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Floodplain inundation response to climate, valley form, and flow regulation on a gravel-bed river in a Mediterranean-climate region

P. Cienciala [a,*], G.B. Pasternack [b]

[a] University of Illinois at Urbana-Champaign, 605 East Springfield Avenue, MC 150, Champaign, IL 61820, USA
[b] University of California, Davis, One Shields Avenue, Davis, CA 95616, USA

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ABSTRACT

Floodplain inundation regime defines hydrological connectivity between river channel and floodplain and thus strongly controls structure and function of these highly diverse and productive ecosystems. We combined an extensive LiDAR data set on topography and vegetation, long-term hydrological records, as well as the outputs of hydrological and two-dimensional hydraulic models to examine how floodplain inundation regimes in a dynamic, regulated, gravel-cobble river in a Mediterranean-climate region are controlled by reach-scale valley morphology, hydroclimatic conditions, and flow regulation. Estimated relative differences in the extent, duration, and cumulative duration of inundation events were often as large as an order of magnitude and generally greatest for large and long duration events. The relative impact of flow regulation was greatest under dry hydroclimatic conditions. Although the effects of hydroclimate and flow impairment are larger than that of valley floor topography, the latter controls sensitivity of floodplain hydroperiod to flow regime changes and should not be ignored. These quantitative estimates of the relative importance of factors that control floodplain processes in Mediterranean, semiarid rivers contributes to better understanding of hydrology and geomorphology of this important class of channels. We also discuss implications of our findings for processes that shape floodplain habitat for riparian vegetation and salmonid fish, especially in the context of ecological restoration.

1. Introduction

The extent, frequency, duration, and timing of overbank flows define hydrological connectivity of the river channel-floodplain system associated with water-mediated exchanges of energy, matter, and organisms (Junk et al., 1989; Bayley, 1995; Poff et al., 1997; Tockner et al., 2000). By regulating these exchanges, inundation regime strongly influences structure and function of the highly diverse and productive riverine-floodplain ecosystem (Naiman and Decamps, 1997; Tockner and Stanford, 2002; Ward et al., 2002; Tockner et al., 2008). For example, supply of water, sediment, plant propagules, and nutrients during overbank flows facilitate the development of soils and riparian vegetation (Osterkamp and Hupp, 2010; Corenblit et al., 2007, 2011; Gurnell et al., 2012; Osterkamp et al., 2012), which may be subsequently disturbed during flood events of extreme magnitude (Friedman and Auble, 1999; Bornette et al., 2008; Tockner et al., 2010; Džubáková et al., 2015). The characteristics of floodplain sediment, soils, and vegetation interact with the inundation regime to heavily influence nutrient storage, fluxes, and cycling (Baldwin and Mitchell, 2000; Pinay et al., 2000; Adair et al., 2004; Merigliano, 2005; Noe and Hupp, 2005; Zehetner et al., 2009; Vidon et al., 2010; Appling et al., 2014; Sutfin et al., 2016). Taken together, this complex interplay between abiotic and biotic processes within the floodplain ecosystem creates important habitats supporting rich wildlife and seasonally utilized by fish as spawning and rearing habitat (Junk et al., 1989; Bayley, 1991; Balcombe et al., 2007; Górski et al., 2010, 2011).

Floodplain inundation regime — also referred to as hydroperiod — is a function of streamflow regime, which in turn depends on climatic variability and change (e.g., Capon et al., 2013). Moreover, streamflow regime is commonly regulated by humans through construction of impoundment dams; in fact, a majority of the world's large rivers have been regulated (Nilsson and Berggren, 2000; Nilsson et al., 2005; Poff and Zimmerman, 2010; Belmar et al., 2013). Floodplain topography is a third important factor controlling inundation regime (Mitsch and Gosselink, 1993; Naiman and Decamps, 1997; Karim et al., 2015). The morphology of river valley floor changes in a semisystematic manner across drainage basins (Howard, 1996; Buffington et al., 2003). Typically, confined headwater reaches have absent or limited floodplains restricted by valley walls (e.g., Grant and Swanson, 1995). Downstream reaches in progressively open, unconfined valleys have more extensive floodplains (e.g., Howard, 1996), unless the channel is incised or bound by flood control levees.

* Corresponding author.
E-mail address: piotrc@illinois.edu (P. Cienciala).

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The rich floodplain ecosystem, maintained by hydrological connectivity with the channel, and the proximity to abundant water resources have for a long time attracted humans as convenient sites for settlement, transportation corridors, fertile lands for agriculture, etc. (Tockner et al., 2008). As a result of river regulation and morphological alteration, floodplain ecosystems are among the most threatened (Nilsson and Berggren, 2000; Tockner et al., 2008), as many riparian species are adapted to specific inundation regimes (Rood et al., 2003; Lytle and Merritt, 2004; Lytle and Poff, 2004; Braatne et al., 2007; Merritt et al., 2010). Widespread habitat degradation and resulting impairment of ecosystem function has led to a surge in efforts to conserve and restore riparian zones as well as flows necessary to sustain them (Marks et al., 2014).

This study uses Yuba River in California as a valuable setting for understanding the basic science of floodplain inundation that bears on management challenges symptomatic of many river-floodplain systems in developed, Mediterranean regions in a changing climate. For example, streamflow in California is strongly dependent on snow storage (e.g., Vicuna and Dracup, 2007; Vicuna et al., 2007), and analyses of historical data has indicated changes in spring snowmelt regime during the last few decades; these changes have been attributed to climate variability (e.g., Cayan et al., 1999) or climate change (Stewart et al., 2005; Hidalgo et al., 2009). Further hydrological changes are expected within the region because of future climate warming (Miller et al., 2003; Dettinger et al., 2004; Maurer and Duffy, 2005; Mote et al., 2005; Cayan et al., 2008; Dettinger, 2011). River regulation by dams is also more common in Mediterranean-climate rivers (*Med-rivers*) in comparison to their counterparts in a temperate climate, and the effects of dams on streamflow regime are stronger because of less total water availability, higher demand for water resources, and desynchronized water demand and availability (Kondolf and Batalla, 2005). As a result, the altered inundation regime in Med-rivers has contributed to substantial changes in floodplain ecosystems and some of the fastest rates of freshwater biodiversity loss (Hermoso and Clavero, 2011; Moyle et al., 2007). In many regions, efforts are undertaken to reverse these changes by restoring hydrological connectivity (Kondolf et al., 1996, 2012; Stromberg, 2001; Stella et al., 2013a).

In accord with this widespread trend, the Yuba River's streamflow regime has also exhibited changes that likely reflect a combination of climatic factors and dam operations (Freeman, 2002; Kondolf and Batalla, 2005; Singer, 2007). These changes have likely contributed to declines in populations of ecologically, culturally, and economically important fish species, such as spring-run Chinook salmon (*Oncorhynchus tshawytscha*), steelhead (*Oncorhynchus mykiss*), and green sturgeon (*Acipenser medirostris*), all listed as threatened under the Endangered Species Act (USACE, 2014). A restricted vegetated floodplain available for rearing salmonids is believed to be an important part of habitat degradation (USACE, 2014). As a result, efforts are currently under way to restore fish populations and degraded riparian habitat in a number of Yuba River reaches (SYRCL, 2013a, 2013b; USACE, 2014) and a better understanding of the inundation regime is necessary to inform and guide future restoration activities (e.g., SYRCL, 2013a).

2. Study objectives and design

The overall goal of this research was to examine the relative importance of primary controls on floodplain inundation regimes and their cumulative effects and to consider implications for the floodplain ecosystem. To this end, we integrated a rich body of data — including field and remote sensing data as well as model outputs — to study the lower Yuba River (LYR) as a model system. Specifically, we focused on three important controls:

(i) Geomorphic factors: we investigated the influence that valley floor morphology and the superimposed alluvial deposits, which codefine floodplain topography, have on inundation regime by comparing relationships between discharge and inundation in three distinct Yuba River reaches.
(ii) Hydroclimatic factors: we assessed the influence of climate on floodplain inundation by linking the relationships described in (i) with discharge records, stratified so as to compare inundation regime metrics under three distinct hydroclimatic year classes (*dry*/*normal*/*wet*).
(iii) Flow regulation: we evaluated the effects of flow regulation on inundation regime by applying the protocol described in (i) and (ii) to previously established unregulated flows and then comparing with that based on historical, regulated flows.

In the following sections, we provide background on LYR field sites, introduce data sets, and provide more detail regarding the employed methods. More information is available in the supplementary materials.

3. Study setting

The 37.1-km lower Yuba River drains 3480 km^2 of hot summer Mediterranean mountains and flows east to west from the Sierra Nevada foothills downstream of Englebright Dam to its confluence with the Feather River (Fig. 1). The river segment is a single-thread channel (~20 emergent bars/islands at bankfull) with low sinuosity, high width-to-depth ratio, and slight to no entrenchment (Wyrick and Pasternack, 2012). The river corridor is confined in a steep-walled bedrock canyon for the upper 3.1 river kilometers (RKM), then transitions first into a wider bedrock valley with some meandering through Timbuctoo Bend (RKM 28.3–34.0), then into a wide, alluvial valley downstream to the mouth. Hydraulic mining sediment was used to train the active river corridor in the wide lowlands to isolate it from the ~4000-ha Yuba Goldfields. The river segment has a mean bed slope of 0.185% and a mean surface substrate diameter of 97 mm (i.e., small cobble). In the bedrock canyon just below Englebright Dam, the mean bankfull wetted width is 51.4 m; but thereafter it is wider with a bankfull wetted width of ~100 m. The geomorphically determined bankfull discharge was estimated as 141.6 m^3 s^{-1}, which has ~82% annual exceedance probability. As a comparison to other rivers, the LYR is classified as a C3 channel by the Stream Type classification method when applied at the segment scale (Rosgen, 1996) and as transitional between straight and meandering by the flow instability method (Parker, 1976).

3.1. Dams

Flow entering the LYR primarily comes from the North, Middle, and South Yuba River tributaries that join upstream of Englebright Dam and secondarily from the small regulated tributary Deer Creek (Fig. 1). Although the North Yuba tributary has a large reservoir (New Bullards Bar) close to its confluence with the Middle Yuba that heavily regulates its outflow year-round, the absence of large reservoirs on the Middle and South Yuba tributaries translates to a broad range of discharges for the lower Yuba River with flows overtopping Englebright Dam during large winter storms and spring snowmelt. The river segment has two major structures that affect flows, hydraulics, and sediment flux. Englebright Dam marks the start of the river segment. It was constructed as a sediment barrier in 1941 to protect the lower Yuba River from further impact associated with the hundreds of millions of tons of sediment blasted off hillsides throughout the watershed during hydraulic gold mining (Gilbert, 1917). While the dam has resulted in downstream incision throughout the valley corridor of ~10 m over 65 years (Carley et al., 2012), the lower Yuba River remains a wandering gravel-bed river owing to the immense transport and storage of sediment. Downstream at RKM 17.8, Daguerre Point Dam is an 8-m-high irrigation diversion structure that creates a slope break and marks the reach-scale transition from net incision upstream to net deposition downstream.