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

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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.

Keywords: floodplain inundation; valley morphology; climate variability; flow regulation; Mediterranean rivers; riparian habitat

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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).

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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.

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

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82 impairment of ecosystem function has led to a surge in efforts to conserve and restore
83 riparian zones as well as flows necessary to sustain them (Marks et al., 2014).
84 This study uses Yuba River in California as a valuable setting for understanding the
85 basic science of floodplain inundation that bears on management challenges
86 symptomatic of many river-floodplain systems in developed, Mediterranean regions in a
87 changing climate. For example, streamflow in California is strongly dependent on snow
88 storage (e.g., Vicuna and Dracup, 2007; Vicunia et al., 2007), and analyses of historical
89 data has indicated changes in spring snowmelt regime during the last few decades;
90 these changes have been attributed to climate variability (e.g., Cayan et al., 1999) or
91 climate change (Stewart et al., 2005; Hidalgo et al., 2009). Further hydrological changes
92 are expected within the region because of future climate warming (Miller et al., 2003;
93 Dettinger et al., 2004; Maurer and Duffy, 2005; Mote et al., 2005; Cayan et al., 2008;
94 Dettinger, 2011). River regulation by dams is also more common in Mediterranean-
95 climate rivers (*Med-rivers*) in comparison to their counterparts in a temperate climate,
96 and the effects of dams on streamflow regime are stronger because of less total water
97 availability, higher demand for water resources, and desynchronized water demand and
98 availability (Kondolf and Batalla, 2005). As a result, the altered inundation regime in
99 Med-rivers has contributed to substantial changes in floodplain ecosystems and some
100 of the fastest rates of freshwater biodiversity loss (Hermoso and Clavero, 2011; Moyle
101 et al., 2011). In many regions, efforts are undertaken to reverse these changes by

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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

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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

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143 Englebright Dam to its confluence with the Feather River (Fig. 1). The river segment is a
144 single-thread channel (~ 20 emergent bars/islands at bankfull) with low sinuosity, high
145 width-to-depth ratio, and slight to no entrenchment (Wyrick and Pasternack, 2012). The
146 river corridor is confined in a steep-walled bedrock canyon for the upper 3.1 river
147 kilometers (RKM), then transitions first into a wider bedrock valley with some
148 meandering through Timbuctoo Bend (RKM 28.3-34.0), then into a wide, alluvial valley
149 downstream to the mouth. Hydraulic mining sediment was used to train the active river
150 corridor in the wide lowlands to isolate it from the ~ 4000-ha Yuba Goldfields. The river
151 segment has a mean bed slope of 0.185% and a mean surface substrate diameter of 97
152 mm (i.e., small cobble). In the bedrock canyon just below Englebright Dam, the mean
153 bankfull wetted width is 51.4 m; but thereafter it is wider with a bankfull wetted width of ~
154 100 m. The geomorphically determined bankfull discharge was estimated as 141.6
155 m^3s^{-1}, which has ~ 82% annual exceedence probability. As a comparison to other rivers,
156 the LYR is classified as a C3 channel by the Stream Type classification method when
157 applied at the segment scale (Rosgen, 1996) and as transitional between straight and
158 meandering by the flow instability method (Parker, 1976).
159
160 *3.1. Dams*
161 Flow entering the LYR primarily comes from the North, Middle, and South Yuba
162 River tributaries that join upstream of Englebright Dam and secondarily from the small
163 regulated tributary Deer Creek (Fig. 1). Although the North Yuba tributary has a large

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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.

Deer Creek is the largest tributary to the LYR and the only one relevant for this study. Because of its limited catchment elevations, the hydrograph is dominated by rainfall, with just a few snowmelt or rain-on-snow events annually. The flow in the creek is impaired by three regulated dams and several small water diversion dams. Because reservoir storage is small, the hydrograph is most impaired early in the water year and

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184 relatively natural otherwise. Further details about Deer Creek's hydrology are available
185 in FDC et al. (2011).
186
187 *3.2. Study reaches*
188 Key characteristics of three study reaches are summarized in Table 1. Timbuctoo
189 Bend reach begins at the onset of the alluvial valley after the Narrows canyon and ends
190 at the bedrock constriction where the Highway 20 bridge is located. This reach is
191 followed by Parks Bar reach, in which increasing valley width enables a wider
192 floodplain, sedimentary bars, islands, and terraces. The third reach, Daguerre Point
193 Dam reach, begins at the Daguerre Point Dam and ends at a slope break with the
194 downstream Hallwood reach. This is the widest reach in the lower Yuba River. The
195 channel is bounded by a training berm to the north and mining tailings on the southern
196 side, and the parallel overflow channel north of the training berm (termed Daguerre
197 Alley) conveys flow upon full inundation between 283 and 425 m^3s^{-1}.
198
199 **4. Data**
200 Field data collection efforts were explicitly intended to characterize hydrologic,
201 geomorphic, vegetative, and hydraulic attributes of the LYR at roughly meter-scale
202 resolution. Observational data included topography and bathymetry (Pasternack, 2009;
203 White et al., 2010; Carley et al., 2012) as well as hydraulic data: water surface
204 elevation, depth, velocity magnitude, and velocity direction (Barker, 2011; Pasternack

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and Wyrick, 2014). Details about spatial coverage, resolution, and accuracy for the digital elevation model (DEM) used in this study have been previously reported and peer reviewed but are briefly summarized herein, with more details provided in the supplementary materials.

4.1. Flow records

Hydrological records for the lower Yuba River are available at two USGS gages (Fig.1), with one located at Smartsville near Englebright Dam (#11418000) and the other at Marysville near the mouth (#11421000). In addition, a USGS gage is located on the small, regulated tributary Deer Creek (#11418500) that flows into the river a short distance downstream of the Smartsville gage. This study used the sum of the daily flows for the Smartsville and Deer Creek gages as the hydrologic input.

In addition to the observed flows, this study made use of calculated natural (i.e., unimpaired) daily flows at Smartsville on the Yuba River determined for relicensing of the Yuba River Development Project (YCWA, 2012). Unimpaired flows represent catchment hydrology without any human intervention. Flow impairment is a result of four major water development projects in the watershed: the Yuba-Bear Project, Drum-Spaulding Project, South Fork Feather River Project, and Yuba River Development Project. These projects are operated to hold or release water for flood control, water supply, recreation, instream flows, and hydropower generation. Computation of unimpaired flows was feasible because several USGS gaging stations are located

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226 throughout the Yuba watershed and the cost of such analysis is borne by the licensee.
227 A full explanation of the heavily reviewed computational steps is beyond the scope
228 herein and is publicly available (YCWA, 2012). Unimpaired flow record is not available
229 for Deer Creek (FDC, 2011), but the effect of its impairment would be extremely small
230 on the flows that generate floodplain inundation on the LYR.
231
232 *4.2. Mapping*
233 River corridor topography and bathymetry were collected for the high-resolution
234 digital elevation model (DEM) using a combination of ground-based, boat-based, and
235 airborne LiDAR methods. Each method involved its own internal performance tests, and
236 comparisons were carried out among the methods in areas of overlapping coverage. All
237 of the different surveys were tied together with a common array of benchmarks and
238 vertical adjustments to a common vertical datum (NAVD 88). After accounting for data
239 quality, acceptable points were visualized in ArcGIS software (ESRI, Redlands, CA) and
240 further edited on a spatial basis to remove obvious errors. In narrow backwater
241 channels and along banks that contained obvious interpolation errors, hydro-enforced
242 breaklines and regular breaklines were created to better represent landform features.
243 Additionally, some bathymetric areas that contained very few points because of
244 obstructions and other problematic features were artificially augmented so that channel
245 characteristics were maintained. A TIN-based DEM was produced as the native terrain
246 model from which derivative rasters and contours were produced as needed. The

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247 supplementary materials provide the details on topographic and bathymetric resolution
248 and accuracy.
249 A vegetation canopy height surface model was developed by Watershed Sciences
250 (Portland, OR) and delivered in the form of a 0.9144-m (3-ft) resolution ESRI grid file as
251 documented in Watershed Sciences (2010). Noise points and secondary returns from
252 the vegetation class were excluded by a two-step automated process classifying all first
253 returns ≥ 0.305 m (1 ft, which is two standard deviations of the expected laser noise
254 range) above a localized corrected ground surface as vegetation points. An elevation
255 raster representing the highest LiDAR return classified as vegetation in each cell was
256 created and then filled with values from the bare Earth TIN in cells with no LiDAR
257 returns. Finally, ground elevations were subtracted from vegetation elevations to obtain
258 canopy heights, with height < 0.61 m excluded. A 0.9144-m raster of vegetation
259 presence/absence was produced from the canopy height raster.
260 *4.3. River hydraulics*
261 Given that the purpose of this study was not to develop novel multidimensional
262 hydrodynamic algorithms or prove their veracity but to extend their utility for analyses
263 that improve scientific understanding, the underpinnings of the hydraulic modeling used
264 in this study and its validation are explained in the supplementary materials. This study
265 built on a previously peer-reviewed and published, meter-scale two-dimensional
266 hydrodynamic model that predicted depth-averaged velocities for ~ 35 river km for
267 discharges ranging from 0.2 to 20 times bankfull (28.3 to 2840 m^3s^{-1}; Barker, 2011; Abu-

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Aly et al., 2014). Given the floods modeled, we chose to use spatially distributed and stage-dependent vegetated boundary roughness (Katul et al., 2002; Casas et al., 2010). Despite the increasing use of 2D models in river science, some uncertainties, errors and limitations exist in this method (Hunter et al., 2008; Legleiter et al., 2011; Jowett and Duncan, 2012) but the same is true for empirical data, simple analytical equations, 1D hydrodynamic models, 3D hydrodynamic models, and multidimensional morphodynamic models. The choice of 2D hydrodynamic modeling was sensible for this study as it captures the effects of topographic steering and convective acceleration at the meter to decimeter scale on floodplain inundation, which was the only model output used herein. The supplementary materials provide modeling details, including performance metrics, which were well within scientific journal norms.

5. Study methods

5.1. Floodplain inundation

A first step in data analysis was to develop a relationship between discharge and the extent of floodplain inundation for the full range of flows present in the historical and unimpaired flow records. We developed such a relationship for each of the study reaches based on the results of the 2D hydraulic model simulations (section 4). Eight simulations that exceeded bankfull discharge (141.6 m^3s^{-1}) were used, specifically 212.4, 283.2, 424.8, 597.5, 849.5, 1195, 2390, and 3126 m^3s^{-1}. Inundated floodplain area for a given flow was defined as the difference between the total inundated area in

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289 the model output and the wetted area for the bankfull flow simulation. Piecewise linear
290 interpolation between the resultant values for each study reach was then used to
291 estimate floodplain inundation extent as a function of discharge (Fig. 2). Piecewise
292 linear interpolation was chosen because it proved to be superior over function fitting
293 (e.g., logarithmic or a polynomial) in terms of representing the details of the
294 relationships between discharge and inundated areas. Inaccuracies of the tested
295 continuous functions were particularly important at the lower end of the range, where
296 errors in fit resulted in different rank orders of study reaches in terms of inundation
297 extent. Because a few historical flows exceeded the highest modeled flood discharge,
298 the values of inundated floodplain area for these extreme events were extrapolated
299 linearly based on the slope fitted to the two largest flows for which simulations were
300 available.

301 To account for different reach lengths, we normalized the inundated area by the
302 thalweg length, thus expressing the results as the average width of the inundated
303 floodplain (note that this value includes floodplain areas on both sides of the channel). A
304 comparison of the discharge-floodplain inundation relationships as well as statistical
305 descriptors of the floodplain inundation regime in the three study reaches provided an
306 opportunity to assess the importance of valley floor topography (i.e., geomorphic
307 control).

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5.2. Water year classification (hydroclimatic conditions)

This study used 33 years of hydrological data observed on the LYR from 1 October 1975 to 30 September 2008 (i.e., water years 1976-2008). Hydrological studies often use all years in one bulk analysis, which assumes that the days in all years belong to the same probability distribution. However, depending on interannual to decadal quasi-periodicities in the coupled ocean-atmosphere system driving climate (e.g., El Niño Southern Oscillation and Pacific Decadal Oscillation), years and days in years may not be identically distributed, hence requiring stratification of the data into similar climatic sets. In the case of the Yuba River, the hot summer Mediterranean climate is characterized by significant interannual variability in precipitation and streamflow, with much of it explained by quasi-periodic climatic trends. A common approach used to account for this in California is to classify hydrological data into water year types on the basis of seasonal and/or annual flow metrics. For example, the Yuba River Index is computed as 20% of the previous year's unimpaired total annual flow plus 30% of the current year's unimpaired flow October through March plus 50% of the current year's unimpaired flow April through September (YCWA, 2012). Thus, it gives the highest weight to spring snowmelt runoff and also considers antecedent conditions. In this study, the goal was to have an index that focused on the current year exclusively and with no preference for snowmelt over rainfall as the water source, so the combined total annual unimpaired flow (in units of millions of cubic meters, MCM) from the Yuba record at Smartsville was used to segregate water years into three distinct classes: dry (0-1900

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MCM), normal (1901-3800 MCM), and wet (> 3801 MCM). The actual range of observed annual values was 410-1773, 2048-3637, and 3913-6048 MCM, respectively, with no values within 100 MCM of either threshold. The classes were also separated by slope breaks in the rank distribution plot, which suggests their distinctiveness (Fig. S1 in Supplement). As a result, the data set used in this study included 13 dry years (1976, 1977, 1981, 1985, 1987, 1988, 1990, 1991, 1992, 1994, 2001, 2007, 2008), 10 normal years (1978, 1979, 1989, 1993, 1999, 2000, 2002, 2003, 2004, 2005), and 10 wet years (1980, 1982, 1983, 1984, 1986, 1995, 1996, 1997, 1998, 2006). Daily and monthly flow records for the years within each class were evaluated together to gain an understanding of the common attributes.

5.3. Inundation time series

For each study reach the relationship between discharge and inundated floodplain width was applied to each daily flow value to yield an annual time series of inundated floodplain width. The annual time series for all years on record were then stratified according to water year class. The time series for years within each water year class were then ordered chronologically and concatenated. A comparison of statistics representing floodplain inundation regimes that correspond to the three water year classes enabled an assessment of the importance of hydroclimatic controls.

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350 *5.4. Uniform continuous above-threshold (UCAT) analysis*

351 In statistical analysis of floodplain inundation regimes we aimed to capture various
352 aspects of inundation patterns: magnitude/extent, duration, and cumulative duration
353 (which, when expressed as a proportion of total record, is closely related to event
354 frequency). The Uniform Continuous Above Threshold (UCAT) method is a form of time
355 series analysis and, as the name implies, focuses specifically on continuous events
356 above certain thresholds. We chose this method in addition to simple descriptive
357 statistics because, from the point of view of floodplain ecosystems, the continuous
358 nature of inundation is critically important. The method was described in detail by Capra
359 et al. (1995), Parasiewicz (2008), and Castelli et al. (2011). Therefore, below we provide
360 only a general account. The UCAT analysis was conducted for each of the three study
361 reaches and applied to the subsets of data corresponding to different hydroclimatic
362 conditions (section 5.2). It was also carried out separately for the regulated (i.e.,
363 observed) flow and the reconstructed unimpaired flow (section 4.1).

364 The UCAT procedure followed in this paper involved three steps, which were applied
365 to each of the study reaches and water year classes. In the first step, a series of
366 representative thresholds of floodplain inundation width was chosen to represent
367 different event magnitudes. We chose to focus on inundation widths of 10, 20, 50, 100,
368 and 200 m as values representative of a range of overbank floods on this river. The
369 largest value exceeds the floodway width for Timbuctoo Bend reach, is virtually that for
370 Parks Bar reach, and is 64% of that for Daguerre Point Dam reach. When inundation

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exceeds floodway width in this valley, then alluvial terraces and/or valley hillsides are inundated. In the second step, we split the data according to water year class and determined duration of all events in all the annual time series of floodplain inundation for a given water year class (hydroclimatic conditions) that exceeded each of these thresholds. The events for the same inundation width threshold were then grouped in subsets according to their duration, which ranged from 1 day to the maximum value identified in the data set. The third UCAT step involved calculations of the cumulative duration of all events (expressed as the proportion of the total time) for a given continuous duration and inundation threshold. This was done separately for each of the water year classes. In UCAT plots, the continuous durations were then plotted against the corresponding cumulative durations, and each inundation width threshold had its own curve.

The shapes of the UCAT curves can be used to interpret the duration-magnitude-frequency relationship (for a certain duration, the cumulative duration is related to event frequency). For example, steep curve slope may be indicative of rare events, with continuous duration much longer than shorter events of the same magnitude. Such a pattern is more common in the left side of the plot space, where low frequency (low cumulative duration) events are plotted. The opposite is true for curves with gentle slopes. The UCAT curves may also display clear breaks in slope, which authors in the past used to describe subsets of events as *typical*, *persistent*, or *catastrophic*, presumably in terms of known geomorphic or ecological problems associated with those

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392 conditions (e.g., Parasiewicz, 2008). However, in the absence of any such previously
393 reported geomorphic or ecological thresholds for floodplain ecosystems in general or for
394 the Yuba in particular associated with UCAT slope breaks, this additional step was not
395 performed in this study.

396 Although this study encompassed a full range of continuous durations of floodplain
397 inundation identified in the data, we focused particularly on four selected values
398 deemed to be representative: 1-, 7-, 14-, and 21-day floods. For example, 1-day floods
399 (herein *short duration*) are important for biogeochemical reactions such as nitrogen or
400 carbon fluxes and processing in soils (e.g., Wilson et al., 2011; Ostojić et al., 2013).
401 Research in other rivers of the semiarid climatic zone indicated that they also play a role
402 in recharging soil moisture, although longer duration events have more effect in this
403 respect (Doble et al., 2012). Recently, researchers working in the Sacramento River
404 watershed in California proposed that 7-day floods (*moderate duration*) are critical for
405 function of the entire floodplain ecosystems and were termed *floodplain activation floods*
406 (Williams et al., 2009; Opperman et al., 2010). In addition to the above roles, 14-day
407 events (*long duration*) are important for recharge of groundwater and may regulate
408 riparian vegetation dynamics. For example, prior research indicated that seedling
409 survival of common riparian tree species such as cottonwood (*Populus fremontii*) is
410 strongly and negatively affected by inundation lasting more than 2 weeks (Auchincloss
411 et al., 2012). Finally, 21-day floods (*very long duration*) were used as representative of

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long inundations, known to benefit juvenile Chinook salmon that rear and feed on the floodplain (Sommer et al., 2001, 2005; Jeffres et al., 2008).

6. Results

6.1. Valley form controls

Relationships between discharge and inundated floodplain width revealed commonalities and differences between the reaches with distinct floodplain topography. The common feature of all relationships was that they were approximately logarithmic (logarithmic function: r^2 of 0.95 for Daguerre Point Dam reach and over 0.99 for the other two reaches). Power function also yielded a good fit for higher discharges, in excess of ~ 400 m^3s^{-1}, but not for the entire range of flows. However, even though log functions captured the general trends, for the purposes of quantifying inundation width, piecewise linear interpolation provided a more accurate representation of incremental inundation. The geomorphically controlled differences in floodplain hydroperiod were evident because, on average, for a given discharge inundated floodplain width in Parks Bar reach was roughly double and in Daguerre Point Dam reach triple that in Timbuctoo Bend reach (Fig. 2A). However, the between-reach differences in inundated floodplain width varied with discharge. The difference between Timbuctoo Bend and Parks Bar reaches increased relatively steadily as a logarithmic function of discharge. A more complex trend in Daguerre Point Dam reach may be associated with a substantial portion of flow outside of the main channel being confined to the flood runner instead of

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433 spreading over a larger area of shallow floodplain flow (Fig. 3). This effect is controlled
434 by large sedimentary training berms. Meanwhile, Parks Bar reach has some high
435 artificial terraces that once inundated no longer impede the increase in inundation width,
436 providing more room for flow to expand above that stage.

437 Because of variable length of the study reaches, a slightly different picture emerged
438 when the discharge-inundated area relationship was assessed (Fig. 2B). Inundated
439 floodplain areas in Daguerre Point Dam and Parks Bar reaches were approximately
440 double of that in Timbuctoo Bend reach at flows just above bankfull and as much as
441 triple at the peak modeled flow of 3126 m^3s^{-1}. On the other hand, Daguerre Point Dam
442 and Parks Bar reaches had, on average, similar values of inundated area (slightly larger
443 in the former reach up to Q = 1195 m^3s^{-1} and in the latter reach above that threshold).

444 A general trend of progressive increase in inundation from Timbuctoo to Parks Bar
445 to Daguerre Point Dam reach, expressed as percentiles of daily inundation values, is
446 illustrated in Fig. 4. For example, under normal hydroclimatic conditions, the median of
447 inundated width in Timbuctoo Bend reach was equivalent to 0.58 of that in Parks Bar
448 reach, which in turn was 0.71 of that in Daguerre Point Dam reach. When the inundated
449 floodplain area is considered, median values in Parks Bar Reach and Daguerre Point
450 Dam reach are almost identical and more than double those in Timbuctoo Bend reach
451 (Fig. 4 C-D).

452 A plot of overbank events' peak magnitude against continuous duration (Fig. 5)
453 provides a more nuanced insight into between-reach differences, revealing trends

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toward progressively larger peak magnitudes and more frequent high-magnitude inundation events in Daguerre Point Dam relative to Parks Bar and in Parks Bar relative to Timbuctoo Bend reach.

Lastly, UCAT analysis enables a comparison of reaches that considers magnitude and duration of inundation events jointly (Figs. 6 and 7). The UCAT curves for all study reaches had similar shapes because of the common flow input but indicated that floodplains in reaches with a less confined valley floor were inundated for a larger proportion of time for events of a given continuous duration and exceeding a given magnitude threshold (Fig. 6). The influence of valley topography generally increased with the magnitude thresholds. For example, under wet climatic conditions the cumulative duration of 1-day events in Parks Bar reach was ~ 0.81 of that in Daguerre Point for inundation in excess of 25 m (8.5% vs. 10.5% of time), 0.67 for inundation in excess of 50 m (4.35% vs. 6.5% of time), and 0.5 for inundation above 100 m (2% vs. 4% of time; Fig. 7). In addition, the relative difference between the reaches also increased with continuous duration of the inundation. For example, comparing reaches under wet climatic conditions, the cumulative duration of 7-day events in Parks Bar reach was ~ 0.72 of that in Daguerre Point for inundation in excess of 25 m (6.2% vs. 8.7% of time), 0.52 for inundation in excess of 50 m (2.3% vs. 4.4% of time), and 0.24 for inundation above 100 m (0.5% vs. 2% of time) (Fig. 7). In other words, relative differences between inundations in reaches with different valley topography were larger for long duration-large magnitude events.

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475

476 *6.2. Hydroclimate effects*

477 Our results showed that different hydroclimatic conditions, as expressed through
478 three water year classes, exerted a tremendous influence on flow regime and,
479 consequently, floodplain hydroperiod. While annual hydrographs generally displayed
480 broadly similar patterns (see examples in Fig. 8), the mean daily flow under normal
481 conditions was approximately half of that during wet years; and the mean daily flow
482 under dry conditions was half of the value in normal years (Fig. 9A, inset). The
483 differences in hydrological regimes were reflected in longer duration of flow exceeding
484 any given discharge under progressively wetter hydroclimate (Fig. 9A) as well as a
485 larger mean overbank discharge (Fig. 9A, inset). For example, in dry years, bankfull
486 discharge was exceeded < 0.1% of time, in normal years 5.8% of time, and in wet years
487 23.9% of time. The increase in mean overbank flow magnitude in normal years relative
488 to dry years was only 3.8%, while that increase was 46.5% in wet years when compared
489 to normal years.

490 The extent of inundated floodplain also displayed substantial differences between
491 water year classes (Fig. 4). For example, ratios of median inundation widths in wet
492 years to normal years was 0.39 in Timbuctoo Bend reach and Parks Bar reach and 0.4
493 in Daguerre Point Dam reach. Floodplain inundation events in progressively wetter
494 conditions had higher peak magnitude and longer continuous duration (Fig. 5). The
495 scatter in Fig. 5 is noteworthy, indicating a poor relationship between event magnitude

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and duration. This is a consequence of the dynamic hydrological regime in the Sierra Mountains, which is influenced by significantly different seasonal antecedent moisture conditions (yielding different rainfall-to-runoff ratios) and diverse storm event types that vary within and between seasons (Fig. 8), which may result in various flood-generating mechanisms (Senter et al., in press). For example, early wet season, intense rains driven by remnant monsoons from the western Pacific Ocean might fall on extremely dry soils and produce little runoff that is entirely captured by unfilled reservoirs. However, the same intensity of rain during the spring snowmelt runoff season would yield much runoff, exacerbate snowmelt, and might overflow full reservoirs. Thus, runoff magnitude, duration, and frequency may display relatively weak relationships with one another.

The UCAT curves also indicated that discharge fluctuations associated with varying hydroclimatic conditions constitute a strong control on floodplain hydroperiod (Fig. 6). In dry years, hardly any overbank flows took place. Any inundation event under such conditions lasted only 1 day, covered a floodplain width of < 30 m, and their cumulative duration constituted < 1% of total time. In contrast, under normal conditions, the largest events in Daguerre Point Dam reach exceeded 200 m of floodplain inundation for 1-day events and small events (width in excess of 10 m) lasted for up to 13 days. The shapes of UCAT curves were broadly similar between normal and wet conditions and, just like in the case of between-reach differences, differed mostly in terms of scale. These scale differences increased with event magnitude. For example, the proportion of time that at

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517 least 25 m of floodplain width in Daguerre Point Dam reach was inundated for 1 day
518 during normal years was equivalent to < 0.12 of the corresponding value under wet
519 conditions (1.3% vs. 10.7%; Fig. 7). Corresponding values for floodplain width
520 thresholds of 50 and 100 m were, respectively, 0.08 and 0.07 (0.6% vs. 6.5% and 0.3%
521 vs. 4.1%). Once again, in analogy to between-reach patterns, differences between
522 water year classes seemed to increase with event duration. For example, under normal
523 hydroclimatic conditions, the cumulative duration of 7-day inundation events in
524 Daguerre Point Dam reach that exceeded 25 m of floodplain width constituted only 0.05
525 of the cumulative duration of equivalent events under wet conditions (0.5% vs. 8.7%).
526 Overall, the effect of hydroclimate exceeded that associated with geomorphic controls.
527
528 *6.3. Flow regulation effects*
529 Comparison of the observed flow record with the estimated unimpaired streamflow
530 record suggested that regulated discharge is, on average, equivalent to 0.77 (dry and
531 wet climate) and 0.67 (normal climate) of the natural streamflow (Fig. 9B, inset).
532 However, the mean of the overbank discharge was either similar (dry years) or only
533 slightly lower (unimpaired/impaired ratio ~ 0.92 in wet and 0.88 in normal years).
534 Our results indicated that, as a consequence of these differences between the
535 regulated and unregulated flow regimes, median regulated inundation floodplain width
536 was about 75% of that for unimpaired flow in wet conditions, 50% for normal conditions,
537 and 40% for dry conditions. Furthermore, in absence of flow regulation, floodplains

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would be inundated for a substantially larger proportion of time, and this difference was higher with progressively drier conditions. For example, total duration of overbank flows was 1.6 higher in wet years (38.7% vs. 22.9% of time), ~ 5 times higher in normal years (27.6% vs. 5.2%), and as much as 60 times higher in dry years (5.6% of time vs. <0.1%). Larger peak magnitude of floodplain inundation width and longer cumulative duration of overbank events in progressively wetter conditions are clearly illustrated in Fig. 10. Overall, these findings suggest that the drier hydroclimatic conditions, the larger relative impact of flow regulation on floodplain inundation.

The UCAT analysis also suggested that the cumulative duration of events differed substantially under regulated and unregulated streamflow regimes and that relative differences were most pronounced for dry hydroclimatic conditions and smallest in wet water class years (Fig. 11). For example, the percent of time a given extent of floodplain was inundated in wet years and under impaired flow was 50% smaller than that under unimpaired flow regime. For normal water class years, cumulative duration of inundation under regulated flow was approximately one-eighth of the value under unregulated flow, and for dry water class the inundation was one-fifteenth or less of the extent under unregulated regime. The differences appeared to be similar in all study reaches and for different continuous durations, although only 1-day and 7-day events could be compared directly (as 14-day and 21-day events were almost absent under regulated streamflow; Fig. 12).

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7. Discussion

This study provides a unique opportunity to quantitatively characterize the relative influence that valley floor morphology, hydroclimatic conditions, and flow regulation have on floodplain inundation regime of three reaches of the lower Yuba River. All key aspects of floodplain hydroperiod — inundation extent, continuous event duration, and frequency — varied substantially under different examined scenarios.

Our findings regarding the geomorphic controls on inundation regime (Fig. 13) reveal two general points. First, broadly similar form of the nonlinear relationships between discharge and inundation width in our study reaches suggest that they may be, to some extent, generalizable to similar, partially confined valleys. Importantly, confined and partially confined channels have been shown to constitute most of the drainage network length, especially in the headwater and piedmont portions of mountainous river basins (O'Brien and Wheaton, 2014; Kasprak et al., 2016; Portugal et al., 2016). Despite that, to date, research on floodplain inundation was primarily conducted in large, lowland rivers with extensive floodplains. Reasonable fit of power law for large inundation events may also indicate some commonalities with the relationships identified in braided rivers (e.g., Smith et al., 1996; Smith and Pavelsky, 2008). However, we wish to caution and highlight that variation in the coefficients of functions fitted in our study reaches is large, indicating that the exact form of the discharge-inundation relationship is site specific. Moreover, considering various possible geometries of the valley cross sections, it is unlikely that logarithmic, power law, or any other relationship will hold universally (e.g.,

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580 Bjerklie et al., 2003). In addition, the importance of the sedimentary berm and
581 secondary channel in the Daguerre Point Dam reach in terms of flow routing shows that
582 local morphological features of the valley floor (natural or man-made) can alter the
583 effect of gross valley shape.

584 The second ramification of between-reach differences in the discharge-
585 inundation relationship is that the reaches with high rates of increase in inundation per
586 unit flow will also display high sensitivity to fluctuations and alterations of hydrological
587 regime caused by climatic factors or flow regulation. In other words, the reaches with
588 more extensive floodplains covering relatively flat terrain will be more sensitive to a
589 certain reduction in streamflow in the sense that they will experience higher reduction in
590 the inundated floodplain width.

591 Our analysis shows that hydroclimatic factors exerted primary influence on the
592 current floodplain inundation regime in LYR. Importantly, the functional relation between
593 flow and inundation extent involved non-linear amplification, so the impact of climate on
594 measures of inundation was disproportionate compared to its impact on the central
595 tendency of streamflow. This work may be relevant to other rivers in a Mediterranean
596 and semiarid climate that also have rapid increases in width as flow increases (e.g.,
597 Lespinas et al., 2009; Morán-Tejeda et al., 2010).

598 As noted in section 1, climate variability and change have been a major concern for
599 California's water resources, with the most important effects attributed to temperature
600 and resulting snowmelt processes (Cayan et al., 2001, 2008). However, it is important

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601 to emphasize that the magnitude of differences between the flow regimes under the
602 three hydroclimate scenarios analyzed in this study cannot be taken as representative
603 of potential effects of climate change. Climate warming scenarios based on historical
604 data from Sierra Nevada watersheds are still rudimentary but suggest a reduction in
605 snowmelt that ranges between <10% and 70% (depending on elevation) for a simplistic
606 2°C temperature increase and between about 20% and >90% for a simplistic 6°C
607 temperature increase (Young et al., 2009). As a result, mean annual flow in these
608 watersheds is preliminarily projected to decrease 3-9% for the same range of
609 temperature increases (Null et al., 2010). Similar results were obtained by Brekke et al.
610 (2004), whose findings suggested that inflows in San Joaquin reservoirs will be reduced
611 5% by 2025 and 14% by 2065. In light of these preliminary projections, our hydroclimate
612 scenarios represent a substantially exaggerated magnitude of potential differences in
613 streamflow and floodplain inundation associated with shifting climate norms. On the
614 other hand, scenarios developed based on our data reflect the historical range of
615 variability; therefore, we believe they are representative of the magnitude of fluctuations
616 that can be expected to occur in other Med-rivers similar to LYR at annual-to-decadal
617 time scales (e.g., associated with El Niño Southern Oscillation: Cayan et al., 1999; or
618 Pacific Decadal Oscillation: Benson et al., 2003).

619 This research complements past work on the effect of dams on flow regimes in the
620 Sierra Nevada, including the Yuba River (e.g., Kondolf and Batalla, 2005) and extends it
621 to floodplain inundation. Our assessment of inundation regime under the modeled

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622 unregulated discharge suggests a profound impact of dam operations on floodplain
623 hydroperiod in the LYR. We believe that the differences between impaired and
624 unimpaired flow may be relatively modest in comparison to other regulated Med-rivers.
625 Compared to other major rivers draining to the San Joaquin and Sacramento rivers in
626 the Central Valley, the Yuba is different because the large water supply reservoir is not
627 on the mainstem and thus only captures the flow from a single tributary. As a result,
628 there is a much more dynamic flood regime on the lower Yuba River than on its regional
629 counterparts (Escobar-Arias and Pasternack, 2011). Thus, while the purpose of flow
630 regulation on the LYR is to capture high flows for storage and redistribution to dry
631 periods, similar to dams in other parts of the United States (e.g., Magilligan and Nislow,
632 2005; Graf, 2006), the LYR is a rather unique case of regulated rivers in that it has
633 regular overbank floods. Consequently, we hypothesize that the influence of flow
634 regulation on floodplain inundation in other regulated rivers may be even larger than
635 that observed in this study.
636

637 **8. Floodplain ecosystem implications**

638 Findings of this study demonstrate that spatial and temporal variations in a
639 hydroperiod driven by different valley floor topography and flow regimes are likely to
640 result in distinct floodplain habitat conditions. The differences between scenarios
641 considered in our analysis are largest for high magnitude-long duration events, such as
642 those reported as critical for riparian plants and salmonid juveniles (represented in our

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643 analysis by 2- and 3-week durations). Although in section 3 we defined relevance only
644 by duration, implicitly, sufficiently large spatial extent of inundation is necessary for the
645 ecological benefits to accumulate to a meaningful level (Opperman et al., 2010).
646 One implication of these findings is that, through reduced hydrological connectivity,
647 climatic factors and dam operations may act to inhibit riparian plants' establishment and
648 growth and that these negative effects are likely to be nonuniform in space. Specifically,
649 the areas that are inundated only during large overbank events are likely to be affected
650 to a larger degree. Currently, riparian vegetation on the LYR floodplain frequently
651 occurs in downstream-elongated bands, which run in close proximity to the main
652 channel as well as chute and secondary channels. This may imply that hydrological
653 factors (inundation duration and frequency but presumably also distance to water table)
654 dominate over geomorphic disturbance, which is expected to be most severe near the
655 channel because of high hydraulic forces (Friedman and Auble, 1999). Research on
656 other Mediterranean rivers has demonstrated that declines in riparian species such as
657 poplar (*Populus nigra*) were correlated with changing climate (Stella et al., 2013a,
658 2013b), presumably as a result of physiological stress associated with changes in
659 inundation regime (Singer et al., 2013). Therefore, some modifications of current dam
660 operations would be essential for mitigating the effects of climate change and variability
661 on the floodplain hydroperiod and for restoration of riparian vegetation in the LYR.
662 We wish to highlight, however, that in this study we focus exclusively on surface
663 water connectivity and ignore other relevant factors that codefine the dynamics of

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riparian vegetation. Such factors include, for example, substratum characteristics (e.g., Harris, 1987, 1988) as well as groundwater dynamics that interact with overbank surface flow (Sophocleous, 2002) and subsurface hillslope flow (Jung et al., 2004). Nevertheless, recent work in a reach of the Merced River relatively similar to the LYR suggests that restored hydrological connectivity and substrate can greatly enhance riparian vegetation development (Sellheim et al., 2016).

Substantial reduction in large extent-long duration inundation events may also hinder growth of juvenile salmonds, especially if compounded with impaired productivity of riparian vegetation. In warmer climatic conditions (associated with climate variability or change), this effect would be further exacerbated by increased metabolic rates. Research on the Cosumnes and Sacramento rivers showed that Chinook salmon use lowland floodplains for rearing as soon as it became connected to the channel (Moyle et al., 2007) and grow significantly faster when the connectivity with floodplain habitat is maintained for a long enough period (Sommer et al., 2001; Jeffres et al., 2008). The benefits of floodplain rearing are thought to be related to lower flow velocities, high productivity of such an ecosystem — with high levels of primary production (Ahearn et al., 2006) and secondary production of invertebrates (Grosholz and Gallo, 2006) — as well as food web structure that facilitates energy flow to salmonids (Bellmore et al., 2013). Inundation not only provides access to these resources but also drives a boost in productivity (Jenkins and Boulton, 2003).

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However, the landscape setting in the LYR is very different from the study sites on the Cosumnes and Sacramento rivers, and this must be accounted for. The floodplain on the Yuba is more limited with a broad parafluvial zone dominated by coarse sediment and has relatively little vegetation cover in the study reaches. Therefore, structure and function of food web may be quite different. Nevertheless, increased overbank inundation on the Lower American River, where floodplain has a more similar character and extent to the LYR, was correlated with increased abundance of juvenile salmonids (Sellheim et al., 2015). Preferential use of floodplain by juvenile salmonids was also observed in the mountainous Elwha River (Pess et al., 2008). Therefore, we believe that a major restoration of vegetated floodplain habitat and possible adjustments to the negotiated flow regime could significantly contribute to recovery of Chinook populations in the LYR, pending careful scientific study. Such restoration efforts may be critical given that research elsewhere associated declines in salmonid stocks with reduced streamflow (Crozier and Zabel, 2006). Salmonids inhabiting snowmelt-dominated streams appear to be particularly vulnerable to the effects of climate change (e.g., Mantua et al., 2010).

9. Conclusions

In this paper we combined extensive remote sensing data on topography and vegetation (aerial LiDAR), almost four decades of hydrological records, and the outputs of a hydrological and 2D hydraulic model to examine how floodplain inundation regimes

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in the lower Yuba River are controlled by reach-scale valley morphology, hydroclimatic conditions, and flow regulation. Estimated relative differences in the extent, duration, and frequency (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. While the effects of hydroclimate and flow impairment are larger than that of valley floor topography, the latter control dictates sensitivity of the floodplain hydroperiod to climatic variability and change as well as dam-related flow alteration. Cumulative effects of flow regulation and climate seem to have particularly far-reaching consequences for channel-floodplain connectivity of the Yuba River.

These findings provide insight into hydrological and geomorphic controls on floodplain processes that may operate in confined or partially confined (Wheaton et al., 2015; Fryirs et al., 2016), Mediterranean climate rivers. We also consider implications of our results in light of relevant literature and suggest that the reduced hydrological connectivity of the floodplain caused by climate- and dam-related changes in streamflow is likely to strongly limit the potential for supporting riparian vegetation and production of salmonids.

In summary, this work highlights that conservation and restoration of channels similar to the Yuba River requires careful water resource planning which considers both ecological and human requirements (Grantham et al., 2010; Viers and Rheinheimer, 2011) and accounts for variable and changing climate (Thompson et al., 2011; Beechie

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et al., 2013; Rivaes et al., 2013). Our findings can also serve to inform the choice of target reaches for restoration of riparian vegetation and salmonid fish so as to maximize the gains in lateral connectivity between a river and its floodplain. Specifically, our work underscores that, given the impact of climate variability and change, restoration of such connectivity in the Yuba River would benefit greatly from flow augmentation particularly during dry water years.

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Figure captions:

Fig. 1. Location map of the lower Yuba River (LYR) showing the three study reaches, gaging stations, and other features of interest superimposed over the wetted area map for a flow of 1194.97 m^3/s.

Fig. 2. Relationship between discharge and floodplain inundation width (A) and area (B). Note that the inundation width includes areas on both banks of the river.

Fig. 3. Floodplain inundation maps for the three study reaches at (A) 141.58 m^3/s, (B) 1194.97 m^3/s, and (C) 3126.18 m^3/s.

Fig. 4. Floodplain inundation extent: width (A and B) and area (C and D) under normal (A and C) and wet (B and D) hydroclimatic conditions. The box indicates median, 25th, and 75th percentiles of inundated width. Whiskers are set to show 5th and 95th percentiles. Note that only data representing overbank conditions were taken into account.

Fig. 5. Peak inundation width and continuous duration of overbank events: dry hydroclimate (A); normal hydroclimate (B); wet hydroclimate (C). Different symbols denote different reaches.

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Fig. 6. The UCAT curves for different reaches (columns) and hydroclimatic conditions (rows). Each graph shows continuous duration of inundation events and their corresponding cumulative duration, expressed as the proportion of total time. Different threshold of the extent of inundation width are represented in different line patterns.

Fig. 7. Differences in continuous duration between the study reaches (A and B) and water years (C and D) for selected continuous durations, expressed in relative terms as ratios. Note the statistics in (A) and (B) refer to wet water year class and those in (C) and (D) to Daguerre Point Dam reach.

Fig. 8. Representative floodplain inundation time series for the three study reaches for each water year type.

Fig. 9. Discharge statistics in the lower Yuba River under regulated (A) and unregulated (B) flow regime. The main panels show cumulative distribution functions for the entire flow record and modeled for impaired flow (respectively). Solid and dashed lines denote distinct hydroclimatic conditions, while the dotted vertical line indicates bankfull discharge. The insets show the mean of all daily flow data and the mean of the daily overbank discharge (in B, impaired relative to unimpaired flow).

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Fig. 10. Peak inundation width and continuous duration of overbank events under the estimated unregulated flow regime: dry hydroclimate (A); normal hydroclimate (B); wet hydroclimate (C). Different symbols denote different reaches.

Fig. 11. The UCAT curves for different reaches (columns) and hydroclimatic conditions (rows) under the estimated unregulated flow regime. Each graph shows continuous duration of inundation events and their corresponding cumulative duration, expressed as the proportion of total time. Different thresholds of the extent of inundation width are represented in different line patterns.

Fig. 12. Differences in continuous duration between the study reaches for selected continuous durations and under the estimated unregulated regime, expressed in relative terms as ratios. Note these statistics refer to wet water year class.

Fig. 13. River-corridor hypsographs for the three study reaches within the 1194.97 m^3/s inundated area.

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Table 1

Characteristics of the study reaches (see Wyrick and Pasternack (2012) for more metrics and classes).

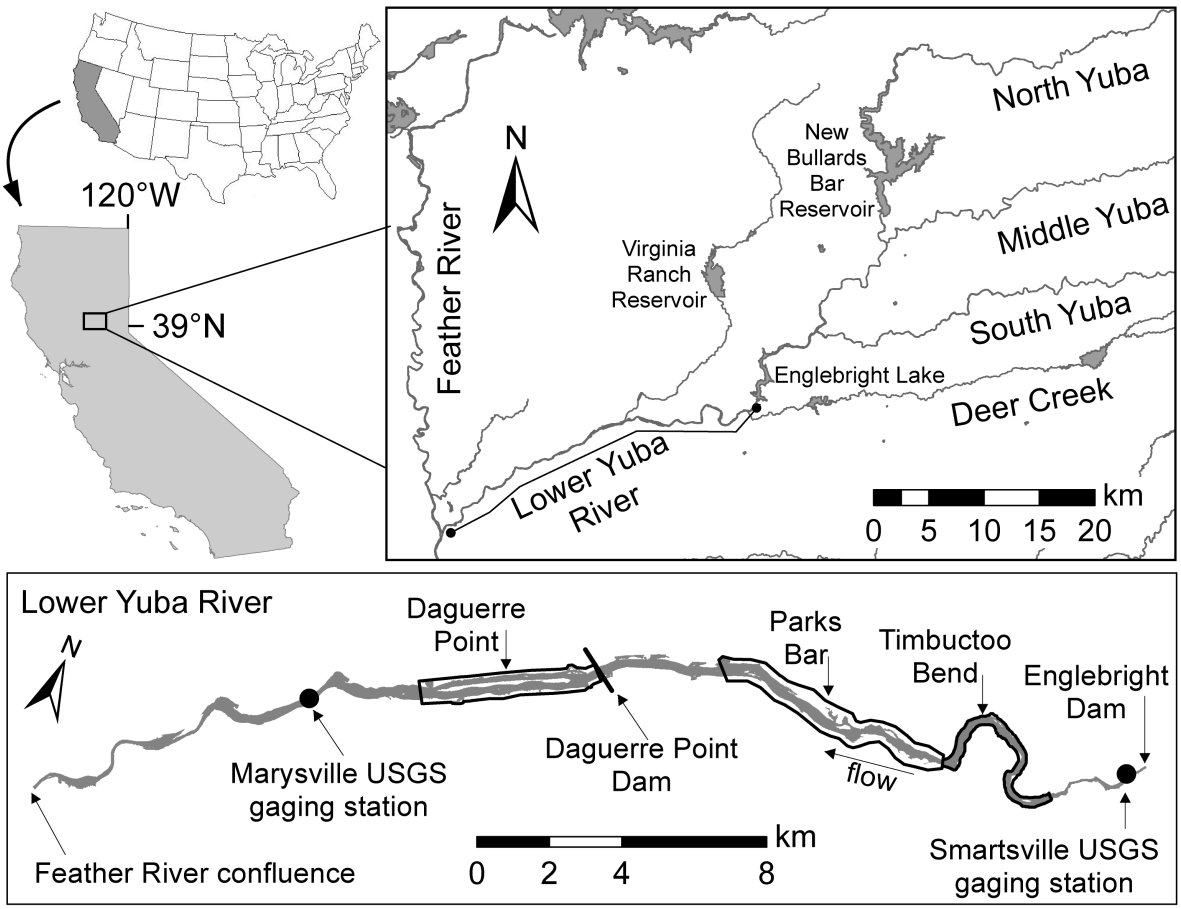
	Timbuctoo Bend	Parks Bar	Daguerre Point Dam
Mean slope (%)	0.2	0.19	0.18
Mean bankfull width (m)	84	96	120
Floodway width[a] (m)	134	207	313
Entrenchment ratio[b] (m/m)	2.1	2.9	3.5
Weighted mean substrate (mm)	164	117	87
Thalweg length (m)	6337	7919	5639

[a] Calculated as the inundated width at 587.5 m^3s^{-1}.

[b] Calculated as the ratio between the width at which depth is twice the bankfull depth and the bankfull width (Rosgen, 1996). The higher the value the less confined the valley is.

accepted, uncorrected

1279 **Figures**



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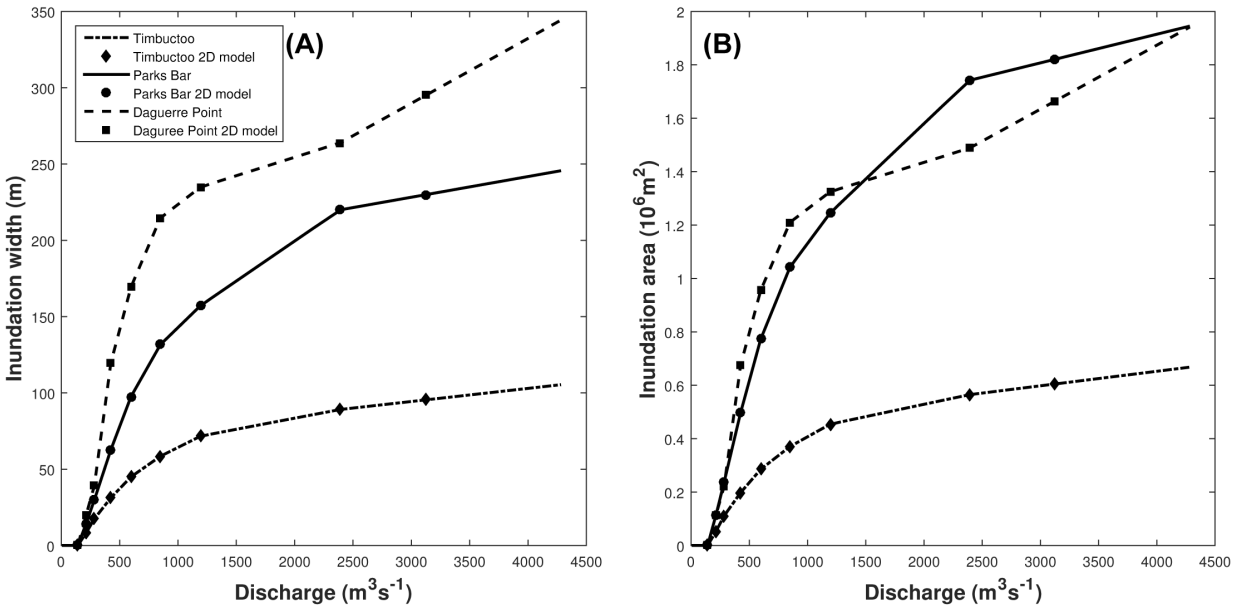

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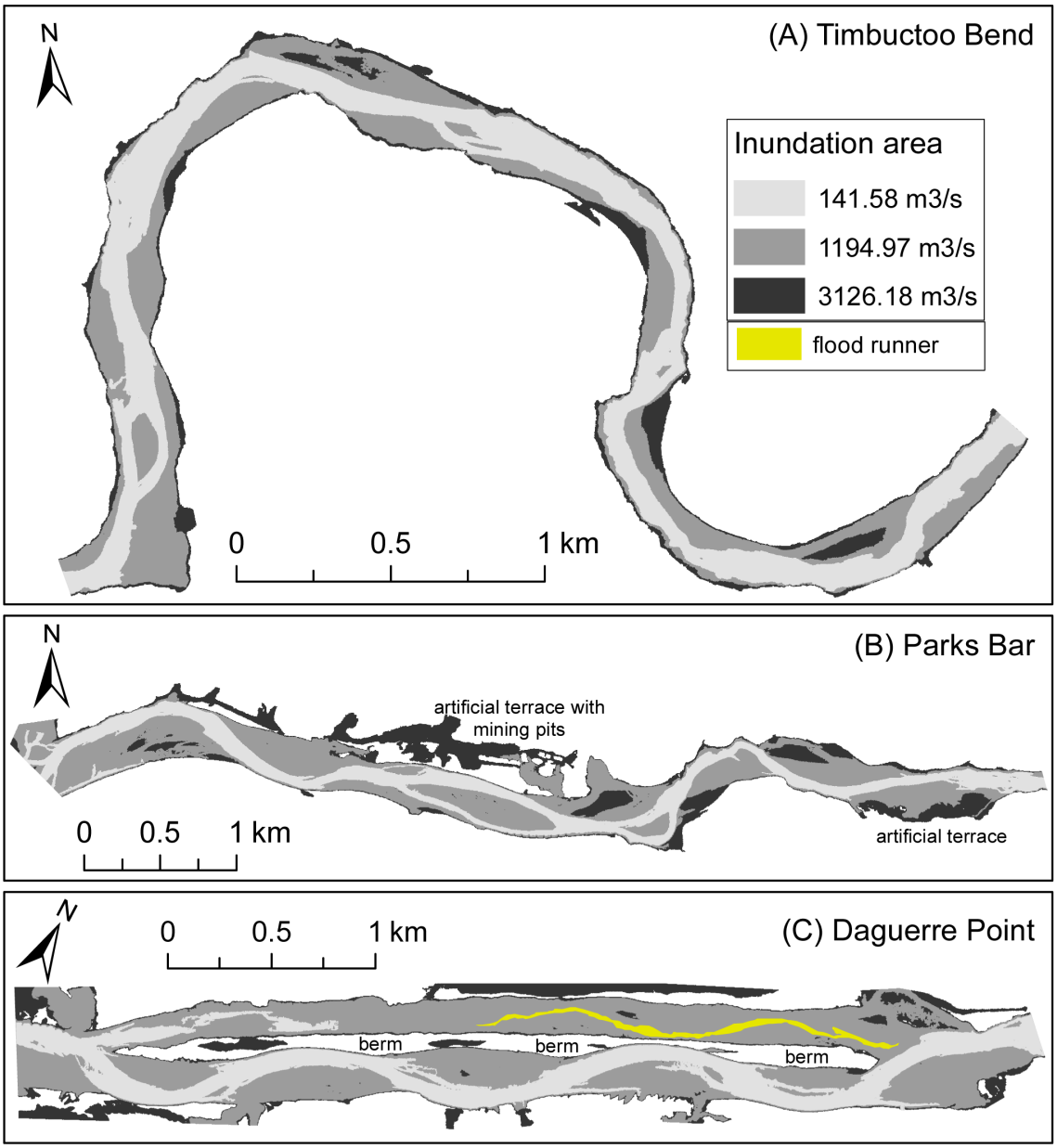
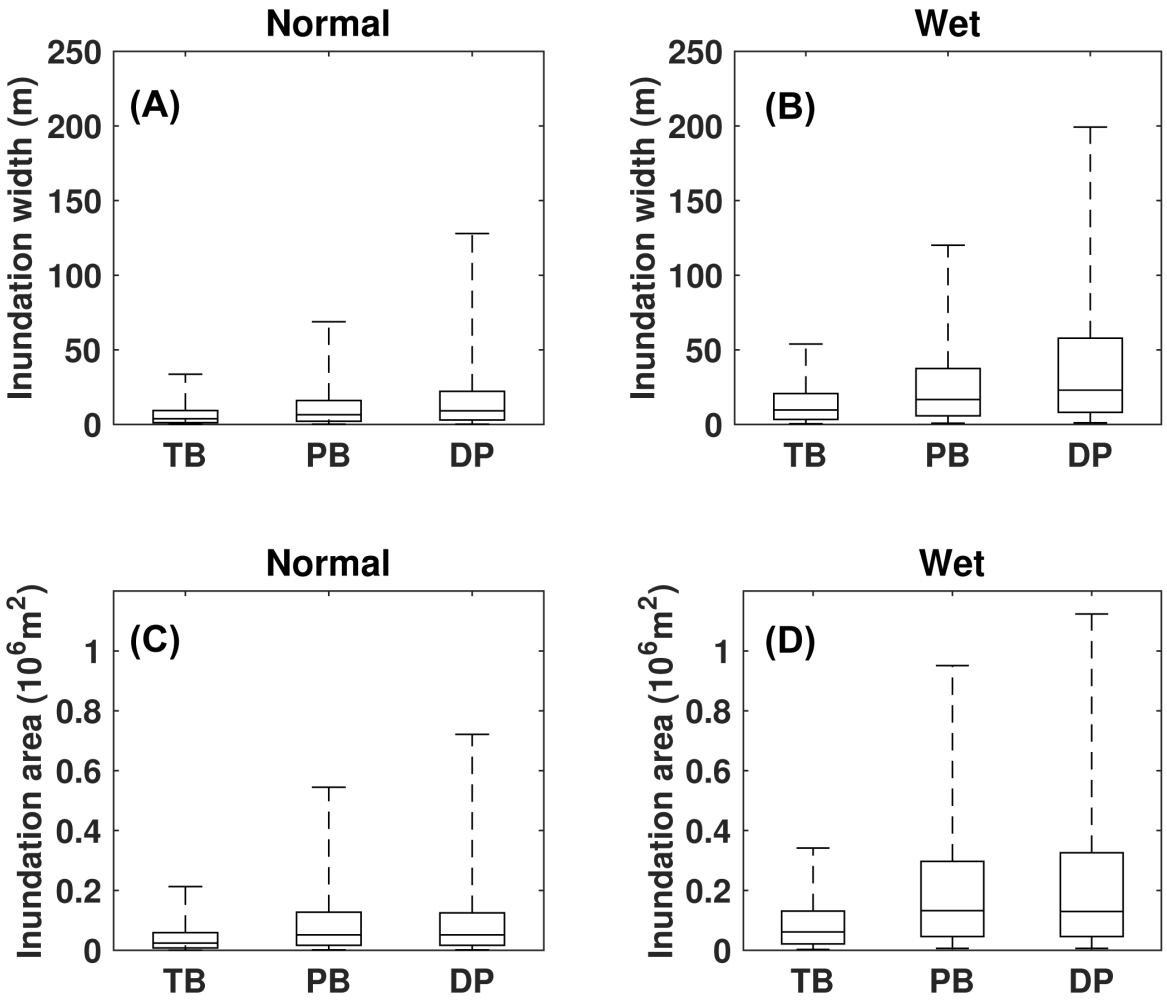

(A) Timbuctoo Bend
N
Inundation area
141.58 m3/s
1194.97 m3/s
3126.18 m3/s
flood runner
0
0.5
1 km
(B) Parks Bar
N
artificial terrace with
mining pits
0
0.5
1 km
artificial terrace
(C) Daguerre Point
N
0
0.5
1 km
berm
berm
berm

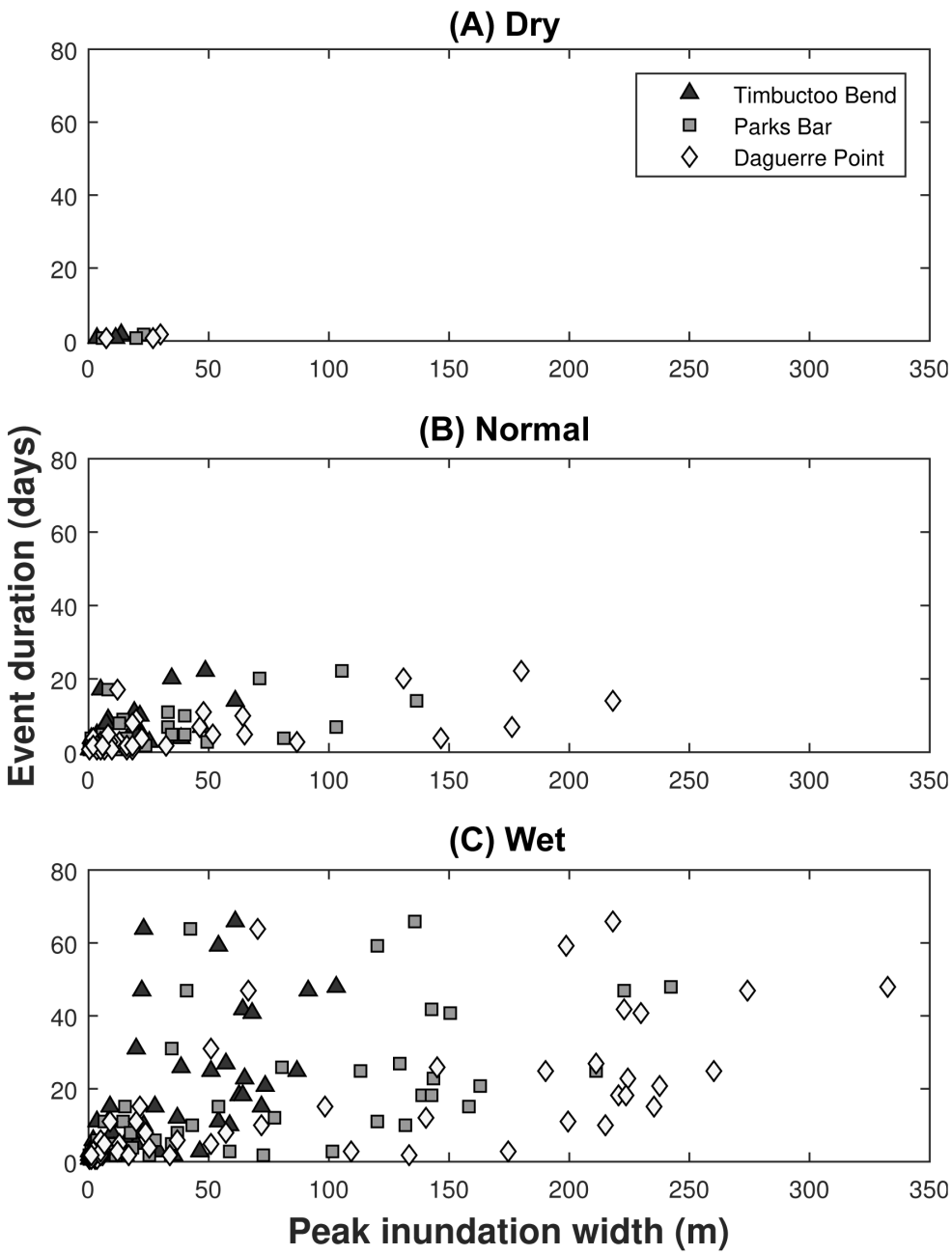
1282

1283

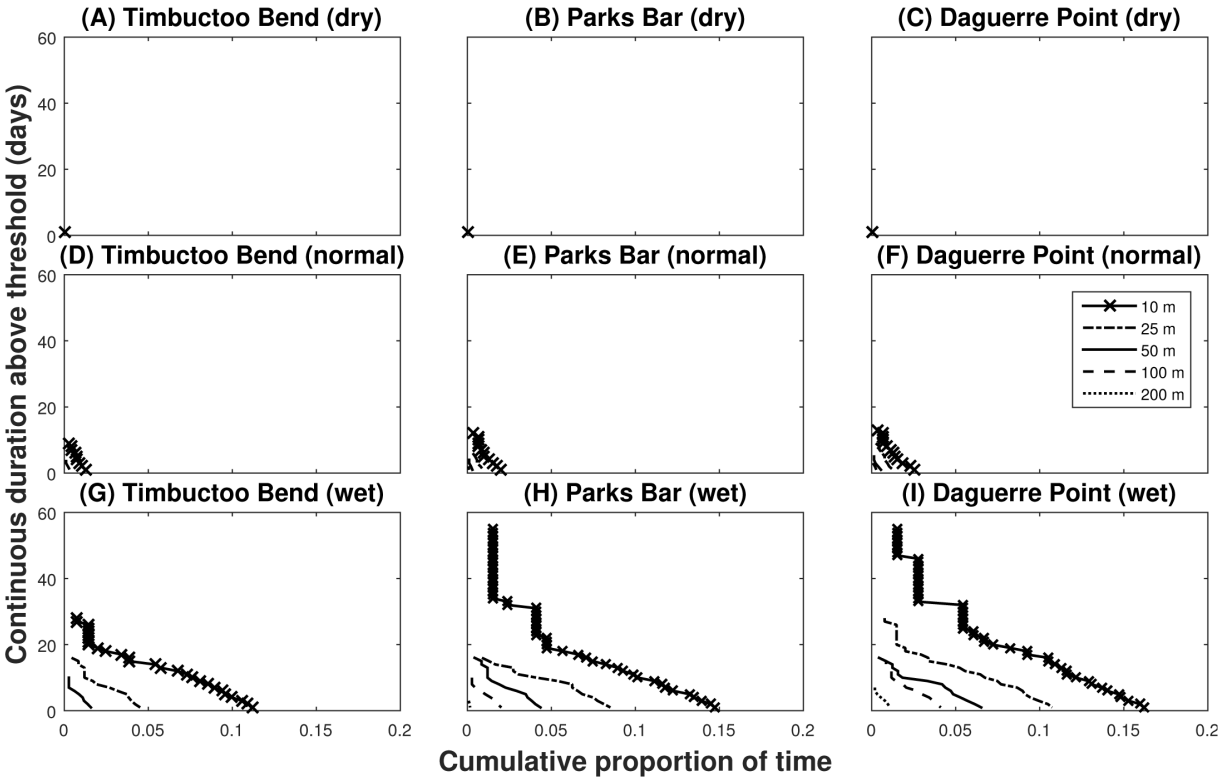

Normal
Wet
(A)
(B)
(C)
(D)
Inundation width (m)
Inundation area (10^6m^2)
250
200
150
100
50
0
1
0.8
0.6
0.4
0.2
TB
PB
DP

1284

accep

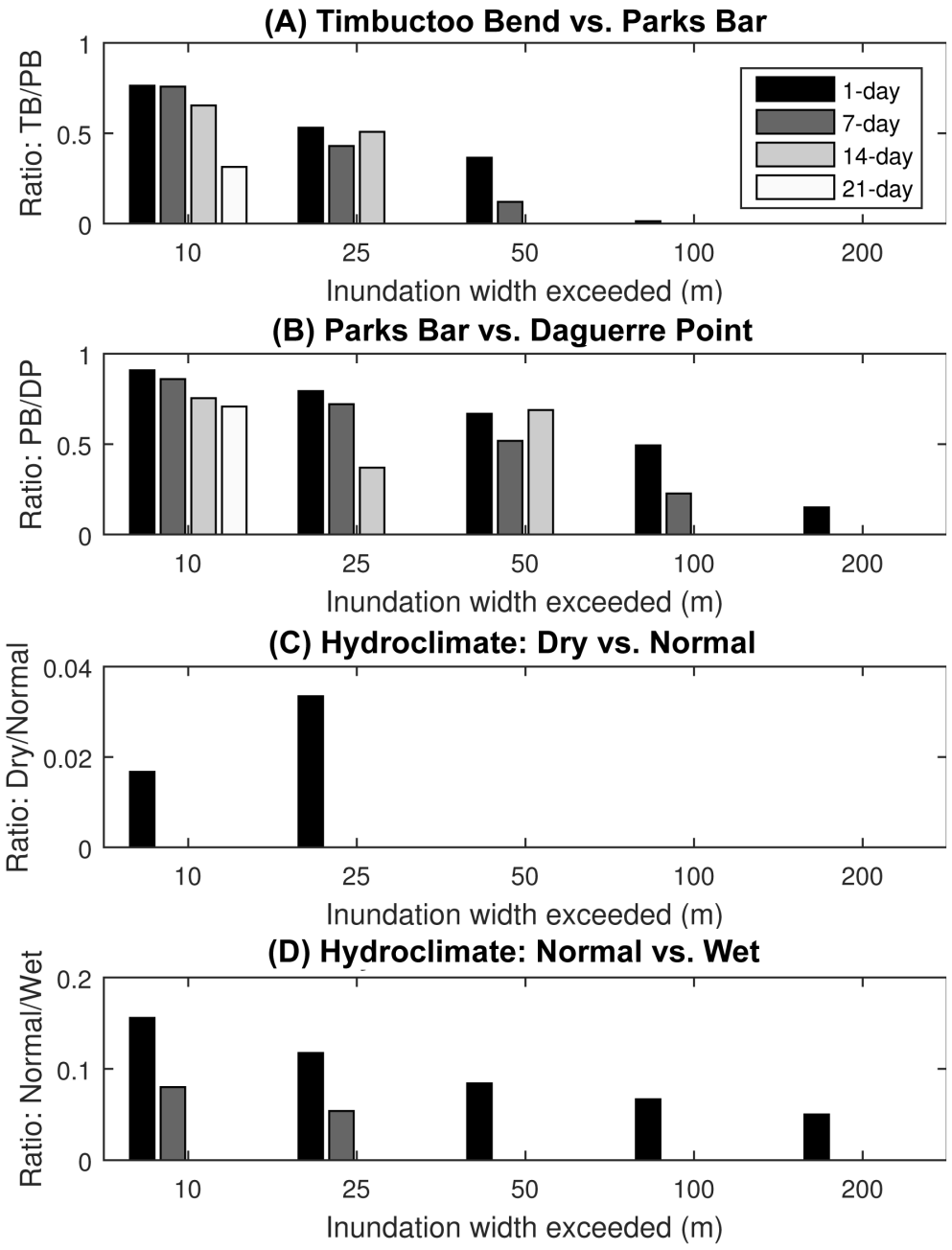

(A) Dry
(B) Normal
(C) Wet
Timbuctoo Bend
Parks Bar
Daguerre Point
Event duration (days)
Peak inundation width (m)
0
20
40
60
80
0
50
100
150
200
250
300
350

1285

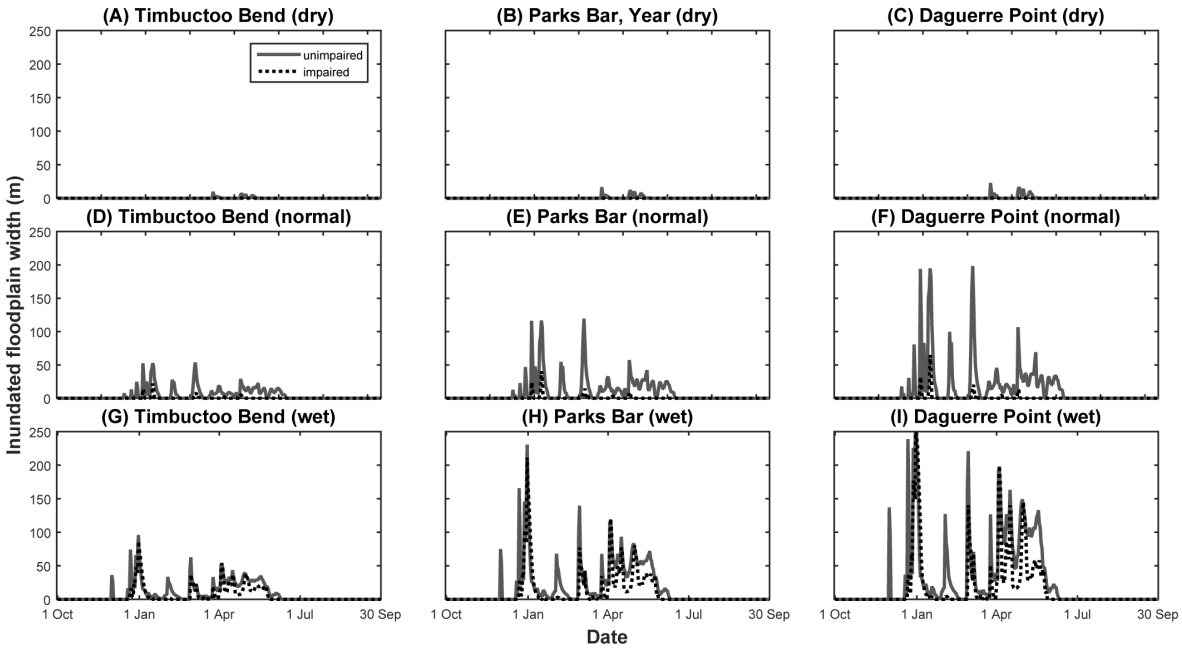


1286

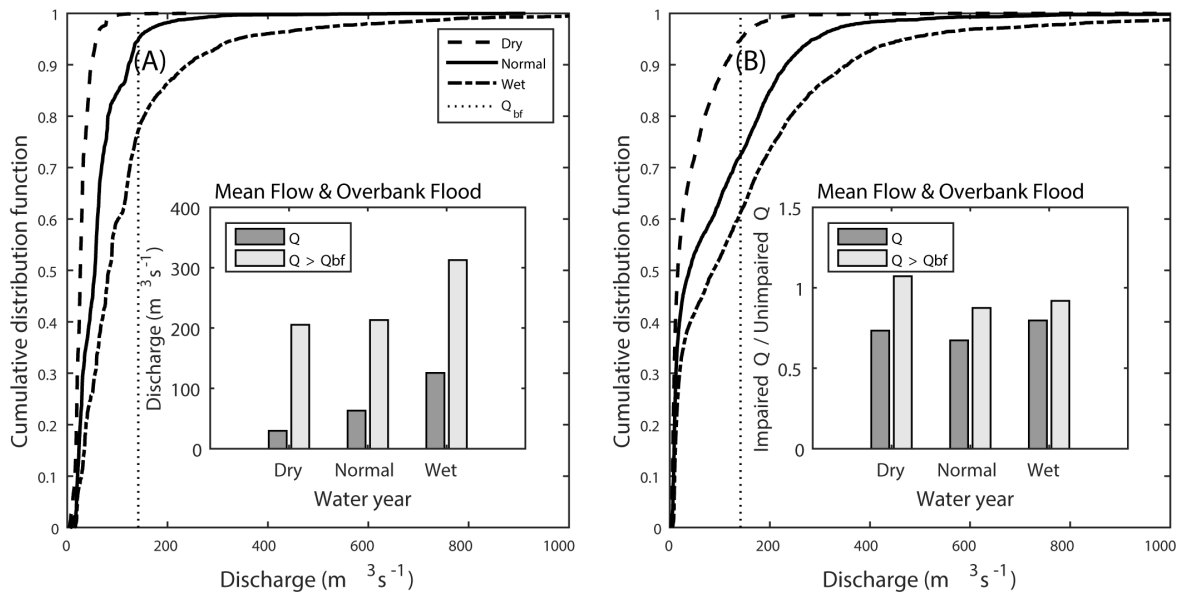
accepted, G


(A) Timbuctoo Bend vs. Parks Bar
Ratio: TB/PB
1-day
7-day
14-day
21-day
Inundation width exceeded (m)
(B) Parks Bar vs. Daguerre Point
Ratio: PB/DP
Inundation width exceeded (m)
(C) Hydroclimate: Dry vs. Normal
Ratio: Dry/Normal
Inundation width exceeded (m)
(D) Hydroclimate: Normal vs. Wet
Ratio: Normal/Wet
Inundation width exceeded (m)

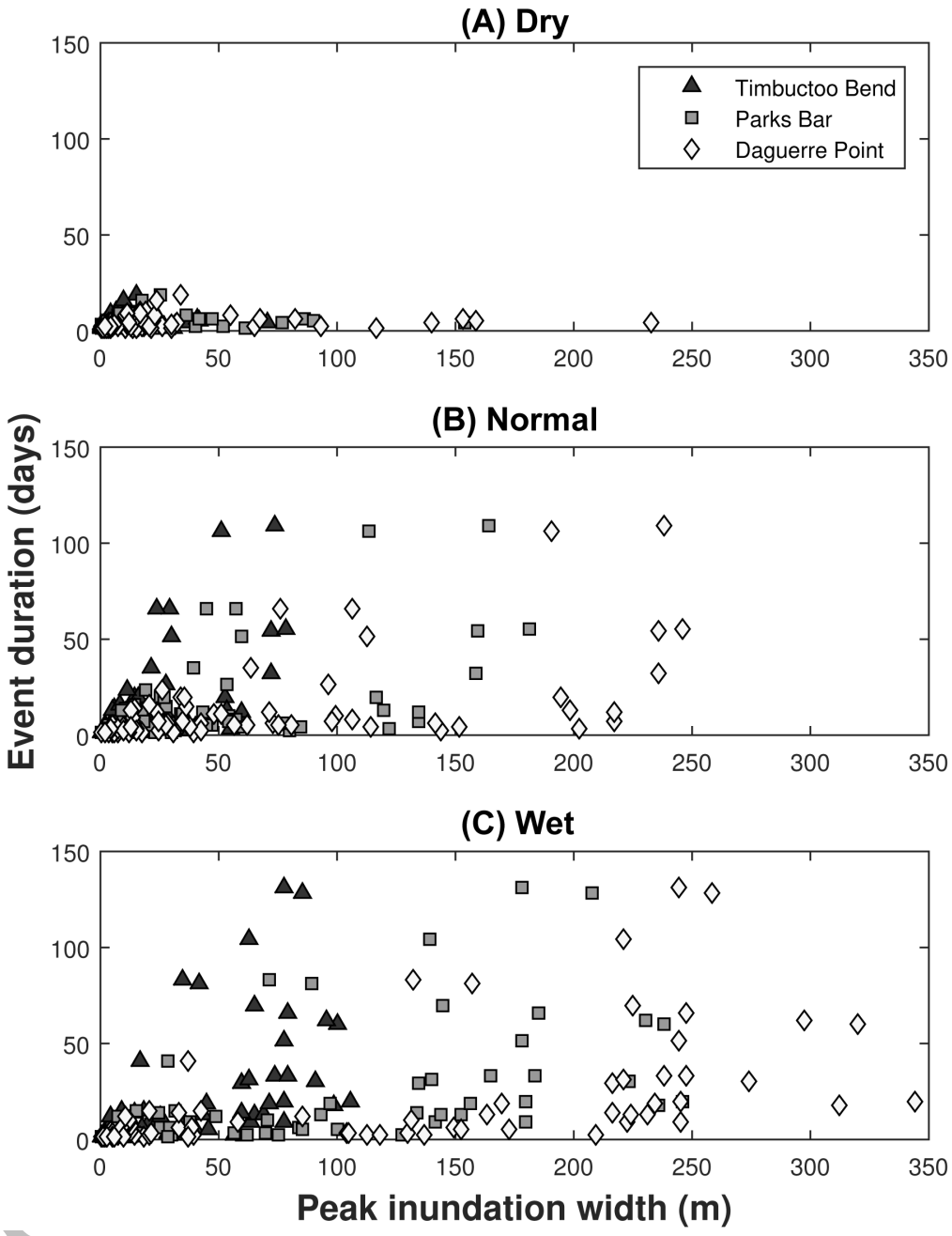
1287


(A) Timbuctoo Bend (dry)
(B) Parks Bar, Year (dry)
(C) Daguerre Point (dry)
(D) Timbuctoo Bend (normal)
(E) Parks Bar (normal)
(F) Daguerre Point (normal)
(G) Timbuctoo Bend (wet)
(H) Parks Bar (wet)
(I) Daguerre Point (wet)
unimpaired
impaired
Inundated floodplain width (m)
1 Oct
1 Jan
1 Apr
1 Jul
30 Sep
Date

1288

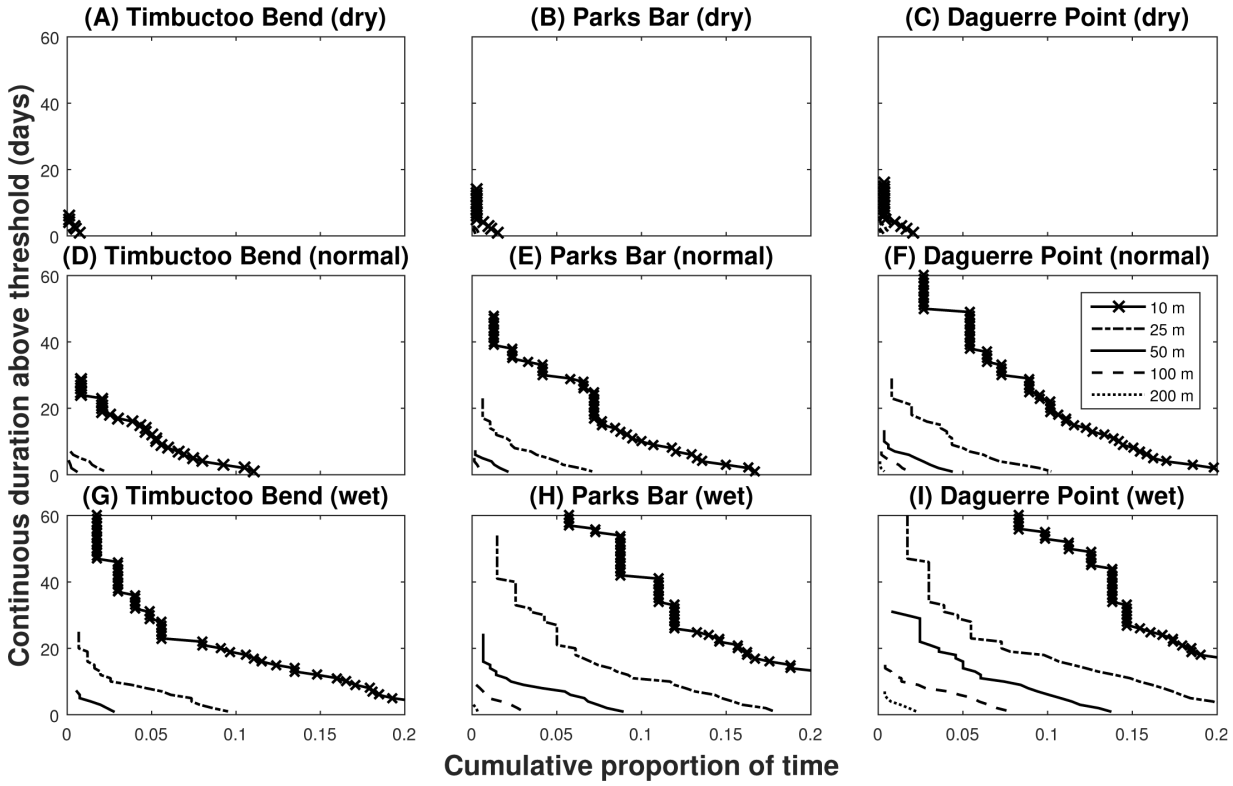

(A)
(B)
Dry
Normal
Wet
Q bf
Cumulative distribution function
Discharge (m 3 s -1)
Mean Flow & Overbank Flood
Q
Q > Qbf
Dry
Normal
Wet
Water year
Impaired Q / Unimpaired Q

1289


(A) Dry
(B) Normal
(C) Wet
Timbuctoo Bend
Parks Bar
Daguerre Point
Event duration (days)
Peak inundation width (m)
0
50
100
150
200
250
300
350

1290

1291



1292

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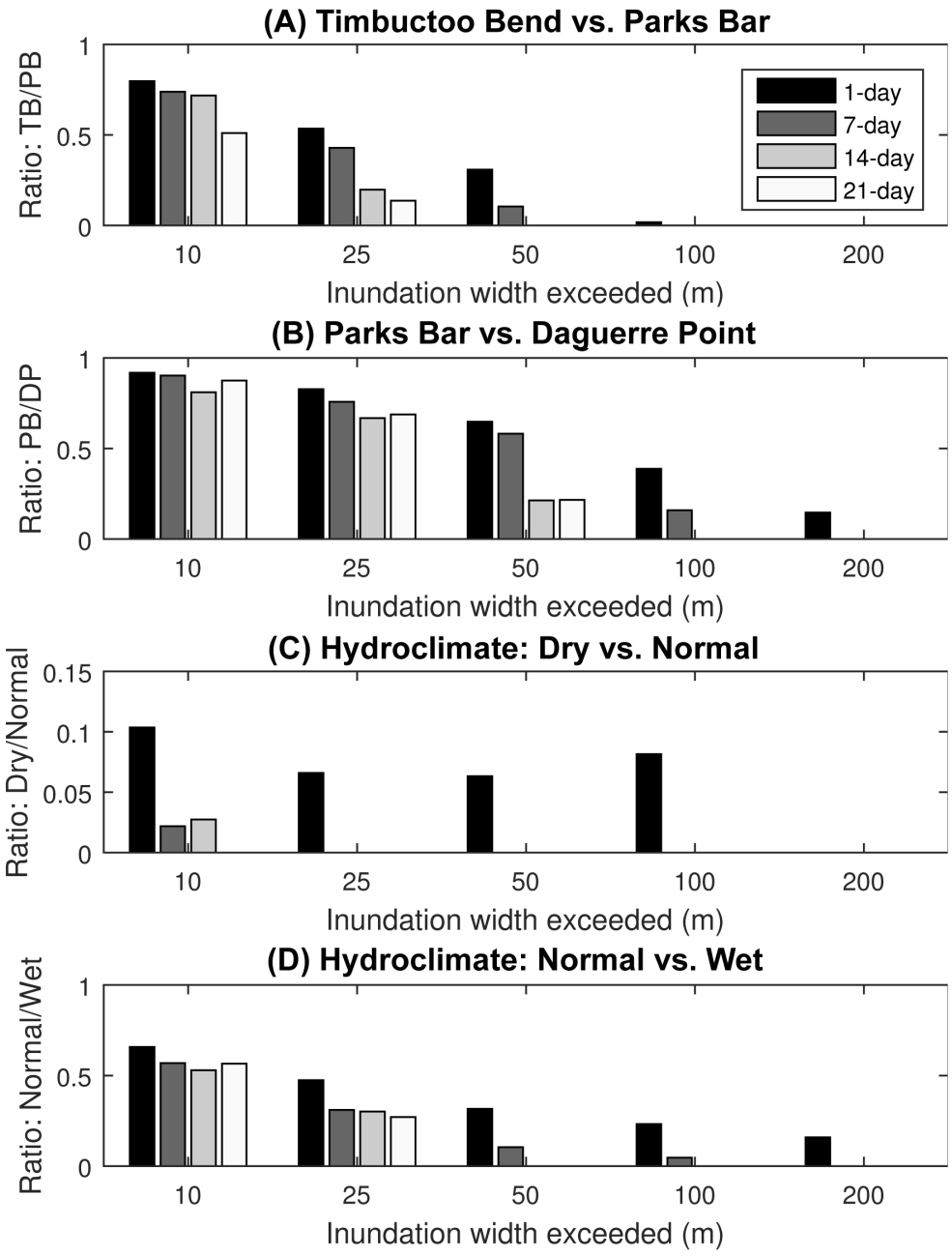
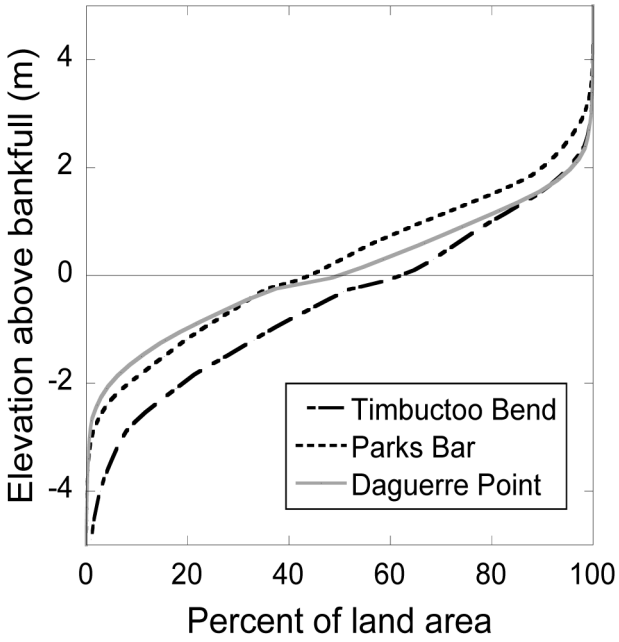

(A) Timbuctoo Bend vs. Parks Bar
Ratio: TB/PB
1-day
7-day
14-day
21-day
Inundation width exceeded (m)
(B) Parks Bar vs. Daguerre Point
Ratio: PB/DP
Inundation width exceeded (m)
(C) Hydroclimate: Dry vs. Normal
Ratio: Dry/Normal
Inundation width exceeded (m)
(D) Hydroclimate: Normal vs. Wet
Ratio: Normal/Wet
Inundation width exceeded (m)

1293



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