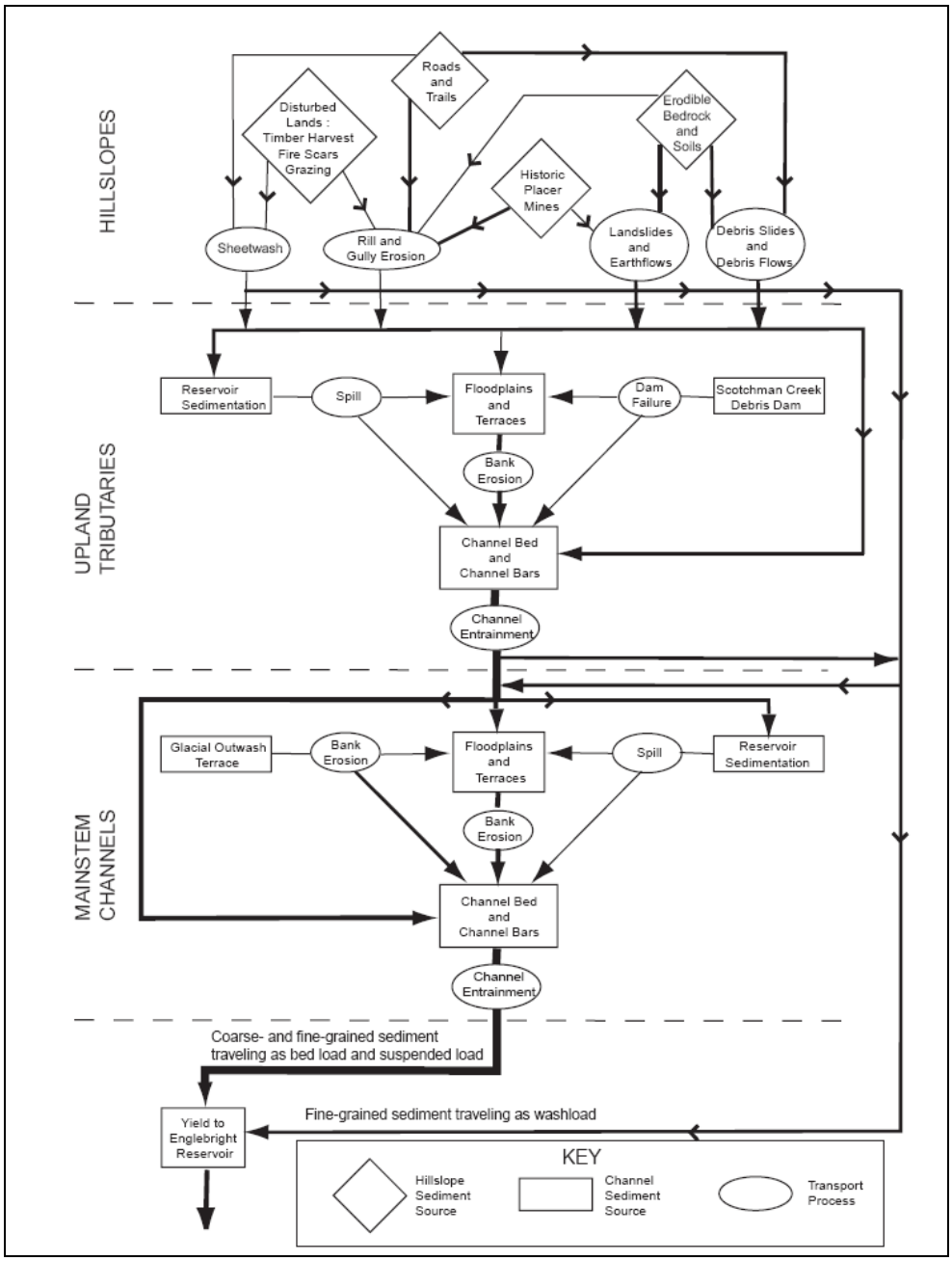

Figure 2 A conceptual model of sediment processes partitioned into three components: hillslopes, upland tributaries, and mainstem channels. The three components are further compartmentalized into hillslope sediment sources, channel sediment-storage elements, and transport processes. Arrows with variable line thickness denote linkages between compartments and transport directions. The hypothesized relative magnitude of basin-wide sediment transport is indicated by line thickness (i.e., thicker lines represent greater transport). Note: figure reproduced from Curtis et al. (2005a) Figure 3.

develop a matrix of landscape attributes governing hillslope erosion processes with scaling factors and relative multipliers assigned based on field observations. The scaling factors signify the inferred or measured range of values associated with each landscape attribute and the multipliers indicate the comparative importance, with larger values indicating greater importance. In the second step, landscape attributes were defined for each 30-meter grid cell using a digital elevation model and digital maps of geology, soils, vegetation, roads, hydrography, and mined

areas. An estimate of total potential evapo-transpiration (PET) for the month of April was simulated using climate data and the digital elevation model. In the final step, a calculation of hillslope erosion potential was developed that accounts for all contributing factors based on landscape attributes. The final calculation used to produce a hillslope erosion-potential map was additive, where hillslope erosion potential equals [elevation * 6]+ [(slope * geology + kfactor) * 9] +[(roads + mines + mass wasting sites + stream crossings) * 10] – [PET *4] - [vegetation cover * 6].

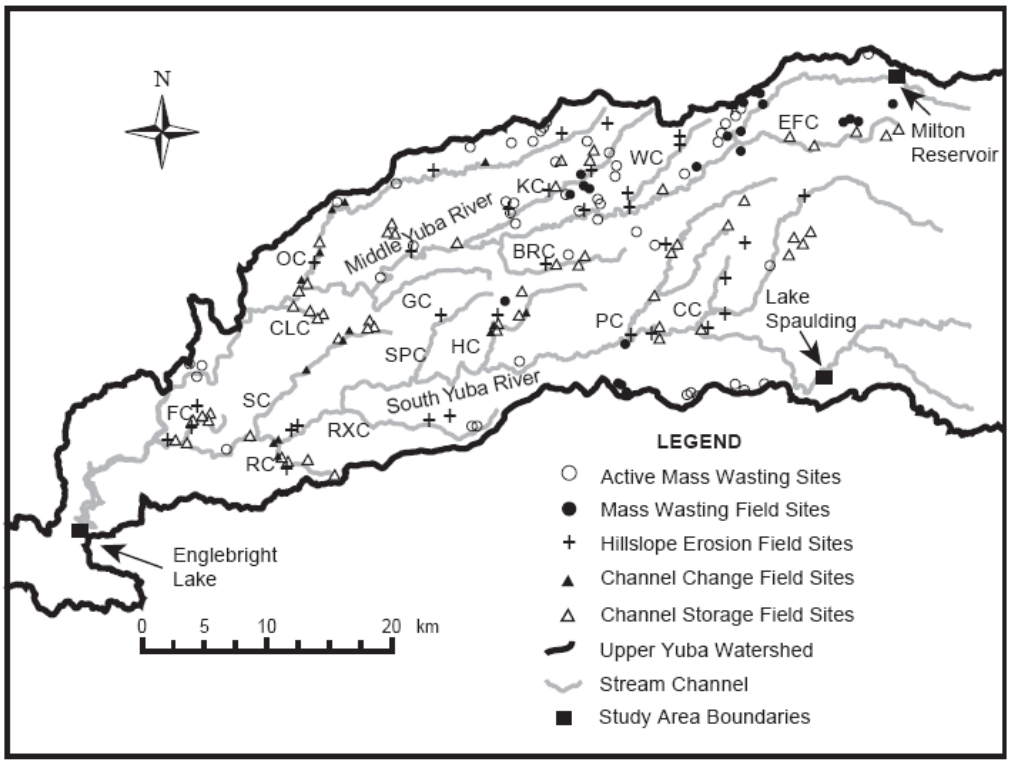

Figure 3 Map of study area showing field sites. Abbreviations for upland tributaries labeling are: FC, French Corral Creek; SC, Shady Creek; RXC, Rock Creek; SPC, Spring Creek; HC, Humbug Creek; PC, Poorman Creek; CC, Canyon Creek; CLC, Clear Creek; OC, Oregon Creek; GC, Grizzly Creek; BRC, Bloody Run Creek; KC, Kanaka Creek, WC, Wolf Creek; EFC, East Fork Creek.) Note: figure reproduced from Curtis et al. (2005a) Figure 4.

Sediment Rating Curves to Characterize Sediment Transport: To verify the conceptual model and help calibrate the deterministic watershed model developed for this study site, a series of seasonal suspended-sediment and bedload rating curves were developed for the Middle Yuba River and South Yuba River gaging locations shown in Figure 1 (Curtis et al., 2005b). Suspended-sediment rating curves that describe seasonal variations in suspended-sediment supply were developed using depth-integrated, single vertical suspended-sediment samples. The measured data indicate that seasonal variability in sediment supply dramatically influences sediment transport in the upper Yuba River watershed and that a single suspended-sediment rating curve cannot represent these varying conditions. Therefore, a series of group-average sediment rating curves that describe average, summer/fall, first flush, winter, and spring snowmelt conditions were developed for the Middle Yuba River and South Yuba River gage locations using non-linear least-squares regression.

Bed-load rating curves were estimated using an empirical bed-load transport relation (Wilcock and Crowe, 2003). Calculating the bed-load transport rate for a given stream discharge required estimates of the surface grain-size distribution, water-surface slope, and bed-shear velocities. Laboratory analyses of bed material from the Middle Yuba River and South Yuba River gage sites were used to define surface grain-size distributions. Water-surface slopes were determined from longitudinal surveys of water-surface elevations measured using a surveyor's transit level and a stadia rod along 500 feet of channel distance. Bed-shear stress can be partitioned into skin friction (the portion of stress that is exerted on individual grains and responsible for transport) and form drag (attributable to

large roughness elements, such as bedforms, boulders, bedrock outcrops, or large trees within the active channel). Because bed-shear stresses in the upper Yuba River include a significant component of form drag, this term was removed before computing the bed-shear velocities.

Annual sediment discharge was calculated at the Middle Yuba River and South Yuba River gage locations for water years 2001, 2002 and 2003 using sediment rating curves. Suspended-sediment discharge was calculated using seasonal suspended-sediment rating curves (developed using measured data) and mean daily streamflow data. Bed-load discharge was calculated using bed-load rating curves (developed using estimated data) and 15-minute streamflow data.

RESULTS

Field observations of hillslope sediment sources indicate low hillslope erosion rates throughout the study area. Based on field measurements, 95% of the upper Yuba River watershed exhibits negligible to moderate hillslope erosion potentials (Figure 4). Evidence of active hillslope erosion (rilling, gullying, and mass wasting) was documented at 44% of the 39-hillslope sites shown in Figure 3. Mass wasting was documented at 88% of the eroded sites and dominates surface erosion, which was observed at 41% of the eroded sites.

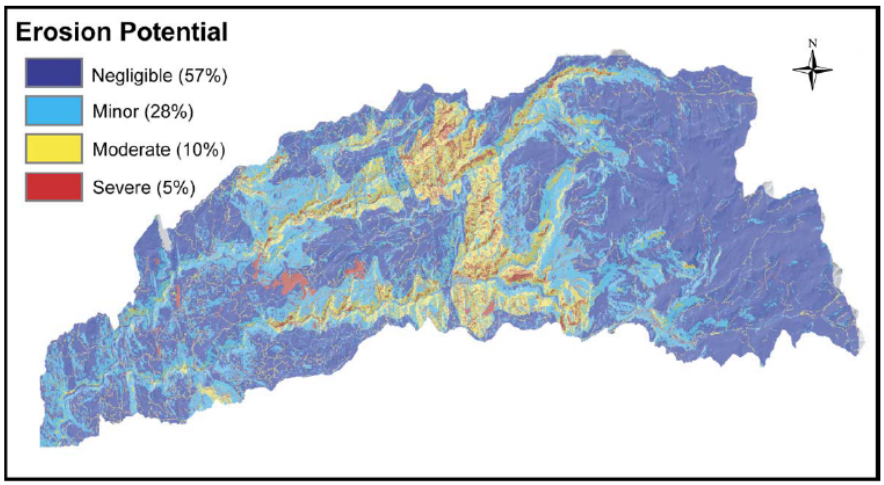

Figure 4 Hillslope erosion potential map generated using GIS calculations. The relative erodibility classes (negligible, minor, moderate, and severe) are based on field data from 39 hillslope sites. Note: figure reproduced from Curtis et al. (2005a) Figure 5.

Analysis of field measurements spatially distributed using GIS indicate that approximately 482 million m^3 of sediment is stored above the thalweg in zero- through fifth-order upper Yuba River channels. Debris jams store the majority of sediment in zero-order channels whereas 62% to 93% of alluvium in first- through fifth-order channels is stored in well-vegetated terraces that are for the most part inactive and stable. Large volumes of hydraulic mining sediment are stored in several low-order upland tributaries and an extensive glacial outwash terrace is preserved on the mainstem South Yuba River.

Suspended-sediment concentrations generally increase with increasing streamflow, however the slopes of seasonal suspended-sediment rating curves differ significantly (Figure 5). Variations in the slopes of the rating curves indicate changes in suspended-sediment supply throughout the water year. During average and below-average precipitation conditions such as those which occurred during the study period, sediment supply is greatest during the first flush of the water year; consequently the first-flush rating curves display the greatest slopes. Sediment supplies decreased following the first flush; thus, the slopes of the winter rating curves are lower than the first-flush curves. The spring and summer/fall rating curves had the lowest slopes, indicating lower sediment supplies during spring snowmelt conditions and throughout the dry summer and fall months.

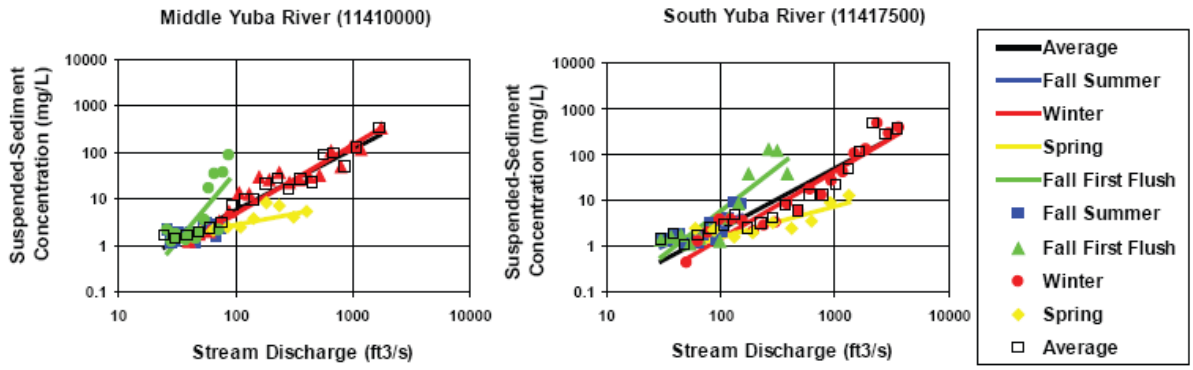

Figure 5 Group-average non-linear regressions between suspended-sediment concentration and instantaneous streamflow for the Middle Yuba River and South Yuba River gaging stations in the upper Yuba River watershed, California.

Estimated annual sediment discharges at the Middle Yuba River gage were significantly lower than those at the South Yuba River gage even when normalized by drainage area (Table 1). The main contributing factor to the difference in sediment loads is that 88 percent of the Middle Yuba River watershed lies upstream of Log Cabin and Our House Reservoirs. This effect is compounded by significant flow diversions above the Middle Yuba River gage, which resulted in a median daily flow for the project period of 1.6 m^3/s at the Middle Yuba River gage compared with 2.8 m^3/s at the South Yuba River gage. Because the South Yuba River has higher flows and no man-made restrictions to sediment movement in the lower basin, it is able to transport a greater and coarser sediment load. The percentage of annual sediment discharge transported as bed load was less than 1 percent throughout the study period, which was quite low and unexpected, given the abundance of bed material available for transport. Below-average to average precipitation conditions occurred throughout the project period, which likely influenced the volume of bed-load transport.

Table 1. Annual sediment discharge and bed-load estimates.

Year	Annual suspended-sediment discharge (tons/yr)	Annual bed-load discharge (tons/yr)	Total annual sediment discharge (tons/yr)	Annual sediment yield (tons/km^2/yr)
South Yuba River (SYG, Station ID 11417500 [drainage area 798 km^2])				
2001	660	1	661	1
2002	4,300	16	4,316	5
2003	6,900	89	6,989	9
Average annual sediment discharge			3,989	5
Middle Yuba River (MYG, Station ID 11410000 [drainage area 513 km^2])				
2001	140	0	140	0
2002	830	3	833	2
2003	1,800	19	1,819	4
Average annual sediment discharge			931	2

CONCLUSIONS

A conceptual model was used to evaluate sediment sources, erosion, and sediment transport in a dominantly bedrock basin impacted by hydraulic mining. Field observations and the conceptual model were used to develop a deterministic watershed-scale sediment-transport model. Sediment rating curves were used to assess the seasonal variability in sediment transport and to calibrate the watershed model. Field measurements indicate that mass wasting dominates surface erosion throughout the study area; however hillslope erosion rates are relatively low. The large volume of sediment stored in active to semi-active channel locations represents the dominant sediment source. GIS analyses further indicate that principal sediment sources are located in the central portion of the watershed

where the greatest hillslope erosion potential is displayed and large quantities of active alluvium are stored. During average and below-average precipitation conditions, such as those which occurred during the study period, sediment supply is greatest during the first flush of the water year. Sediment supplies decreased following the first flush; thus, the slopes of the winter rating curves are lower than those of the first-flush curves. The spring and summer/fall rating curves had the lowest slopes indicating relatively low rates of suspended-sediment transport during snowmelt conditions and during the dry season. Due to its larger drainage area, higher streamflow, and absence of man-made structures that restrict sediment movement in the lower basin, the South Yuba River (5 tonnes/km^2/yr) transports a greater and coarser annual sediment load than the Middle Yuba River (2 tonnes/km^2/yr). In both rivers, estimated bed-load represented 1 percent or less of the total annual load throughout the three-year project period. Owing to relatively dry conditions during the project period, the calculated average annual sediment transport rates may not represent longer-term conditions.

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