Sediment Transfer through the Fluvial System (Proceedings of a symposium held in Moscow, August 2004).
IAHS Publ. 288, 2004

Relative effects of fluvial processes and historical land use on channel morphology in three sub-basins, Napa River basin, California, USA

SARAH A. PEARCE & ROBIN M. GROSSINGER
San Francisco Estuary Institute, 7770 Pardee Lane, Oakland, California 94621, USA
sarahp@sfei.org

Abstract Fluvial geomorphology and historical geomorphology studies were conducted on three sub-basins in the Napa River basin. Despite proximity of the sub-basins, differing physical and climatic settings, land-use histories, and channel modifications have resulted in substantially different sediment sourcing, storage, and transport to the Napa River. We present three examples in which the partnering of field-based fluvial geomorphic data and archival data has fostered a greater understanding of the observed channel morphology and fluvial processes, and how the channel has responded to anthropogenic modifications. Comparatively, sediment sourcing and transport to the Napa River is greatest in Sulphur Creek, followed by Carneros and Soda Creeks, respectively.

Key words California; channel modification; channel morphology; historical ecology; land use; Napa River; sediment supply

INTRODUCTION

It is generally recognized that channel conditions observed in a given watershed are the product of a combination of physical, climatic, and anthropogenic processes. Identifying which factors are most responsible for observed conditions is often a challenge, typically necessitating the involvement of other disciplines in addition to applied fluvial geomorphology. Through a series of related studies in the Napa River basin, we had the opportunity to conduct synchronized field geomorphology and historic geomorphology studies in three sub-basins. Due to excess sediment in the Napa River and associated habitat degradation of key native fish species (Stillwater Sciences, 2002), and the need to determine the contribution of local basins to the overall sediment budget of the San Francisco Bay (McKee *et al*., 2002), there is substantial current interest in determining the natural variation and anthropogenic influence on channel morphology, sediment supply, and sediment transport through small tributaries.

Despite close geographic proximity (within 30 km of each other), and generally similar, semi-rural settings, each sub-basin has distinctly different underlying lithology, annual precipitation totals, historic and current land use, and extent of anthropogenic modification to the fluvial system. From these studies, we quantify and describe the three distinct sub-basin scale channel morphologies, dominant geomorphic processes, primary sediment sources, styles of sediment storage, and relative volumes of sediment supply to the Napa River. We present evidence from example locations that illustrate how historic land use and channel modification have affected modern channel morphology, process and management priorities.

STUDY AREA

The Napa River basin comprises an 1103 km^2 area that drains into the San Francisco Bay, in northern California, USA. The basin has a Mediterranean climate, receiving an average of 90% of annual precipitation between November and April. Precipitation depth varies generally with elevation from about 500 mm at the river mouth (sea level) to about 1500 mm in the headwaters (maximum elevation 1325 m). Headwater first order drainages exhibit gradients of up to 30%. Large variability exists in the amount of water and sediment delivered to the main stem by the 46 named tributaries. This paper details studies that were completed on three tributary sub-basins: Soda, Sulphur, and Carneros Creeks during 2001 and 2002 (Fig. 1). The primary goal of these studies was to understand the relative influences of natural and human activities on sediment processes in a subset of physical settings within the larger Napa River basin.

METHODS

Fluvial geomorphology study

Process-based field studies focused on collecting detailed data for each channel, including: identifying sediment sources, storage volumes and locations, and transport processes and relative volumes; measuring in-channel large woody debris (LWD) densities; and measuring

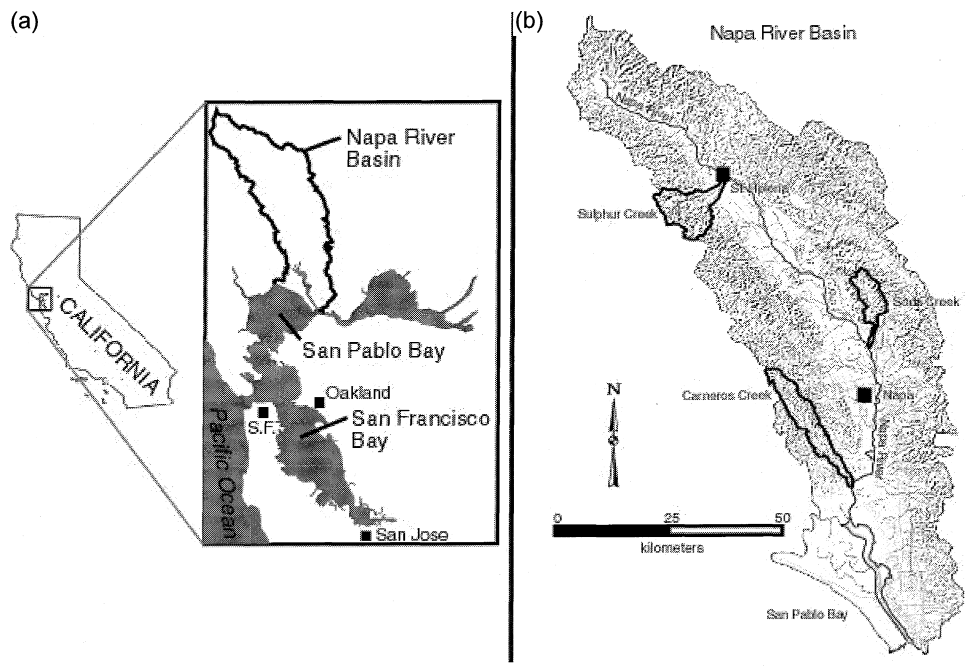

Fig. 1 (a) Map of San Francisco Bay and the Napa River basin area. (b) Map of the Napa River Basin showing the location of the Soda Creek, Carneros Creek, and Sulphur Creek sub-basins, and the towns of Napa and St Helena.

pool depths, spacing, and sediment in-filling. A stratified random sampling plan was developed to collect detailed data in 10 sample reaches (each reach is 25 bankfull widths in length) of each creek. These sample reaches were selected to represent the natural variability found within each sub-basin, allowing interpretation of the form and function of the entire channel length from a smaller but more detailed sample reach dataset.

Historical geomorphology study

Archival research techniques were used to build a reliable historical dataset for analysing questions about historical land use and channel change in the three sub-basins. Many types of historical data were utilized, including: aerial photographs, maps, land grant surveys and court documentation, historical documents, long-time resident interviews, field documentation of residual features, and historical climatic records. The historical dataset was calibrated and synthesized using techniques described in Grossinger (2001). Data from both study components were collected iteratively and analysed together, in order to determine the physical processes responsible for sediment supply and transport through each basin.

RESULTS

Current channel morphology in each sub-basin reflects a unique adjustment to physical, climatic and anthropogenic processes. The following details major findings in each sub-basin (Table 1).

Table 1 Geomorphic and historic characteristics of three Napa River sub-basins.

	Soda Creek	Carneros Creek	Sulphur Creek
Primary source of sediment	Hillslopes, bank erosion	Bank erosion, land use, landslides	Landslides
Total volume of measured sediment in storage (m^3)	1447	3053	9848
Volume of sediment storage per unit channel length ($m^3\ m^{-1}$)	0.2–2.3	0.5–3.2	0.2–14.1
Primary storage location	Large in-channel bars	In-channel bars and terraces	Alluvial fan, in-channel bars, terraces
Current relative supply to the Napa River	Low	Moderate	Moderate to High
Spanish era grazing?	No	~25 years intensive grazing	No
First railroad crossing the creek	None	1905	1866
Extensive historical logging/clearing?	No (?)	Yes	Yes
Substantial channel reaches rerouted?	Yes, 600 m	No	Yes, 600 m
Mouth of channel relocated?	Yes	No	No
Flood control channel?	No	No	Yes

Soda Creek

Soda Creek is a 12.2 km^2 sub-basin underlain by Plio-Pleistocene pyroclastic Sonoma Volcanics, with 610 (mouth) to 914 mm (headwaters) mean annual precipitation and comparatively low sediment production and transport to the Napa River. The channel transitions from a narrow headwater stream with little sediment storage, to a broad channel with many bedrock outcrops in the middle reach, to an entrenched alluvial channel in the lowest reach. Generally, the channel bed has a coarse grain size distribution, largely dominated by cobble and boulders, with very little fines. The current primary source of sediment is from hillslope interactions with small zero-order channels as well as from localized bank erosion. The highest volume of bank erosion was measured in the modified lowest reach (1.5 m^3 m^{-1}). However, this reach also stores the most sediment, in the form of a few large bars. Throughout the sub-basin, stored sediment volume ranged from 0.2 to 2.4 m^3 m^{-1} of channel. Shear stress analyses suggest that only two of 10 sampled reaches have ratios of total to threshold shear stress low enough to encourage channel aggradation.

Soda Creek has experienced relatively non-intensive land use since the time of European contact (*c.* 1810). The lowest reach of Soda Creek, however, has experienced significant channel modification that had not been previously recognized. Historical maps and photographs show that Soda Creek was disconnected from approximately 5 km of its historical drainage system by the filling of a 600 m section of stream channel, and the relocation of the channel mouth (Fig. 2). Prior to this diversion, the creek joined the neighbouring sub-basin along with two other creeks, before joining with the Napa River farther downstream than its current confluence. This tributary system had low channel gradient, stored large volumes of sediment as large bars and flood plain deposits, and likely provided high quality riparian habitat for animals and anadromous fish such as a local endangered trout species (*Oncorhynchus mykiss*). Between 1938 and 1942, the channel was redirected from its previous tributary system, to a more direct connection with the Napa River, presumably to allow faster drainage of Soda Creek while increasing the area available for agriculture.

Today, the redirected reach of Soda Creek is entrenched, sinuous, and highly dynamic, contains deep pools and large bars, and has the highest rates of bank erosion measured in the entire sub-basin. In addition, this reach now experiences backwater flood hazards when the Napa River is in flood. Evidence for flooding over the current Soda Creek banks towards its former route is provided by local recollections and bank stabilization efforts at that location. The likely effects of changing the course of Soda Creek include: an adjustment in grade to the new local base level and associated increased sinuosity, a greater connectivity for sediment delivery to the main stem Napa River, decreased length and quality of fish habitat, increased bank erosion associated with channel incision, decreased access to the flood plain, and increased backwater flood hazards during high Napa River stages. These findings provide context for any future channel restoration of this reach.

Sulphur Creek

Sulphur Creek is a 24.2 km^2 sub-basin underlain by Cretaceous and Jurassic Franciscan Formation (accretionary wedge prism) notorious for its erosion potential, with 886 mm mean

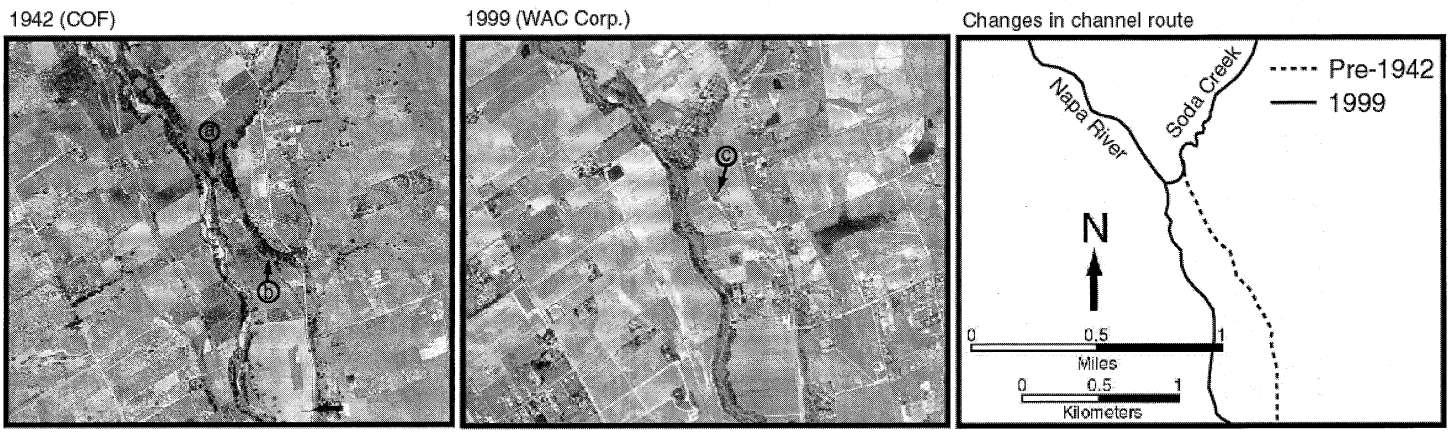

Fig. 2 Comparison of the lower reaches of Soda Creek. Aerial photographs from 1942 (COF) and 1999 (WAC Corp.). (a) Young riparian vegetation suggesting recent channel relocation. (b) Previous route of Soda Creek. Notice the mature vegetation. (c) Agricultural reservoir occupying the previous channel location. Third panel highlights the changes in channel route visible in the photographs.

annual precipitation, high sediment production, and comparatively moderate to high transport of sediment to the Napa River. The channel transitions from a narrow, boulder dominated headwater stream to a wider alluvial channel, to a broad, braided alluvial channel on the alluvial fan, finally to a highly entrenched and modified flood control channel in the lowest reach. The primary source of sediment is from landslides and other hillslope mass-movements that are directly connected with the fluvial system, including a single large slide named Devil's Slide that has been documented back to 1869. Sediment contribution from bank erosion attains a maximum of 17 $m^3 m^{-1}$ in reaches where landslides impinge on the channel. Sulphur Creek's large alluvial fan is the most significant location for sediment storage; however other areas such as terraces and bars downstream of landslides are locally significant. Throughout the sub-basin, stored sediment volume ranges from 0.3 to 14.1 $m^3 m^{-1}$ of channel, with the highest volumes measured in the alluvial fan reaches. The abundant sediment supply maintains a gravel bed texture, despite high bed shear stresses that would otherwise be expected to produce channels armoured with cobbles and boulders. Not surprisingly, the lowest shear stress values were calculated for the alluvial fan reaches.

In comparison to Soda Creek, Sulphur Creek has experienced a relatively dynamic and intensive land-use history. At the time of European contact, the basin was managed by native California peoples, who used controlled burns to shape vegetation patterns. After Europeans arrived, portions of the upper watershed were grazed and logged. Beginning in the late 1800s, gravel mining operations took advantage of the gravel storage in the alluvial fan and its natural replenishment during wet season floods. The mine was in operation until 1999, and provided much of the material for railroad and roadbeds throughout the Napa Valley. Over the past half century, the growing town of St Helena gradually encroached upon the creek, eventually necessitating channel modifications, including channel redirection and a flood control channel. Recent changes in land use, including increased road densities and hillside viticulture, are increasing the overall sub-basin sediment supply. However, our findings suggest that the contribution from landslides still far outweighs contributions from other sources.

Many major, but differing, channel modifications were also identified in this sub-basin, especially in the alluvial fan reach. The high natural sediment supply (documented by early descriptions of large landslides) in this watershed helped to develop the alluvial fan, with its large bars and terraces. However, for over a century, this sediment storage was counterbalanced by anthropogenic extraction of gravel from the channel. Interviews with gravel miners confirmed the methods and volumes of historic gravel withdrawal, and the seasonal natural replenishment of sediment in the extraction reach. Nearly 5 years have elapsed since the cessation of mining, and interviews with locals suggest that substantial channel aggradation has occurred. If this trend continues, the alluvial fan reach of Sulphur Creek may cause flood hazards for the community.

Carneros Creek

Carneros Creek is a 23.0 km^2 sub-basin underlain by Cretaceous and Miocene sandstones, siltstones and mudstones, with 710 mm mean annual precipitation and comparatively moderate sediment production and transport to the Napa River. The channel transitions from a narrow, boulder dominated headwater reach, to a channel with bedrock outcrop and high rates of bank erosion in the middle reaches, into a highly entrenched channel with some large bars and fine sediment deposits in the lowest reaches. The primary source of sediment is localized bank erosion, with smaller contributions from hillslope landslides and slumps, and land uses such as grazing and viticulture. The highest volumes of bank erosion were measured in the middle reaches, averaging 3.7 m^3 m^{-1}. Sediment storage occurs as active channel deposits (annually mobile sediment in riffles, glides and runs) in the upper middle reaches, large bars in the lower-middle reaches, and pool deposits in the lowest reaches, with volumes ranging from 0.5 to 3.2 m^3 m^{-1} of channel. Shear stress analyses suggest the lowest reaches have a very low threshold shear stress, indicating that the stored volumes of fine sediment in the long, slow-velocity pools can be easily re-entrained.

Carneros Creek has experienced a complex agriculturally-oriented land use-history, yet with few major direct modifications to the channel. Due to the proximity of the Sonoma Mission (one of 21 Spanish missions in California), the Carneros lands were used as pasture for cattle and sheep as early as the 1820s. Later, the basin was developed for a series of agricultural crops, and continued grazing. In recent decades, viticulture has mostly replaced orchards and grains. Land use since European contact has likely increased the volume of sediment supplied to the channel. The primary sediment supply, bank erosion in the middle reaches, is likely caused by historic and recent intense cattle grazing. Interviews with landowners confirm that bank trampling and nearly complete removal of vegetation on the banks by grazing occurred, providing a likely cause for the current measured high rates of erosion. Grazing operations have ceased in this location, allowing re-vegetation of the banks, and the potential for future bank stability. Upstream, some grazing still occurs, but efforts to fully fence cattle out of the channel are contributing to increased bank stability.

Despite the intensive and prolonged land use, there is only evidence of minor changes to channel banks and little evidence of major channel modifications on the order of those documented in Soda and Sulphur Creeks. Analysis of historic maps indicates that Carneros Creek has experienced little redirection, straightening, meander loss, or incision since European contact (Fig. 3). Although the highly entrenched lower reach is providing a source of sediment to the channel, conclusive evidence of recent channel incision was not found. However, evidence of channel widening, or bank lay-back was documented. Aerial photographic comparisons show that the total width of the riparian canopy in this reach has been expanding since the first available images (1942). Currently, the banks are lined with a single row of mature bay laurel trees (approximately 50 to 100 years old), which are severely undercut. This suggests that the banks have been dynamic over this time period, possibly due to natural adjustments in channel morphology, or possibly due to a period of increased incision caused by early grazing. This process likely will continue to occur, contributing sediment to the channel, until the banks reach an angle of equilibrium.

CONCLUSIONS

Using both field and archival geomorphic methods, we studied three tributary sub-basins of the Napa River. Despite the proximity of these basins, each has a unique suite of dominant physical processes, channel morphologies, land use and channel modification histories. We have found that studies in historical ecology and geomorphology are natural partners to traditional field geomorphology studies, often providing critical information to understanding

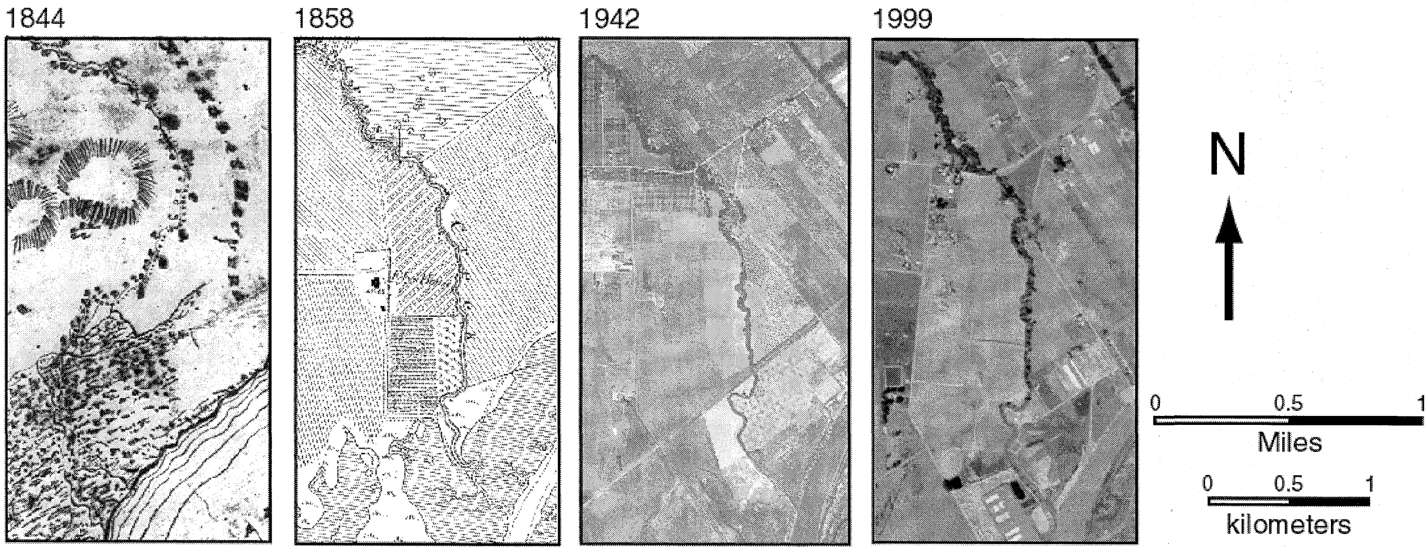

Fig. 3 Comparison of the lower reaches of Carneros Creek. Panels include: 1844 Huichica land grant (O'Farrell, 1844), 1858 US Coast Survey (USCS), 1942 (COF) and 1999 (WAC Corp.) aerial photography. Note the similarity of channel location and pattern through time.

the observed processes and morphologies, and recommending appropriate management practices. Relative contributions of sediment to the Napa River are highly variable throughout the Napa River basin, as well as between the three example sub-basins. Comparatively, Sulphur Creek contributes more sediment than Carneros Creek, while Carneros contributes more than Soda Creek. The lowest reach of Soda Creek is still responding to a 1940s era redirection of the channel, causing high bank erosion, backwater flood hazards, and increased sediment transport to the Napa River. In light of high natural sediment loads, Sulphur Creek residents must address the ramifications of increased channel bed aggradation in the alluvial fan since the cessation of gravel mining. Carneros Creek residents must address the supply of sediment to the fluvial system from high rates of bank erosion, likely caused by historic and recent grazing, in both the middle and lower reaches. Due to changing land uses and channel modifications (mainly channel simplification), the relative contribution of sediment supply and transport to the Napa River appears to have increased from pre-European contact in all three sub-basins.

Acknowledgements The authors thank the following individuals and groups for support during these studies: Napa County Resource Conservation District, USDA Natural Resources Conservation Service, the Carneros Creek Stewardship Group, the Sulphur Creek Stewardship Group, landowners of Soda Creek, Matt O'Connor and Brenda Rosser of O'Connor Environmental Inc., Lester McKee and Chuck Striplen of San Francisco Estuary Institute, and Elise Brewster of Brewster Design Arts. Funding was provided by CALFED and a Clean Water Act 205(j) grant.

REFERENCES

COF (1942) Aerial photography of the Napa Valley. 1:20 000, black and white, stereo overlap. Source: Napa County Resource Conservation District, California, USA.

Grossinger, R. (2001) Documenting local landscape change: the bay area historical ecology project. In: *The Historical Ecology Handbook: A Restorationist's Guide to Reference Ecosystems* (ed. by D. Egan & E. Howell). Island Press, Washington, DC, USA.

McKee, L., Leatherbarrow, J., Pearce, S. & Davis, J. (2002) A review of urban runoff processes in the Bay Area: Existing knowledge, conceptual models, and monitoring recommendations. A report prepared for the Sources, Pathways and Loading Workgroup of the Regional Monitoring Program for Trace Substances. SFEI Contribution 66. San Francisco Estuary Institute, Oakland, California, USA.

O'Farrell, J. (1844) Diseño Rancho de Huichica. Map D-11 in the Land Case "Huichica, Jacob P. Leese, Claimant, 50 ND." [literal attribution on map: "Jaspar Farral Agremensor y Arquitecto San Rafael"; Obtained from The Bancroft Library].

Stillwater Sciences (2002) Napa River basin limiting factors analysis. A report prepared for the San Francisco Bay Water Quality Control Board, and the California State Coastal Conservancy. Stillwater Sciences, Berkeley, California, USA.

United States Coast Survey (USCS) (1858) Napa Creek and Napa City California, Plane Table Sheet XXXII, Register no. T777.

WAC Corporation (1999) Aerial photography, 1:24 000, natural color, stereo overlap.