Impact Scales of Fluvial Response to Management along the Sacramento River, California, USA: Transience Versus Persistence

Michael Bliss Singer

> *'We…have acquiesced to the destruction and degradation of our rivers, in part because we have insufficient knowledge of the characteristics of rivers and the effects of our actions that alter their form and process.' (Leopold 1994)*

Abstract Most large rivers in industrialized nations are managed carefully to maximize their benefits (e.g., water supply, hydroelectricity), while limiting their hazards (e.g., floods). Management strategies employed in lowland river systems such as large dams, levees, and bypasses affect flow regimes, sediment supply to channels, and the net flux of sediment through river reaches fairly soon after construction. Therefore, equilibrium approaches to fluvial geomorphology are typically inadequate to characterize the effects of anthropogenic activity on management timescales (10–102 years). Each human alteration to the fluvial system has an 'impact scale' in time and space, and these impacts may manifest as persistent (steady, localized influence) or transient (dying away with distance and/or time) landscape responses. The cumulative effects of transient and persistent fluvial responses influence flood risk, the state of aquatic and riparian habitat, and the fate and transport of contaminants. Whereas some persistent impacts are straightforward to anticipate (e.g., reduced flood peaks), transient impacts may result from emergent behavior in fluvial systems and are not easily predicted. This chapter outlines the differences between these divergent landscape responses to perturbations in managed fluvial systems using examples from the Sacramento River in California. The discussion focuses on: (1) persistent local signals of altered flow regimes below large dams that attenuate in lowland valleys, (2) transient longitudinal sediment redistribution due to changes in sediment supply by dams, (3) transience in the magnitude and frequency of flow over flood control weirs into flood bypasses, and (4) persistent overbank sedimentation in localities that favor the export of sediment from chan-

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nels to floodplains. The chapter shows that persistent and transient fluvial processes coexist and interact in large, lowland river basins subject to anthropogenic perturbations in a manner that can produce unanticipated outcomes that are relevant to aquatic and riparian ecosystems, river management, as well as to human communities living in lowland floodplains. It suggests the need for more careful examination of the impact scales of river management to clarify trajectories of landform evolution.

Keywords Hydrology · Sediment transport · Levees · Flood control · Crevasse splay · Floods · Climate change

1 Introduction

1.1 Background

Rivers are fundamentally variable in space and time, and this has profound implications for existing theory in fluvial geomorphology. The theoretical framework in fluvial geomorphology is largely built upon limited observations from a range of fluvial systems with varying internal dynamics and external forcing, and which are often formalized through equilibrium-based principles imported from other disciplines. Since river management strategies generally rely on such equilibrium theoretical paradigms, river management may be limited in efficacy and sustainability. Spatiotemporal variability in geomorphic processes and fluvial forms over decadal timescales affects the 'impact scales' (spatial and temporal) of major river management projects. For example, upstream dam construction affects downstream hydrographs and sediment supply, which produce localized effects, but may also interact to create unanticipated emergent river behavior from 10s to 100s of river kilometers away from the dam site, over years to centuries with potential impacts to flood risk, habitats, etc. Likewise, along-channel embankments designed to increase channel conveyance capacity, a fundamental component of flood control systems, may affect longitudinal sediment budgets on various spatial and temporal scales and thus undermine the efficacy of engineered levees and floodways. Furthermore, interaction between external forcing (e.g., climate changes) and internal dynamics in fluvial processes may produce spatial patterns and temporal evolution of river channel boundaries and floodplain topography. These morphological changes will in turn affect engineering works constructed along large rivers, existing habitat availability and quality, as well as large-scale river rehabilitation efforts, which are increasingly implemented to counter the unforeseen negative consequences of past river engineering. However, there are great challenges to predicting the impact scales of river management. Multifaceted perspectives on existing fluvial datasets are needed to tie river management of large rivers systems to the trajectories of evolution (in time and space).

Geomorphology over the last several decades has applied quantitative principles, some developed in other disciplines, to studies of river behavior and form including the physical expenditure of energy (e.g., minimum variance (Langbein and Leopold 1966; Scheidegger and Langbein 1966)), self-similarity hypotheses (i.e., there is inherent fractal organization of drainage basins (Rodriguez-Iturbe et al. 1994; Stølum 1996)), 'ergodic' principles (e.g., space-for-time substitutions that allow for inventories of existing fluvial landforms (Paine 1985; Scheidegger and Langbein 1966), and 'geomorphic transport laws' (e.g., stream power incision (Dietrich et al. 2003). Most of these methods/concepts assume equilibrium in fluvial systems, which is rarely satisfied over human timescales (1–100 years), especially in large river basins subject to spatial variability in geology, tectonics, and climate (Dunne et al. 1998; Fischer 1994; Hack 1960; Howard 1965; Montgomery 1999; Roe et al. 2002; Slater and Singer In Press; Stark et al. 2010), and where external perturbations such as anthropogenic activity and climate change may affect fluvial system forcing in unexpected ways.

Over these human timescales, large river systems may be more realistically viewed within the construct of dynamic equilibrium (Hack 1960), where there is (are): (1) inherent transience of fluvial forms, (2) trajectories of fluvial form evolution, (3) a spatial range of landscape sensitivity (Brunsden and Thornes 1979), and (4) where differences in relief and form may be explained in terms of their spatial relationships rather than of monotonic evolutionary development (Hack 1960). In their review, Brunsden and Thornes (1979) outline the basis for transience in landscape evolution. They suggest that characteristic landforms in a drainage basin are created under constant forcing and that external perturbations may create transient behavior. The manifestation of this transience is likely to be temporally and spatially complex and may lead to diversity of landforms. Indeed various landform outcomes have been produced by driving landscape evolution models with stochastic climate variables (Tucker and Bras 2000) and by driving sediment flux models stochastically based on probability distributions of geomorphic processes themselves (Benda and Dunne 1997a, b). It has also been shown in large continental datasets that exhibit higher rates of landform change (bed elevation) in regions with more variable hydrology (Slater and Singer 2013). Brunsden and Thornes (1979) suggest that landscape stability or equilibrium of landforms is a function of the temporal and spatial distributions of the resisting and perturbing forces, which are unlikely to be well balanced on management timescales.

In this context, probability distributions of measurable fluvial system forms and fluxes could yield insight into the range of physical processes and their resultant forms over a period of decades. This is especially possible in basins endowed with excellent historical datasets on streamflow, sediment transport, storage, and topography. We might benefit from contextualizing 'mean' behavior exhibited in such datasets within more complete information on entire data distributions, especially the 'tails', which may actually have disproportionate control on the manifestations produced by the spatial and temporal integrals of fluvial processes. Furthermore, we may be able to better distinguish between fluvial forms and processes that are persistent over the relevant time scale versus those that are transient, or passing by in space or away with time. Such perspectives will provide stronger frameworks for anticipation and prediction of fluvial adjustment to perturbations, as well as defining the space and time scales over which such adjustments to management and restoration should be expected. In essence, we may view the river in terms of impact scales and the persistent and transient responses that may result from external or internal perturbations (changes in forcing) to governing physical processes, especially in managed settings where constraints are discontinuous in space and time. In this chapter, evidence for persistent and transient large river adjustment in a system that has been the object of major engineering works for nearly 100 years and, similar to many other large rivers, is currently targeted for major river rehabilitation efforts designed to ameliorate some of the negative consequences of these are presented.

1.2 Spatial and Temporal Perspectives

An individual observer traveling upstream or downstream a particular river may witness dramatic spatial differences in fundamental river characteristics (e.g., width–depth ratio, slope, sinuosity, grain size, or floodplain vegetation), many of which may exhibit abrupt transitions rather than smooth monotonic gradients. Thus, the choice of study site(s) is likely to have important implications for the interpretations of fluvial forms and processes. Likewise, when the observer returns to the same location on the river, changes in river form and functioning that occurred in the interim, may be visible and measurable, depending on the timescale of adjustment and the magnitude of the local divergences (e.g., in sediment flux). For example, an upstream dam installation or widespread deforestation in the contributing drainage basin may impact streamflow distributions and sediment supply, leading to modifications of fluvial forms at the observer's location. It is also possible that such upstream changes are propagating downstream and may not yet have reached the observer's location, potentially producing an incomplete understanding of the impending consequences of the upstream perturbations. Further, there is potential for the effects of the upstream disturbance to dissipate longitudinally, such that the observer's location is buffered from the impact of the upstream event.

Thus, problems in fluvial geomorphology must clearly be undertaken explicitly in four dimensions (i.e., planform, topography, and time), where the appropriate spatial and temporal scales must be carefully chosen to tackle the scope of a particular question. This selection of scales, especially in response to management, will determine whether a particular variable is independent or dependent to the system evolution and the trajectory of adjustments (Hudson et al. 2008; Schumm and Lichty 1965). Spatial biases may be minimized by developing synoptic vantage points from which to view the river, wherein spatial variability can be characterized by one of an increasing number of remote sensing methods (e.g., Gilvear and Bryant 2005; Kilham et al. 2012), by generalizing synchronous data from a network of monitoring stations (e.g., Singer 2007; Singer and Aalto 2009), by combining detailed contemporary field sampling with historical data and process modeling (e.g., Singer 2010; Singer et al. 2013a; Singer and Michaelides 2014) and/or by using geochronology to develop spatial links between synchronous geomorphic events (Aalto et al. 2003; Gomez et al. 1998; Walling 1999). So, for at least an instant in time (and indeed over temporal domains of aerial photography and satellite observations), we have suitable methods to describe and quantify how different parts of fluvial system compare and contrast in terms of measurable properties.

Temporal variability presents more complex challenges, primarily due to the short history of detailed, quantitative direct human observation of river systems. However, there are notable examples of long historical records of streamflow in particular regions, for example, that have fomented understanding of the controls of synoptic teleconnections (Andrews et al. 2004; Eltahir 1996) or the decadal influence of impoundments on streamflow (Magilligan and Nislow 2001; Singer 2007). Similarly, sedimentary records have been exploited in forensic geomorphic analyses (Daniels 2008; Knox 1987), although recent research has suggested potential biases in sediment records based on the overlaps in frequency of sediment delivery, hiatuses, and preservation (Jerolmack and Paola 2010; Jerolmack and Sadler 2007; Sadler 1981; Schumer et al. 2011; Schumer and Jerolmack 2009). The subject becomes increasingly complicated when we address the combined effects of spatial and temporal variability in fluvial systems. In the above example, the observer could develop a range of perspectives on the downstream impacts arising from the upstream perturbation. Spatially, this will depend on the location and the resolution of measurements. Temporally, it will depend on the frequency of visitation and the duration of the observer's career in field research. Of course, this field perspective can be aided by datasets that span great areas of a basin over decades to centuries. Fortunately, such intensive data collection is often undertaken in large river basins, where detailed understanding is required for river management that has economic dimensions (water supply, electricity generation) and implications for infrastructure and public safety (flood risk). In such basins, much can be ascertained about the external forcing and internal dynamics, by looking at these spatially extensive and long data records in creative ways. This chapter will discuss a body of work on one such river that provides a window into persistent controls and transient fluvial adjustment to perturbations. River responses to large dams and to engineered flood control levees are addressed, and a context of the river's functioning and form that may yield new, generalizable understanding of large, managed river systems is provided.

The broader goal of this discussion is to provide clearer context for management and rehabilitation of large, embanked river systems, within an understanding of large-scale environmental changes (climatic and anthropogenic). These large fluvial systems typically bisect major population centers and zones of intensive agriculture, and they support major industrial activity (e.g., power generation). As regional climate changes and these rivers and floodplains become increasingly modified by humans, the effects of these shifts in forcing variables get expressed in ways that are inherently unpredictable by conventional perspectives and models. This contribution highlights some of the less well appreciated aspects of river corridor evolution. It is hoped that the examples presented here provide a window into the potential challenges of predicting response to river management under unsteady forcing.

2 Sacramento River

2.1 Background

The Sacramento River of Northern California (Fig. 1) is the state's largest river and one of the major rivers in the American West. It supplies water to millions of California residents (many of them outside the basin boundaries) and contains some of the last great lowland habitats for fish and waterfowl within the Central Valley (Sommer et al. 2001a). Flooding in the basin is dominated by large, winter frontal storms that produce intense rainfall basinwide, albeit mostly concentrated in the mountains (Jones et al. 1972; Singer and Dunne 2004a; Thompson 1960), and snowmelt provides a smaller and diminishing source of water in spring (Knowles et al. 2006). The river flows through the 96 km wide, 418 km long Sacramento Valley, a broad, alluvial, structurally controlled lowland basin between the Sierra Nevada Mountains and the Coast Range on a bed of mixed gravel and sand (Bryan 1923; Harwood and Helley 1987; Singer 2008a). Where the river enters the synclinal trough known as the Central Valley, it assumes the character of an alluvial channel, alternating between active meandering, anastomosing, and straight sections, building bars on a discontinuously armored bed (Singer 2008a; Singer 2010). The channel lies between intermittent natural levees that demarcate a relatively high floodplain composed of fine sands, silts, and clays (Brice 1977; Singer and Aalto 2009; Water Engineering & Technology 1990), which is vegetated by a mix of riparian forest that has been extensively converted to agricultural land over the last century, but is now being restored (Fremier 2003; Golet et al. 2006; Greco and Plant 2003; Micheli et al. 2004). This forest in the riparian corridor interacts with the channel in ways that may influence bank erosion and thus lateral migration rates (Micheli and Kirchner 2002; Tal and Paola 2007), although sediment supply and local floodplain materials and local engineered hard points may be of more importance (Constantine 2006; Constantine et al. 2009; Dunne et al. In Review; Hudson and Kesel 2000; Michalková et al. 2011), particularly in rivers such as the Sacramento where tree roots do not generally penetrate deeply into high banks and therefore provide little protection against erosion of the bank toe. In such systems, entrainment of large woody debris may merely be a by-product of pore pressure failure of banks (Simon et al. 2000). Bank erosion rates in the historical period average 7.7 m y^{-1} (Larsen et al. 2006a), about 6 % of which is comprised of chute cutoff (Micheli and Larsen 2011).

2.2 Controls on River Behavior

As is the case with many large alluvial river systems (Dunne et al. 1998; Schumm and Winkley 1994), the trunk streams of the Sacramento Valley are naturally affected by valley tectonics and geology, as well as by the valley's sedimentary history. River position within the valley is generally controlled by valley tilting, faulting

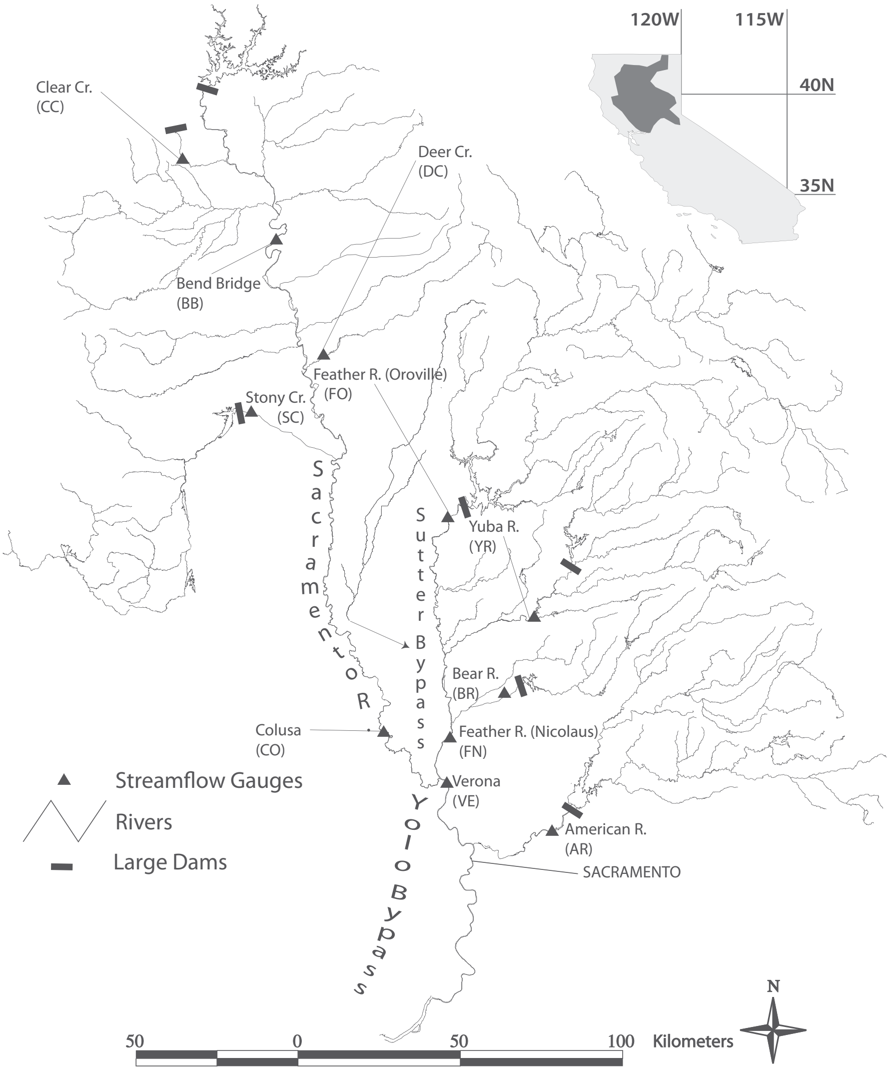

Fig. 1 Map of study area showing major streams, gauging stations, and dams in the Sacramento Valley. Adapted from (Singer 2007)

and folding, resistant outcrops and intrusive rocks, and large Pleistocene alluvial fans (Fischer 1994; Harwood and Helley 1987; Water Engineering & Technology 1990). For example, the alignment of the Sacramento River is affected by the buried Colusa Dome beneath the city of Colusa, composed of relatively resistant uplifted Cretaceous rocks (Harwood and Helley 1987), which causes a major eastward deflection of the river course. This condition results in a decrease in downstream channel capacity, from 7000 $m^3 s^{-1}$ upstream of Colusa to 2000 $m^3 s^{-1}$ downstream, and sequestration of water and sediment in the reach of the Sacramento Valley upstream of the deflection (Singer 2007; Singer and Dunne 2001, 2004b). The reduction in downstream channel capacity during floods causes backwaters to form in the Lower Sacramento and Feather Rivers, the latter of which joins the Sacramento near Verona, 100 km downstream of Colusa. Similarly, the ancestral Pleistocene fan of Cache Creek, a west-side tributary of the Sacramento, apparently pushed the river northeastward downstream of Knights Landing in the vicinity of Fremont Weir so that its course to Verona trends west-east, instead of in the direction of the prevailing north-south valley slope. Within the confines of such geologic, tectonic, and sedimentary controls, the trunk streams meander over aggraded beds. The rivers construct natural levees. by frequent flooding into relatively low natural flood basins that occupy the majority of the land area in the Sacramento Valley (Bryan 1923; Gilbert 1917; Kelley 1998), modulated by the influence of major runoff-producing cyclonic frontal storms and high postglaciation sediment supply.

Under presettlement conditions flow and sediment into the valley was generated in mountainous headwaters (Porterfield 1980). In the lowland valley streamflow and associated sediment discharge into flood basins from the main channels tended to occur at low points along the levee, and where levee materials were inadequate to prevent crevasse formation. Such exit locations, often at the entrance to sloughs (Kelley 1966), were typically coincident with tectonic and geologic controls that forced repeated occupation of flow through levee weak points. Flooding would thus fill the contiguous flood basins, resulting in the development of a seasonally persistent ‘inland sea’ that is well documented elsewhere (Kelley 1998). While valley flooding is essentially a seasonal phenomenon, its depth and areal extent are maximized during extreme floods. Based on flood history in the Sacramento River (US Army Corps of Engineers 1998), large, basin-filling floods have occurred in 17 % of the years between 1878 and 2001 and likely occurred at a similar frequency prior to flood records (Singer et al. 2008), and these seem to be accentuated by ‘atmospheric rivers’ (Dettinger 2011), or synoptic events often driven by ocean-atmosphere teleconnections (Hirschboeck 1988) that produce widespread flooding (Singer and Dunne 2004a). Since the subsiding (Fischer 1994; Ikehara 1994) land surface outboard of the natural levee is lower in elevation than floodplains along the river corridor, sediment carried primarily in suspension was transported by advection out of the channel through these exit loci into the bounding natural flood basins (Singer and Aalto 2009). The resulting pattern of sediment accumulation near the channel margins has been documented as alluvial splays, natural levees along the Sacramento River, as well as accumulation in oxbow lakes (Constantine et al. 2010; Robertson 1987; Singer and Aalto 2009) in patterns similar to other fluvial systems (Bridge 2003; Hudson and Heitmuller 2003).

The various natural controls described above typically produce persistent impacts on the fluvial system at various locations through the basin. For example, at locations where the river interacts with geologic outcrops or tectonic tilting, river channel slope and geometry may be affected (Singer and Dunne 2001), with implications for reach-scale fluvial system behavior. River management strategies are superimposed on the natural environment, such that some of the effects of these structural controls are still apparent and influence management operations (Singer et al. 2008).

2.3 Management Context

The basin has been subjected to a range of management actions, including dams, levees, bank protection, and mining operations, which have affected the geomorphic character of the river and its floodplain. In the 150 years since the discovery of gold in the Sierra Nevada, the Sacramento River valley has been transformed by extremely productive agriculture and human settlement and thus by radical flood control policies intended to ensure the survival of these floodplain activities (Kelley 1998). Hydraulic mining in the Sierra produced huge masses of sediment that clogged up lowland water courses and increased already high-flood risk within the Sacramento Valley. This resulted in lawsuits and ultimately the US government created an integrated flood control plan. This flood control system was designed to convey water and sediment as efficiently as possible through the main stem Sacramento River using straightened channels and high levees built upon protected river banks to prevent overbank flooding and bank erosion, and subsequent lateral channel migration. Since it was acknowledged that the Sacramento River would never have the capacity to carry its entire flood flow (Singer et al. 2008), the system was designed with 'pressure release valves' where flood waters overflow into two major flood bypasses, Sutter and Yolo, via a system of weirs which were constructed to convey water into existing lowland flood basins (Figs. 1 and 2). These floodways divert water in high flows and provide multiuse zones of agriculture and habitat in drier seasons (Singer and Dunne 2001; Sommer et al. 2001a; Sommer et al. 2001b).

Thus, the water courses of the Sacramento Valley are managed through a sequential flood control plan that began in the early twentieth Century to provide flood protection to its low-lying population centers (e.g., Sacramento) and to maximize land for agricultural reclamation. The Sacramento River drains 68,000 km^2 and is controlled by seven large dams (storage $>1\times10^8$ m^3, Fig. 1) that are operated for various combinations of hydroelectricity, water supply, flood control, irrigation, and recreation (Singer 2007). Dams were installed between 1940 and 1970 in the uplands to augment the existing flood control system, for power generation, and to provide water for various downstream uses. Many of the largest dams are located in the foothills of mountain ranges (elevation <600 mASL) and were primarily designed to dampen the largest winter flood peaks and store spring snowmelt runoff for summer irrigation in the valley (Singer 2007).

2.4 River Rehabilitation

In the nearly 100 years since the flood control plan began to be implemented, many important impacts to the Sacramento fluvial system have been documented, including altered flow regimes (Singer 2007), degradation of aquatic habitats (Kondolf 1995), loss of riparian forests (Thompson 1961) and floodplain functioning, contamination of waterways, floodplains, and ecosystems (Conaway et al. 2007; Domagalski 2001; Hornberger et al. 1999; Springborn et al. 2011), and impairment

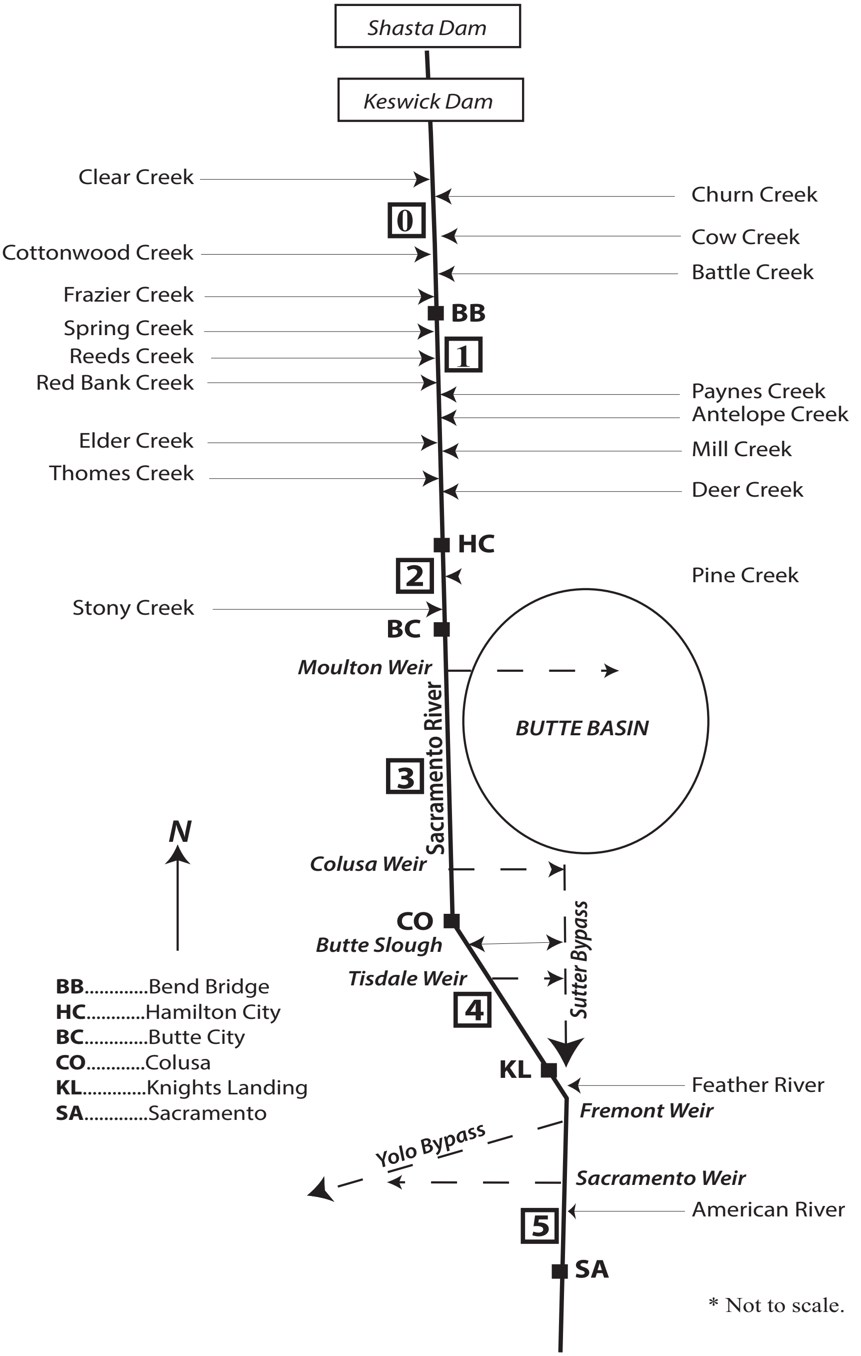

Fig. 2 Schematic map of flood control system indicating primary gauging stations on the main-stem Sacramento River and its tributaries, and where flow is diverted into flood bypasses. Adapted from Singer and Dunne (2001)

and risks to the flood control system itself (Mount and Twiss 2005; Singer et al. 2008). In response, the Sacramento River and its floodplain have been targeted for major river rehabilitation designed to restore the appearance and functioning of the river system (Golet et al. 2006; Larsen et al. 2006b, 2007; Singer and Dunne 2006). Apart from widespread re-plumbing of the river system, which included construction of a peripheral canal to safely divert water around the delta into the State Water Project upstream of the salt wedge that threatens water quality, and bolstering of early twentieth century levees, many of which have become porous and susceptible to failure by earthquakes (Mount and Twiss 2005), several restoration strategies have been proposed that address ecological functioning.

First, to ameliorate the impact of impoundments on the flow regime, flow alteration below major dams has been suggested to better represent natural flow and inundation regimes (Junk et al. 1989; Poff et al. 1997) and this has been attempted for limited periods below some dams (e.g., Glen Canyon Dam-Colorado R. and Shasta Dam-Sacramento R.). Ultimately, a complete and adaptive flow regime must be developed that compromises between ecological needs (Kondolf and Wilcock 1996; Richter and Richter 2000; Richter and Thomas 2007) and intended dam purposes (e.g., hydroelectricity generation, irrigation, flood control), and which must treat the nonstationarity in climatic drivers that may affect the magnitude, timing, and spatial location of streamflow generation. Ultimately a complete and spatial understanding of streamflow alteration and relevant impacts to ecosystems is required to improve design (Richter et al. 1998; Richter et al. 1996; Singer 2007).

To mitigate the negative impacts of flood control levees (embankments) that have constrained bank erosion and river migration, levee setbacks have been proposed (Laddish 1997; Larsen et al. 2006b; Singer and Dunne 2006) to increase the width of the riparian corridor and to allow for natural processes of bank erosion and bar construction (Constantine et al. 2009; Dunne et al. In Review), to recruit coarse sediment from floodplains to channels to fortify anadramous spawning habitat (Kondolf and Wolman 1993; Moir and Pasternack 2010), to increase area of flood retention, and to replenish fine sediments and associated nutrients to and from bounding floodplains (Tockner et al. 1999). Finally, to replenish sediment supplies that have been disrupted and/or diminished by dams, gravel-mining operations, and bank protection, sediment (typically spawning gravel) augmentation has been proposed and attempted on a limited basis in the Sacramento, Merced, and Yuba Rivers to restore natural geomorphic processes and in-stream habitat.

3 Adjustment to Dams

There has been much discussion in the scientific literature about the influence of dams on streamflow regimes (Dynesius and Nilsson 1994; Magilligan and Nislow 2001, 2005; Richter et al. 1996; Singer 2007) and on sediment dynamics and river morphology (Andrews 1986; Gregory and Park 1974; Schmidt and Wilcock 2008; Singer 2008a; Singer 2010; Williams and Wolman 1984). Outstanding issues in-

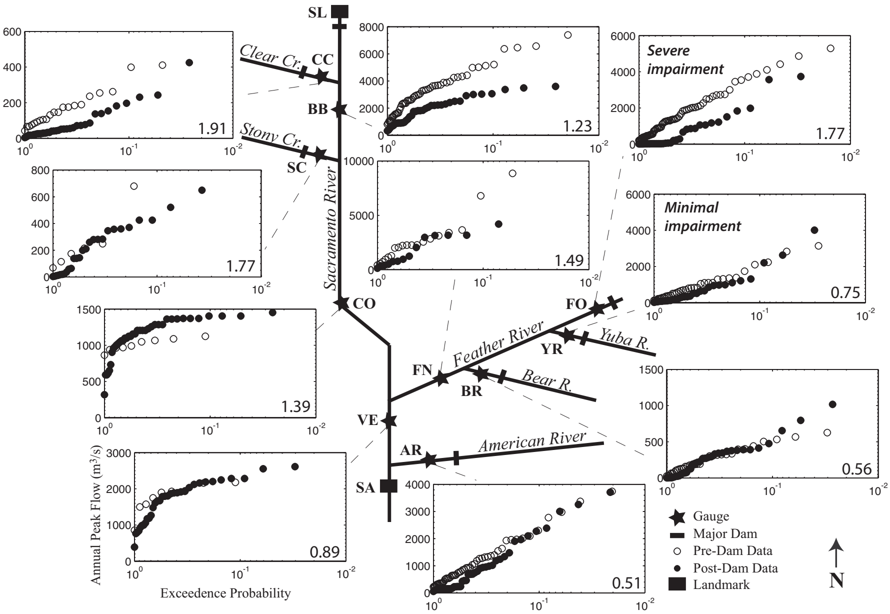

Fig. 3 Streamflow implications of dams. Each panel shows the empirical flood frequency curve (annual streamflow peak) for the indicated gauging station. The value of the impoundment runoff index (IRI) is listed in the lower right-hand corner of each panel; higher values indicate higher level of flow impairment. Station codes are listed in Fig. 1. Adapted from Singer (2007)

clude how individual dams or cascading sequences of dams affect various hydrograph characteristics (which have varying relevance to downstream flood retention and ecology) and the supply of sediment to valley floors. Important measures of the hydrograph that may be affected by dams include flood peak, time-to-peak (rising limb of the hydrograph), drawdown time (falling limb), and annual flood volume. The various dams of the Sacramento Valley, constructed over several decades in the foothills on the periphery of the valley, have had important impacts to fluvial system functioning.

3.1 Dam Impacts on Streamflow

Impoundment by dams allows for a range of flexible release strategies to benefit one or more of several management objectives (water supply, hydroelectricity generation, flood control, etc.). A straightforward measure of such flexibility is the impoundment runoff index (IRI), defined as the ratio of reservoir capacity to median annual flood runoff volume (Singer 2007), a slight modification from the definition in Batalla et al. (2004). This index crudely identifies to what degree downstream streamflow has been altered by dams (Fig. 3). Dams that have high storage capacity relative to annual flood volume (i.e., high IRI) are likely to cut off flood peaks and store them for subsequent release following flood termination (e.g., site codes BB, CC, FO, Fig. 3). Such practice may also reduce time-to-peak and drawdown time, lower annual flood volume, and increase flood interarrival times (Table 1) because small and moderate sized floods are completely cut out of the hydrologic record. Dams with low IRI, on the other hand, do not have adequate storage capacity to completely cut off flood peaks. To control floods, they must instead be operated to lengthen the rising (early release) and falling (late release) limbs of the hydrograph (e.g., sites BR, YR, AR, Fig. 3). Generally, the hydrograph is extended on both limbs (increasing time-to-peak and drawdown time), but there are some late release dams (SC), which lengthen the falling limb without affecting the rising limb.

Detailed analysis over space (many stations around the basin) and time (several decades of daily records) allows for insight into local and downstream impacts of such impoundments. Such an approach provides more direct assessment of historical hydrology and the complex role of many dams with different operating rules than using one of a number of basin-scale hydrologic models (e.g., Lettenmaier and Gan (1990)). It is clear from this analysis in the Sacramento basin that large dams generally have a persistent, localized impact on streamflows, especially annual peaks (indeed, many are designed for flood control), but the whole basin view reveals that the impact of these dams typically dissipates with increasing distance downstream through the fluvial network (Fig. 3) into the lowland valley (Singer 2007). This is because dams are only capable of controlling high flows locally, but since they are located along the basin periphery, there are often large downstream contributing areas that add flow to lowland channels and provide floodplain storage of overbank flows. These factors can diminish the persistent impact of dams in this basin, rendering it localized.

3.2 Evaluating Impacts of Altered Streamflows

The above empirical analysis leaves open the question of prediction—what should we expect the future evolution of streamflow to look like in the context of these dams and associated with projected climate changes? One alternative is to use the wealth of historical records for the basin in a creative way to glean more information on potential decadal adjustments to perturbations and/or modifications of the fluvial system. A stochastic flood-event generator was used that combines flood flow from important tributaries in the basin and routes the combined flows through the mainstem. The philosophy is that the largest source of uncertainty is due to the variability in flow, rather than to the temporal variability in local hydrologic and geomorphic processes (Benda and Dunne 1997a, b). Each 30-year simulation, constructed of semi-randomly selected flood events from the major tributaries based on empirical analysis of synchronous flood event correlation across the basin, produces a distinct flood frequency curve at any point along the mainstem. Analysis of an ensemble of 50 simulations allows for characterization of expected average system behavior, as well as the potential range (tails of

Table 1 Table of hydrograph characteristics (flood peak, flood trough, flood volume, time to peak, drawdown time, and interarrival time) showing the significant directionality of change for the median of each flood frequency distribution based on the Kolmogorov-Smirnoff statistic. Adapted from Singer (2007)

Station	Peak	Trough	Volume	Time to Peak	Drawdown	Interarrival
CC	↓	↑	↓			
BB	↓	↑			↑	↓
DC						
SC		↓			↑	
CO						
FO	↓	↓	↓	↓	↓	↑
YR		↑				
BR		↑		↑	↑	
FN		↑				
VE		↑				
AR	↓	↑		↑	↑	↑

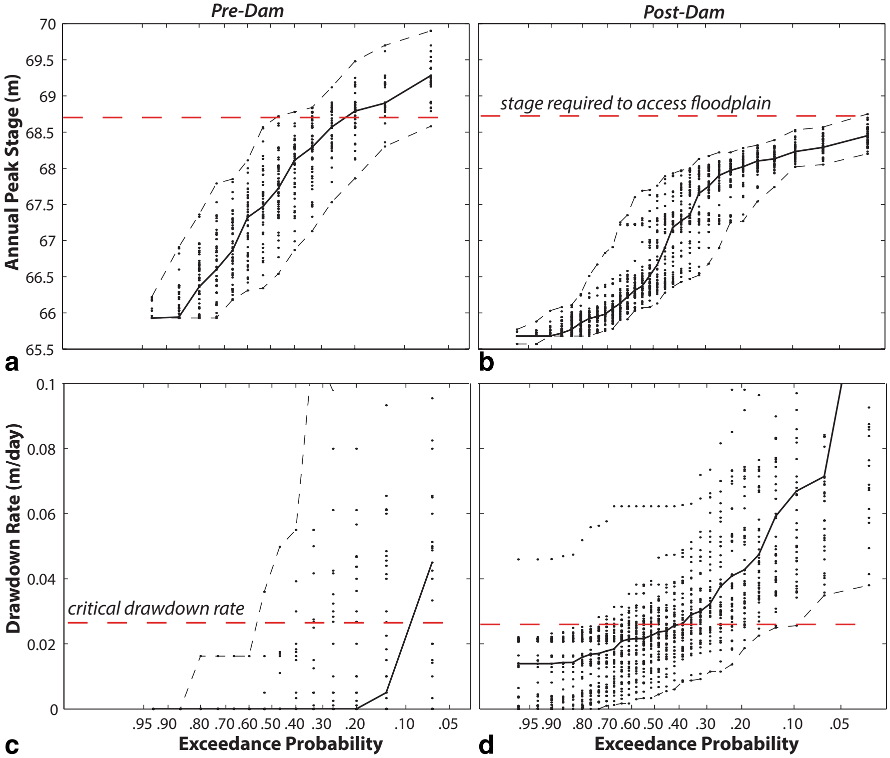

Fig. 4 Influence of dams on floodplain inundation and water table decline. **a** pre-dam hydrological simulations. *Red dashed line* depicts stage required to inundate the floodplain and thereby provide suitable recruitment habitat for cottonwood seedlings. Median of 30 simulations is indicated by bold black line and dashed black lines represent the upper and lower bounds of all simulations; **b** post-dam simulations of peak stage; **c** pre-dam simulations of water table decline. *Red dashed line* indicates threshold rate of water table decline above which cottonwood seedlings will not get established (Mahoney and Rood 1998); and **d** post-dam simulations of water table decline. Adapted from Singer and Dunne (2004a)

the distribution) based on hydrologic uncertainty due to various combinations of tributary inputs to the mainstem. A set of hydrologic simulations (Fig. 4) indicates how ensembles of information may be used to assess hydrologic restoration strategies in river corridors (i.e., re-creation of natural flow regimes). The results present a hypothetical analysis of a local cottonwood forest restoration effort on the floodplain. According to prior work, cottonwood forests develop only if two conditions are satisfied: (1) floodplains are wet during seedling release, requiring flow stage to exceed a threshold (68.7 mASL in this case), and (2) seedling roots must remain in contact with the water table, requiring a rate of water table decline less than 2.5 cm/day (Mahoney and Rood 1998). The analysis shows that in the era before the construction of Shasta Dam, the primary large dam on the Sacramento River, both conditions were satisfied the majority of time. The floodplain is wet in most years and the drawdown rate only exceeds the critical threshold ~ 10 % of the time (Fig. 4a & 4c). However, since dam construction, flow stage has not exceeded the threshold, so the floodplain is essentially stranded from the channel (Fig. 4b), and the water table declines faster than 2.5 cm/day about 40 % of the time (Fig. 4d). These are consequences of dam operation that will dramatically impact the hydrology in the riparian corridor, which has knock-on effects for any proposed restoration effort intended to expand forests in the riparian corridor and for trees that are already established (Singer et al. 2013b; Singer et al. 2014).

The response of stream hydrology to dam installation and operation is nonlinear and dependent on various factors. Thus, analysis of the distribution of flows, including various hydrograph characteristics such as flood peaks and hydrograph shape, provides more complete information on the direct downstream hydrologic impact and also indicates how these characteristics will be affected with increasing distances downstream of the dam perturbation (Singer 2007). When considered within a stochastic analysis framework, these empirical records for a basin can provide analytical support for assessing river rehabilitation strategies (Singer and Dunne 2004a, b; Singer and Dunne 2006). The impact of dams on hydrology may be considered to be persistent. Whereas the operation rules may change through time based on the water allocation needs, etc., the nature of such changes average out over the long term and become dampened by the localized impact of the dam on streamflow alteration, which remains relatively constant and can be tracked as it dissipates downstream.

3.2.1 Dam Impacts on Sediment Flux and Storage

What about dam impacts on sediment transfer and channel characteristics? These are usually discussed in terms of the local ‘hungry water’ effect, wherein clear water discharged below dams has high transport capacity and therefore entrains disproportionately high sediment loads, producing river incision. However, such incision generally produces localized river armoring that limits the extent of vertical incision. However, there is much less certainty about the downstream translation of the dam signature on sediment dynamics, although some basic metrics on sediment deficit have been proposed (Schmidt and Wilcock 2008). A straightforward indicator of the role of dams in disrupting sediment passage is a longitudinal grain size distribution (GSD) in the channel, which can be thought of as the first degree of freedom the river has to adjust to perturbations (Church 2006). This may be assessed through the analysis of bed-material sediment, which reflects the integration of geomorphic processes operating on the bed. Another obvious candidate variable is downstream topography, which reflects the sediment mass balance (e.g., through the evolution of fluvial landforms; Singer and Michaelides 2014).

The longitudinal GSD along the Sacramento River has been analyzed based on subaqueous, boat-based (Singer 2008b) samples of channel bed sediments at > 100 cross sections (several samples per cross section) spanning ~ 400 river kilometers (Singer 2008a) (Fig. 5). This work showed that whereas the gravel-to-sand transi-

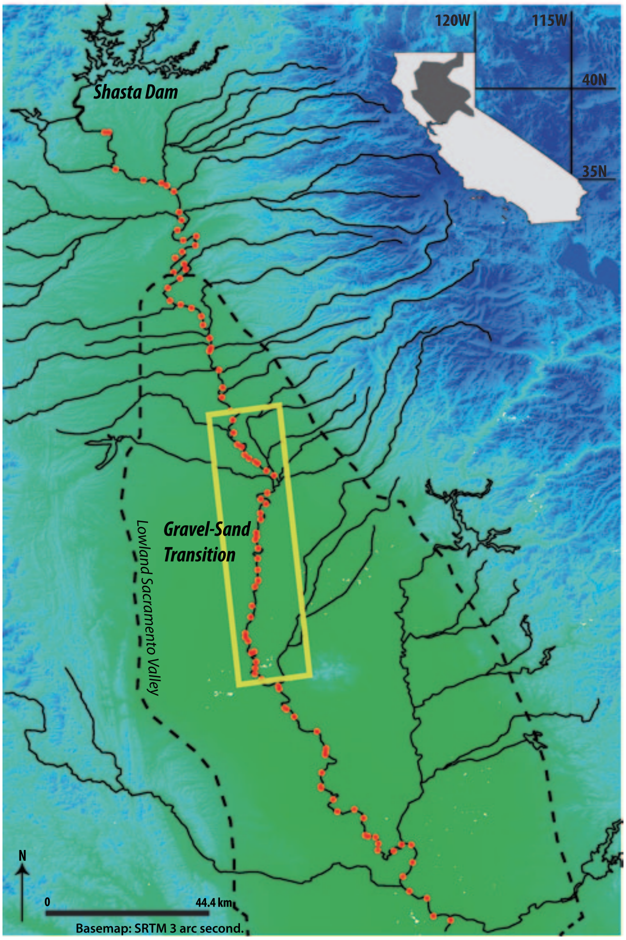

Fig. 5 Map of bed-material sampling locations obtained by boat via Cooper Scooper (Singer 2008b) along the Sacramento River. The yellow box highlights the protracted gravel-sand transition within the lowland Sacramento Valley, which is hypothesized to emerge as a redistribution of sediment from below Shasta Dam to downstream lowland sites of deposition. Tributaries play a small role in affecting Sacramento bed-material grain size because of the great distances they travel across the lowlands within the synclinal trough of the Sacramento Valley

tion in rivers (i.e., the point at which the median grain size changes from gravel to sand) is generally abrupt (Ferguson et al. 1996; Ferguson 2003; Sambrook Smith and Ferguson 1995), its expression in the bed of Sacramento River is protracted over ~ 125 km, as the median grain size (d_{50}) oscillates between coarse and fine sections (Figs. 5 & 6). This gray area in Fig. 6 corresponds to a region of the river where the values of sorting (a measure of GSD spread) are highest, suggesting a broad range of grain sizes are accumulating in this zone, where shear stress oscillates and declines (Fig. 6). This previously unknown phenomenon was interpreted

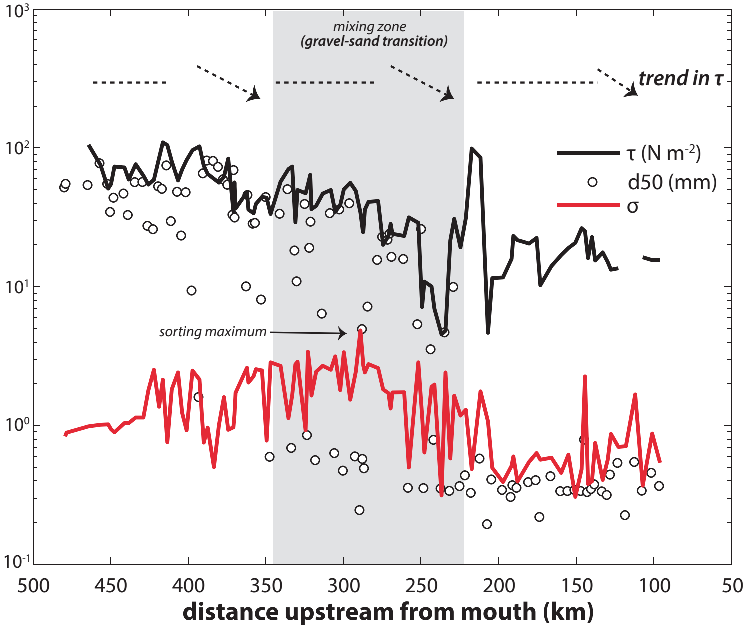

Fig. 6 Grain size characteristics (d_{50} and sorting coefficient, σ) and shear stress (τ) v. distance. Local (*reach-scale*) trends in τ are indicated at the top. Maximum sorting (*most poorly sorted*) part of the river system is located within the shaded gray area, the protracted gravel-sand transition shown in Fig. 4. Here median grain size fluctuates rapidly from sand to gravel associated with a suppressed decline in shear stress. Adapted from (Singer 2010)

as a response to sediment trapping by upstream dams and ‘hungry water’ vertical winnowing downstream of dams, which is known to affect downstream GSDs (Dietrich et al. 1989). These processes lead to a stranding of river bars, such that they are no longer engaged in active sediment transport (Lisle et al. 1993), thus leaving coarse bars as relict features in the landscape, reflective of a former balance between sediment transport and GSD (Singer 2008a; Singer 2008b). Consequently, bar GSDs become much coarser than channel ones (Fig. 7a). Concomitantly, distributions become truncated (narrower) in upstream coarse sections and extended (broader) in downstream fine sections (Fig. 7b), as fines are displaced from upstream to downstream. This can be thought of as a field elaboration of a phenomenon observed in laboratory flumes whereby pulsed sediment transport develops in ‘transitional’ reaches due to selective availability of bed material (Iseya and Ikeda 1987). Morphologically, the redistribution of sediments manifests in localized deposition, reflected as a hump in the longitudinal profile that can be observed in bed slope and curvature (Fig. 8a, 8b), in a region that is already characterized by a reduction in width that probably reflects the loss of gravel bars (Fig. 8c). The hydraulics suggest that dimensionless shear stress (or dimensionless Shields number) is suppressed in this zone of the river (Fig. 8d), such that both grain size populations (fine and coarse) may be nearly equally transported within the gravel-sand transition (Singer 2010).

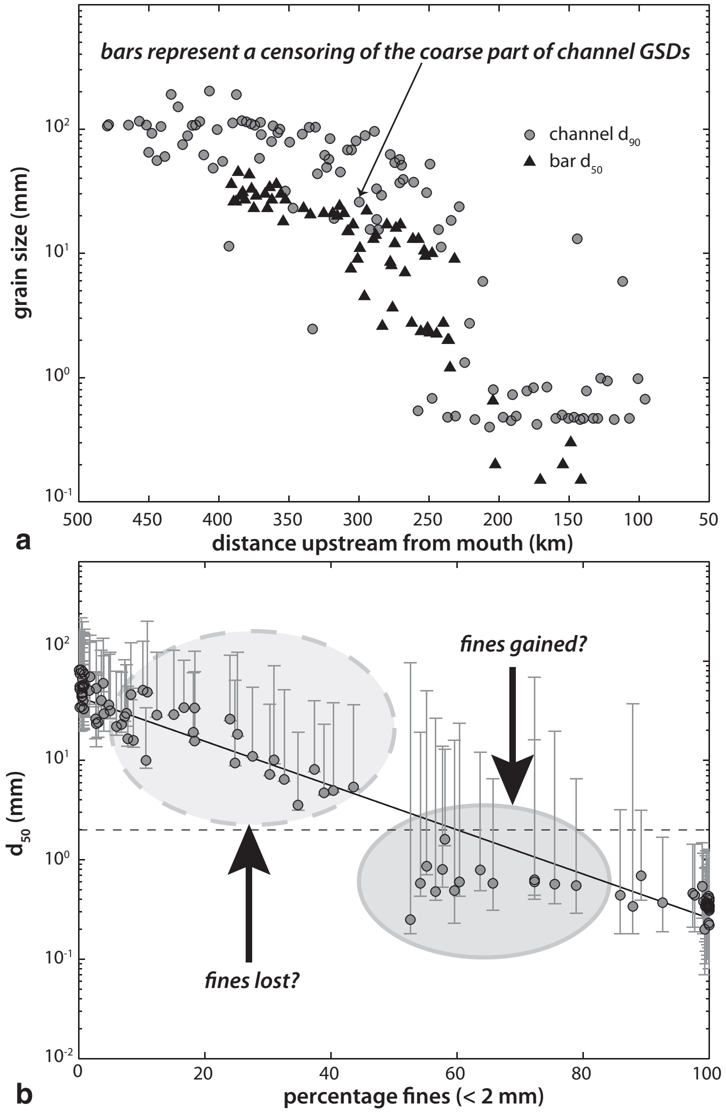

Fig. 7 Grain sizes and hypothesized changes **a** v. distance downstream for channel and bar samples and **b** grain size distributions v. percentage of fines in the sample. Grain sizes shown in **a** indicate that the bars are very coarse compared with the channel (i.e., the median size in the bar is equivalent to the 90th percentile of the channel), indicating they may be relict landforms no longer participating in active sediment transport. The error bars in **b** represent the 10th and 90th percentiles of each measured grain size distribution. Ovals represent opposite trending distributions wherein grain sizes are hypothesized to be truncated at the upper or lower ends due to a transient adjustment to upstream dams trapping gravel. The data demonstrate that in coarse river cross sections (*largely upstream*), d50 is very close to d10 (*bottom error bar*), but that there are nearly no fines in these locations. Also, in sections dominated by fines (where the distribution is composed of >50% fines), d50 is near the bottom of the distribution. These findings can be interpreted as a winnowing of coarse beds and fining of mixed beds (containing gravel and fines). Adapted from (Singer 2008a)

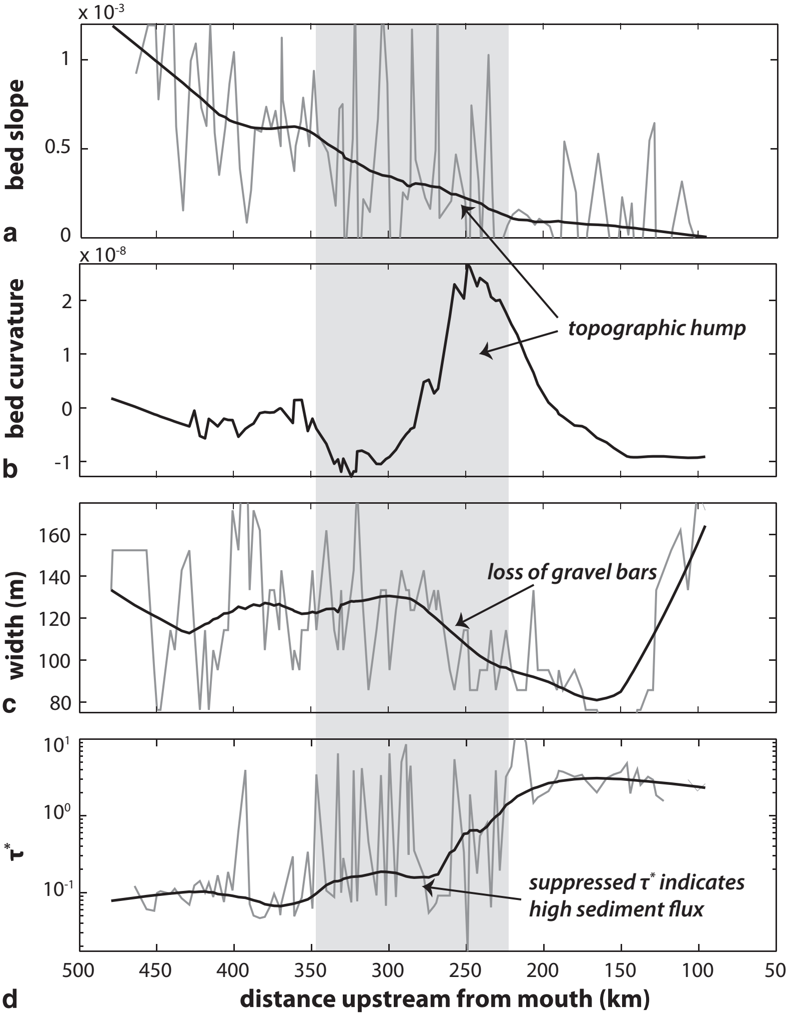

Fig. 8 Morphologic and hydraulic characteristics. **a** bed slope, **b** bed curvature, **c** channel width, **d** Shields number. Original topographic data were extracted/computed from 0.6 m bathymetric data for the Sacramento River. Shields number was computed using a the depth-slope product from hydraulic model output (HEC-RAS) and measured grain sizes from a field campaign that sampled riverbeds ~ 125 cross sections along the Sacramento by boat and a fit-for-purpose sampling device (Singer 2008b). Smoothed curves were obtained using robust LOWESS (0.25 span). These data support the hypothesis that the protracted gravel-sand transition is an emergent phenomenon that will re-coalesce into a more abrupt form at a point upstream, once the dam-related sediment redistribution ceases. Adapted from (Singer 2010)

These processes have extended the gravel-sand transition upstream and lengthened it from ~40 to ~125 km. However, this is not expected to last because if low gravel supply from upstream persists, the fines delivered from upstream will replace the remaining gravels and will smooth the long profile (removing the topographic hump). Ultimately, the fines accumulating will migrate downstream and further encroach on the predominantly gravel reach until the two fine regions are linked and the long profile is smoothed, facilitating transport that re-segregates gravel and fines longitudinally. At this point, the gravel-sand transition will have shifted upstream by 10s of kilometers, though its precise delineations and the timing of its coalescence are subject to speculation. In other words, the longitudinal GSD undergoes a transient response to upstream anthropogenic activity, largely due to gravel trapping by dams. However, the length scale of this sedimentary impact is not easily predicted because of the transient nature of this process.

Importantly, there is a clear distinction between hydrologic and sedimentary responses/adjustments to upstream dams. Although anthropogenic perturbations are often thought to function in tandem, the adjustments of hydrology and sediment dynamics outlined here appear to be disconnected from each other. The hydrologic impacts are localized and persistent, while sediment response is transient and nonlocal (e.g., the response translates downstream). Sediment transport theory typically treats sediment entrainment as a local process dependent only local hydraulics and sedimentary characteristics (i.e., all sediment transported are locally derived). However, the example provided here suggests that nonlocal aspects of sediment supply to any particular location (Stark et al. 2009) may be fundamental to thresholds for local transport, as well to the development of sedimentary conditions and morphology.

4 Adjustment to Levee-bypass System

The influence of flood control levees or embankments on hydrology and sediment transport in large river systems is a topic that has received far less attention in the literature than adjustment to dams, in spite of the ubiquitous nature of these features in lowland floodplains. Some notable research has investigated the impact of such lateral controls on river incision, grain size, and the net transfer of sediment through the channel and into floodplains (Asselman 1999; Hobo et al. 2010; Kesel and Yodis 1992; Simon and Rinaldi 2006; Steiger et al. 1998; Wyzga 2001), while other work has investigated the impact of removing these channel constraints on bank erosion rates, river migration, and sediment mass balances (Laddish 1997; Larsen et al. 2006b; Singer and Dunne 2006). Clearly flood control levees, especially when built upon channel banks, affect river depth and slope and thereby influence local hydraulics and sediment transport—knowledge that was not lost on the engineers who have built irrigation canals around the world for centuries. However, it is less well understood how fluvial adjustment to embankments persists through time and whether it affects fluvial functioning consistently in space (given similar boundary conditions).

Along the Sacramento River, flood control levees are nearly continuous, although they are set back in particular reaches. These structural controls, even when set back, have been shown to impact river alignment and longitudinal sediment budgets (Singer and Dunne 2001), but it is important to place these lateral controls within the broader context of natural geomorphic controls in the Central Valley.

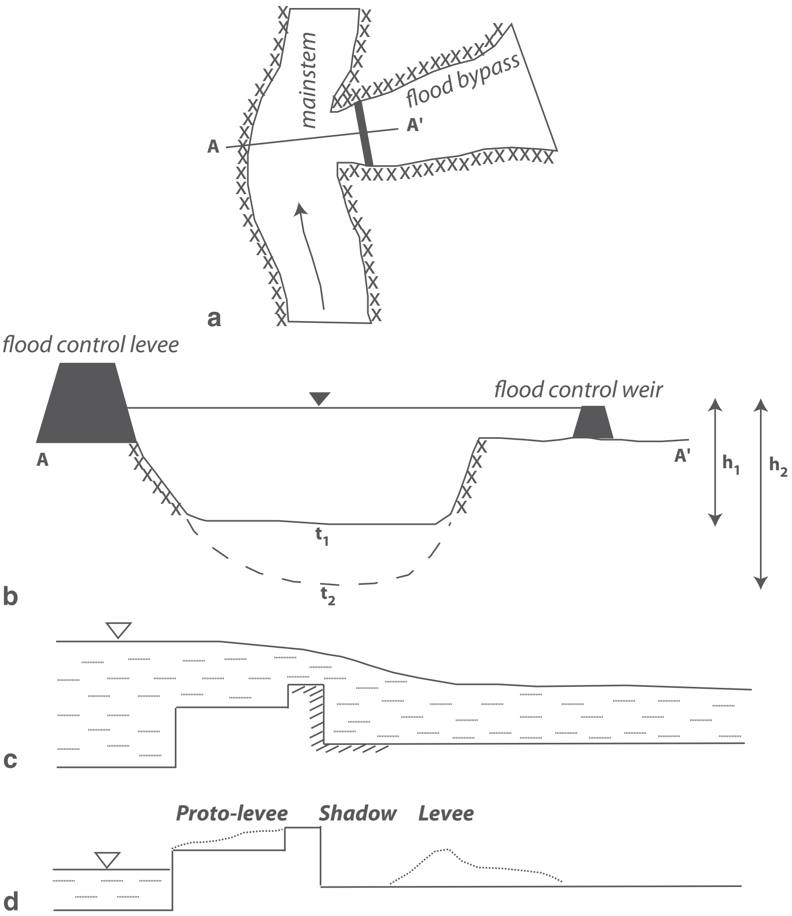

Fig. 9 Bypass schematic showing the operation of the flood-bypass system. **a** planform view, **b** cross-sectional view showing how changes to channel bed elevation affect flow over the weir, **c** the weir being overtopped during a flood; and **d** the sediment deposits produced by the passing flood, which affect subsequent flow over the weir. Adapted from Singer and Dunne (2006) and Singer and Aalto (2009)

Neotectonic structures and Pleistocene sedimentary features impact river alignment and the net transfer of water and sediment along the Sacramento River (Singer et al. 2008). Thus, the flood control system, as designed, inherits the long-term legacy of these features, in some cases by design, and this imposes persistent, localized behavior on the fluvial system.

The setup of the typical weir and bypass unit is depicted in Fig. 9. Weirs are generally passive structures that get overtopped during flooding. As flow accumulates in the main channel and reaches the overtopping threshold, it passes into the adjoining bypass through which it is conveyed much farther down the valley (Fig. 9a, 9b). If the boundary conditions change in the region of the channel/floodplain near the flood control weir, via adjustments in channel bed elevation Fig. 9b and/or sediment accumulation in the floodplain (Fig. 9c), the relationship between flow in the channel and flood spilling over the weir will be affected. Under typical operating conditions, flow over the bypasses during floods dramatically reduces the flood wave in the mainstem Sacramento River. This is depicted in Fig. 10, which shows the influence of flood flow over Colusa and Fremont Weirs during a major event in 1964 in reducing mainstem flood peaks at the gauging stations of Colusa and Verona just downstream of these respective weirs (Fig. 10a, 10b). However, detailed analysis of historical flood records at each of these stations (including the spill over the weirs) shows that these two weirs (two of the most critical for the functioning of the flood control system) have become progressively impaired. Over several decades the discharge over both weirs decreased compared with that in the main channel (Fig. 11).

The partitioning of water in the fluvial system, which is variable through time with implications for contaminant transport (Springborn et al. 2011), may evolve in a manner that negatively impacts the flood control system. But how does this occur? Detailed analysis of hydrologic records and floodplain sedimentation via sediment traps, ^{210}Pb geochronology, and topography, reveals the importance of sediment infilling at the margins of the bypass system (Singer and Aalto 2009; Singer et al. 2008; Fig. 9c), as the primary cause of flood weir impairment. As increasing sediment is deposited in the vicinity of the weir, for example, as a levee building process (Singer and Aalto 2009), it progressively limits accommodation space for subsequent floods. However, this process is not stationary; although the locations of sediment arrival into floodplains/bypasses seem to remain consistent (they are largely a function of the natural geomorphic functioning of the system (Singer et al. 2008)), sediment deposition near the weir depends on supply generated from upstream and the arriving sediment must reach a critical volume before it impairs weir/bypass functioning. Subsequently, sediment is occasionally evacuated by management authorities, leading to decreased impairment of the weir (e.g., sediment removal occurred before the 2004 time slice near Fremont Weir in Fig. 11b). It is clear that the interaction between sediment arrival and hydrologic impairment of weirs and bypasses is transient and therefore must be carefully monitored to avoid major problems in the flood control system.

5 Discussion/Conclusion

The examples provided here emphasize the need to address spatial and temporal perspectives in fluvial datasets in order to improve understanding of the impact scales and trajectory of fluvial adjustment to management perturbations. Although persistence of fluvial response to management is more obvious and predictable, transience is an important consideration, especially over human timescales when adjustment to perturbations may extend beyond human lifetimes. Many challenges exist in grasping the nature of fluvial response in large river systems because local perturbations may have nonlocal manifestations. Likewise, adjustments to such perturbations may translate through the fluvial system and not be measurable until

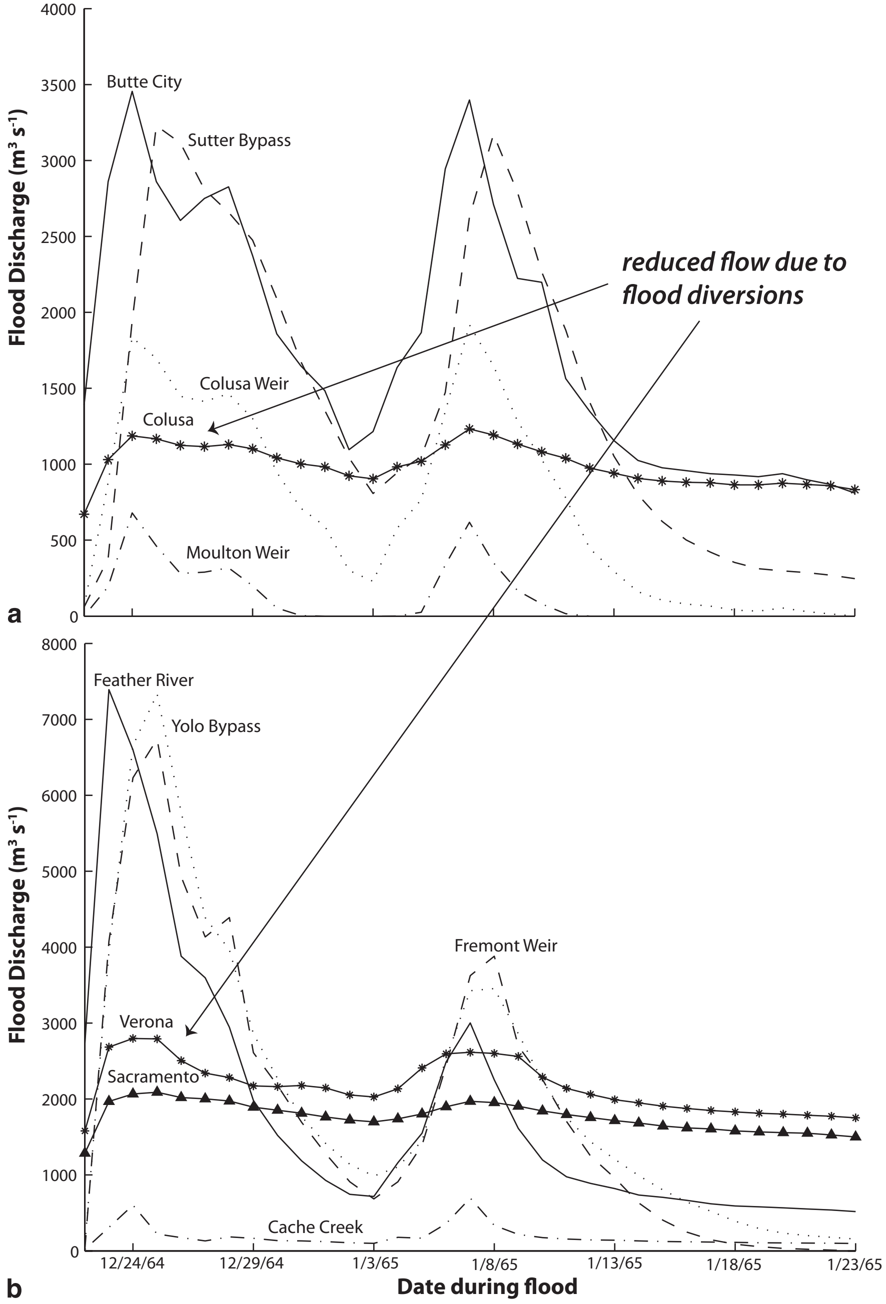

Fig. 10 In-flood hydrology for the 1964 flood event for: **a** the upper part of the flood control system, **b** the lower part. The plot indicates the impact of flood bypasses on mainstem flood flow. Adapted from Singer and Aalto (2009)

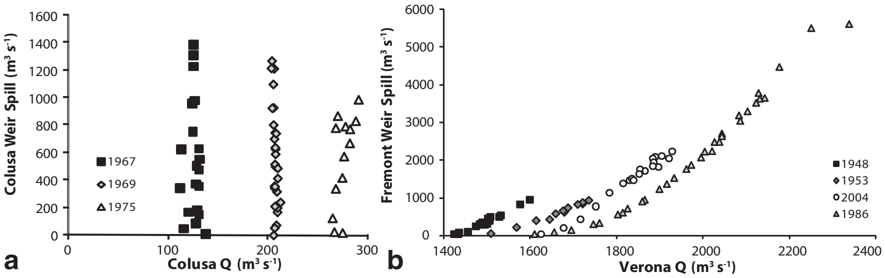

Fig. 11 The impact of bypass impairment by sediment deposition and/or channel erosion. Time series of flow partitioning at **a** Colusa Weir and **b** Fremont Weir. If there were no changes to the channel boundaries, we would expect a systematic relationship between flow in the mainstem Sacramento and spill over each passive weir. In contrast, the data in **a** and **b** show a progressive rightward shift of the x-intercept in these graphs, indicating that spill over the weir occurs under increasing values of mainstem discharge. This can be interpreted as erosion of the mainstem channel boundaries (thus increasing channel capacity) or as sediment accumulation upstream of the weir (thus limiting weir overtopping by flows entering the floodplain). Adapted from Singer et al. (2008)

the effects accumulate above the threshold for detection (e.g., sediment deposition that produces a hump in the longitudinal profile, Fig. 8a, 8b). In addition, transient behaviors in fluvial systems may be superimposed upon persistent ones, creating challenges for interpreting fluvial adjustment.

There are many anthropogenic impacts to river systems that develop as a consequence of a river management structures. Dams and flood control levees are two notable cases that have been described here using data from the Sacramento basin. Both of these produce alterations to hydrologic and sediment regimes with implications for morphological development. Dams (especially large ones) have local persistent impacts to streamflow that generally dissipate with distance downstream. This hydrologic alteration produces a concomitant sediment response directly downstream due to trapping of sediment, and it also generates an unexpected transient response of sediment redistribution with impacts to longitudinal grain size distributions, sediment mass balance, morphology, and the capacity for sediment flux. Flood control levees affect river hydraulics by increasing slope and depth and limiting dynamic adjustments of river width. Flood control systems that are furnished with passive weirs and bypasses have the additional complication of water partitioning during floods. Superimposition of the flood control system upon the natural geomorphic controls within the Sacramento Valley (e.g., neotectonics, volcanic extrusions, Pleistocene megafans, etc.) affects river alignment and leads to emergent behavior, for example, as sediment persistently accumulates in particular locations. Where such locations overlap with the entrances of lateral weirs, flood control impairment may result as the partitioning of water between the mainstem and the flood bypass changes. In other words, in contrast to the impact of dams on the fluvial system, the weir and bypass system produces persistence in sediment dynamics and transience in hydrologic partitioning. Persistent and transient fluvial adjustments coexist and interact in large, lowland river basins subject to anthropogenic perturbations in a manner than can produce unanticipated outcomes.

Given the impacts of river management to river behavior, river rehabilitation scenarios are designed to mitigate the negative effects (usually to habitat, etc.). The impact of three typical restoration scenarios was modeled for river gauging stations spanning ~400 river kilometers along the Sacramento River. Flow alteration, gravel augmentation, and levee setbacks were analyzed for their effects on flows and sediment transport based on a hypothesized stochastic flow distribution, representative of a range of potential flood scenarios (Singer and Dunne 2004a, b). It was found that each rehabilitation strategy would be expected to reduce sediment transport in its target reaches and modulate imbalances in total annual bed-material sediment budgets at the reach scale, although additional risk analysis is necessary to identify extreme conditions associated with variable hydrology that could affect rehabilitation over decades (Singer and Dunne 2006). In other words, emergent landforms that developed via sediment flux imbalances (perhaps in response to management structures such as dams and flood control levees), diminished in modeling output of rehabilitation scenarios designed for other purposes. These results suggest that there may be pathways available to river managers in achieving the benefits of river management, while minimizing the negative consequences of these management implementations.

This discussion is incomplete without at least brief mention of the fluvial responses to climate, which have been identified in various studies (e.g., Rumsby and Macklin 1994). Throughout the entire preceding discussion, the imprint of climate and climatic changes controls stream hydrology and to a lesser extent, sediment supply from drainage basins. Storms do not precipitate evenly across river basin and floods are thus generated in particular parts of drainage basins such that unique combinations of floods in the mainstem of a large river are possible. Such randomness in-flood generation and associated geomorphic responses (Kochel 1988; Slater and Singer 2013) is probably most reasonably represented within a stochastic framework (e.g., Benda and Dunne 1997a, b; Singer and Dunne 2004a) that takes into consideration the probabilities of various system responses to this climatic forcing. These climatic responses may also occur in persistent or transient ways. In the Sacramento River basin, the largest floods are generated by large frontal rainstorms that originate in the warm Pacific and are enabled by a collapse of the Pacific high. Such ‘atmospheric rivers’ (Dettinger 2011) persistently generate the major floods in most Sacramento tributary basins (Singer and Dunne 2004a). These floods, which occur on a nearly decadal timescale, are responsible for most of the geomorphic change in the Sacramento basin (Singer et al. 2008; Singer et al. 2013a). However, since the Sacramento and its tributaries are generally sediment supply-limited, the landform changes associated with individual events are hard to predict. Sediment may be episodically entrained from riverbanks and terraces on a localized basis, but the spatial distribution and probability of such failure is stochastic. Thus, sediment flux and landform response to such persistent large floods is more likely to be transient.

The examples discussed in this paper are relevant to aquatic and riparian ecosystems, but more germane to this volume, to flood control management, the stability of river infrastructure, and to human communities living in lowland floodplains.

As river managers grapple with the impacts of past management strategies and the design of future ones, it is critical to study the impact scales of such anthropogenic activities. How long will a particular impact manifest at a particular location and how will it persist or dissipate with distance? The answer to such questions requires detailed investigation through historical datasets and modeling to address the details of the fluvial response to particular management implementations, including the interactions between various adjustments. Unfortunately, there is no general, prescribed way of doing this. Ultimately, modern river management should involve a well-informed synoptic view of the river/floodplain that emphasizes spatial links through the fluvial system, while maintaining a decadal perspective that permits the construction of probability distributions of relevant fluvial variables.

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