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Title:

Differences in River Ecological Functions Due to Rapid Channel Alteration Processes in Two California Rivers Using the Functional Flows Model, Part 2 – Model Applications

Running Head:

Functional Flows Model Applications

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Abstract

This study applies the functional flows model that integrates hydrogeomorphic processes and ecological functions to assess physical habitat. Functional flows are discharge values that serve ecological uses. The model was adjusted to evaluate gravel-bed riffle functionality for fall-run

Chinook salmon with respect to river rehabilitation on the Mokelumne River and flood-induced channel change on the Yuba River. The goal was to test if differences in ecological performance were traceable to differences in hydrogeomorphic conditions. Ecological functions studied were bed occupation (spawning, incubation, and emergence) and bed preparation (river bed reworking periods)- both reliant on shear stress dynamics. Model outputs included number of days that have functional flows, ranges of functional flows that provide favorable sediment transport stages, and the efficiency of a site to produce functional flows. Statistical significance of results was tested using non-parametric tests. Functional flows analyses before and after geomorphic alteration indicate that river rehabilitation on the lower Mokelume River increased the number of days with functional flows, while the Yuba River May 2005 flood increased the functional ranges of flows for the test sites. Reach-scale analyses indicated similar ecological performance at reference sites in both rivers. A comparison between both rivers showed that despite a greater geomorphic potential of the Mokelumne River sites to have functional flows, Yuba River sites actually experienced better ecological performance for fall-run Chinook salmon freshwater life stages due to greater flow availability. The functional flows model provided an objective tool to assess changes in ecological functionality at hydrogeomorphically dynamic sites.

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Keywords: aquatic habitat evaluation, ecological functions, functional flows, Mokelumne River, gravel augmentation, Yuba River, floods, sediment transport stages

1 Introduction

Hydrogeomorphic processes in rivers determine the conditions of the physical habitat where organisms perform their ecological functions (Knighton, 1998; Marcot and Heyden, 2001; Moyle and Check, 2004). Hydrologic and geomorphologic processes at the watershed scale, such as climate change and landscape evolution, determine the amount of water and sediment that move through catchments and into streams (Poff et al. 1997, Richards et al. 2002). Streamflow and sediment interact dynamically at the reach scale (i.e. defined as a portion of the river with length > 10^2 channel widths) through hydrologic, hydraulic, and sediment transport processes controlling local water depth, velocity, bed form, and substrate composition (Fig. 1) (Lisle et al. 2000, Parker et al. 2003). The rate at which hydrogeomorphic processes at the watershed and reach scales happen vary from long term geologic trends to rapid alterations of water and/or sediment supply (Major and Mark, 2006; Gibbins *et al.*, 2007; May, 2007). Watershed scale events that induce rapid hydrogeomorphic alterations include river engineering projects and convulsive natural events such as floods, volcanic eruptions, storms, hurricanes, wildfires, mass wasting, volcanic eruptions and earthquakes (Knighton, 1998; Major and Mark, 2006; Moody and Kinner, 2006) (Fig. 1). Such events are likely to determine local hydrologic, hydraulic, and geomorphic changes, however the conditions of physical habitat units that make them suitable to be used by organisms to perform their ecological functions have the potential to persist (Maddock et al. 2004, Tipton et al. 2004, Ito et al. 2006).

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Events that cause rapid hydrogeomorphic changes have dramatic impacts on local habitat conditions (May, 2007). Gravel augmentation and natural floods change channel morphology, substrate composition, hydraulics, and floodplain connectivity (Wheaton *et al.*, 2004a; Major and Mark, 2006). These alterations affect ecological functionality of physical habitat for organisms that interact with the water column and the river bed (Tipton *et al.*, 2004; Ito *et al.*, 2006). Before a morphologic alteration, specific flow magnitudes generate certain water depths and velocities causing specific bed mobility stages that may be functional for an organism's life stage. After a morphologic alteration, the same flow magnitudes may generate higher or lower water depths and velocities causing a dissimilar bed mobility stage and associated ecological functionality. Consequently, the functionality of a specific hydrograph can change in river sections where rapid hydrogeomorphic changes occur. Likewise, sites with different morphologies may behave different in terms of their hydraulics and sediment transport stages, causing differences in ecological functionality.

Assessments of flow functionality before and after changes in physical characteristics of the habitat and at sites with different morphologies within a reach allow the identification of the effect of hydrogeomorphic processes and morphology on ecological functionality. The functional flows model was used to address fundamental research questions by analyzing differences in habitat functionality due to gravel augmentation, natural floods, and differences in channel morphology.

The overall goal of this paper was to apply the functional flows model, presented in the preceding article labeled as Part 1 (Escobar-Arias and Pasternack, In Press), to analyze ecological functionality under two types of rapid hydrogeomorphic change processes and under different morphologies. Consequently, the model was used in this study to advance the basic

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scientific understanding of stream ecological response to hydrogeomorphic change, not just report specific metrics for two rivers. The model was tuned for fall-run Chinook salmon (*Oncorhynchus tshawytscha*), a key endangered Pacific Northwest salmon species that is an indicator of ecosystem functionality (Merz et al. 2004, Augerot et al. 2005, Merz and Chan 2005). The model was applied, in two significantly different rivers supporting fall-run Chinook salmon in the same region, to observe the effects of hydraulic and morphologic differences on ecological functionality: the narrow, sediment starved, low-flow lower Mokelumne River that has undergone river rehabilitation through gravel augmentation projects, and the wide lower Yuba River, with an abundance of hydraulic mining sediment in the floodplain and a diverse flow regime, which has undergone rapid morphologic changes due to floods (Fig. 2).

The overall hypothesis of this paper is that differences in hydrogeomorphic conditions induce changes in ecological performance of the physical habitat, with the specific mechanism embedded into the algorithms defining the functional flow model, as outlined in the preceding article (Escobar-Arias and Pasternack, In Press). Research questions 1 to 3 listed below were formulated to test the hypothesis by comparing functional flows before and after morphologic alterations. Such morphologic alterations were caused by rapid hydrogeomorphic changes at habitat units defined as zones with characteristic physical attributes where organisms perform ecological functions (Knighton 1998, Marcot and Heyden 2001, Moyle and Check 2004). Additional research questions 4 and 5 listed below were posited to compare functional flows among sites within the same river reach and between rivers:

1) What are the ranges of flows that are potentially functional?
2) What is the number of days that flows are functional?
3) What is the efficiency of a habitat unit in producing functional flows?

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4) What is the overall functionality of habitat units within a river reach as measured by the ranges of functional flows, number of days with functional flows, and efficiency to produce functional flows?
5) How does functionality of a reach as measured by the ranges of functional flows, number of days with functional flows, and efficiency to produce functional flows compare to other reaches in the river and to other rivers?

In order to answer the research questions, the method used involved 1) performing functional flows analyses for theoretical and actual water years to study the effects of gravel augmentation on ecological functionality on the lower Mokelumne River and to study the effects of flood-induced morphologic changes on ecological functionality on the lower Yuba River and 2) comparing results of the functional flows analyses before and after morphologic alteration, among different habitat units within the same river reach, and between the rivers to observe the utility of applying the model in habitat units with different hydrologic regimes and morphologies. The analyses presented in this paper are an example of the use of the functional flows model that highlights the utility of the tool for basic and applied science and management. The application presented shows that the functional flows analysis provides a uniform measure that can be used to assess and compare ecological functionality among habitat units on a single river and among rivers.

2 Functional Flows Analysis

The Functional Flows Model (FFM) uses assessments of hydrogeomorphic dynamics as indicated by the temporal pattern of shear stress, which is a key factor determining physical habitat for several ecological functions. A functional flow is defined as a discharge that interacts

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with river bed morphology through hydraulic processes providing a shear stress value that serves an ecological use. Depending on the specificity of a given ecological function, functional flows may occur over a range of discharges.

The next subsections present an overview of the functional flows analysis. To classify ranges of flows that are functional, the initial step was to identify relevant ecologic functions for the target species, in this case, fall-run Chinook salmon. Subsequently, habitat units within the two river systems were localized. Data for the calculations was gathered based upon the method to estimate shear stress selected (i.e. discharge time series, cross-section geometry, water surface slope, and grain size distribution). The final task was to build a table of functionality to specify the dependence of ecological functions on river bed sediment transport stages determined by shear stress thresholds and to assign functionality to streamflow time series.

2.1 Ecological Functions

Ecological functions are defined as the ways in which organisms interact with and use their physical habitat (Marcot and Heyden, 2001). Ecological functions related to physical habitat happening during the freshwater life stage of salmon include upstream migration of adults, spawning, embryo incubation, fry emergence, and juvenile rearing. Every year salmon migrate to upstream reaches to spawn in foothill and mountain cold water streams (Reiser and Bjornn, 1979). They initiate the construction of the nest, called redd, by digging a hole to depths that vary depending on the size classes of the females for each species (DeVries 1997, Montgomery et al. 1999). After females lay their eggs and males fertilize them, the females finish the redd construction by covering the embryos with gravel (Groot and Margolis, 1991; DeVries, 1997). During incubation, the embryos remain buried within the gravel. After a period that ranges from 2-8 months, the just-hatched fish, called fry, emerge through the gravel to begin

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their juvenile life in freshwater (Groot and Margolis 1991, Merz et al. 2004, Augerot et al. 2005). To simplify the analysis, ecological functions of interest are grouped as 1) bed occupation functions that occur in periods when the fish interact with the river bed (i.e. spawning, incubation, and emergence), and 2) bed preparation functions that modify river bed surface conditions for the next spawning season (Fig. 3A). High and low flows may be functional or not depending on the timing with respect to the selected ecological functions (Fig. 3B).

2.2 Habitat Units

Physical habitat units in rivers are zones with characteristic physical attributes where organisms perform ecological functions (Knighton, 1998; Marcot and Heyden, 2001; Moyle and Check, 2004). The selection of sites for functional flows applications concentrates on sites where the ecological functions under analysis are expected to occur. Preferred spawning habitat units are areas with low water depths, moderate velocities, and gravel that fish can move for redd construction (Lisle and Lewis, 1992; Kondolf and Wolman, 1993; DeVries, 1997; Gallagher and Gard, 1999; Lapointe *et al.*, 2000; Moir *et al.*, 2004). Flow, bed topography, and sediment sorting at the pool tail provide the bed form and water depth and velocity that salmon seek to carry out their reproductive life stage (Emery *et al.*, 2003). Consequently, pool tail/riffle entrance is one preferred location for spawning (Montgomery et al. 1999, Coulombe-Pontbriand and LaPointe 2004, Moir et al. 2004, Moyle and Check 2004). Other locations include side channels and lateral bars (Webb et al. 2001, Moir et al. 2004, Morley et al. 2005).

2.3 Equations for Shear Stress Calculation

Shear stress is the key parameter that represents the force available to scour the river bed and can be used to delimit ecological functions that are highly dependent on sediment transport

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regimes at selected habitat units (Montgomery *et al.*, 1999). The 1D Saint Venant equation for non-steady non-uniform flow or at least 9 other methods could be used to estimate boundary shear stress from field measurements (Dietrich and Whiting, 1989) for functional flows analysis. For the application presented in this study, the simplified depth-slope product was selected to calculate boundary shear stress

$$\tau_0 = \rho g R S \quad \text{or} \quad \tau_0 = \rho g h S \text{ for wide channels} \tag{1}$$

This method assumes conditions of uniform and steady flow that need to be checked for actual applications. Eq. 1 is used as a first cut approach that incorporates the dominant hydraulic interactions controlling channel sediment transport (Konrad *et al.*, 2002; Buffington *et al.*, 2004; Murray, 2007). Using this simplified expression for shear stress it was possible to focus this study on exploring the interactions among physical processes and ecological functions without the need for calculating shear stress in detail, which is a valuable effort that has been the focus of several studies (Booker, 2003; Rodriguez *et al.*, 2004; Wilson *et al.*, 2006).

"At-a-station" cross-section geometry relations can be used to evaluate depth at a range of discharge values

$$h = cQ^f \tag{2}$$

where c and f are empirical values that control the water depth response to discharge increments at the cross section (Leopold and Maddock, 1953; Parker, 1979). This approach is useful to obtain water depth time series necessary to estimate shear stress time series.

Replacing Eq. 2 in Eq. 1, the shear stress becomes

$$\tau_0 = \rho_w g (cQ^f) S \tag{3}$$

Eq. 3 can be non-dimensionalized to obtain non-dimensional absolute values of shear stress

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$$\tau_0{*} = \frac{\tau_0}{g(\rho_s - \rho)D_{50}} \tag{4}$$

where ρ_s is the sediment density. Functional flows are expressed in terms of non-dimensional shear stress $\tau_o{*}$, which allows a generalized definition of the model. Non-dimensional boundary shear stress can be compared to non-dimensional absolute values of $\tau_o{*}$ that represent the critical magnitude necessary to entrain gravel of a given size, $\tau_{crit}{*}$, or Shields parameter (Buffington and Montgomery 1997, Wheaton et al. 2004a). Substituting Eq. 2 and 3 into Eq. 4, a new form of $\tau_o{*}$ is obtained

$$\tau_0{*} = \frac{\rho g h S}{g(\rho_s - \rho)D_{50}} = \frac{\rho(cQ^f)S}{(\rho_s - \rho)D_{50}} \tag{5}$$

Eq. 5 can be used to evaluate $\tau_o{*}$ for discharge time series and for a given cross section with a specific median grain size. The temporal pattern of shear stress represents geomorphic dynamics that are relevant to identify functional transport stages for fall-run Chinook salmon life stages (Fig. 4).

2.4 Shear Stress Thresholds

The FFM requires specification of bed mobility transport stages delimited by boundary shear stress thresholds for selected ecological functions (Table 1, Column 1) (Kondolf and Wilcock, 1996; Lisle *et al.*, 2000). Bed mobility categories are high flow/full mobility (FM), intermediate high flow/interstitial fines mobility (IFM), intermediate low flow/ superficial fines mobility (SFM), and low flow/stable bed (SB) (Fig. 4). Associated dimensionless critical shear stress values are used to delimit bed mobility stages for gravel-bed rivers according to values found in the literature (Table 1, Column 2B). For the present application of functional flows analysis, a stable bed is assumed when $\tau_o^*<0.01$, intermittent transport when $0.01< \tau_o^*<0.03$,

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partial transport when $0.03<\tau_o^*<0.06$, and full mobility when $0.06<\tau_o^*<0.10$ (Buffington and Montgomery 1997, Lisle et al. 2000). The upper threshold for full mobility is set at 0.10 assuming that beyond this point there is intensive bed load transport that is non-functional to support spawning functions (Lisle *et al.*, 2000). Further details on the thresholds for bed mobility stages are provided in the preceding paper labeled as Part 1 (Escobar-Arias and Pasternack, In Press).

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2.5 Model Structure and Table of Functionality

The FFM algorithm integrates key relations between shear stress and ecological functions that have already been identified and are available in the literature such as the ones presented above. By estimating τ_o^* as a function of discharge time series it is possible to create the “table of functionality” to determine the functionality of sediment transport stages and flows serving ecological functions (Table 1).

In addition to temporal changes in bed mobility stages represented by Eq. 5, it is possible to observe the dependence of the geomorphic dynamics on streamflow. Q can be non-dimensionalized by a combination of variables with length and time dimensions (i.e. $L^{-3}T^{1}$). The formulation by Parker et al. (1979) is used

$$Q^* = \frac{Q}{\sqrt{gD_{50}}\,D_{50}{}^{2}} \tag{6}$$

Eqs. 5 and 6 can be used to produce curves of τ_o^* vs. Q^* to observe shear stress as a function of streamflow (Fig. 5). Curves of non-dimensional quantities allow comparison of channels with a wide range of characteristics and have been used to group and observe trends in data of rivers from different geographic regions (Parker *et al.*, 2003). In this study, the resultant curve τ_o^* vs. Q^*, where τ_o^* is function of S, D_{50}, c and f; and Q^* is function of Q and $D_{50,}$ depicts the variation in bed mobility stages for a cross section with a particular slope, median grain size, and geometry for a range of discharges. Each portion of the curve within thresholds of τ_{c50}^* (0.01, 0.03, 0.06, and 0.1) can be categorized as functional or non-functional. The model was programmed in MATLAB to facilitate calculations. The MATLAB code is available for public use by requesting it from the authors.

The FFM provides an approach to understand the relations among hydrogeomorphic parameters and ecological functions based on a representation of the natural system (Murray, 2007). The analytical algorithm does not provide a predictive model, but an explanatory model conceived to explain links among physical processes and biological systems (van Asselt and Rotmans 2002, Murray 2003). Inputs of the model including discharge (Q), a parameter (f) governing depth response to incremental discharge changes, water surface slope (S), and median grain size (D_{50}) are large-scale parameterizations of the interactions among the most significant variables representing physical and ecological processes. Outputs of the model including functional ranges of Q*, number of days with functional flows, and percent efficiency for a habitat unit and for a water year permit measuring such interactions under different sets of conditions resulting in data that adds to the existing knowledge about hydrogeomorphic and ecologic links. These results are derived from relations among streamflow time series, water depth, and shear stress that have been tested. The validation of these results would require extensive measures of discharge values, sediment transport stages, and ecological functions at all sites all days within a water year. Therefore, the functional flows model constitutes a theoretical analysis with scientific basis and its actual validation is beyond the objective of the present study (Murray, 2003).

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3 Field Sites

The Mokelumne and Yuba Rivers flow generally west, draining watersheds covering 1,624 km^2 and 3,480 km^2 respectively, of the central Sierra Nevada of California (Figure 2). The Mokelumne River is a tributary to the San Joaquin River, while the Yuba River is a tributary to the Feather River. Their watersheds are ~110 km apart. The upstream reaches of both rivers receive ~ 1,200 mm of precipitation annually, while the central region of the watersheds receives ~510 mm (Mount, 1995). Water feeds the rivers mostly as rainfall runoff in the late fall and winter, and then as snowmelt in the spring. Historically, both rivers have been manipulated for dam construction, gold mining, gravel extraction, hydropower generation, water supply, and flood regulation (Pasternack *et al.*, 2004; Pasternack, 2008b). Such anthropogenic influence has caused in-stream physical habitat degradation (Mount, 1995). Recently, both rivers have undergone morphological alterations produced by dissimilar causes: artificial gravel augmentation on the lower Mokelumne River (Wheaton *et al.*, 2004b; Elkins *et al.*, 2007), and natural floods on the lower Yuba River (Pasternack, 2008b). These events have modified channel form and habitat conditions.

3.1 Gravel Augmentation on the lower Mokelumne River

The Mokelumne River has 16 major impoundments, the two largest being Pardee Reservoir (259 million m^3), completed in 1929, and Camanche Reservoir (531 million m^3), completed in 1963 (Pasternack *et al.*, 2004). East Bay Municipality Utility District (EBMUD) manages both reservoirs for water supply serving 1.2 million people east of San Francisco Bay (Merz and Chan, 2005). A statistical analysis of the flows from a gaging station downstream of Camanche Dam (USGS Station # 11323500) using the Indicators of Hydrologic Alteration (IHA)

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software shows the combined effect of both dams on the natural flow regime (Richter *et al.*, 1996; Richter *et al.*, 1997) (Fig. 6A). For instance, median flows for the month of May when the highest spring snow-melt flows occur decrease on average from 95 m^3/s before Pardee Reservoir to 16 m^3/s after Camanche Reservoir (flow records 1905-1929 and 1964-2003, respectively). Since 1964, daily average flows have exceeded the post-dam 10 year return flow interval of 140 m^3/s in three years: 1986, 1997, and 2006. In addition, the dams have acted as gravel traps, minimizing gravel recruitment downstream of Camanche Reservoir (Pasternack *et al.*, 2004). The flow and sediment budget alterations on the lower Mokelumne River have degraded in-stream habitat and are viewed as main causes for fishery declines (Moyle, 1994). Given the unavailability of flows and gravel, the Federal Energy Regulatory Commission recommended performing gravel replenishment projects to improve fish habitat (Pasternack *et al.*, 2004).

River rehabilitation projects to improve habitat for spawning salmon using 8,357 m^3 of gravel and cobble have been built in the 1-km reach downstream of Camanche Dam (Wheaton *et al.*, 2004b) over the period 1999-2006 and annual placements are on-going. The projects have counteracted channel degradation caused by flow regulation and gravel trapping (Merz *et al.*, 2006). Positive ecological effects resulting from the projects include increases in the numbers of fish spawners using the reach, embryo survival to fry stage, macroinvertebrate diversity, and floodplain connectivity (Merz *et al.*, 2004; Merz and Chan, 2005; Elkins *et al.*, 2007).

By reducing water depth, increasing water velocity, and changing the morphology of the river bed, gravel augmentation changes the ecological functionality of a site providing appropriate hydraulic conditions to perform ecological functions despite the controlled hydrology of the river (Pasternack, 2008a). The FFM provides a tool to assess the effect of gravel augmentation on the ranges of flows that are functional for theoretical and actual water

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years, and to assess the changes in the number of days that are functional for specific life stages in a given year. Also, the FFM provides a way to assess how gravel augmentation changes the efficiency of the sites in terms of their capacity to produce functional conditions from the available flows. Performing the analysis in several habitat units is useful to know the overall functionality of restored and un-restored sections of the river and might help explain how gravel augmentation has promoted hydrogeomorphic response and might provide directions on how to proceed in future projects

3.2 Natural Floods on the Yuba River

The largest dam of the North Fork Yuba River is New Bullards Bar Dam (1.2 billion m^3), completed in 1970, and the largest dam of the mainstem Yuba River is Englebright Dam (86 million m^3), built in 1941. The first is a water supply and flood control reservoir, while the latter acts as barrier to block downstream transport of sediment produced during hydraulic mining between 1850 and 1880 (Pasternack, 2008b). IHA analysis of median monthly flows for the mainstem Yuba River (Smartville USGS Station # 11418000) shows a decline in spring-snowmelt flows due to the dams (Fig. 6B). For the month of May, flows decreased on average from 147 m^3/s before to 55 m^3/s after New Bullards Dam (flow records 1942-1969 and 1970-2003, respectively). The powerhouses at Englebright Dam can only pass 125 m^3/s, so discharges greater than that flow overtop the dam. Since 1970, daily average flows have exceeded the post-dam 10-year return flow interval of 2,700 m^3/s in three years: 1986, 1997, and 2005. In May and Dec 2005 hourly high flows at Smartville peaked at 1,200 m^3/s (7.7 yr return interval) and 3,285 m^3/s (24 yr return interval) respectively. Despite the sediment trapping effect of Englebright Dam, millions of metric tons of gravel and cobble are stored on the lower Yuba River valley due to hydraulic mining (Pasternack, 2008b).

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The combined effects of ample sediment present in the river corridor as well as availability of high flows create conditions for the Yuba River to rejuvenate salmon spawning habitat. The particular pool-riffle-run assemblage (500 m long x 250 m wide) located at the apex of Timcubtoo Bend, situated 5 km downstream of Englebright Dam, was repeatedly mapped in 1999, 2004, 2005, and 2006. Digital elevation model differencing was used to assess morphological adjustments caused by flows of different magnitudes (Pasternack, 2008b). From 1999-2004 there were no major floods, but there was some channel incision focused on riffle crests. From 2004-2005 there were significant areas of both scour and deposition, and the flood accentuated pool-riffle relief by 0.42 m. Looking over a longer time period, aerial photos going back to 1937 demonstrate that this riffle-island complex has persisted for over 70 years, as have six other riffles in Timbuctoo Bend (Pasternack, 2008b).

By reworking the coarse hydraulic mining sediment in the river corridor, floods change channel morphology and substrate composition, thus altering local hydraulics. The functional flows analysis of the lower Yuba River provides a tool to analyze the flood-induced changes in 1) the ranges of functional flows, 2) the number of days with functional flows for a given water year, and 3) the efficiency of the sites to produce functional conditions. Performing the analysis in several sites is useful in order to observe the spatial distribution of ecological functionality in this dynamic gravel bed river, which is heavily used by spawning fish.

3.3 Selection of Habitat Units for Functional Flows Analysis

Habitat units were selected within river reaches corresponding to riffles that have undergone detailed topographic monitoring before and after events, and from downstream riffles located at non-restored sites on the lower Mokelumne and at a reference site on the lower Yuba

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River (Fig. 7). On the lower Mokelumne River, sites were selected from riffles located at the furthest upstream reach between Camanche Dam and Mackville Road bridge, which spans 7.8 km and corresponds to 32% of total area of the lower Mokelumne River. Habitat units identified for the analysis included three gravel-augmented and three reference riffles (Fig. 7A; 8A). Cross sections were located at each habitat unit. Cross section XS1 was located 237 m downstream of the dam. Initially, this habitat unit was a chute with fast current flowing through two obstructions; after the 1999 gravel addition it became a riffle with depths varying between 0.15 and 1.5 m for base flows of 11 m^3/s; after the 2004 gravel addition it became a shallower riffle with depths varying between 0.15 and 0.75 m (Fig. 7A). XS2 was located 607 m downstream of the dam. This habitat unit was a degraded deep riffle, and after gravel addition in 2001 it was shaped into a shallow central bar with a downstream riffle (Wheaton *et al.*, 2004b). XS3 was located 295 m downstream of the dam, immediately downstream of XS1, and it became an extension of the XS1 riffle exit after gravel addition in 2005. The section of the river where XS1 and XS3 were located presents a steep right bank with encroaching vegetation, and a low-slope left bank with a connected floodplain that has a recreational use. The section where XS2 was located has a vertical right bank formed by a rock outcrop. The reference sites XS4, XS5, and XS6 were located 1,175 m, 1,560 m, and 2,857 m downstream of the dam, respectively, and represent natural riffles that have not been restored (Fig. 7). All the downstream reference sites have a steep left bank and a gently sloping right bank (Fig. 8B).

In the Yuba River, habitat units were selected in Timbuctoo Bend: three habitat units were selected at the riffle located at the apex of the bend (Moir and Pasternack, 2008) and a reference habitat unit was selected at the next wide riffle in the downstream direction (Fig. 7B, 8C). XS1 and XS2 were located at the riffle entrance and riffle crest respectively, and both

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eroded during the flood. XS3 was located at the downstream run and accreted during the flood. This section of the river has a connected floodplain, with gravel bars, adjacent channels, small extent of vegetation encroachment, and variable morphology. A main feature of the site was a central bar/island that divides the flow into a main channel to the left and a secondary channel to the right. XS4 was located in a wide, shallow riffle that is heavily used by spawning fish located midway between the apex and the downstream end of Timbuctoo Bend (Fig. 8C).

4 Methods

FFM calculations required ecological, geomorphic, hydrologic, and hydraulic input data. In order to use the algorithm, it was necessary to gather site-specific hydrogeomorphic data of cross section geometry, water surface slope, and grain size distribution. In addition, flow records from USGS stations (#11323500 on the lower Mokelumne River and #11418000 on the lower Yuba River) were used to isolate distinct water year types for both rivers and the event years, or the years pre- and post-gravel augmentation on the lower Mokelumne River and pre- and post-May 2005 flood on the lower Yuba River. The table of functionality, hydrogeomorphic data, and water year types were used as input to perform functional flows calculations.

4.1 Water Year Types

Two types of functional flows analysis were performed: a theoretical analysis using representative water year types for characteristic hydrologic conditions in each river, and an actual analysis using water year data corresponding to the years when events occurred (Table 2).

Theoretical water year types were identified using the Flood Regime Characterization (FRC) MATLAB code developed by (Booth *et al.*, 2006)

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(http://watershed.ucdavis.edu/pages/programs.html). The code classifies water year types using mean daily discharge records based on expert input of significant thresholds of flood duration and flood magnitude. One output of the code is the daily flow for each Julian day averaged across all years of the same flood year class.

The flow record used for the lower Mokelumne River was 1963-2006 and for the lower Yuba River was 1941-2006. Two water year flood types identified with the FRC code for the lower Mokelumne River included: WY1 that represents a scenario of highly regulated flows with maximum flow of 25 m^3/s in the snowmelt season that corresponds to the 1 yr return interval flood; and WY2 that represents a scenario with the highest flows that can be released from the dam with a max flow of 95 m^3/s in the rain season that corresponds to the 3 yr return interval flood. Two water year flood types identified with the FRC code for the lower Yuba River included WY1 that represents a scenario of regulated flows with a maximum discharge of 125 m^3/s in the snowmelt season and corresponds to the 1 yr return interval flood, and WY2 that represents a scenario with a max flow of 600 m^3/s in the rain season and represents a 3 yr return interval flood.

Actual water years for the second type of analysis were obtained from daily average flow values from USGS gaging stations. The water years analyzed for the lower Mokelumne River included the pre- and post- gravel augmentation during 1997-2005, and the water years analyzed for the Yuba River included the pre- and post- flood conditions during 2005-2006 (Table 2) (Figs. 9A and 10A; note that WY1 and WY2 were not depicted for limited space).

4.2 Geomorphic Data

Campaigns to collect field data were performed before and after morphologic alterations during the period 1998-2005 on the lower Mokelumne River and during the period 2004-2005 on

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the Yuba River. Detailed river bed topography data (i.e. 0.5-1.5 pt/m^2) was used to build annual channel DEMs using AutoCAD as previously reported (Pasternack *et al.*, 2006; Elkins *et al.*, 2007). Cross sections through selected habitat units were sampled from the pre- and post-gravel augmentation surfaces on the lower Mokelumne River, and pre- and post- flood surfaces on the lower Yuba River. The cross section location was centered within the habitat unit of interest to reduce the water constriction effects caused by channel non-uniformity upstream or downstream. A more sophisticated definition of the functional flows model that could be implemented in the future would analyze the spatial sequencing of shear stress to identify functional flows that assist pool-riffle sequence self-maintenance and other dynamics governed by channel non-uniformity (Lisle and Lewis, 1992; MacWilliams *et al.*, 2006). The assumption of uniform flow is appropriate for a channel that does not change cross section geometry in the downstream direction but may need to be checked depending on the conditions of a site (Brown and Pasternack, 2008; Pasternack *et al.*, 2008). For instance, pool-riffle morphologies experience flow convergence, thus requiring the assessment of the relative importance of non-uniform terms to decide if they need to be included in the calculation of shear stress. One way of checking would be to compare the results of steady hydraulic calculations made with a cross-section analyzer against those made with a 1D hydraulic flow model that accounts for backwater conditions (Brown and Pasternack, 2008).

Water surface slope as an approximation of river bed slope and grain size distribution for XS1, XS2, and XS3 in both rivers was obtained from previous studies and from unpublished data (Pasternack *et al.*, 2004; Wheaton *et al.*, 2004b; Elkins *et al.*, 2007; Moir and Pasternack, 2008; Pasternack, 2008b) (Table 3). Since water surface slope was reported for a set discharge value, a unique value was obtained for each cross section and was used for the depth-slope product

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calculations and for stage-discharge geometry relations. This constitutes an assumption, since the water surface slope may change as discharge increases or decreases.

In addition to the cross sections sampled from existing DEMs, additional data was collected in November 2005 on both rivers for the reference sites (XS4, XS5, and XS6 in the Mokelmune River, and XS4 on the lower Yuba River). Cross section geometry and bed slope of the reference sites were surveyed with an autolevel, tape, and rod, and the coordinates of the sites were obtained with a Trimble Pathfinder Pro XRS, a real-time kinematic GPS.

For habitat units sampled from DEMs and for the reference sites, position and elevation data was used to build stage-discharge relationships using a routine of the functional flows Matlab code. The routine calculates areas for incremental stage values using input cross section geometry and their corresponding velocities using Manning's equation with a typical value of n=0.043 for gravel bed rivers (Pasternack *et al.*, 2004) and with their corresponding water surface slopes. The code was used to calculate hydraulic radius and discharge for incremental stage values to obtain the parameters of Eq. 3. Coefficients and exponents are summarized in Table 3.

4.3 Data Analysis

A total of 50 analyses were performed: 30 for the Mokelumne River corresponding to 6 cross sections analyzed for 5 distinct water years (i.e. theoretical and actual) and 20 for the Yuba River corresponding to the 5 cross sections analyzed for 4 distinct water years. FFM results were graphed to answer the research questions posited. Results depicted in graphs were grouped first by water year and then by cross section in order to observe trends.

Uncorrected Final Manuscript

To answer research question 1, what are the ranges of flows that are potentially functional?, τ_o* vs. Q* curves were graphed indicating the ranges of flows (shaded grey lines) that fell within predetermined bed mobility stages for each water year (Figs. 9B and 10B). Symbols such as circles, squares, or triangles superimposed on the shaded gray lines correspond to the days within a water year that had a functional discharge value that not only fell within specified bed mobility stages but also happened at the time when they were functional for the life stage according to Table 1. Arrows indicate the shift of one cross section from the initial to subsequent locations in the τ_o* vs. Q* space due to hydrogeomorphic changes (i.e. gravel augmentation on the lower Mokelumne River and flooding on the lower Yuba River). Functional ranges of Q* were calculated subtracting the minimum from the maximum functional Q* occurring in a given water year (Table 4). Cases with zero range of Q* correspond to absence of ecological functionality, while cases with the highest values of functional ranges of Q* correspond to a greater opportunity to meet ecological functionality.

To answer research question 2, what is the number of days that flows are functional?, counts of the number of days that presented functional flows for each cross section were graphed (Figs. 9C and 10C; Table 4) . Higher numbers of days with functional flows correspond to higher ecological functionality performance.

To answer research question 3, what is the efficiency of a habitat unit in producing functional flows?, percentage efficiency was estimated as the ratio between functional ranges of Q* and available ranges of Q* (Figs. 11 and 12; Table 4). Higher values of efficiency indicate greater opportunity to meet ecological functionality.

In order to answer research questions 4-5 it was necessary to perform upstream-downstream and between river comparisons. For these comparisons, results were grouped to

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evaluate inputs (i.e. slope, median grain size, parameters c and f) and outputs (i.e. ranges of Q*, number of days with functional flows, and percent efficiency) of the functional flows model before and after gravel augmentation on the lower Mokelumne River (i.e. 15 before vs. 15 after), before and after May 2005 flood on the lower Yuba River (i.e. 9 before vs. 11 after), among sites within each river (i.e. 24 upstream vs. 6 downstream on the lower Mokelumne River, and 18 upstream vs. 2 downstream on the lower Yuba River), and between rivers (i.e. 30 on the lower Mokelumne River vs. 20 on the lower Yuba River) (Table 5). Given that datasets presented differences in standard deviations, they were analyzed with non-parametric statistics. Non-parametric statistics have been widely applied in earth sciences (Pasternack and Brush, 1998). The non-parametric Kolmogorov-Smirnov (KS) two-sample test was performed to determine statistical significance of the difference between data groups to facilitate comparison in research questions to confirm or reject the hypothesis that differences in geomorphic variables caused differences in ecological functionality. This statistical procedure was appropriate to test the relationship between the data groups for the available sample size without making assumptions about the distribution of the data (Statsoft, 1998). The threshold to determine that differences were statistically significant above the 95% confidence level was set at p-level <0.05 (Table 5).

Table 5 provides KS results (12 for each comparison group), organized in matrices with 3 columns (functional flow outputs) and 4 rows (input variables). First we determined if geomorphic variables (i.e. S, D_{50}, c and f) were in fact statistically different between the two data sets. Then we determined if ecological functionality (i.e. ranges of Q*, number of days with functional flows, and % efficiency) was different between the two groups. True, or T, was assigned when datasets were statistically different, and False, or F, was assigned when datasets

Uncorrected Final Manuscript

were not statistically different. Then we confirmed or rejected hypothesis following this set of rules: T→T=T, T→F=F, F→F=T, and F→T =F.

5 Functional Flows Analysis Results

Each subsection of the FFM results corresponds to research questions 1 through 5. In addition to description of graphs and presentation of calculation outputs, each subsection refers to the KS test reported in Table 5 for confirmation or rejection of the overall hypothesis.

5.1 Change in functional ranges of Q*

For the lower Mokelumne River, results indicated that river rehabilitation caused a vertical shift in τ_o* vs. Q* curves for XS1 and XS3 from a non-functional domain (i.e. SB) to a partially functional domain (i.e. IFM or FM) for all water years (Figs. 9B). The range of functional flows was increased at XS1 and XS3 for all water years and at XS2 for WY1. Note that in this case the increase in range of functional flows does not imply achieving full functionality because the ranges of functional flows (i.e. falling in either IFM or FM but not in both) did not support all of the essential functions (i.e. missing IFM or FM). The effect of gravel augmentation on geomorphic variables S, D_{50}, c, and f was statistically significant above the 95% confidence level ($p<0.01$, <0.05. <0.01, <0.005 respectively), but was not statistically significant ($p<0.10$) for functional range of Q* . The hypothesis was rejected for all 4 combinations of functional ranges of Q* with hydrogeomorphic variables (Table 5A).

For the lower Yuba River, results indicated that natural floods caused a lateral shift in τ_o* vs. Q* curves for XS1 and XS2 maintaining them within a functional domain. τ_o* vs. Q* curves for XS3 presented a diagonal shift (Figs. 10B). Lateral shifts to the right and a diagonal shift

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increased the ranges of functional flows for all cross sections for all water years. Changes before and after the flood on hydrogeomorphic variables S, D_{50}, c, and f and on the functional ranges of Q* was statistically significant above the 97.5 confidence level ($p<0.001$, <0.001, <0.025, <0.0025, <0.005 respectively). The hypothesis was accepted for all 4 combinations of functional ranges of Q* and geomorphic variables (Table 5A).

5.2 Change in the number of days that are functional

For the lower Mokelumne River, results indicated that river rehabilitation increased the number of days with functional flows for XS1 and XS3 for all water years, while it increased the number of days with functional flows for XS2 for WY2 only (Figs. 9C). On the lower Mokelumne River, the mean value of days with functional flows was 60 before and 138 after gravel augmentation. The effect of gravel augmentation on the number of days with functional flows was statistically significant above the 95% confidence level ($p<0.05$). The hypothesis was accepted for all 4 combinations of number of days with functional flows and geomorphic variables (Table 5A).

For the lower Yuba River, results indicated the May 2005 natural flood maintained the number of days with functional flows for WY1 and WY2 while it increased the number of days with functional flows for the year when the event happened for XS1 and XS2 (Figs. 10C). Also, the flood increased the number of days with functional flows for all 4 water years for XS3. Even though the mean value of days with functional flows across all 4 water years was 157 before and 174 after the May 2005 flood, the change in the number of days with functional flows was not statistically significant ($p>0.10$). The hypothesis was rejected for all 4 combinations of number of days with functional flows and geomorphic variables (Table 5A).

Uncorrected Final Manuscript

5.3 Change in efficiency of a habitat unit to produce functional flows

For the lower Mokelumne River, results indicated that after gravel augmentation XS1 and XS3 increased their efficiency to produce functional flows for all water years, while XS2 increased its efficiency to produce functional flows for WY2 only. The change in efficiency was not statistically significant ($p<0.10$). The hypothesis was rejected for all 4 combinations of % efficiency and geomorphic variables (Table 5A).

For the lower Yuba River, results indicated that the May 2005 natural flood maintained the efficiency to produce functional flows for XS1 and XS2 for WY1 and WY2, reduced the efficiency for XS3 for WY2, and increased the efficiency for all cross sections for the actual WY. The change in % efficiency was not statistically significant ($p>0.10$). The hypothesis was rejected for all 4 combinations of % efficiency and geomorphic variables (Table 5A).

5.4 Overall functionality of a river reach

The overall functionality of each river reach was analyzed by comparing the functionality of habitat units located at detailed monitoring and reference sites within the same river. For the Mokelumne River, the differences in the values of c and f between upstream and reference sites were statistically significant ($p<0.001$ and $p<0.05$ respectively), while the differences in values of S, D_{50}, and functional flows results were not statistically significant ($p>0.10$). Reference sites of the lower Mokelumne River presented some degree of functionality measured from the occurrence of days with functional flows and from the efficiency to produce functional flows. Curves of τ_o* vs. Q* for XS4 and XS6 were within the functional domain for WY1 and WY2, while the curve of τ_o* vs. Q* for XS5 presented a small section within the functional domain for WY2 only. XS4 and XS6 presented days with functional flows for both water years, while XS5

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presented days with functional flows for WY2 only. XS4 and XS6 presented above average efficiency for WY1 and WY2, while XS5 presents above average efficiency for WY2 only (Table 4). The hypothesis was confirmed for 6 and rejected for 6 combinations of functional flows outputs and hydrogeomorphic variables inputs (Table 5B).

For the lower Yuba River, hydrogeomorphic variables and functional flows outputs of upstream and downstream sites were statistically similar ($p > 0.05$). XS4 located at the reference site presented lower functionality than upstream reaches for WY1 as shown by its lower section of the τ_o^* vs. Q^* curve within the functional domain and by the low number of days with functional flows. In contrast, XS4 presented functionality comparable to upstream reaches for WY2 represented by its high section of the τ_o^* vs. Q^* curve within the functional domain and by its high number of days with functional flows. XS4 presented lower than average efficiency for WY1 and higher than average efficiency for WY2 (Table 4). The hypothesis was confirmed for all 12 combinations of functional flows outputs and hydrogeomorphic variables inputs (Table 5B).

5.5 Comparison among rivers

The lower Yuba River presented better flow functionality than the lower Mokelumne River determined by the location of τ_o^* vs. Q^* curves for all cross sections within the functional domains and by a higher number of days with functional flows. In addition, the efficiency of the lower Yuba River sites was higher on average than that of the lower Mokelumne River sites. Slope, D_{50}, c, and functional flows outputs were statistically different ($p<0.001$) while f was statically similar ($p>0.10$). The hypothesis was accepted for 9 combinations of functional flows outputs and hydrogeomorphic variables inputs (Table 5C).

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6 Discussion

The analysis of ecological functionality using functional flows reflects how changes of geomorphic variables due to hydrogeomorphic processes modify the suitability of in-stream physical habitat for fall-run Chinook Salmon. For each habitat unit, ranges of flows, number of days that flows are functional, and efficiency to produce functional flows were obtained from Eqs. 5 and 6. Rewriting Eq. 5 in terms of Q* yields:

$$\tau_0{}^* = \frac{\rho}{(\rho_s - \rho)} \frac{S}{D_{50}} c(g^{1/2} D_{50}{}^{5/2} Q^*)^f$$

where each input variable influences the final result depending on its effect on the value of $\tau_o{}^*$. The exponent f determines the slope of the curve $\tau_o{}^*$ vs. Q*, the D_{50} is related non-linearly to $\tau_o{}^*$, and S and c are related linearly to $\tau_o{}^*$. Overall, within the ranges found at the cross sections studied, lower values of f promoted lower depth response to discharge increments that may be beneficial for spawning habitat (i.e. such response is found in shallow riffles), large values of D_{50} promoted higher upper thresholds of Q* increasing the ranges of functional flows, and higher values of c and S promoted the vertical shift up of $\tau_o{}^*$ vs. Q* curves from stable bed to functional transport regimes (i.e. superficial fines mobility, interstitial fines mobility, and full mobility).

The next subsections include a discussion of results obtained analyzing the effect of geomorphic variables on functional flows output exclusively. Although measured increases in the numbers of fish spawners using the reach, embryo survival to fry stage, macroinvertebrate diversity, and floodplain connectivity are metrics of ecological improvement, they are not comparable to ranges of functional flows, number of days with functional flows and percent efficiency. In order to use field data to compare to FFM results, it would be necessary to perform

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field campaigns to measure whether or not each day's flow that was classified as functional was in fact functional by testing whether or not fish used the habitat for a specific ecologic function.

6.1 Effect of geomorphic changes on functional ranges of Q*

The rejection of the hypothesis that changes in geomorphic variables due to gravel augmentation modified the ecological response for bed occupation and bed preparation as measured by the difference in functional ranges of flows on the lower Mokelumne River indicates that the alteration of the morphologic variables S, D_{50}, c and f did not cause an ecological improvement of the habitat. The positive change of S into higher values that caused a shift of the τ_o* vs. Q* curves from a stable bed into functional transport regimes together with the positive change of the variable f into lower values that signify a lower depth response to increments in discharge increased the functional ranges of flows to some level. The positive effects of S and f were counteracted by the negative change of D_{50} into a larger value that reduced the upper threshold of the ranges of Q observed in the lateral shift to the left of the τ_o* vs. Q* curves. The manipulation of the morphology of the channel alone was not sufficient to create a statistically significant difference after gravel augmentation of the functionality of the habitat as measured by the increase of functional ranges of flows and cannot substitute the need for larger flows that would increase the ranges of functional flows to a level that is statistically significant.

The confirmation of the hypothesis that changes in geomorphic variables due to the May 2005 flood modified the ecological response as measured by the difference in functional ranges of flows on the lower Yuba River indicates that the changes in the morphologic variables S, D_{50}, c and f were sufficient to improve the ecological conditions of the habitat. Despite the fact that

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the variable f increased changing into values that are theoretically less functional promoting greater depth increments to increments in discharge that may be negative to the habitat, the combined effect of a lower slope, smaller grain size, and available flows provided the conditions to increase the functional ranges of flows.

6.2 Effect of geomorphic changes on number of days with functional flows

The confirmation of the hypothesis that changes in geomorphic variables due to gravel augmentation modified the ecological response as measured by the difference in the number of days with functional flows on the lower Mokelumne River suggests that achievement of a lower depth response to increments in discharge by reducing the values of f and the achievement of a functional sediment transport stage by increasing the values of S allowed the available low flows to provide functional habitat conditions during some of the crucial spawning life stages.

The rejection of the hypothesis that changes in geomorphic variables due the May 2005 modified the ecological response as measured by the difference in the number of days with functional flows on the lower Yuba River indicates that the geomorphic improvements after the flood were not sufficient to improve the number of days with functional flows. An explanation of this result is that sites presented a high count of days with functional flows even before the flood, and the geomorphic changes after the flood did not impact the results significantly. This suggests that there may be a threshold of number of days with functional flows for sites, depending on hydrologic conditions, above which it is unlikely to increase.

6.3 Effect of geomorphic changes on the efficiency to produce functional flows

The efficiency of a habitat unit to produce functional flows is a metric that combines the

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hydrologic and geomorphic response with the ecological requirements for life stages. The complex, non-linear interaction among variables yields a variety of hydrogeomorphic responses and the consequent variability in efficiency to produce functional flows. The available ranges of flows may fall within a non-functional domain causing the absence of functional ranges of flows or the available ranges of flow may fall within a functional domain in which case the presence of functional ranges of flows depends on the time series of flows that may or may not produce functional sediment transport regimes at the appropriate times for each life stage.

Despite the given conditions to increase efficiency at both rivers due to the increase of number of days with functional flows on the lower Mokelumne River and due to the increase of functional ranges of flows on the lower Yuba River, the hypothesis that changes in geomorphic variables modified the ecological response as measured by % efficiency was rejected, indicating that this metric did not reflect the habitat improvement shown by the other two functional flows outputs.

6.4 Functional flows analysis at the reach scale

In the context of comparing cross sections within the same reach, geomorphic similarity can be defined for cross sections with geomorphic variables that are statistically similar (i.e. the results of the KS statistical test are negative). Likewise, the similarity of the ecological performance can be defined for cross sections with functional flows outputs that are statistically similar. The confirmation of the hypothesis that similarity of the geomorphic variables S and D_{50} caused similarity of ecological performance as measured by functional ranges of flows, number of days with functional flows, and efficiency between restored and un-restored sites within the same river reach on the lower Mokelumne River indicates that un-restored sites may not need the same level of channel morphology modification that restored sites underwent. The rejection of

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the hypothesis for the geomorphic variables c and f indicates that un-restored sites may need channel geometry improvements such as reduction of f values to decrease depth response to discharge increments and decrease incision that generated positive effects on the restored sites.

The confirmation of the hypothesis that similarity of all the geomorphic variables analyzed caused similarity of ecological performance as measured by functional ranges of flows, number of days with functional flows, and efficiency between pre and post-flood sites within the same river reach at the Yuba River indicates that the larger scale processes that control the geomorphology of the reach also control ecological performance of the habitat in this section of the river.

6.5 Functional flows analysis at the regional scale

In the context of comparing rivers within the same region such as the Sierra Nevada, statistical differences of geomorphic variables and ecological performance reflect the importance of the geomorphology and history of each watershed. The confirmation of the hypothesis that differences of geomorphic variables S, D_{50}, and c cause differences of ecological performance as measured by the functional ranges of flows, number of days with functional flows, and efficiency between the lower Mokelumne River and the lower Yuba River indicates that processes at each watershed, such as geomorphic controls and local human impacts, rather than regional processes, such as climate, control the ecological performance of each river. Higher values of S and higher values of D_{50} have the potential to cause lower functionality on the lower Yuba River with respect to the lower Mokelumne River by reducing the span of τ_o* vs. Q* curves within functional sediment transport domains. However, values of functional ranges of Q*, number of days with functional flows, and % efficiency are larger on the lower Yuba River than on the lower Mokelumne River. Lower values of c may contribute partially to the effect of greater

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functionality on the lower Yuba River because they cause a higher span within functional sediment transport stages. Yet the largest factor contributing to better functional flows outputs on the lower Yuba River is larger flow availability, which promotes ecological functionality despite the overall lower geomorphic performance of the lower Yuba River with respect to the lower Mokelumne River.

6.6 Key Lessons

Gravel augmentation on the lower Mokelumne River between 1999-2006 has increased the number of days with functional flows for fall-run Chinook salmon for the study sites but has not impacted significantly the functional ranges of flows. Hydrogeomorphic variables have reached a functional stage after gravel augmentation as observed by the location of τ_o* vs Q* curves in functional domains. The next possible stage to increase ecological functionality in the restored sites is to increase available ranges of flows at the appropriate times during the year in order to increase functional ranges of flows.

The May 2005 flood on the lower Yuba River increased functional ranges of flows by shifting τ_o* vs Q* laterally. Although the May 2005 flood increased the number of days with functional flows at the study sites, there was a high occurrence of days with functional flows before the flood and the consequent effect of the flood on this analysis output is insignificant.

The metric of percentage efficiency did not reflect the ecological improvements of number of days with functional flows on the lower Mokelumne River and of functional ranges of Q* on the lower Yuba River. This is a complex metric that requires several steps for calculation and involves several variables that may counteract each other. According to the results of this study, the work invested in obtaining this metric does not provide additional information that is helpful for understanding ecological functionality in rivers.

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Detailed monitoring sites and reference sites present similar ecological functionality in both rivers. Despite the local effects of gravel augmentation that have changed local geometry on the lower Mokelumne River sites, ecological functionality of reference sites is similar to that of restored sites indicating that reference sites may not need abrupt gravel augmentation projects to improve their habitat. In the Yuba River, study cross-sections at the apex of Timbuctoo Bend and the reference site present similar ecological functionality, indicating the uniformity of conditions within the reach to provide habitat quality for fall-run Chinook salmon.

The lower Mokelumne and Yuba Rivers in general present differences in ecological functionality. Overall, the lower Mokelumne River has a characteristic geomorphic functionality that comes from the combination of hydrogeomorphic variables such as slope, grain size distribution, and cross section geometry that produce ecological functionality despite low flow availability. On the other hand, the lower Yuba River also presents geomorphic functionality that is complemented by a hydrologic functionality that comes from ample flow availability for an optimal combination of hydrologic and geomorphologic conditions for ecological functionality.

7 Conclusions

Differences in local geometry, within a river reach and between rivers, may affect how habitat units respond to functional flows metrics such as number of days with functional flows or ranges of functional flows. Such hydrogeomorphic and ecologic functionality differences are governed by site specific conditions and processes. Rapid geomorphic changes are one type of river processes that have the capacity to alter hydraulics that in turn affect sediment transport stages and ecological response of the river bed. Depending on the direction of the morphologic change, such alterations may be positive for the physical habitat. When geomorphic change

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promotes the proper combination of geomorphic variables and hydrology it also induces the conditions for improved ecological functionality. Sites with suitable combinations of slope, grain size distribution, and cross section geometry may have the potential to create ecological functionality. However, ecological functionality will only be provided if there is ample availability of functional ranges of flows working with local morphology and hydraulics to provide sediment transport stages that are functional for fall-run Chinook salmon life stages. The application of the functional flows analysis presented in this paper contributes to the current knowledge of interactions between hydraulics, geomorphology, and ecology indicating the pertinence of this approach to the crucial understanding of the effects of physical processes on ecological response.

Uncorrected Final Manuscript

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Figures Captions

Figure 1. Interaction of hydrogeomorphic processes that control physical habitat conditions for ecological functionality.

Examples of each process or function are given inside each circle. Convulsive events are in italics.

Figure 2. Location of Mokelumne River and Yuba River study reaches

Figure 3. Life stages of Fall-run Chinook salmon in relation to flow magnitude and timing

A) Bed occupation and bed preparation ecological functions timing for fall-run Chinook salmon freshwater life stage; B) Water year flow magnitudes at the Yuba River, CA and examples of functional flows for the ecological functions in A).

Figure 4. Functional flows classification for fall-run Chinook salmon ecological functions

Non-dimensional shear stress time series for riffle cross section on the lower Yuba River with $S=0.046$ and $D_{50}= 0.068$ for the water year depicted in 3B) with functional (solid line) and non-functional (dashed line) transport regimes according to Table 1. After day 330 BO stands for Bed Occupation, N-f stands for non-functional, and F stands for functional.

Figure 5. τ_o* vs Q* curve for example in Figure 4

Non-dimensional shear stress vs non-dimensional discharge for identification of functional ranges of flows using same example in Figs. 3 and 4. Available Q* (gray line) refers to ranges of flows within a water year that fall within specified bed mobility stages, Functional Q* (triangle symbol) refer to ranges of flow within a water year that fall within specified bed mobility stages and happen at the time when they are functional for the life stage. FM stands for full mobility, IFM stands for interstitial fines mobility, SFM stands for superficial fines mobility, and SB stands for stable bed

Figure 6. IHA-RVA analysis of flow records

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A) Mokelumne River USGS Station # 11323500, B) Yuba River USGS Station # 11418000. RVA refers to “range of variability approach” targets defined by Richter et. al. 1997. Middle RVA low and middle RVA high correspond to 25th and 75th percentile levels of the monthly average flows.

Figure 7. Habitat units for functional flows analysis

Projected coordinate system: NAD_1983_StatePlane_California_III for Mokelumne River, and NAD_1983_StatePlane_California_IV for Yuba River,. Coordinates in meters for A) Mokelume River sites XS1 (1,953,735, 691,786), XS2 (1,953,739, 691,672), XS3 (1,953,383, 691,716), XS4 (1,953,435, 691,661), XS5 (1,953,697, 691,777), XS6 (1,953,696, 691,690); and B) Yuba River sites XS1 (2,059,431, 674,116), XS2 (2,059,388, 674,141), XS3 (2,059,179, 674,222), XS4 (1,928,546, 803,447)

Figure 8. Cross sections geometry

A) Mokelumne River cross sections at restored riffles before (dashed line) and after (solid line) gravel augmentation, B) Mokelumne River cross sections at reference riffles, C) Yuba River cross sections before (dashed line) and after (solid line) May 20005 natural flood and reference site (XS4).

Figure 9. Functional flows analysis of restored riffles for Actual WY at Mokelumne River

A) Julian water year discharge time series for water years before and after gravel augmentation, B) τ_o^* vs Q^* curves - gray lines correspond to the actual ranges of Q^* produced by the water year and symbols correspond to the days with functional ranges of Q^* that produced a functional sediment transport stage for a specific ecological function according to the table of functionality (Table 1), symbols are not depicted when days with functional ranges of Q^* are absent for the

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specific site and ecological function, C) Count of number of days with functional flows for water year in A)

Figure 10. Functional flows analysis of all sites for Actual WY at Yuba River

A) Julian water year discharge time series for actual water years before and after May 2005 flood, B) and C) captions are the same as Fig. 9. See insert in Figure 10B for a detail of the curves for year 04-05 for all three cross sections.

Figure 11. Efficiency of habitat units to produce functional flows for Mokelumne River

Empty circles indicate minimum and maximum available Q* for the water year, and solid circles indicate minimum and maximum functional Q* for the water year for A) Restored sites, B) Reference sites

Figure 12. Efficiency of habitat units to produce functional flows for Yuba River

Empty circles indicate minimum and maximum available Q* for the water year, and solid circles indicate minimum and maximum functional Q* for the water year.

Tables Captions

Table 1. Table of functionality.

Flow magnitude and bed mobility stages delimited by Shields stress are used to determine functionality for bed occupation and bed preparation ecological functions during the spawning life stage. “Functional” refers to flow magnitudes associated with bed mobility stages that favor the life stage. “Non-functional” refers to flow magnitudes associated with bed mobility stages that hinder the life stage.

Table 2. Summary of functional flows analysis

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Type of analysis is theoretical for WY1 and WY2, and Actual for water years when the events occurred. Timeline of events represent water years (horizontal arrows) and the approximate date of the events occurrence (vertical arrows). Sites marked with * are reference sites. Sites marked with ** were analyzed twice for WY1 and WY2 due to the occurrence of two different gravel augmentation projects at the same site. A total of 30 analysis were performed on the lower Mokelumne River, and a total of 20 analysis were performed on the lower Yuba River.

Table 3. Summary of physical parameters for functional flows analysis

Cross sections geometry, slope, and median grain size were obtained from data reported in previous studies as indicated next to each value and from data collected for this study. Data sources are (1) Merz et al 2005 , (2) Elkins et al 2007 , (3) Wheaton 2003, (4) This Study, (5) Moir and Pasternack Submitted. Parameters c and f were obtained from cross section geometry relations developed for each cross section geometry.

Table 4. Summary of functional flows analysis comparison criteria and outputs

Comparison criteria are before/after gravel augmentation on the lower Mokelumne River or flood on the lower Yuba River (B/A), and detailed monitoring sites or reference site (D/R). Functional flows outputs are available ranges of Q*, functional ranges of Q*, # days with functional flows, and % efficiency (100*functional ranges of Q*/available ranges of Q*).

Table 4. Summary of functional flows analysis comparison criteria and outputs (Continuation)

Table 5. Hypothesis testing and statistical significance of comparisons among geomorphic input variables and functional flows outputs datasets.

Differences between datasets were considered statistically significant for p-level<0.05. Table contains p-level and Kolmogorov-Smirnov (KS) test results for each dataset comparison. A)

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Before and after rapid alteration of channel morphology, B) Detailed monitoring sites vs. reference sites, C) Mokelumne River vs. Yuba River. rQ* stands for functional ranges of Q*, #DFF stands for # days with functional flows, %Eff stands for % efficiency. Hypothesis: statistically significant differences in hydrogeomorphic conditions cause statistically significant differences in ecological performance of the physical habitat. Hypothesis confirmation or rejection is indicated at the crossing of inputs (left column) vs. outputs (top row) for datasets compared. Confirmation of the hypothesis is provided according to material conditional truth rules T→T=T, T→F=F, F→F=T. The combination F→T was considered F.

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1	2A	2B	3	4	5	6
Flow Magnitude/ Bed Mobility Stage	**Functional Flows Delimiters**		**Bed Occupation**			**Bed Preparation**
	In terms of τ_o vs τ_{c50}	**In terms of τ_o* vs Shields #**	**Spawning**	**Embryo Incubation**	**Emergence**	
High/ Full mobility (FM)	$\tau_o > \tau_{c50}$	$0.06 < \tau_o^* < 0.1$	Non-functional	Non-functional	Non-functional	Functional
Intermediate High/ Interstitial fines mobility (IFM)	$\tau_o = \tau_{c50}$	$0.03 < \tau_o^* < 0.06$	Non-functional	Non-functional	Non-functional	Functional
Intermediate Low/ Superficial fines mobility (SFM)	$\tau_o < \tau_{c50}$	$0.01 < \tau_o^* < 0.03$	Functional	Functional	Functional	Non-functional
Low/ Stable bed (SB)	$\tau_o << \tau_{c50}$	$\tau_o^* < 0.01$	Functional	Non-functional	Functional	Non-functional

Type of Analysis		**Theoretical**				**Actual**							
Water Year		**1**	**1**	**2**	**2**	**97-98**	**98-99**	**99-00**	**00-01**	**02-03**	**03-04**	**04-05**	**05-06**
Timeline of Events		Gravel Augmentation/ Flood		Gravel Augmentation/ Flood		Gravel Augmentation		Gravel Augmentation		Gravel Augmentation	Gravel Augmentation		Flood
Mokelumne River	**XS1**	Pre**	Post**	Pre**	Post**	Pre	Post			Pre	Post		
	XS2	Pre	Post	Pre	Post			Pre	Post				
	XS3	Pre	Post	Pre	Post						Pre	Post	
	XS4*	Pre		Pre									
	XS5*	Pre		Pre									
	XS6*	Pre		Pre									
Yuba River	**XS1**	Pre	Post	Pre	Post							Pre	Post
	XS2	Pre	Post	Pre	Post							Pre	Post
	XS3	Pre	Post	Pre	Post							Pre	Post
	XS4*	Pre		Pre									

River	XS Name	Date Surface/ Surveyed	S	D_{50}	c	f
Mokelumne River	**XS1**	**97-98**	0.0001 (1)	40.0 (1)	0.38	0.45
		98-99	0.0038 (1)	50.0 (1)	0.22	0.39
		02-03	0.0020 (2)	50.4 (2)	0.18	0.43
		03-04	0.0080 (2)	50.4 (2)	0.17	0.39
	XS2	**99-00**	0.0003 (3)	68.0 (3)	0.35	0.41
		00-01	0.0006 (3)	55.0 (3)	0.30	0.39
	XS3	**03-04**	0.0003 (1)	47.5 (1)	0.34	0.46
		04-05	0.0018 (4)	71.0 (4)	0.22	0.39
	XS4	**Nov 2005**	0.0034 (4)	67.0 (4)	0.12	0.52
	XS5	**Nov 2005**	0.0012 (4)	53.0 (4)	0.16	0.38
	XS6	**Nov 2005**	0.0052 (4)	40.0 (4)	0.11	0.51
Yuba River	**XS1**	**03-04**	0.0069 (5)	101.1 (5)	0.16	0.37
		04-05	0.0046 (4)	60.7 (4)	0.09	0.47
	XS2	**03-04**	0.0069 (5)	101.1 (5)	0.18	0.35
		04-05	0.0046 (4)	78.0 (4)	0.15	0.39
	XS3	**03-04**	0.0046 (5)	179.8 (5)	0.13	0.41
		04-05	0.0039 (4)	69.3 (4)	0.14	0.42
	XS4	**Nov 2005**	0.0011 (4)	66.0 (4)	0.10	0.50

Comparison						Functional Flows Analysis			
River	Water Year Type	XS	Site	Before/ After	Detailed monitoring site/ Reference	Available Range Q*	Functional Range Q*	# Days with functional flows	% Efficiency
Mokelumne River	WY1	XS1	97-98	B	D	10,948	-	0	0
			98-99	A	D	10,948	10,948	248	100
			02-03	A	D	10,733	9,715	179	91
			03-04	A	D	10,733	8,176	185	76
		XS2	99-00	B	D	5,076	-	0	0
			00-01	A	D	8,627	-	0	0
		XS3	03-04	B	D	12,446	-	0	0
			04-05	A	D	4,557	2,290	75	52
		XS4	Nov05	B	R	5,267	4,768	179	91
		XS5	Nov05	B	R	9,464	-	0	0
		XS6	Nov05	B	R	19,126	19,126	250	100
	WY2	XS1	97-98	B	D	81,580	-	0	0
			98-99	A	D	46,699	31,461	190	67
			02-03	A	D	45,778	38,363	174	84
			03-04	A	D	45,778	25,687	185	56
		XS2	99-00	B	D	21,650	-	0	0
			00-01	A	D	36,798	16,450	50	45
		XS3	03-04	B	D	53,089	10,200	14	19
			04-05	A	D	19,435	18,853	174	97
		XS4	Nov05	B	R	22,467	15,136	200	67
		XS5	Nov05	B	R	40,369	20,605	73	51
		XS6	Nov05	B	R	81,580	45,777	185	56
	Actual WY	XS1	97-98	B	D	95,006	-	0	0
			98-99	A	D	45,064	15,129	232	34
			02-03	A	D	27,742	1,729	179	6
			03-04	A	D	35,626	23,809	155	67
		XS2	99-00	B	D	15,559	-	0	0
			00-01	A	D	3,608	-	0	0
		XS3	03-04	B	D	23,785	-	0	0
			04-05	A	D	15,125	5,600	43	36

Comparison Criteria						Functional Flows Analysis Outputs			
River	Water Year Type	XS	Site	Before/ After	Detailed monitoring site/ Reference site	Available Range Q*	Functional Range Q*	# Days with functional flows	% Efficiency
Yuba River	WY1	XS1	03-04	B	D	10,160	10,054	184	99
			04-05	A	D	36,405	36,024	190	99
		XS2	03-04	B	D	10,160	10,054	179	99
			04-05	A	D	19,458	19,254	162	99
		XS3	03-04	B	D	2,409	1,219	86	51
			04-05	A	D	26,099	25,826	160	99
		XS4	Nov05	A	R	29,506	2,924	7	10
	WY2	XS1	03-04	B	D	58,405	21,645	177	37
			04-05	A	D	209,272	77,559	176	37
		XS2	03-04	B	D	58,405	21,645	177	37
			04-05	A	D	111,852	41,454	170	37
		XS3	03-04	B	D	13,847	13,136	112	95
			04-05	A	D	150,030	55,603	173	37
		XS4	Nov05	A	R	169,615	148,392	101	87
	Actual WY	XS1	03-04	B	D	10,944	4,954	182	45
			04-05	A	D	306,674	199,965	265	65
		XS2	03-04	B	D	10,944	4,954	216	45
			04-05	A	D	163,912	163,912	254	100
		XS3	03-04	B	D	2,595	1,874	99	72
			04-05	A	D	219,859	219,859	255	100

A. **Mokelumne River (n=15 before vs. n=15 after)**

			rQ*	#DFF	%Eff
	p-level		$p < .10$	$p < .05$	$p < .10$
		KS test	F	T	F
S	$p < .01$	T	F	T	F
D_{50}	$p < .05$	T	F	T	F
c	$p < .01$	T	F	T	F
f	$p < .005$	T	F	T	F

Yuba River (n=15 before vs. n=15 after)

		rQ*	#DFF	%Eff
p-level		$p < .005$	$p > .10$	$p > .10$
	KS test	T	F	F
$p < .001$	T	T	F	F
$p < .001$	T	T	F	F
$p < .025$	T	T	F	F
$p < .025$	T	T	F	F

B. **Mokelumne River (n=24 restored vs. n=6 reference)**

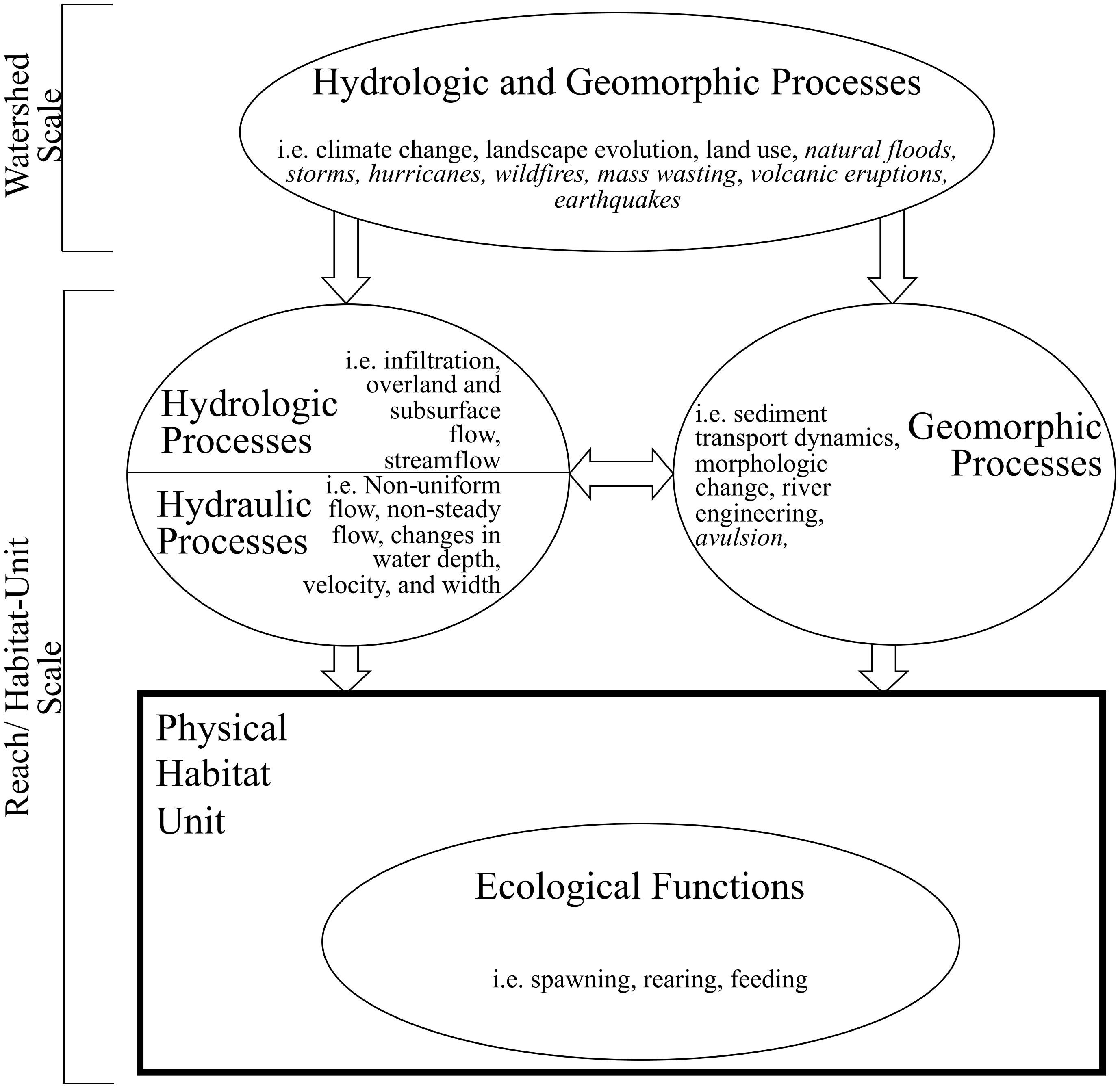
			rQ*	#DFF	%Eff
	p-level		$p > .10$	$p > .10$	$p > .10$
		KS test	F	F	F
S	$p > .10$	F	T	T	T
D_{50}	$p > .10$	F	T	T	T
c	$p < .001$	T	F	F	F
f	$p < .05$	T	F	F	F

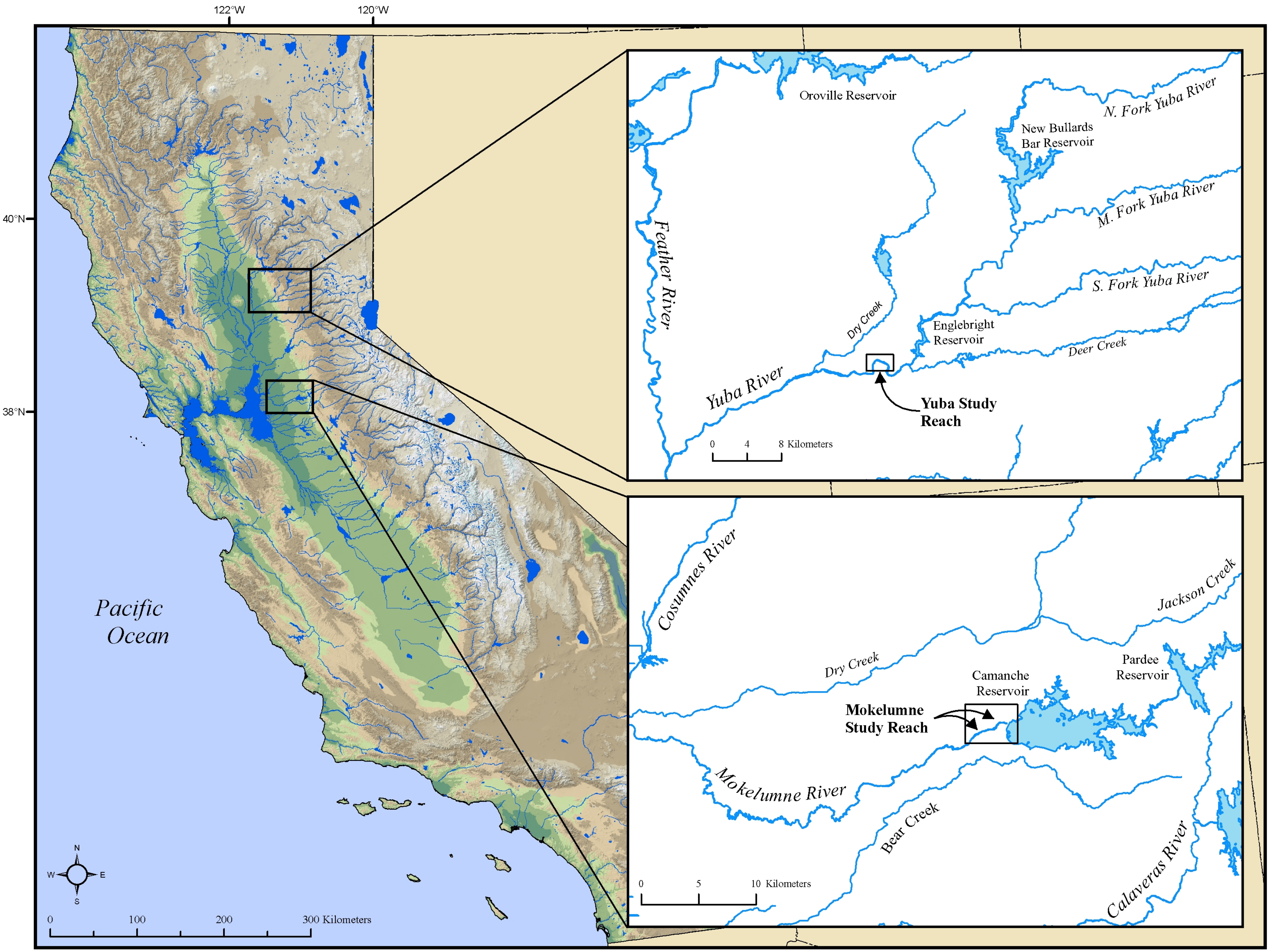
Yuba River (n=18 apex vs. 2 reference)

		rQ*	#DFF	%Eff
p-level		$p > .10$	$p > .10$	$p > .10$
	KS test	F	F	F
$p < .10$	F	T	T	T
$p > .10$	F	T	T	T
$p > .10$	F	T	T	T
$p < .10$	F	T	T	T

C. **Mokelumne River (n=30) vs. Yuba River (n=20)**

			rQ*	#DFF	%Eff
	p-level		$p < .05$	$p < .01$	$p < .025$
		KS test	T	T	T
S	$p < .001$	T	T	T	T
D_{50}	$p < .001$	T	T	T	T
c	$p < .001$	T	T	T	T
f	$p > .10$	F	F	F	F


Watershed Scale
Reach/ Habitat-Unit Scale
Hydrologic and Geomorphic Processes
i.e. climate change, landscape evolution, land use, *natural floods, storms, hurricanes, wildfires, mass wasting, volcanic eruptions, earthquakes*
Hydrologic Processes
i.e. infiltration, overland and subsurface flow, streamflow
Hydraulic Processes
i.e. Non-uniform flow, non-steady flow, changes in water depth, velocity, and width
Geomorphic Processes
i.e. sediment transport dynamics, morphologic change, river engineering, *avulsion,*
Physical Habitat Unit
Ecological Functions
i.e. spawning, rearing, feeding


122°W
120°W
40°N
38°N
Pacific
Ocean
N
W
E
S
0
100
200
300 Kilometers
Oroville Reservoir
New Bullards
Bar Reservoir
N. Fork Yuba River
M. Fork Yuba River
S. Fork Yuba River
Feather River
Dry Creek
Englebright
Reservoir
Deer Creek
Yuba River
Yuba Study
Reach
0
4
8 Kilometers
Cosumnes River
Jackson Creek
Dry Creek
Camanche
Reservoir
Pardee
Reservoir
Mokelumne
Study Reach
Mokelumne River
Bear Creek
Calaveras River
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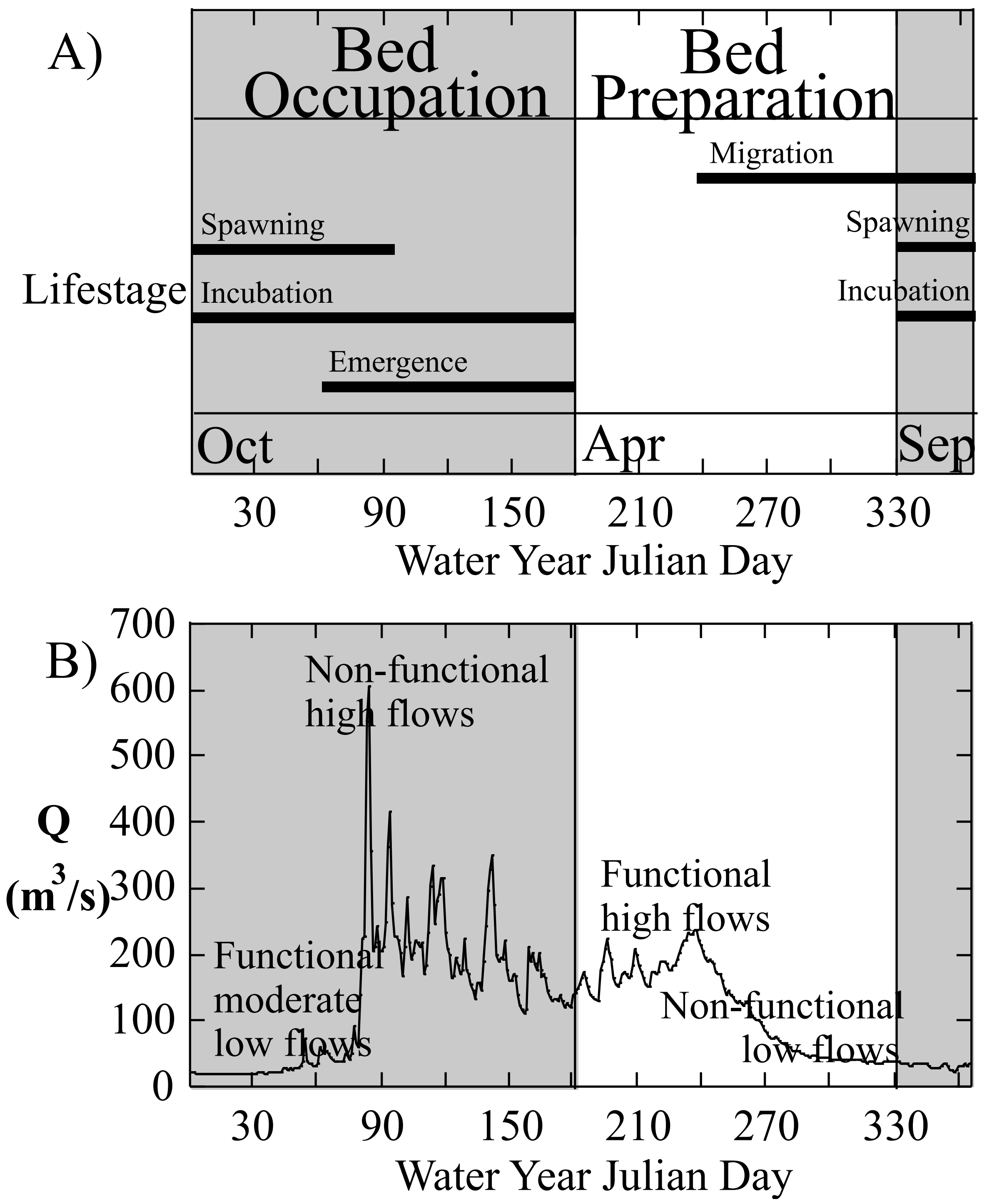
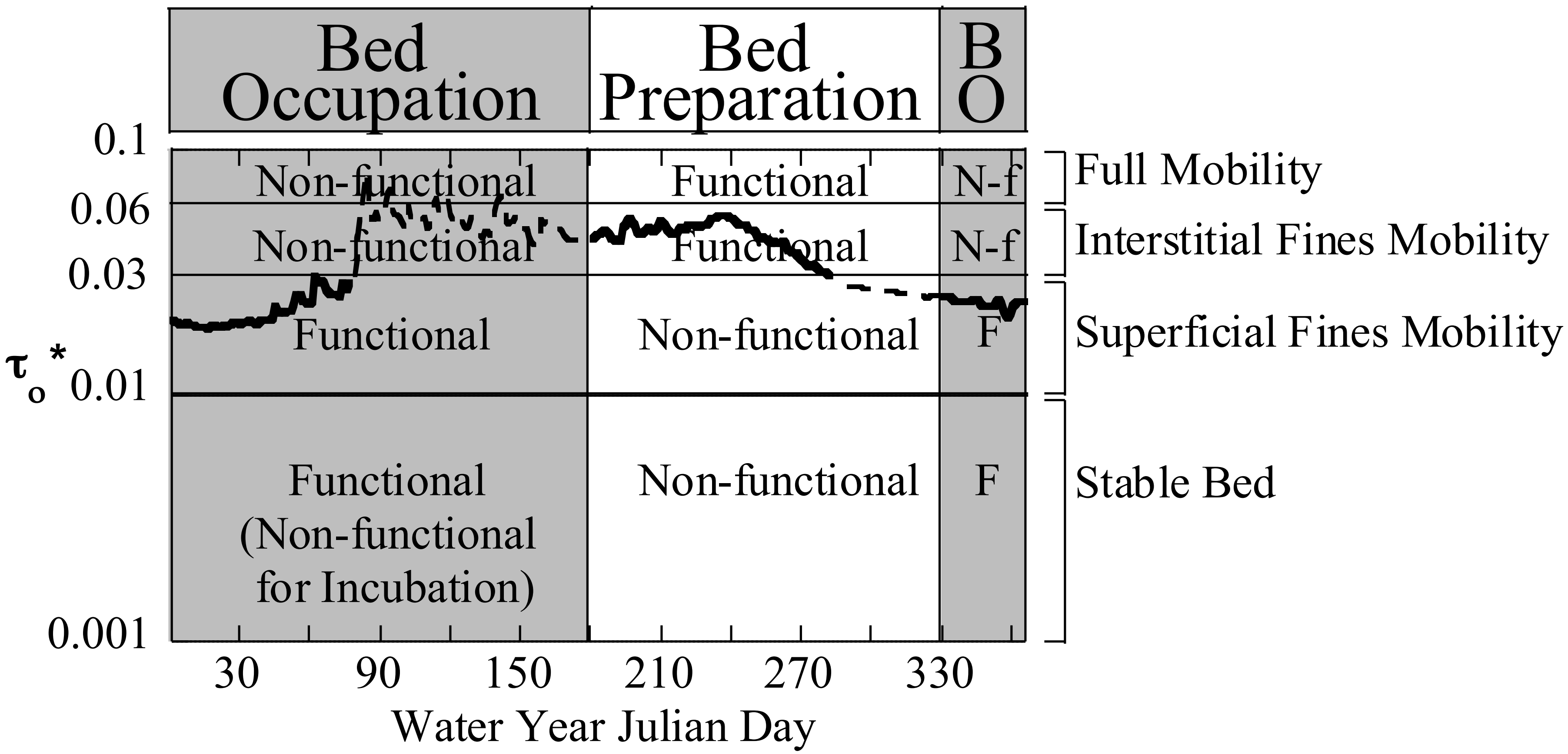
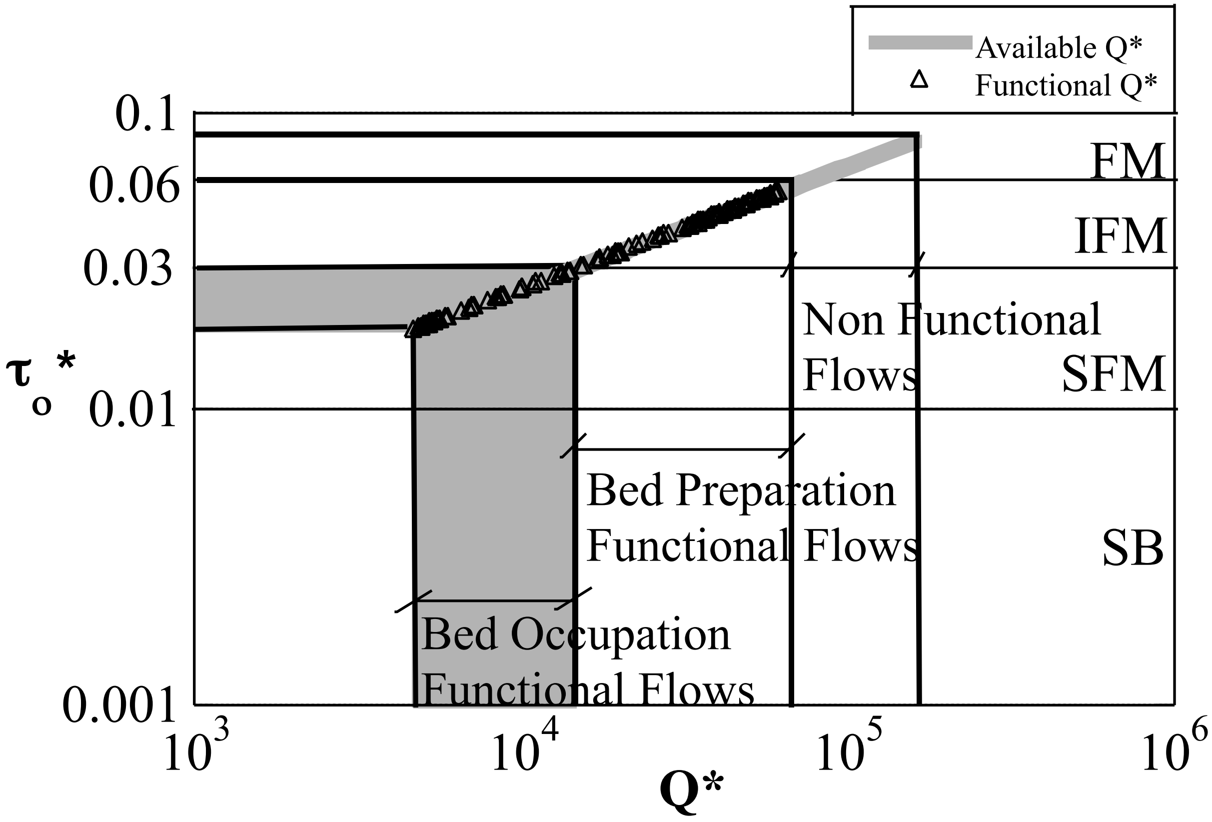
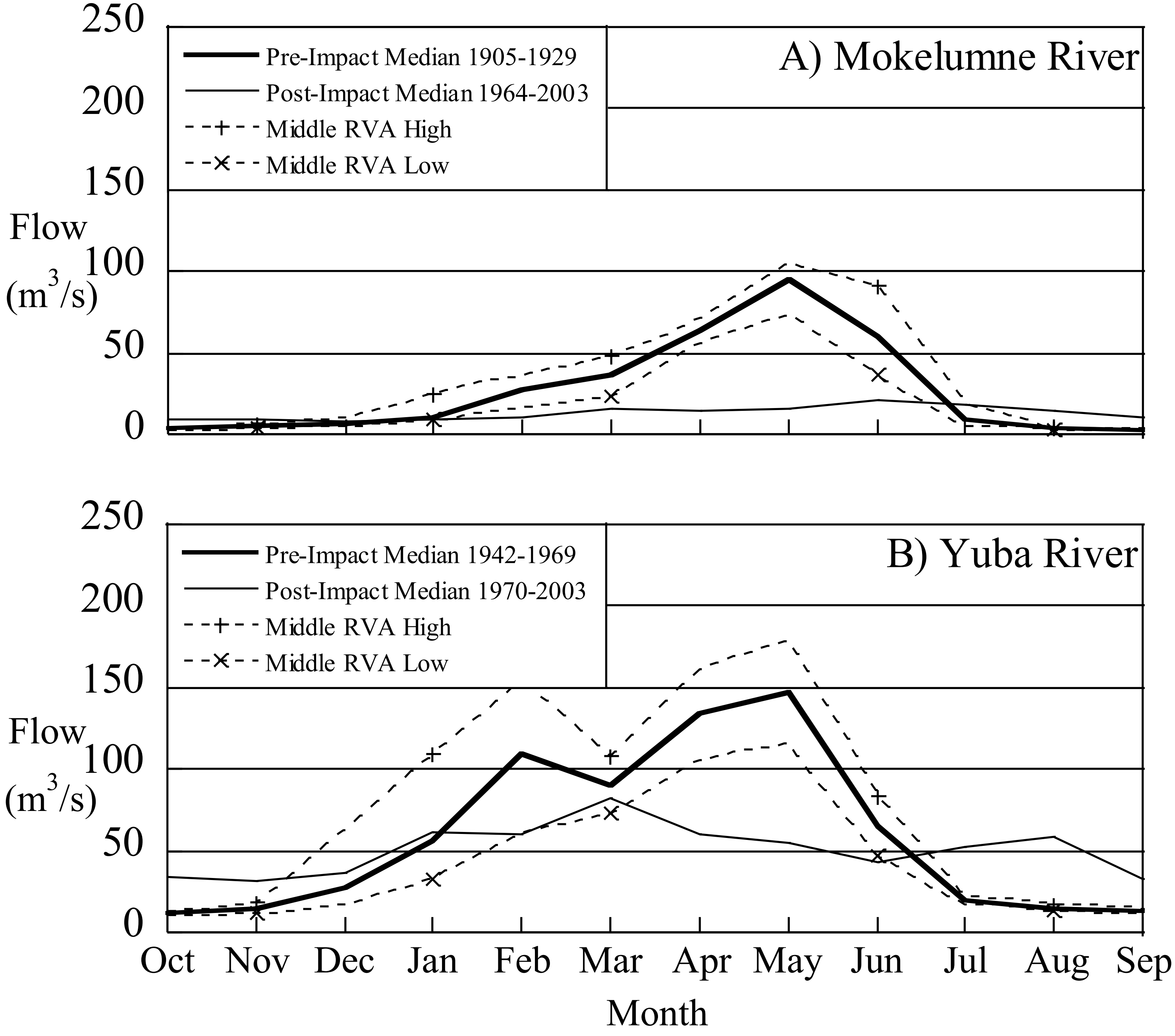
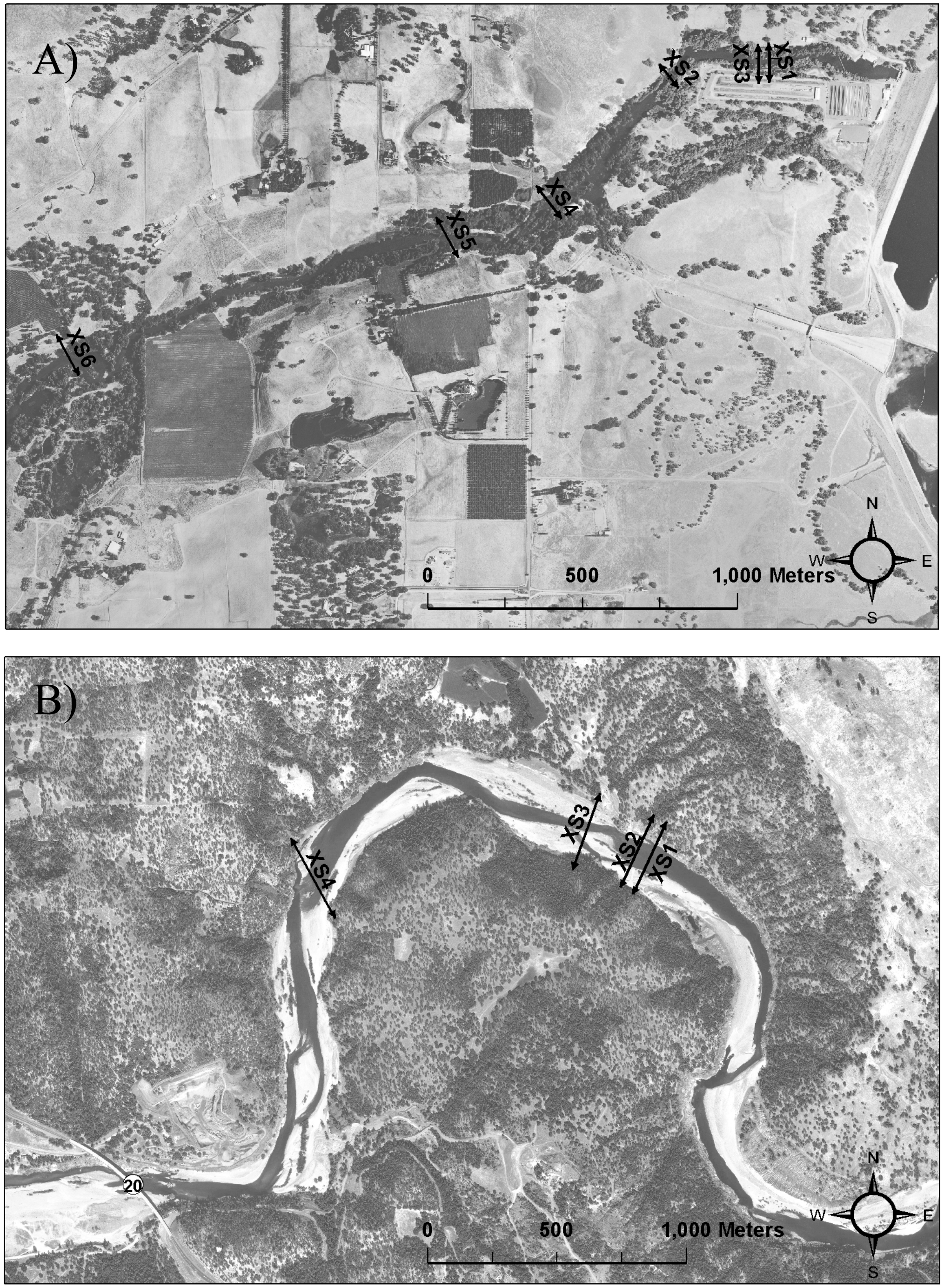
10 Kilometers

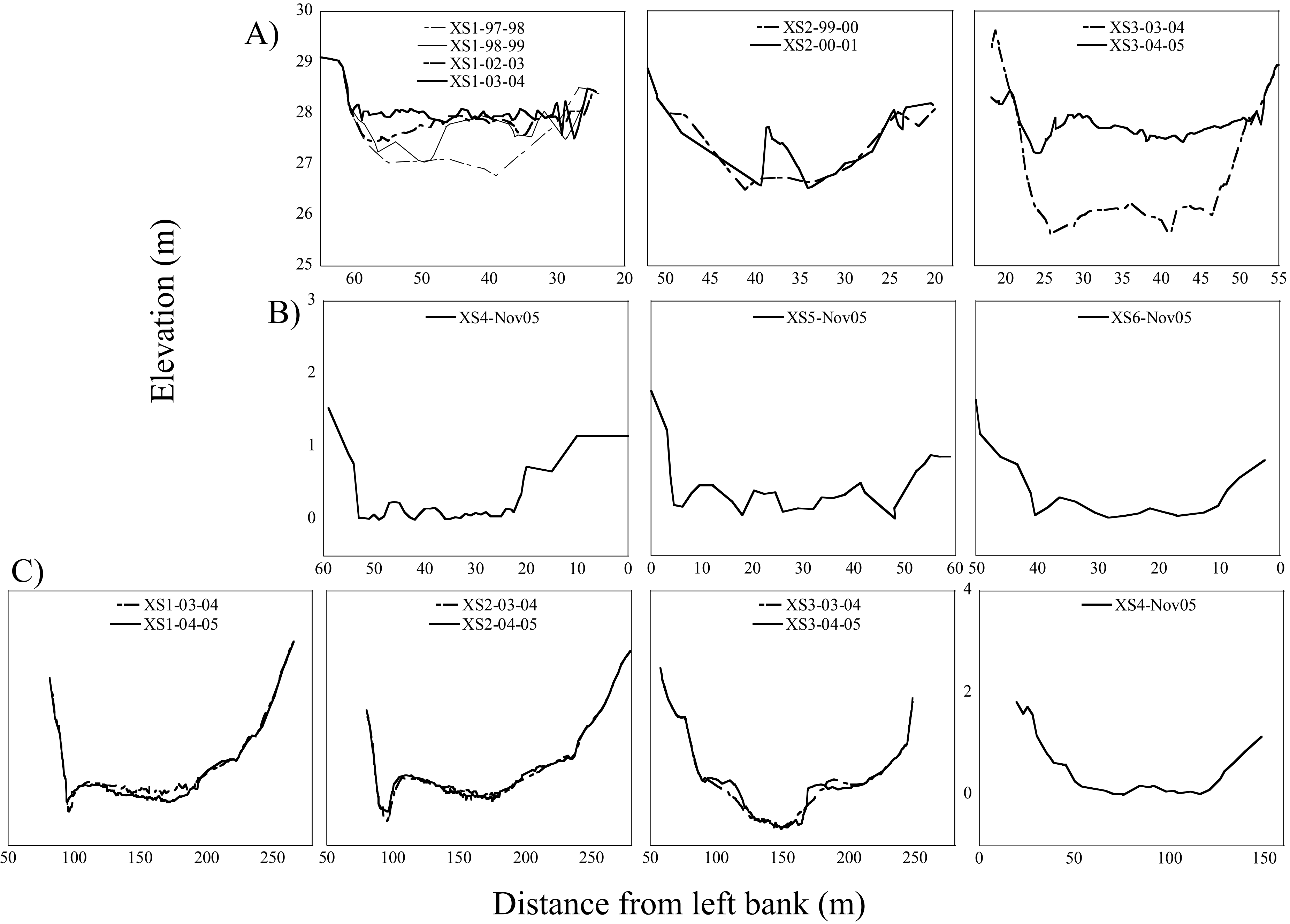

A)
Bed Occupation
Bed Preparation
Lifestage
Migration
Spawning
Incubation
Emergence
Spawning
Incubation
Oct
Apr
Sep
30
90
150
210
270
330
Water Year Julian Day
B)
Q (m^3/s)
700
600
500
400
300
200
100
0
Non-functional high flows
Functional moderate low flows
Functional high flows
Non-functional low flows
30
90
150
210
270
330
Water Year Julian Day

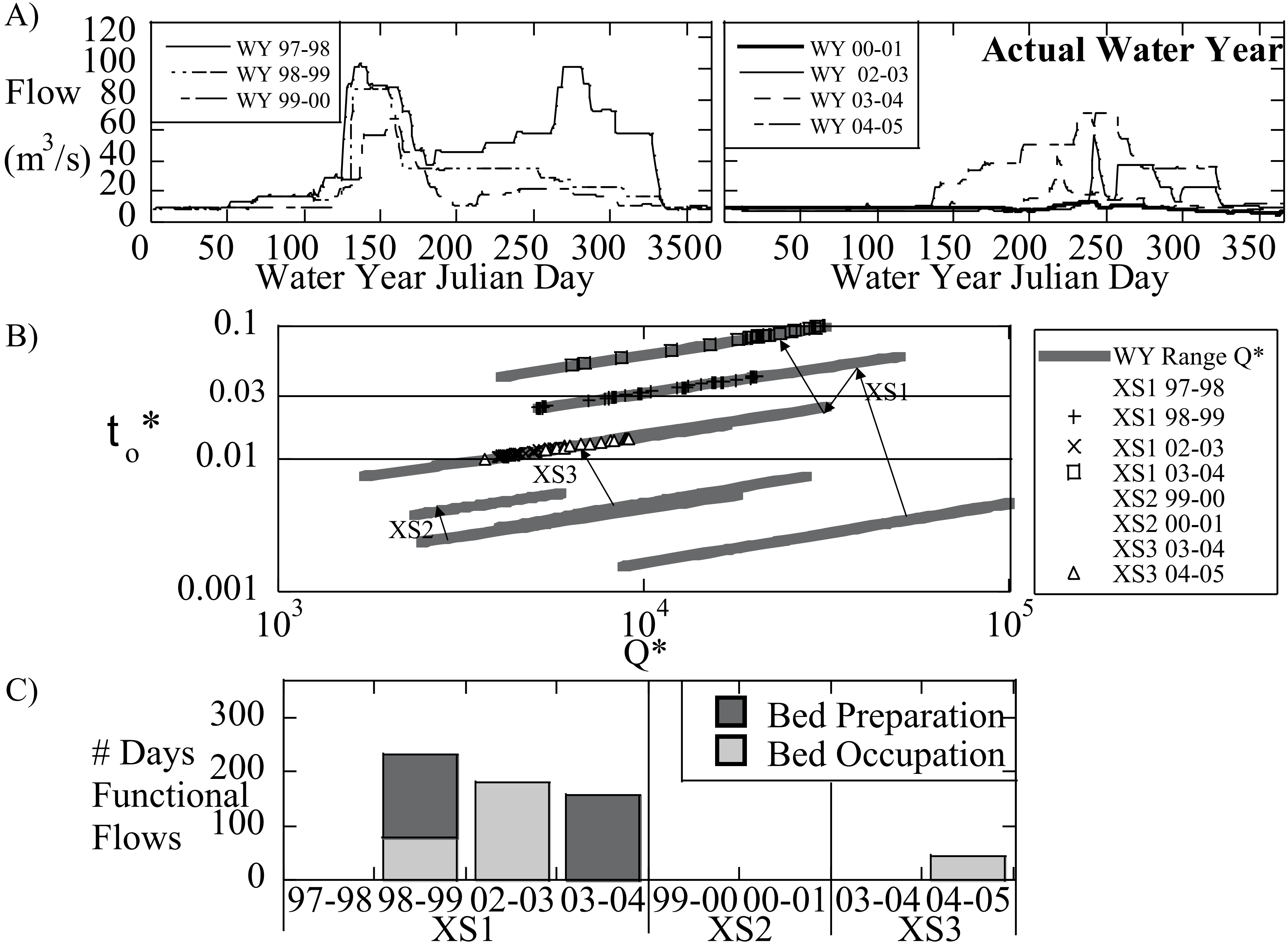

Bed Occupation
Bed Preparation
B O
0.1
0.06
0.03
τ_o^* 0.01
0.001
Non-functional
Non-functional
Functional
Functional (Non-functional for Incubation)
Functional
Functional
Non-functional
Non-functional
N-f
N-f
F
F
Full Mobility
Interstitial Fines Mobility
Superficial Fines Mobility
Stable Bed
30
90
150
210
270
330
Water Year Julian Day

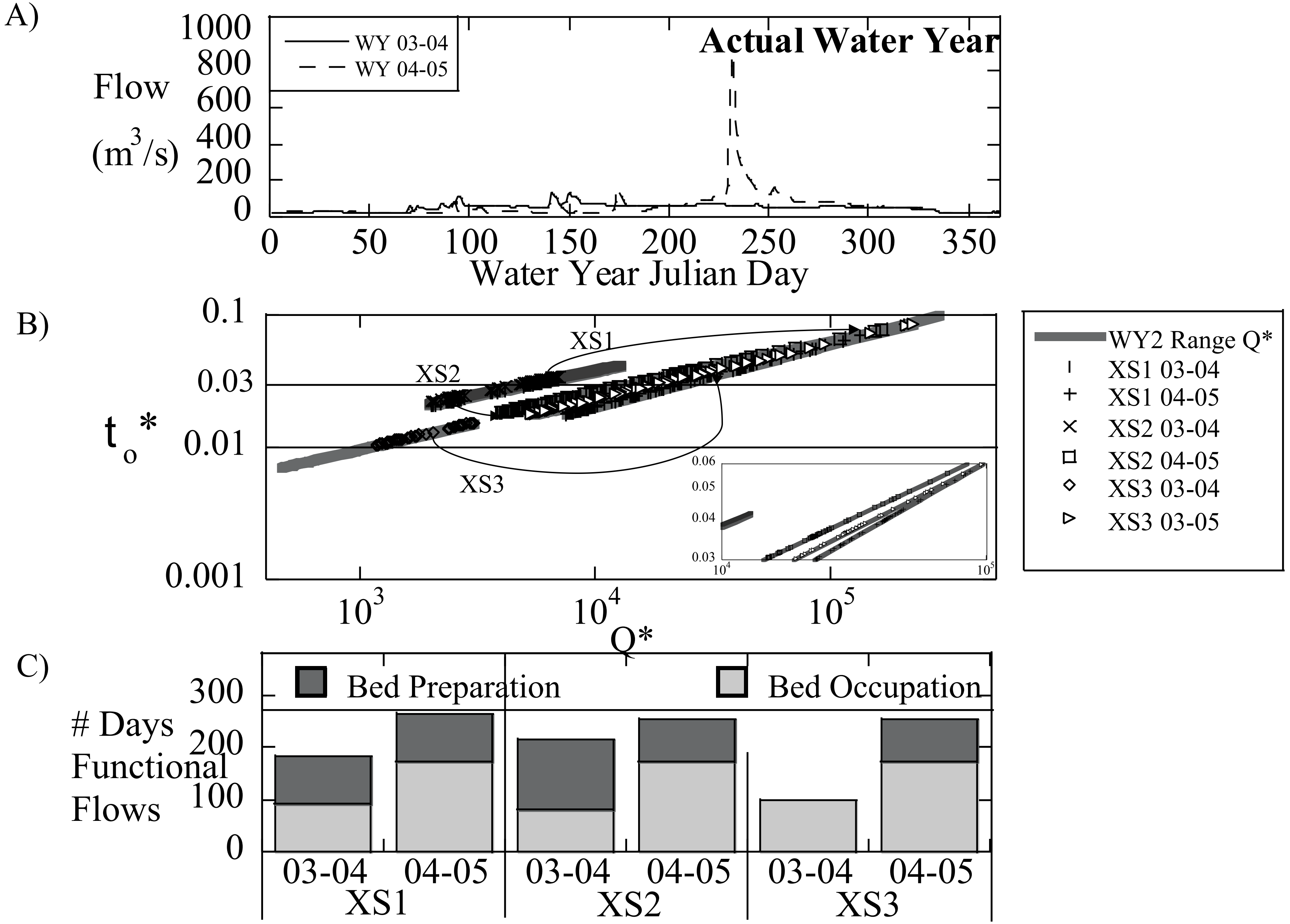

Available Q*
Functional Q*
0.1
0.06
0.03
0.01
0.001
τo*
FM
IFM
SFM
SB
Non Functional Flows
Bed Preparation Functional Flows
Bed Occupation Functional Flows
10^3
10^4
10^5
10^6
Q*


A) Mokelumne River
Pre-Impact Median 1905-1929
Post-Impact Median 1964-2003
Middle RVA High
Middle RVA Low
B) Yuba River
Pre-Impact Median 1942-1969
Post-Impact Median 1970-2003
Middle RVA High
Middle RVA Low
Flow
(m^3/s)
250
200
150
100
50
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Month

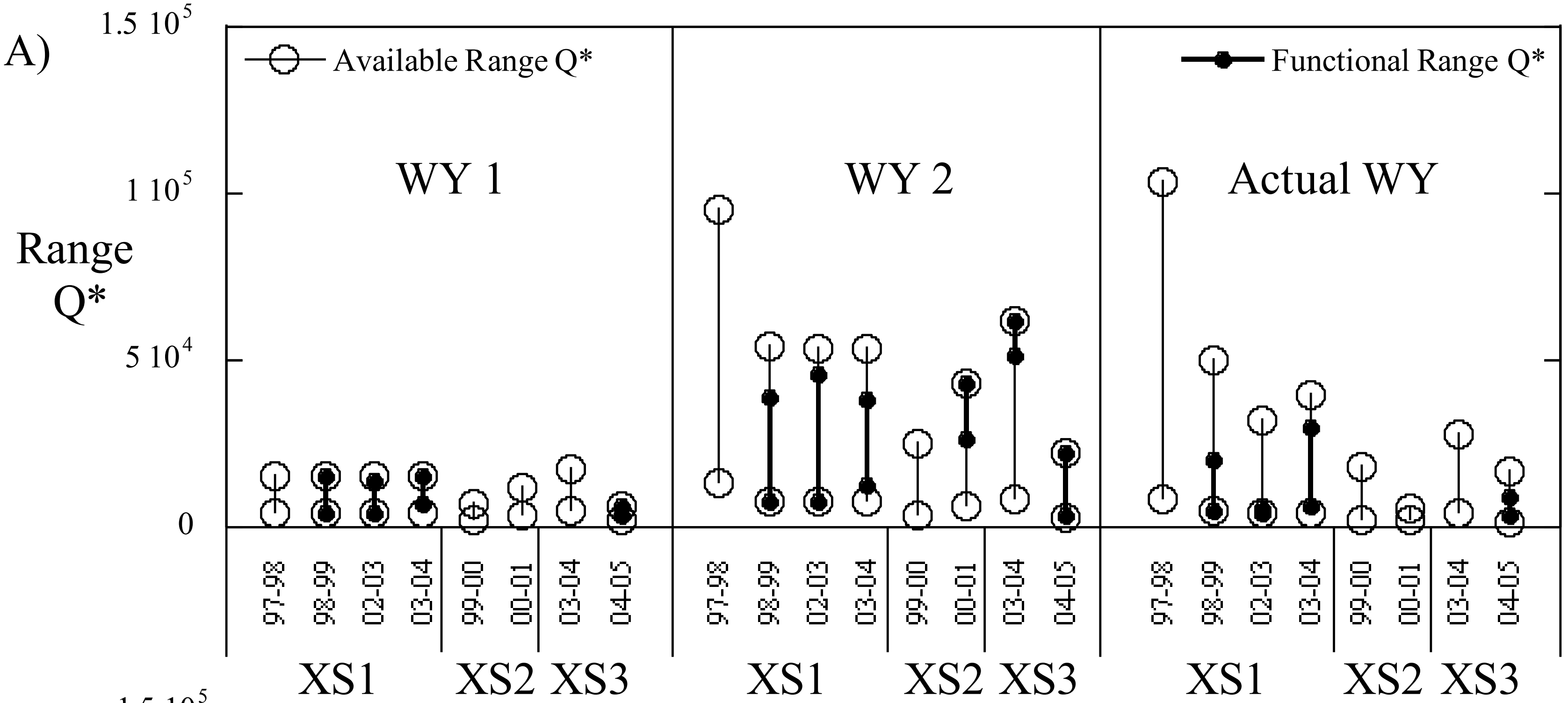

A)
XS1
XS3
XS2
XS4
XS5
XS6
0
500
1,000 Meters
N
W
E
S
B)
XS4
XS3
XS2
XS1
20
0
500
1,000 Meters
N
W
E
S


A)
B)
C)
XS1-97-98
XS1-98-99
XS1-02-03
XS1-03-04
XS2-99-00
XS2-00-01
XS3-03-04
XS3-04-05
XS4-Nov05
XS5-Nov05
XS6-Nov05
XS1-03-04
XS1-04-05
XS2-03-04
XS2-04-05
XS3-03-04
XS3-04-05
XS4-Nov05
Elevation (m)
Distance from left bank (m)
30
29
28
27
26
25
60
50
40
30
20
50
45
40
35
30
25
20
20
25
30
35
40
45
50
55
3
2
1
0
60
50
40
30
20
10
0
0
10
20
30
40
50
60
50
40
30
20
10
0
75
70
65
50
100
150
200
250
50
100
150
200
250
50
100
150
200
250
4
2
0
0
50
100
150

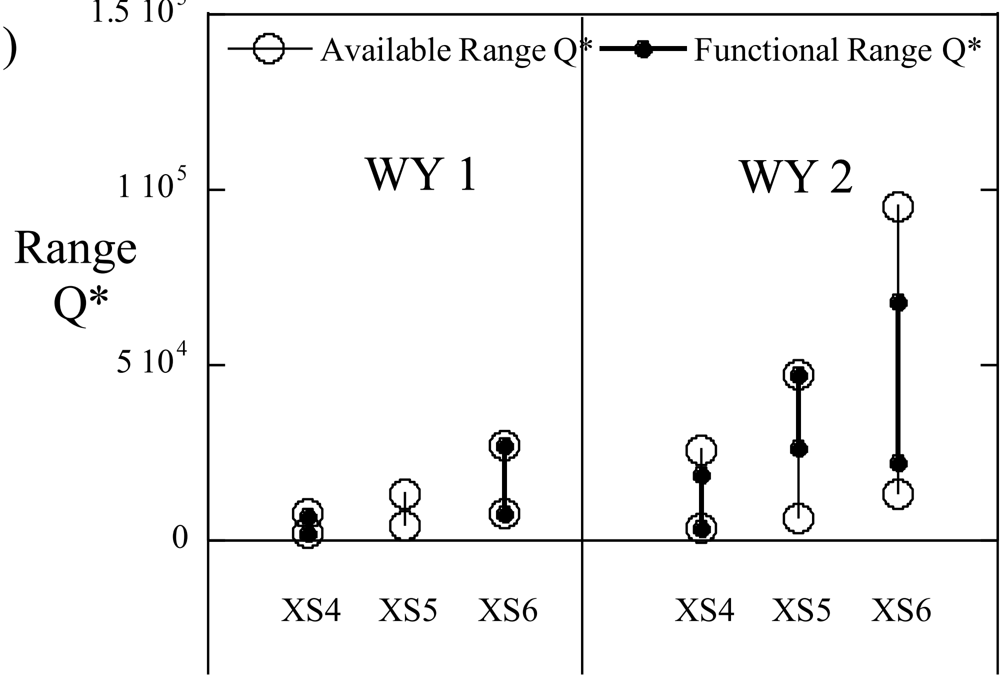

A)
Flow (m^3/s)
120
100
80
60
40
20
0
WY 97-98
WY 98-99
WY 99-00
0
50
100
150
200
250
300
350
Water Year Julian Day
WY 00-01
WY 02-03
WY 03-04
WY 04-05
Actual Water Year
50
100
150
200
250
300
350
Water Year Julian Day
B)
t_o*
0.1
0.03
0.01
0.001
10^3
10^4
10^5
Q*
XS1
XS2
XS3
WY Range Q*
XS1 97-98
XS1 98-99
XS1 02-03
XS1 03-04
XS2 99-00
XS2 00-01
XS3 03-04
XS3 04-05
C)
Days Functional Flows
300
200
100
0
Bed Preparation
Bed Occupation
97-98
98-99
02-03
03-04
XS1
99-00
00-01
XS2
03-04
04-05
XS3

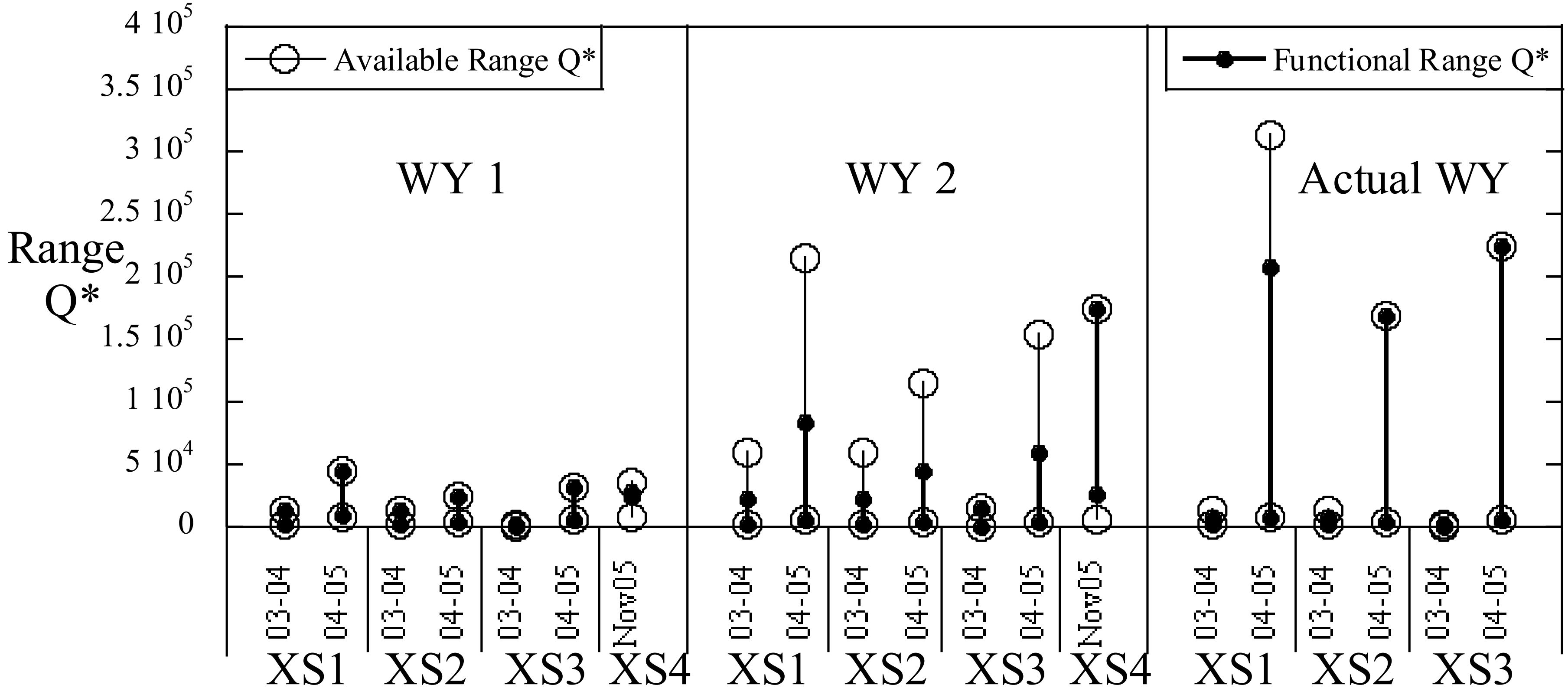

A)
Flow
(m^3/s)
1000
800
600
400
200
0
WY 03-04
WY 04-05
Actual Water Year
0
50
100
150
200
250
300
350
Water Year Julian Day
B)
t_o*
0.1
0.03
0.01
0.001
XS1
XS2
XS3
0.06
0.05
0.04
0.03
10^4
10^5
10^3
10^4
10^5
Q*
WY2 Range Q*
XS1 03-04
XS1 04-05
XS2 03-04
XS2 04-05
XS3 03-04
XS3 03-05
C)
Days
Functional
Flows
300
200
100
0
Bed Preparation
Bed Occupation
03-04
04-05
XS1
03-04
04-05
XS2
03-04
04-05
XS3

A)


Available Range Q*
Functional Range Q*
WY 1
WY 2
Actual WY
Range Q*
1.5 10^5
1 10^5
5 10^4
0
97-98
98-99
02-03
03-04
99-00
00-01
03-04
04-05
XS1
XS2
XS3

B)


Available Range Q*
Functional Range Q*
WY 1
WY 2
Range Q*
1.5 10^5
1 10^5
5 10^4
0
XS4
XS5
XS6


Available Range Q*
Functional Range Q*
WY 1
WY 2
Actual WY
Range Q*
4 10^5
3.5 10^5
3 10^5
2.5 10^5
2 10^5
1.5 10^5
1 10^5
5 10^4
0
03-04
04-05
Nov05
XS1
XS2
XS3
XS4