Integrating flow, form, and function
for improved environmental water management

By

BELIZE ARELA ALBIN LANE
M.S. (University of California, Davis) 2014
B.S. (University of California, San Diego) 2010

DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Hydrologic Sciences

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

_____
(Samuel Sandoval-Solis, Chair)

_____
(Gregory B. Pasternack)

_____
(Helen E. Dahlke)

Committee in Charge
2017

To Simon and my family, for everything.

Acknowledgements

I would also like to express my immense gratitude for all the people who worked for me throughout my PhD. A huge thank you to Dennise Allatorre for the endless hours of work she poured into the field campaign. She was really the person who kept all the pieces moving and made the field campaign such a success, and her attention to detail and organizational skills were dazzling. Another huge thank you to my wonderful field technicians for such hard work and positive attitudes throughout the field campaign. John Deane and Brianna Ordung never complained no matter how challenging the field conditions or the group dynamics, and were a pleasure to work with. Thank you also to Daisy Guitron, Sam Schoevaars, Kelly Kane, Justin Pascual, Ale Urcelay, Josue Moreno, and many more undergraduate students from ESM 121 for their help with field collection and data analysis. It was their hard work and dedication that allowed me to accomplish as much as I did during my PhD, and it was my honor to get to work with and mentor each and every one of them.

Endless gratitude to the broader Hydrologic Sciences Graduate Group community for being my extended family over the past five years and making Simon and my experience in Davis so wonderful. Leah Kammel, Matt Weber, Pablo Ortiz, Katie Markovitch, Steve Maples, Gus Tolley, Pablo Silva, Jason Weiner, Tiffany Kocis, Amy Yoder… Thank you for the potlucks, ultimate frisbee, Cool Runnings, mountain biking, rafting, and skiing that have maintained my sanity, health, and passion for the Earth sciences throughout my graduate career.

Finally, to my family. Thank you for being the most supportive, enthusiastic, inspiring, loving group of people to grace this planet. My parents Steven Lane and Selora Albin, my sisters Monet and Cezanne, my husband Simon, and my dog Melipal have supported and encouraged me and really made this entire journey possible.

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Belize A. Lane, Ph.D.

University of California Davis, 2017

Supervisor: Dr. Samuel Sandoval Solis

Rivers are complex, dynamic natural systems. The performance of river ecosystem functions, such as habitat availability and sediment transport, depends on the interplay of hydrologic dynamics (flow) and geomorphic settings (form). However, most river restoration studies evaluate the role of either flow or form without regard for their dynamic interactions. Despite substantial recent interest in quantifying environmental water requirements to support integrated water management efforts, the absence of quantitative, transferable relationships between river flow, form, and ecosystem functions remains a major limitation. This research proposes a novel, process-driven methodology for evaluating river flow-form-function linkages in support of basin-scale environmental water management. This methodology utilizes publically available geospatial and time-series data and targeted field data collection to improve basic understanding of river systems with limited data and resource requirements. First, a hydrologic classification system is developed to characterize natural hydrologic variability across a highly altered, physio-climatically diverse landscape. Next, a statistical analysis is used to characterize reach-scale geomorphic variability and to investigate the utility of topographic variability attributes (TVAs, subreach-scale undulations in channel width and depth), alongside traditional reach-averaged attributes, for distinguishing dominant geomorphic forms and processes across a hydroscape. Finally, the interacting roles of flow (hydrologic regime, water year type, and hydrologic impairment) and form (channel morphology) are quantitatively evaluated with respect to ecosystem functions related to hydrogeomorphic processes, aquatic habitat, and riparian habitat. Synthetic river corridor generation is used to evaluate and isolate the role of distinct geomorphic attributes without the need for intensive topographic surveying. This three-part methodology was successfully applied in the Sacramento Basin of California, USA, a large, heavily altered Mediterranean-montane basin. A spatially-explicit hydrologic classification of California distinguished eight natural hydrologic regimes representing distinct flow sources,

hydrologic characteristics, and rainfall-runoff controls. A hydro-geomorphic sub-classification of the Sacramento Basin based on stratified random field surveys of 161 stream reaches distinguished nine channel types consisting of both previously identified and new channel types. Results indicate that TVAs provide a quantitative basis for interpreting non-uniform as well as uniform geomorphic processes to better distinguish linked channel forms and functions of ecological significance. Finally, evaluation of six ecosystem functions across alternative flow-form scenarios in the Yuba River watershed highlights critical tradeoffs in ecosystem performance and emphasizes the significance of spatiotemporal diversity of flow and form for maintaining ecosystem integrity. The methodology developed in this dissertation is broadly applicable and extensible to other river systems and ecosystem functions, where findings can be used to characterize complex controls on river ecosystems, assess impacts of proposed flow and form alterations, and inform river restoration strategies. Overall, this research improves scientific understanding of the linkages between hydrology, geomorphology, and river ecosystems to more efficiently allocate scare water resources for human and environmental objectives across natural and built landscapes.

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Introduction

Rivers are highly complex, dynamic systems. Temporally varying streamflows interact with the river channel and floodplain to influence the structure and function of river ecosystems and sustain river biota. However, anthropogenic changes to flow and sediment regimes and channel morphology have led to large-scale hydrogeomorphic alteration, dramatically degrading river ecosystems worldwide. Reinstatement of a more natural flow regime for environmental benefits (i.e., environmental flows) is an emerging approach for mitigating the negative ecological impacts of hydrologic alteration while maintaining water management functions (Richter et al. 1996; Poff et al. 1997; Richter and Thomas 2007; Arthington 2012). There is also growing recognition that the geomorphic context of the flow regime is critical for determining how ecosystems will respond to hydrologic disturbances.

Alluvial rivers are generally thought to adjust their morphology and sediment regime to their flow regime (Wolman and Miller 1960; Leopold et al. 1964; Andrews 1980; Poff et al. 1997). Under these circumstances, reinstating the natural flow regime would be expected to intrinsically promote natural geomorphic functions. However, this notion is often inaccurate for intensively altered river systems such as those found throughout much of the Western US due to dams, flow diversion, land use changes, and channelization. Channel form and sediment regime are often partially or entirely uncoupled from flow in such altered systems, limiting the efficacy of restoring the natural flow regime alone (Jacobson and Galat 2006; Wohl et al. 2015). Further complicating this relationship between flow and form, different types, spatial distributions, and magnitudes of hydrologic and geomorphic alteration have varying effects on resulting ecosystem functionality.

Numerous studies have stressed the persisting need for an integrated hydro-geomorphic framework to improve interdisciplinary scientific understanding of river systems, citing a lack of integration between existing hydrologic, geomorphic, and biological river classifications and an absence of transferable methods with application outside of the areas (usually basin or sub-basin scale) for which they were developed (Newson and Large 2006; Meitzen et al. 2013). The interdisciplinary field of eco-hydromorphology, defined as the interactions of the biological entities and ecological processes of a river with the hydrologic and geomorphic form and dynamics, has emerged to capture the integration of these fields (Clarke et al. 2003; Vaughan et al. 2009). Despite substantial scientific and management interest, the absence of quantitative,

transferable relationships between surface hydrology (flow), fluvial geomorphology (form), and riverine ecology (function) under natural conditions remains a major limitation to developing process-based environmental flow targets with regional application (Poff et al. 2010; Poff and Zimmerman 2010).

This disconnect between flow- and form-based research highlights a critical need to evaluate the separate and combined influences of hydrologic and geomorphic dynamics on river ecosystem functions. Addressing this need is expected to improve quantitative understanding of how streamflows interact with the river corridor to sustain ecological integrity. From a management perspective, this will help distinguish stream reaches that are flow- or form-limited for future management efforts, and guide ecologically functional river management.

Background

Environmental flows

It is well established that the structure and function of river ecosystems and adaptations of native biota are governed in part by the natural flow regime (e.g., Poff et al. 1997; Naiman et al. 2008) and that different components of the flow regime support different ecological functions of rivers (e.g., Bunn and Arthington 2002; Poff and Zimmerman 2010). The flow regime - described by the magnitude, timing, duration, frequency, and rate-of-change of streamflow - acts as a major control over fluvial geomorphic (Montgomery and Buffington 1997) and biogeochemical processes (Poff et al. 1997). These flow-driven physical processes heavily influence the composition and performance of riverine species. Furthermore, many aquatic and riparian biota have evolved under predictable patterns of natural flow variability such that their life-history, behavioral traits, or physiology are dependent on these conditions (Lytle and Poff 2004). More broadly, the flow regime can be thought to drive ecosystem functions through numerous mechanisms by which rivers act as: a resource or habitat for biota; a vector for connectivity and exchange of energy, materials, and organisms; or as an agent of geomorphic change and disturbance (Sponseller et al. 2013).

Alterations to the natural flow regime for anthropogenic water management objectives such as flood control, food production, water supply maintenance, and hydropower have degraded river ecosystems worldwide (Stanford and Ward 1996; Poff et al. 2010). Ecological impacts can be linked directly to streamflow alteration through reductions in river connectivity and the de-

coupling of species requirements and evolved life history strategies from biological and geochemical processes (Bunn and Arthington 2002), or linked indirectly through the mediating influence of geomorphic processes (Williams and Wolman 1984).

Re-operating reservoirs to provide environmental flows presents an opportunity to improve environmental water management through soft engineering methods whereby deliberate operational decisions based on established linkages between streamflow inputs and ecosystem response can replace the need for major structural changes and expenditures (e.g., dam construction or de-construction) (Bunn and Arthington 2002). The scientific study of environmental flows characterizes these linkages through the development of streamflow targets to support desired ecosystem functions (Postel and Richter 2003).

Environmental flows science has evolved substantially in recent decades based on advances in scientific understanding and technological capabilities (Postel and Richter 2003; Arthington 2012), resulting in over 200 methods for estimating environmental flow requirements (see Tharme 2003 for review). Because the streamflow requirements needed to sustain river ecosystems are fundamentally difficult to isolate and quantify, scientists have historically relied on simplistic annual or seasonally varying minimum streamflow requirements to represent flow targets (Jager and Smith 2008). More recently, recognition that simple minimum flow thresholds are insufficient for sustaining natural ecosystem functions has shifted objectives towards maintaining the natural range of hydrologic variability (Poff et al. 1997) and supporting the hydrologic and hydraulic needs of particular species of interest (Bovee 1982).

However, despite decades of supporting ecological theory and empirical evidence, environmental flows have proved very challenging to implement (Arthington et al. 2006; Konrad et al. 2012). Relatively few field validations of environmental flow targets have been attempted (Poff and Zimmerman 2010), and those flow experiments that have received substantial research and resource support have reported limited success (e.g., Grand Canyon, Melis et al. 2012; Bill Williams River, Shafroth et al. 2010). This may be partially due to the fact that classical requirements of scientific experimentation (Hairston 1989) are difficult to meet in flow manipulation experiments due to high spatiotemporal variability, the physical complexity of river systems, and the need to implement experiments within long-term, often conditional, reservoir operational policies that complicate the testing of discrete hypotheses (Konrad et al. 2012).

Geomorphic considerations in environmental water management

A major limitation to the success of environmental flows applications is the dominance of hydrologic analysis without sufficient consideration of geomorphic setting and processes (Meitzen et al. 2013). Geomorphology occupies a critical, and often ignored, realm in environmental flows science, representing the process-based interactions among river flow, sediment, and morphology influencing ecological conditions across space and time (Poff and Ward 1990; Thoms and Parsons 2002; Meitzen et al. 2013). Although streamflow inputs alone may drive ecosystem functions, constraints imposed by the particular geomorphic setting in which flows occurs (e.g., channel confinement, incision, sediment composition, slope) often influence the potential functional response of a given flow regime (Newson and Large 2006; Tague and Grant 2004). This is because the hydraulic environment in which riverine species exist is constrained by interactions among geomorphic processes subject to boundary conditions that act as independent variables over long time frames (Montgomery and Buffington 1997). The common presumption of distinct flow – response relationships (Poff et al. 1997) may be inappropriate for scales and regions with highly heterogeneous geomorphic characteristics (Newson and Large 2006). Identifying and separately managing geomorphically homogenous (but spatially discontinuous) stream reaches within a landscape has been proposed to improve the predictive power and physical basis of flow-response relationships (Poff et al. 2010).

Numerous physical characteristics influence the geomorphic settings and resulting potential flow-driven ecosystem functions of a river reach. Valley confinement is widely used to classify process domains and stream reach morphology for its significant control, alongside valley slope, on fluvial processes and hillslope–channel coupling (Brierley and Fryirs 2005; Montgomery 1999; Montgomery and Buffington 1997; Rosgen 1996; Schumm 1977). For example, confined reaches generally have greater stream power and sediment transport capacity than unconfined reaches (Montgomery and Buffington 1997). Alternatively, unconfined reaches tend to support a wider range of habitats and species assemblages, and act as filters to remove and process organic matter in river systems (Bellmore and Baxter 2013). Channel composition is also important for constraining potential ecosystem functions, with implications for sediment transport (Schumm 1981), water biogeochemistry, and habitat suitability for aquatic biota (Wood and Armitage 1997).

The need for a novel environmental water management paradigm

A review of the environmental flows literature revealed a methodological dichotomy between (1) ecohydrologic (flow-based) and (2) ecohydraulic (form-based) methods for estimating environmental flow targets. The natural flow paradigm (Poff et al. 1997) stands out among ecohydrologic approaches for its frequent management application and scientific interest worldwide (Arthington et al. 2006). Methods under this heading characterize key components of the natural flow regime under the assumption that a suite of native species will be intrinsically supported by the recovery of the natural hydrologic variability to which they are adapted (Poff 1996). However, the natural flow paradigm is often in direct conflict with water management interests that seek to dampen high flows and augment low flows (Enders et al. 2009), and scientists are struggling to identify and validate the specific natural flow regime components critical to river ecosystems (Meitzen et al. 2013; Arthington et al. 2006; Konrad et al. 2012).

Alternatively, ecohydraulic approaches provide a geomorphic basis for flow targets that can be field-validated. However, such approaches require substantial resource and data requirements and are generally site- or species-specific and assume ecological knowledge of relevant hydraulic habitat needs (Newson and Newson 2000). (Newson and Newson 2000). Numerous techniques exist for determining the hydraulic habitat requirements of selected species and for defining flow regimes to maximize these conditions under a set of physical constraints (Mosely 1982; Leclerc et al. 1995; Wheaton and Pasternack 2004; Stewart et al. 2005). Limitations of both methods highlight the need to reconcile this methodological dichotomy to improve the estimation of environmental flows into a novel environmental water management paradigm: *flow, form and function*.

Interactions between flow, form, and function

The ecosystem functions performed by a river are the result of spatiotemporally variable hydrologic and geomorphic processes acting within the river corridor, and greater integration is needed to characterize the feedbacks between flow and form and their influence over ecosystem functions (Clarke et al. 2003; Vaughan et al. 2009). The flow regime and geomorphic setting of a reach interact to dictate the relative dominance of flow-driven ecosystem functions (Wohl and

Merritt 2005). In mountain streams, for example, channels with different morphologies and compositions have been shown to respond differently to similar streamflow inputs, with varying rates of sediment scour, transport, and deposition driving a spatially distributed functional response to streamflow inputs along the river corridor (Montgomery and Buffington 1997). These complex interactions are further compounded in heavily altered rivers where morphology may be essentially independent of flow (Graf 2006; Jacobson and Galat 2006; Tracy-Smith et al. 2012).

Proposed research framework: flow, form and function

   This dissertation proposes a novel framework for characterizing spatially-explicit flow and form settings and evaluating the separate and combined roles of flow and form in the performance of ecosystem functions. Figure 1 illustrates these three components and their interactions as evaluated in the three chapters of this dissertation. Figure 2 outlines the key inputs, outputs, and driving processes of this research methodology for evaluating flow-form-function linkages that are described in more depth later in this document.
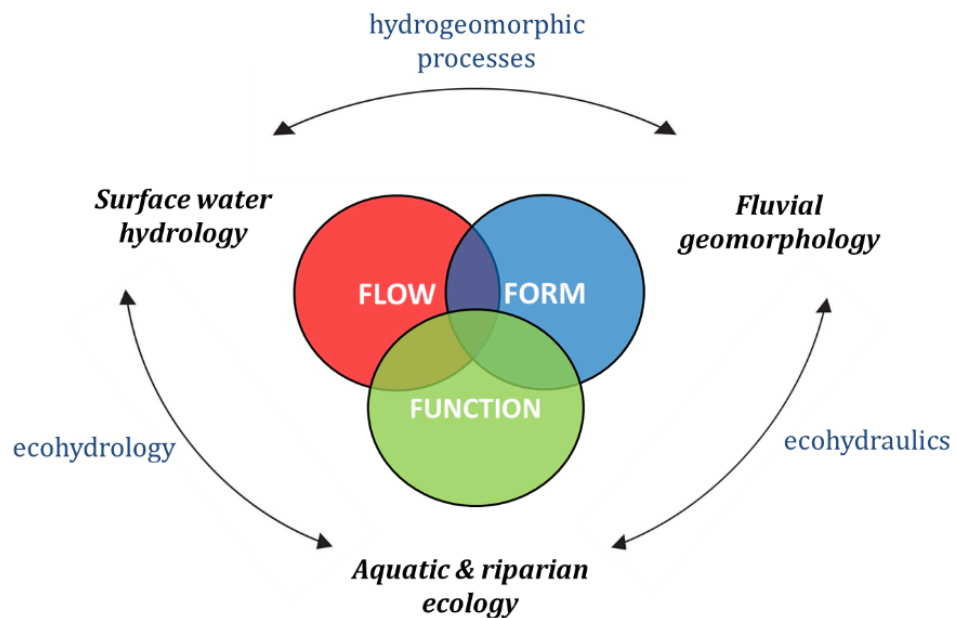
Figure 1. Schematic of the linkages between river flow, form, and function that are addressed in this dissertation.
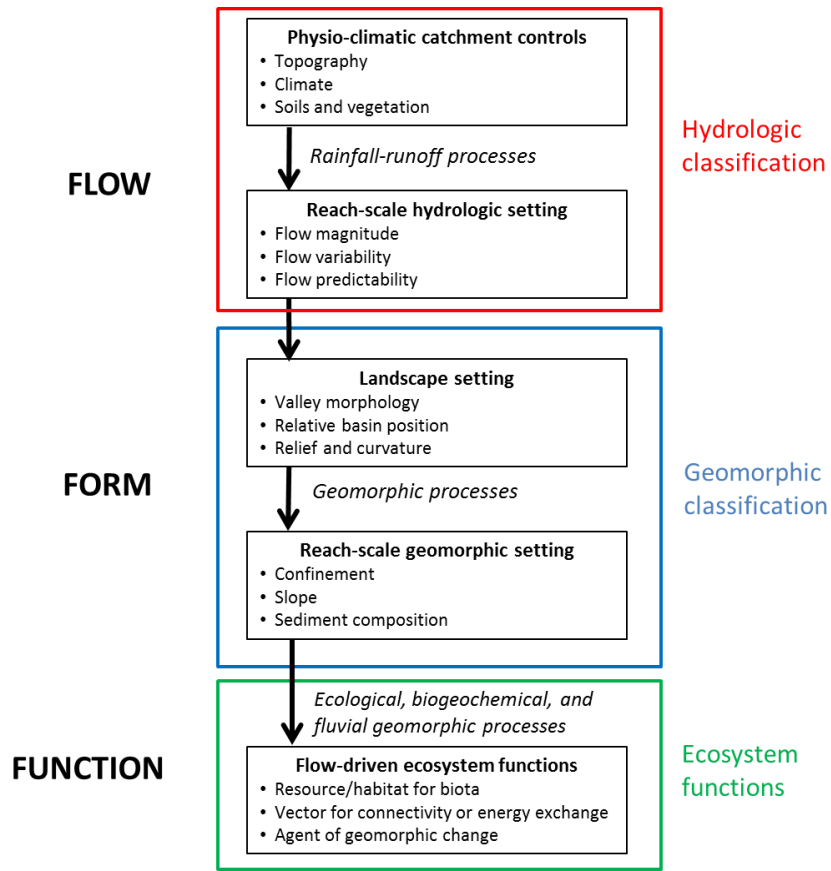
Figure 2. Process-driven research framework indicating dominant inputs, outputs, and driving processes of each of the three chapters

Application to Mediterranean-montane rivers

As a highly degraded ecosystem with well-studied functions and substantial data availability, California's Mediterranean-montane rivers provide an ideal setting in which to evaluate flow-form-function interactions. Many ecosystem functions critical to native Mediterranean biota depend on the performance of ecologically relevant hydraulic parameters (e.g., depth, velocity, shear stress) that vary as a function of flow and form (Gasith and Resh 1999). Riparian vegetation recruitment, for example, requires a combination of large scouring flows and sufficient inundation width and duration to establish seedlings (Mahoney and Rood 1998).Similarly, salmonid redds require sufficient inundation depths and intragravel flows in certain channel locations at particular times of year (USFWS 2010). The hydraulic parameters associated with these conditions depend on the interaction between hydrologic dynamics and channel morphology, explicitly integrating flow and form. Furthermore, different channel forms

exhibited by these rivers provide differing capacities to support specific functions (e.g., Moir et al. 2006; Small et al. 2008; Brown and Pasternack 2008).

The ability to distinguish the roles of flow and form in California's highly complex and altered Mediterranean-montane rivers would demonstrate the applicability of the proposed framework. With more than 70% of annual precipitation occurring over winter months and high topographic and geologic variability, native aquatic and riparian species are highly adapted to the temporal and spatial variability of biotic and abiotic stresses (Gasith and Resh 1999; Yarnell et al. 2015). However, the natural occurrence of water in California in time (Fig. 3) and space (Fig. 4) highly differ from the location and timing of maximum human water demand, driving intensive water management efforts (Hanak et al. 2011). Water management activities to address these offsets in supply and demand, such as flood control and hydropower, have dramatically decreased spatial and temporal variability in river systems, disrupting the complex natural patterns of ecosystem, functionality (Graf 2006; Moyle et al. 2011). As a result of this intensive management, less than 2% of the state's total stream flow remains unaltered (Mailligan and Nislow 2005), and over 80% of the native fish species are now imperiled or extinct (Moyle et al. 2011).
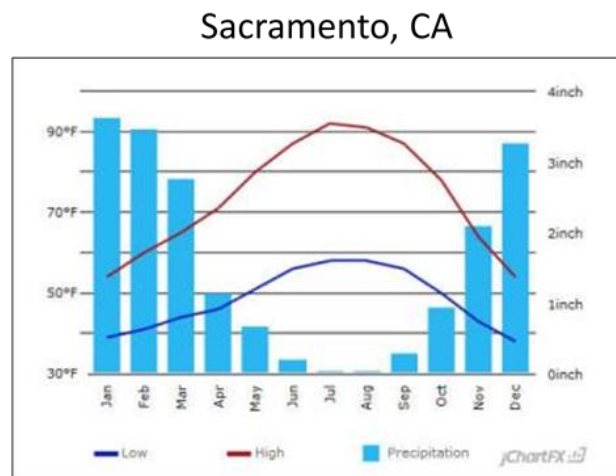
Figure 3. The Sacramento Basin, CA, has warm dry summers and cool wet winters, but the majority of water demand occurs in the summer.
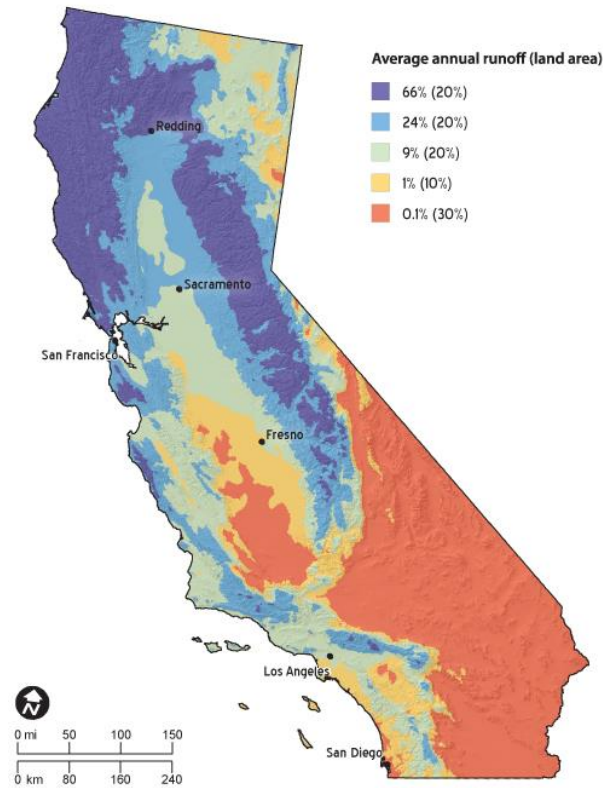
Figure 4. Map of the distribution of average annual runoff by land area in California (Hanak et al. 2011). The majority of runoff occurs in the north while the majority of the water demand occurs in the south.

Application of this research to Mediterranean-montane rivers has a practical goal of supporting the quantification of spatially explicit, reach-scale, rapid environmental flow targets for the State of California. Primary benefits of the proposed approach to defining environmental water management targets include the ability to distinguish distinct natural hydro-geomorphic settings and associated flow-driven ecosystem functions within the region, and to develop broadly applicable physical relationships between flow, form, and function. Results also support improved environmental management through application to reservoir re-operation policy development and subsequent adaptive management under data and resource limitations.

The development of a process-based framework for examining watershed-scale flow-form-function relationships is expected to elucidate key processes underlying spatial and temporal dynamics of Mediterranean-montane river ecosystems and improve understanding of ecosystem resilience and the potential for rehabilitation projects under current and future hydrogeomorphic alterations. Furthermore, while addressing specific systems and scientific questions of intrinsic significance, the general framework developed in this dissertation is readily extensible to

different regions and ecosystem functions to support large-scale river management efforts worldwide.

Objectives

The overall aim of this dissertation is to develop a quantitative framework for evaluating linkages between river flow, form, and ecosystem functions. Specifically, a hydrologic classification and a geomorphic sub-classification are developed to characterize spatiotemporal patterns of dominant flow and form attributes, respectively, and a suite of ecosystem functions is evaluated across alternative flow-form scenarios derived from these classifications. Based on the basic scientific knowledge gained through this research, more process-driven, resource-efficient quantification of environmental water management objectives will be possible.

The key objectives of this dissertation are to:

1- Evaluate the diversity and spatial distribution of dominant natural hydrologic regimes and catchment controls present in a large Mediterranean region

2- Characterize reach-scale geomorphic variability and investigate the utility of topographic variability attributes in distinguishing channel types and dominant geomorphic processes across a heterogeneous landscape

3- Develop a process-driven framework for evaluating the interactions between hydrologic and geomorphic variability as they relate to critical river ecosystem functions by quantifying spatiotemporal patterns in ecohydraulic response

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CHAPTER 1

REVEALING THE DIVERSITY OF NATURAL HYDROLOGIC REGIMES IN CALIFORNIA WITH RELEVANCE FOR ENVIRONMENTAL FLOWS APPLICATIONS

Abstract

Alterations to flow regimes for water management objectives have degraded river ecosystems worldwide. These alterations are particularly profound in Mediterranean climate regions such as California with strong climatic variability and riverine species highly adapted to the resulting flooding and drought disturbances. However, defining environmental flow targets for Mediterranean rivers is complicated by extreme hydrologic variability and often intensive water management legacies. Improved understanding of the diversity of natural streamflow patterns and their spatial arrangement across Mediterranean regions is needed to support the future development of effective flow targets at appropriate scales for management applications with minimal resource and data requirements. Our study addresses this need through the development of a spatially explicit reach-scale hydrologic classification for California. Dominant hydrologic regimes and their physio-climatic controls are revealed using available unimpaired and naturalized streamflow time-series and generally available geospatial datasets. This methodology identifies eight natural flow classes representing distinct flow sources, hydrologic characteristics, and catchment controls over rainfall-runoff response. The study provides a broad-scale hydrologic framework upon which flow – ecology relationships could subsequently be established towards reach-scale environmental flows applications in a complex, highly altered Mediterranean region.

1.1 Introduction

Alterations to natural flow regimes for human water management objectives have degraded river ecosystems worldwide. These alterations are particularly profound in Mediterranean regions such as California with strong climatic variability and aquatic and riparian species highly adapted to the resulting flooding and drought disturbances (Gasith and Resh 1999). The modification of reservoir operations to control the timing, magnitude, and duration of flow releases for environmental benefits (i.e., environmental flows) is an emerging approach for mitigating the negative ecological impacts of dams while preserving essential water management functions (Richter et al. 1996; Richter and Thomas 2007; Arthington 2012; Ai et al. 2013; Lane et al. 2014). However, defining effective environmental flows targets has proven very challenging (Konrad et al. 2012; Meitzen et al. 2013) due to natural complexity and

heterogeneity as well as widespread human intervention (Benda and Dunne 1997; Egger et al. 2012; Wyrick et al. 2014). These challenges are often exaggerated in Mediterranean regions by extreme hydrologic variability and intensive water management legacies (Bejerano et al. 2010).

Hydrologic classification is one strategy to improve our understanding of complex catchment function (Pardé 1933; Dooge 1986; Sauquet et al. 2000; Sivapalan 2005; Wagener et al. 2007) and to ascribe catchments to empirically-based functional groups (e.g., Rosgen 1994; Brandt 2000; Montgomery and Buffington 1997). By identifying and categorizing dominant catchment functions as revealed through a suite of hydrologic response characteristics (e.g., streamflow indices) and catchment attributes (e.g., climate, topography, geology), hydrologic classification allows for the regional transfer of hydrologic information. This ultimately improves the predictive power and process basis of flow — ecology relationships towards the future development of effective environmental flow targets with minimal data and resource requirements (e.g., Richter et al. 1996; Poff et al. 2010; Liermann et al. 2011; Olden et al. 2012).

Hydrologic classification has established a central role in environmental flows science (Olden et al. 2012) to support the assessment of baseline conditions (e.g., Tavassoli et al. 2014; Hersh and Maidment 2010; Richter et al. 1996) and the development of flow — ecology relationships (Apse et al. 2008; Kennen et al. 2007; Carlisle et al. 2010). In the past decade, such regional classifications have been developed for New Zealand (Snelder et al. 2005), Turkey (Kahya et al. 2008), France (Snelder et al. 2009), Australia (Kennard et al. 2010), Canada (Monk et al. 2011), various basins in Spain (Baeza Sanz and García de Jalón 2005; Bejarano et al 2010; Belmar et al. 2011) and in the United States for Colorado (Sanborn and Bledsoe 2006), Michigan (Seelbach et al. 1997, Brenden et al. 2008), Texas (Hersh and Maidment 2010), New Jersey (Kennen et al. 2007), Pennsylvania (Apse et al. 2008), Missouri (Kennen et al. 2009), Washington (Liermann et al. 2011), and Oregon (Wigington et al. 2013).

In spite of the marked value of hydrologic classification as an environmental water management tool and the evident need for such a tool in Mediterranean regions, relatively few hydrologic classifications have been developed for this climate setting. An evaluation by the authors indicated that, of 50 regional hydrologic classifications developed in the past 40 years [based on the subset of regional hydrologic classifications reviewed by Olden et al. (2012)], only 10% fell within dominantly Mediterranean regions (Köppen climate classes Csa and Csb) (Köppen and Geiger 1930) (Turkey, Kahya et al. 2008; Spain, Baeza and García de Jalón 2005;

Washington State, Liermann et al. 2011; Oregon State, Wigington et al. 2013). Furthermore, 71% of studies were based in fully humid regions while only 10% fell within seasonally dry climates [see *Appendix A*]. While based on a subset of regional classifications, these findings emphasize the need for further classification of Mediterranean rivers and streams to inform the development of environmental flow targets given their disproportionate regulation and degradation and underrepresentation in the literature.

Study Objectives

The goal of this study is to develop a hydrologic classification for the Mediterranean region of California by applying established hydrologic and ecological techniques at appropriate scales for environmental flows applications with minimal resource and data requirements. To the best of the authors' knowledge, this study represents the first attempt at a statewide hydrologic classification for the State of California, supporting the future development of environmental flow targets for the region's severely degraded river ecosystems at a time of increasing sociopolitical impetus to address these problems (Magilligan and Nislow 2005; Moyle et al. 2011; Hanak et al. 2011). This study advances scientific understanding of the diversity and spatial distribution of dominant hydrologic regimes and catchment controls present in a large Mediterranean region. To achieve these goals this study aims to address four key questions: (1) What distinct dominant hydrologic regimes can be distinguished within the study region? (2) Do physical catchment attributes help to explain the distinguished hydrologic regimes? (3) How do the identified hydrologic regimes compare to those found in existing California-based and national or global hydrologic classifications? (4) What insights does the resulting hydrologic classification provide for environmental flows applications in California?

1.1.2. Study Region

The study region comprises the State of California (425,000 km^2), a highly heterogeneous region with respect to physical and climatic characteristics that contains both the highest (4,418 m) and lowest (-86 m) points in the contiguous United States and extends from 32° to 42° latitude. California primarily exhibits a Mediterranean climate with cold, wet winters (Oct - Apr) and warm, dry summers (May - Sep). Within the state, climate is determined by the interactions between atmospheric circulation, ocean proximity, and topography (Leung et al. 2003). For

example, ocean-derived moisture from the west causes the western slopes of the Sierra Nevada to be generally wetter than the eastern slopes, with winter precipitation at higher elevations falling as snow. High inter-annual variability associated with large-scale circulation patterns [e.g., El Niño Southern Oscillation (Cayan et al. 1999) and the Pacific Decadal Oscillation (Mantua and Hare 2002)] adds additional complexity to regional rainfall-runoff patterns. California's geologic setting is highly heterogeneous, ranging from the volcanic dominated Modoc Plateau to the thick sedimentary strata of the Coastal Range, and is often organized into eleven geomorphic provinces consisting of prominent tectonics, lithology, and topographic relief (CGS 2002). Soils composition also varies widely based on soil texture, depth, and rock fragment content. A statewide range of soil water storage capacity from 0 to 71 cm highlights this variability and is expected to influence the region's hydrology (CSRL 2010).

California's legacy of intensive and widespread hydrologic alteration for mining, water supply, flood control, land use change, and hydropower has severely degraded the state's river ecosystems (Healey et al. 2008; Hanak et al. 2011), emphasizing the need for a broad-scale hydrologic framework for environmental flows management. Less than 2% of California's total streamflow remains unaltered (Mailligan and Nislow 2005), while over 80% of the native fish species are now imperiled or extinct (Moyle et al. 2011). Further, most of the state's approximately 1,400 jurisdictional dams and 10,000 smaller impoundments are currently operated with minimal consideration for their effects on river ecosystems (Viers 2011; Grantham et al. 2014). Releasing environmental flows has been shown to substantially improve environmental conditions below dams while preserving essential water management functions. For instance, adjusting the timing of flow releases to correspond with natural seasonal fish spawning and rearing cues in a California stream promoted the expansion and maintenance of native-dominated fish assemblages without reducing the annual volume of water delivered to downstream irrigators (Kiernan et al. 2012).

1.1.3. Data

For this study we considered all gauge stations with >15 years of continuous daily unimpaired or naturalized streamflow records (see Kennard et al. 2010 for definition of unimpaired and naturalized). For the 20-year time period from 1968-1988, 75 unimpaired gauge stations were identified from the Hydro-Climate Data Network GAGESII database based on an

index of cumulative upstream disturbance by anthropogenic stressors (Falcone et al. 2010). An unimpaired streamflow record refers to a time series that is minimally influenced by upstream disturbances of infrastructure, land use change, or water diversions. An additional 16 gauge stations for which simulated non-regulated (i.e., naturalized) streamflow time-series are available [20-year period (1989-2009)] were added to the analysis to increase both sample size and physiographic range of reference gauge stations (CDWR 2007). The resulting 91 reference gauge stations ranged in elevation from 7 to 2,286 m above sea level (a.s.l.) and in drainage area from 54 to 8,063 km^2, covering a wide range of physical and climatic catchment characteristics (Fig. 1-1). It should be noted that no reference gauge stations were available for the southeastern desert part of California. Results of trend tests for climate non-stationarity (Kendall 1975) and autocorrelation (Durbin and Watson, 1950) in the streamflow records indicated minimal monotonic climate trends over the time periods considered in this analysis, supporting the use of selected streamflow records for the calculation of hydrologic indices and subsequent classification development [see *Appendix A*].
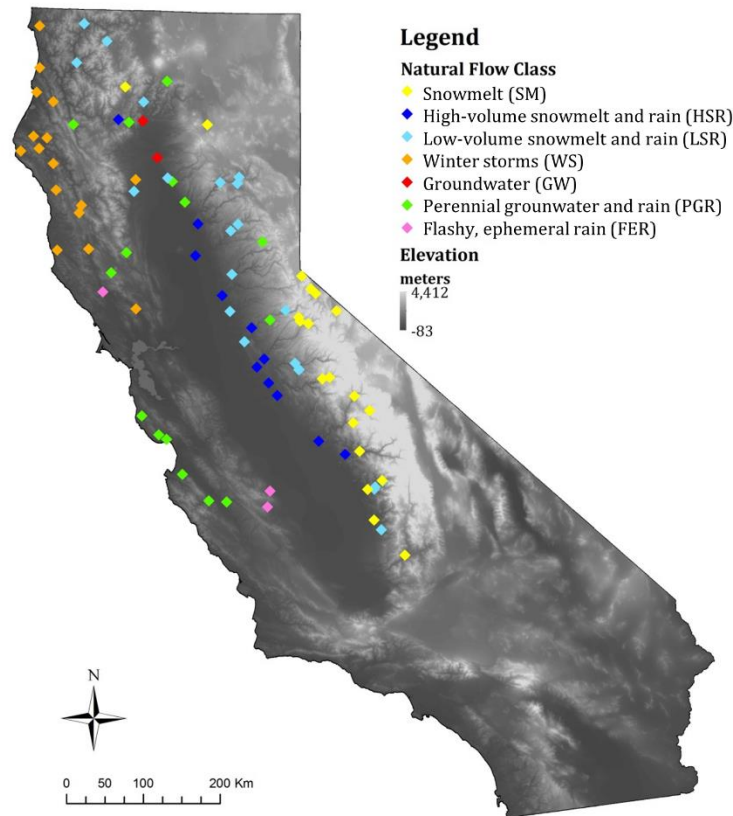
Figure 1-1. Reference gauge stations considered in development of hydrologic classification.

Geospatial data for 27 catchment attributes were considered in the hydrologic classification to derive physical explanations for the dominant hydrologic regimes. These attributes were also used to transfer the dominant hydrologic regimes from gauged reference catchments to ungauged catchments (Table 1-1). The 27 attributes represent three primary controls on hydrologic behavior: topography, geology, and climate (Wolock et al. 2004). Topographic attributes included upstream contributing area, elevation, drainage density, basin geometry, and numerous other terrain indices; geologic attributes included dominant geology, surficial geologic materials, underlying aquifers, and riparian soils composition; and climatic attributes consisted of measures of precipitation, temperature, and seasonality (Markham 1970). In an effort to capture flow regime seasonality, the months of January and August were chosen to represent the peak of the wet and dry seasons, respectively. July climatic attributes were considered in addition to August attributes to capture the expected difference in late spring recession rates across the state. All catchment attributes were calculated for each reference gauge station or reach based on its entire upstream watershed. Table 1-1 provides a complete list of catchment attributes considered, including their spatial resolution, data source, and method of derivation.

Table 1-1. Catchment attributes considered in this study as potential controls on hydrologic response.

Variable	Description	Units	Time period	Resolution	Citation
Basin-scale topographic					
ELEV_MEAN*[a]	Mean basin elevation	m	N/A	10-m grid	USGS 2008
AREA*[a]	Drainage area	km^2	N/A	10-m grid	USGS 2008
SLOPE_PCT*[a]	Mean slope	%	N/A	100-m grid	USGS 2008
STRAHLER[a]	Mean Strahler stream order	N/A	N/A	10-m grid	USGS 2008
STRAHLER_MAX[a]	Maximum Strahler stream order	N/A	N/A	10-m grid	USGS 2008
STRM_DENSITY*[a]	Stream density, length of streams per watershed area	km/km^2	N/A	10-m grid	USGS 2008
1ST_ORDER*[a]	Percent of watershed stream lengths which are Strahler first-order	%	N/A	10-m grid	USGS 2008
BAS_COMPACT	Watershed compactness ratio = area/perimeter^2 * 100	N/A	N/A	1:24,000 - 1:100,000	USGS 2008
RRMEDIAN	Dimensionless elevation to relief ratio, calculated as (median elev – min elev)/(max elev – min elev)	N/A	N/A	100-m grid	USGS 2008
TOPWET	Topographic wetness index, ln(a/S); a is the upslope area per unit contour length and s is the slope at that point	N/A	N/A	1-km grid	Wolock and McCabe 1995
MAINSTEM_SIN	Sinuosity of mainstem stream line	N/A	N/A	10-m grid	USGS 2008; Rosgen 1994
Basin-scale climatic					
JUL_TMP	Mean July temperature	C°	1971-2000	800-m grid	PRISM
T_AVG_BASIN	Mean annual air temperature	C°	1971-2000	800-m grid	PRISM
T_MAXSTD	Mean maximum monthly air temperature	C°	1971-2000	800-m grid	PRISM
T_MINSTD	Mean minimum monthly air temperature	C°	1971-2000	800-m grid	PRISM
JUN_PPT*	Mean June precipitation	cm	1971-2000	800-m grid	PRISM
AUG_PPT*	Mean August precipitation	cm	1971-2000	800-m grid	PRISM
PPTAVG_BASIN	Mean annual precipitation	cm	1971-2000	800-m grid	PRISM
PRECIP_SEAS_IND	Precipitation seasonality index; measure of how much annual precipitation falls seasonally (high values) or is spread out over the year (low values)	N/A	1971-2000	800-m grid	Markham 1970; PRISM
SNOW_PCT_PRECIP	Percent of total precipitation as snow	%	1901-2000	1-km grid	McCabe and Wolock 2009
WD_BASIN	Mean annual number of days of measurable precipitation	days	1961-1990	2-km grid	PRISM
WDMAX_BASIN	Mean monthly maximum number of days of measurable precipitation	days	1961-1990	2-km grid	PRISM
Reach-scale channel					
SAND_AVE	Mean sand content in riparian soils	%	N/A	200 m	Wolock 1997
SILT_AVE	Mean silt content in riparian soils	%	N/A	200 m	Wolock 1997
CLAY_AVE*	Mean clay content in riparian soils	%	N/A	200 m	Wolock 1997

1.2 Methodology

The hydrologic classification was developed in four steps: (1) statistical analysis of streamflow data, (2) cluster analysis of hydrologic indices to identify distinct dominant hydrologic regimes, (3) classification of dominant hydrologic regimes based on physical and climatic catchment attributes, and (4) prediction of natural flow classes for ungauged reaches (Fig. 1-2). Steps 1 and 2 address the first study question, and steps 3 and 4 address the second question. The third and fourth study questions are considered in the subsequent discussion.
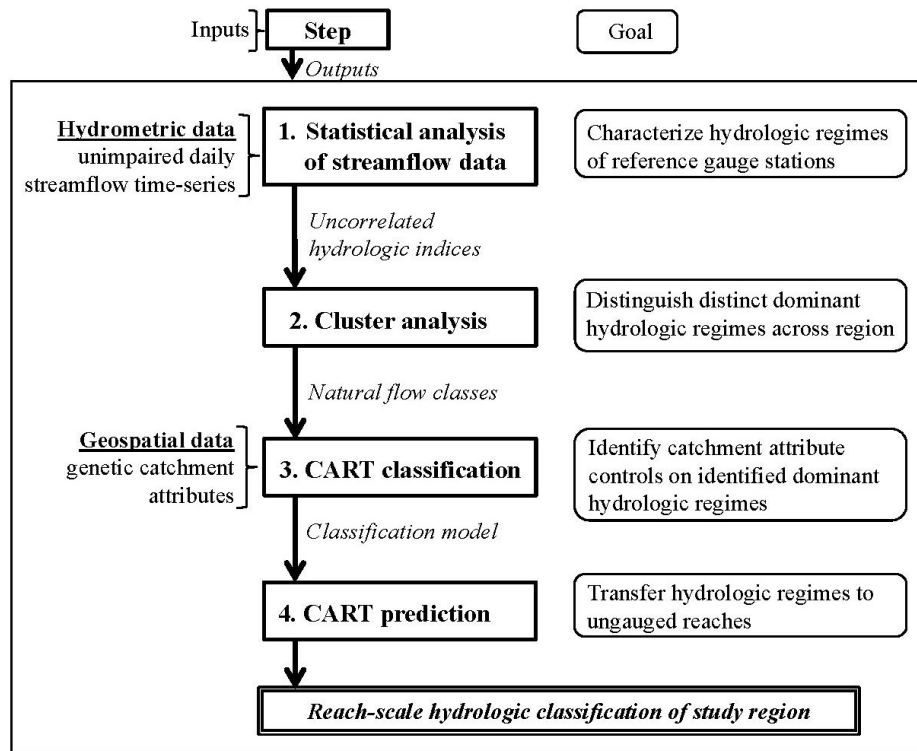
Figure 1-2. Hydrologic classification methodology, including key steps and associated goals.

1.2.1. Identification of dominant hydrologic regimes

Statistical analysis of streamflow data

Using the publicly available Indicators of Hydrologic Alteration (IHA) software (Richter et al. 1996; Matthews and Richter 2007), ecologically-relevant hydrologic indices were calculated for the 75 unimpaired gauge stations for the 1968-1988 period and for the 16 naturalized gauge stations for the 1989-2009 period. A normalized subset of hydrologic indices meeting probabilistic independence was used for subsequent cluster analysis (Table 1-2). First, calculated indices were normalized with feature scaling to range from 0 to 1 to remove potential differences in index magnitudes leading to differential weighting in the cluster analysis. The coefficient of correlation was then used to identify an independent subset of indices ($r < 0.8$) with the objective of reducing the dimensionality of the dataset while retaining as much of the variation inherent in the original streamflow data as possible; hydrologic indices supported by the literature to be of particular ecological importance (e.g., mean annual flow and high flow duration) were excluded from this selection process and included in the analysis regardless of their correlation (Postel and Richter 2003). Finally, a principal components analysis (PCA) based on correlations between

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hydrologic indices was used to evaluate the loadings of indices on the first four PCs in order to examine which variables explained the majority of variation between natural flow classes (Jolliffe 1986).

Table 1-2. Hydrologic indices used in cluster analysis to distinguish dominant hydrologic regimes across California based on the 91 available reference gauge stations.

Hydrologic Index	Type	Description
Mean annual flow	Summary	Mean daily streamflow value over period of record
Annual C.V.	Summary	Coefficient of inter-annual variation, defined as the standard deviation divided by the mean daily streamflow
Flow predictability	Summary	Standard deviation of daily streamflow
% of floods in 60d period	Summary	Percentage of floods that occur during a given 60 day period in all years
med_Oct	IHA	Median daily October streamflow over period of record
med_May	IHA	Median daily May streamflow over period of record
1-day minimum	IHA	Median of 1-day minimum annual flows
Date of minimum	IHA	Median Julian date of 1-day minimum annual flows
Date of maximum	IHA	Median Julian date of 1-day maximum annual flows
Low pulse duration	IHA	Median number of days of low flow pulses per year
High pulse count	IHA	Median number of high flow pulses per year
Extreme low duration	EFC	Median number of days of extreme low flow pulses per year
Extreme low timing	EFC	Median Julian date of minimum extreme low flow
High flow duration	EFC	Median number of days of high flow pulses per year
High flow timing	EFC	Median Julian date of peak high flow
Small flood duration	EFC	Median number of days of small flood events per year
Small flood frequency	EFC	Median frequency of small flood events per year
Large flood duration	EFC	Median number of days of large flood events per year
Large flood timing	EFC	Median Julian date of peak large flood
Large flood fall rate	EFC	Median daily rate of negative change in large flood events

Cluster analysis

To identify dominant hydrologic regimes (i.e., natural flow classes) among the 91 reference gauge stations, a non-hierarchical k-means cluster analysis was performed on the hydrologic indices (Hartigan and Wong 1979; Kaufman and Rousseeuw 1990) (Table 1-2, Fig. 1-3). K-means is known for its efficiency to handle large datasets, sensitivity to noise (Purviya et al. 2014), and repeated successful application in hydrologic classification studies (e.g., Poff and Ward 1989; Dettinger and Diaz 2000; Liermann et al. 2011). A hierarchical "Ward's linkage" algorithm was first applied to evaluate the natural data partitioning (Johnson 1967) (Fig. 3) and k-means was then applied for k = 2 - 9 k-values. The optimal k was determined by the Davies-

Bouldin internal clustering validation index (DBI) (Davies and Bouldin 1979). The stability of the identified natural flow classes was assessed with the cluster stability index (CSI) (Hennig 2007), calculated as the average proportion of gauges reassigned to their original clusters based on nonparametric bootstrapping with replacement (50 replications, leave out 10) (Hubert and Arabie 1985). CSI values <0.5 represent dissolved clusters whereas values >0.6 indicate true patterns (Hennig 2007). An additional cross-validation assessed the classification's robustness to the addition of naturalized gauge stations based on the adjusted Rand index (Hubert and Arabie 1985; Santos and Embrechts 2009).
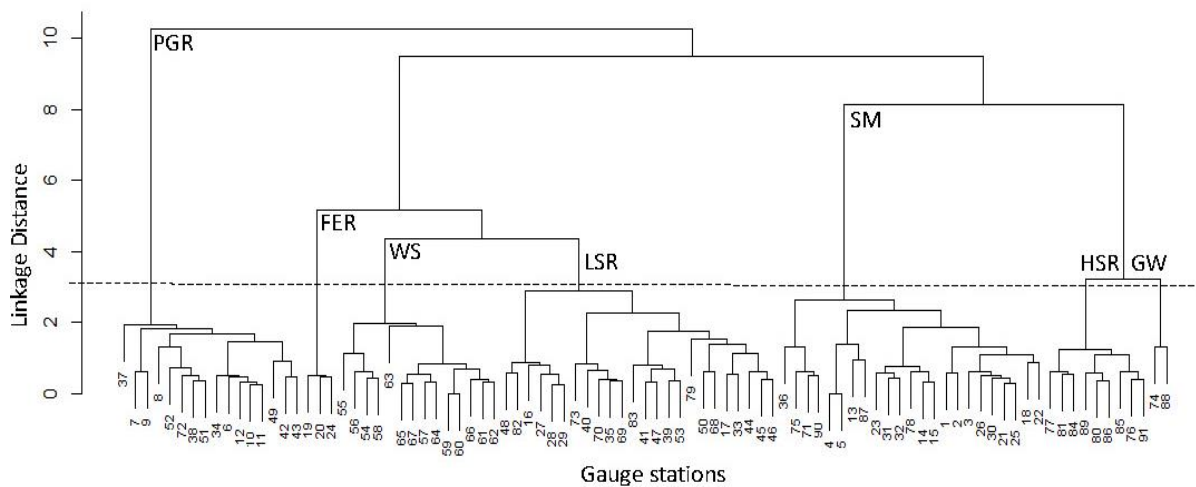
Figure 1-3. Hierarchical cluster diagram shows commonalities among 91 reference gauge stations based on their hydrologic indices, corroborating the identification of seven distinct clusters (defined in text) as distinguished by the nonhierarchical k-mean cluster analysis. SM, snowmelt; HSR, high-volume snowmelt and rain; LSR, low-volume snowmelt and rain; WS, winter storms; GW, groundwater; PGR, perennial groundwater and rain; FER, flashy ephemeral rain.

1.2.2. Physical and climatic catchment controls on hydrologic regimes

In order to identify physical and climatic controls on the flow regime of a catchment and to predict the flow regime (i.e., natural flow class) of ungauged reaches, we applied Classification and Regression Trees (CART), a recursive-partitioning algorithm that classifies the data space defined by the input variables (catchment attributes) based on the output variable (natural flow class) (Breiman et al. 1984) (Step 3, Fig. 1-2). The CART analysis was conducted using the statistical R package 'rpart' (Therneau et al. 2010). Input variables for the CART analysis consisted of the 27 catchment attributes (see Table 1-1). The Gini impurity criterion was used to determine optimal variable splits (minimum parent node size: n=5; minimal terminal node size: n

= 2) (De'ath and Fabricus, 2000), and optimal tree size was based on a ten-fold cross-validation (Therneau et al. 2010). The fitted misclassification rate (Breiman et al. 1984) was used to assess how well the catchment attributes explain the spatial variability of natural flow classes across reference gauge stations. The random forest classifier out-of-bag error rate (Breiman 2001) provided a probabilistic measure of model accuracy that compared model predictions of natural flow class with randomized subsets of reference gauges withheld.

1.2.3. Prediction of natural flow classes

The classification model was then used to transfer the identified natural flow classes to over 100,000 National Hydrography Dataset [(NHD, 1:100,000 scale, Simley and Carswell (2009)] stream reaches in California based on their upstream catchment attributes (Step 4, Fig. 1-2). Prediction of natural flow classes was conducted for reaches with a Strahler order of two or higher derived from the NHD (average reach length 2 km); Strahler first-order reaches were excluded to improve processing time. All catchment attributes were calculated for each reach based on its entire upstream watershed using the Catchment Attribute Allocation and Accumulation Tool in ArcGIS (version 10.2, ESRI Inc.) (Horizon System Corporation 2008).

1.3 Results

Eight natural flow classes were distinguished across California, representing statistically distinct and physically interpretable dominant hydrologic regimes and physical and climatic catchment controls. Both the hierarchical and *k*-means cluster analyses identified seven distinct hydrologic regimes as the most probable classification (DBI=1.45) (Fig. 1-3). However, further analysis of classification results indicated that one of the seven classes was better distinguished by splitting it into two sub-classes, resulting in eight final natural flow classes. This splitting process is described later in this section.

Identification of dominant hydrologic regimes

The hierarchical and *k*-means cluster analyses each identified seven clusters as the most probable classification (DBI=1.45) (Fig. 1-3). Probability of cluster membership ranged from 60 to 99%, with an average of 80%, suggesting strong support for the seven-tier classification. The bootstrapping test produced CSI values >0.5 for all seven clusters (mean=0.71), indicating a parsimonious clustering solution (Hennig 2007). An adjusted Rand index of 1 between cluster

analysis results using only unimpaired gauge stations and using both unimpaired and naturalized gauge stations further corroborates the stability of the seven-tier clustering solution to the dataset augmentation.

The standardized annual hydrographs (Fig. 1-4) and range of hydrologic indices of each natural flow class (Fig. 1-5) illustrate the clear differences in seasonal and annual streamflow patterns as well as streamflow timing, magnitude, duration, frequency, and rate-of-change characteristics (Table 1-2) exhibited by each flow regime. The annual hydrographs illustrate the median of the standardized average monthly streamflow volumes across all years and gauges within each flow class. Loadings of hydrologic indices on the first four PCs indicate that the components (and associated hydrologic indices) of the flow regime best capable of distinguishing between natural flow classes are (i) low flow characteristics (flood-free season, number of zero-flow days, and extreme low flow timing), (ii) high flow characteristics (date of maximum, high flow timing and frequency, large flood duration), (iii) seasonality (flood-free season, high and low flow timing, duration, and frequency), and (iv) predictability (flow predictability, constancy/predictability, base flow index, low and high flow duration) (Table 1-3).
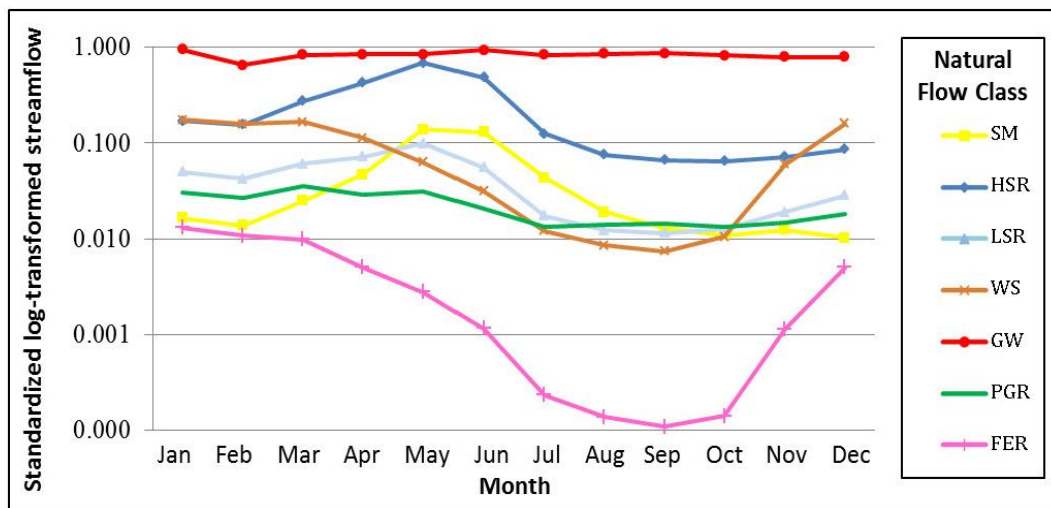
Figure 1-4. Standardized log-transformed (log(Q)) annual hydrographs of the initial seven hydrologic regimes identified in the cluster analysis. The annual hydrographs illustrate the median of the standardized average monthly streamflow volumes across all years and gauges within each flow class. Classes are defined as follows: SM, snowmelt; HSR, high-volume snowmelt and rain; LSR, low-volume snowmelt and rain; WS, winter storms; GW, groundwater; PGR, perennial groundwater and rain; FER, flashy ephemeral rain.
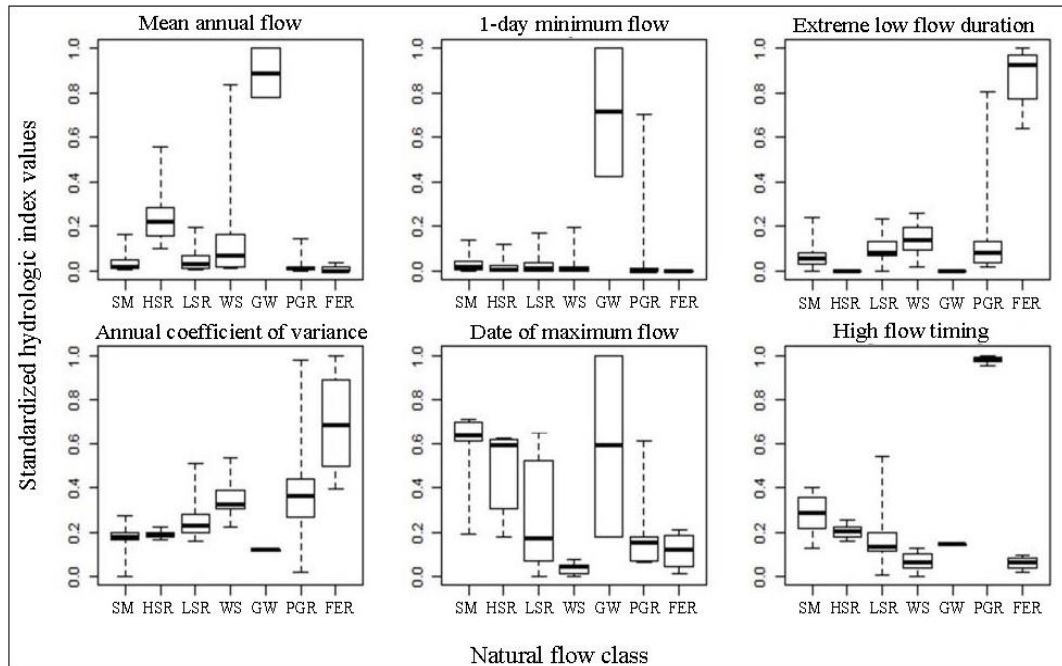
Figure 1-5. Box-and-whisker plots of selected hydrologic indices used in the cluster analysis to separate the initial seven hydrologic regimes based on daily streamflow data from the 91 reference gauge stations. classes are defined as follows: SM, snowmelt; HSR, high volume snowmelt and rain; LSR, low-volume snowmelt and rain; WS, winter storms; GW, groundwater; PGR, perennial groundwater and rain; FER, flashy ephemeral rain.

Table 1-3. Key flow components distinguishing natural flow classes with expected significance for setting environmental flow targets including: (1) low flow characteristics, (2) high flow characteristics, (3) seasonality, and (4) predictability.

Class	Low Flow Characteristics	High Flow Characteristics	Seasonality	Predictability
SM	Many zero-flow days; Extended extreme low flow duration	Latest peak flows; Short flood duration	Very high	Very high
HSR	Long flood-free season; Very short extreme low flow duration; No zero-flow days	Longest flood duration; Early spring peak flows	High	High
LSR	Extended extreme low flow duration	Late spring peak flows	Very high	Very high
RGW	High one-day minimum flow; No zero-flow days	Early summer peak flows	Low	Mid
WS	Extended extreme low flow duration	Winter peak flows; Frequent wet season high flows	High	High
GW	Extremely high one-day minimum flow; No zero-flow days	No floods	Very low	High
PGR	High one-day minimum flow	Winter peak flows	Low	Mid
FER	Most zero-flow days; Longest extreme low flow duration	Short large flood duration; Winter peak flows	Mid	Very low

By qualitatively interpreting classification results, clusters (i.e., groups of reference gauge stations) were characterized by their dominant flow sources and subsequently referred to as follows (Table 1-4): snowmelt (SM), high-volume snowmelt and rain (HSR), low-volume snowmelt and rain (LSR), winter storms (WS), groundwater (GW), perennial groundwater and rain (PGR), and flashy ephemeral rain (FER). Of the 91 reference gauge stations, 20 were classified as SM (22%), 11 as HSR (12%), 22 as LSR (24%), 16 as WS (18%), 2 as GW (2%),

16 as PGR (18%), and 4 as FER (4%). SM sites exhibit highly seasonal hydrologic regimes with spring snowmelt peak flows, predictable recession curves, very low summer flows, and minimal winter rain influence. These sites exist along the crest of the Sierra Nevada with most sites in the southern, higher elevation portion of the mountain range. LSR and HSR sites exhibit similar seasonality but illustrate a transition towards earlier snowmelt peak and increasing winter rain contributions which follows their general downstream transition towards the Central Valley lowlands. WS sites exhibit distinct duration and timing of high flows from the snowmelt influenced sites, driven by winter rain storms. These sites are characterized by high interannual flow variance due to the variability of winter storm patterns, and generally follow the spatial distribution of strong orographic precipitation in the north coast region. GW sites are distinguished by significantly higher and more stable flows year-round, despite uncertainty associated with the fact that only two reference gauge stations were used to distinguish this flow class. PGR sites combine the stable, base flow-driven conditions of GW sites with the winter rain dominated conditions of WS sites in catchments with low annual streamflow. FER reaches are characterized by the highest interannual flow variance, extended extreme low flows and large floods, and the lowest average daily streamflows of any class, although this class is also limited by reference gauge availability (n=3).

Table 1-4. Summary of dominant hydrologic characteristics and physical and climatic catchment controls on hydrologic response for the natural flow classes identified in California.

Class	Name	Hydrologic Characteristics	Physical and Climatic Catchment Controls
SM	Snowmelt	• Large spring snowmelt pulse (~May 24) • Very high streamflow seasonality index • Extreme low flows (<10th percentile) Sep-Feb	• High elevation catchments (>2,293 m), major snow influence and minimal rain influence
LSR	Low-volume snowmelt and rain	• Transition between Classes SM and HSR • Bimodal snow—rain hydrograph driven by spring snowmelt pulse and winter rain	• Mid-elevation catchments with limited area (<2,144 km^2) (low winter temperatures [Jan temp <−5°C], high stream density [>0.65 km/km^2])
HSR	High-volume snowmelt and rain	• Spring snowmelt pulse (~May 4) • High seasonality but larger winter storm contributions • Retain high base flow throughout summer low flow season • Bimodal snow-rain hydrograph	• Mid-elevation catchments (1,126-2,293 m), large contributing area (>2,144 km^2) *not* underlain by volcanic geology (high stream density [>0.65 km/km^2], mild winter temperatures [Jan temp >−5°C]) **OR** • Low elevation (<1,125 m) with very large contributing area (>15,420 km^2) and high riparian soils clay content (>17% clay) (substantial winter precipitation [Jan precip 16-28 cm])
RSG	Rain and seasonal groundwater	• Bimodal hydrograph driven by winter rain pulse and percolating winter rain appearing as base flow pulse later in year	• Low elevation catchments (<1,126 m) with limited winter precipitation (Jan precip <28 cm) and low slopes (<24%) **AND** • Underlain by igneous and metamorphic rock materials **AND** • Coastal catchments with small aquifers driving short residence times
WS	Winter storms	• Predictable large fall and winter storms • Earliest peak flows (in January)	• Low elevation catchments with substantial winter precipitation (Jan precip >28 cm) **OR** • Low elevation, mid-slope (31-24%) catchments with low winter precipitation but high riparian soils clay content (>23%), underlain by unconsolidated sand and gravel aquifers covered by thick alluvial sediments
GW	Groundwater	• Highest mean annual flows and minimum flows • Low seasonality and high predictability	• Mid-elevation catchments with large area (>2,144 km^2) underlain by volcanic (basaltic and andesitic) geology (low stream density [<0.65 km/km^2]) **OR** • Low elevation catchments with limited winter precipitation, very large contributing area (>15,420 km^2) with low riparian soils clay content (<17%), underlain by igneous and metamorphic-rock aquifers
PGR	Perennial groundwater and rain	• Low seasonality and mean annual flow • Transition between WS and GW, with winter storms but generally stable flows	• Low elevation catchments with low riparian soils clay content (<23%) (low stream density [<1.1 km/km^2]) **AND** • Catchments primarily underlain by residual sedimentary rock materials
FER	Flashy, ephemeral rain	• Lowest mean annual flows • Highest coefficient of annual variation, lowest predictability • Longest extreme low flow duration	• Low elevation catchments with high riparian soils clay content (>23%) and high slopes (>31%) (high stream density [>1.15 km/km^2])

The prediction of numerous LSR reaches throughout southern California, the central coast, and the central valley despite the evident lack of snowmelt influence indicated an inability of the classification model to accurately distinguish hydrologic regimes in these areas. This is not surprising given the lack of reference gauge stations in southern California (Fig. 1-1). Recognizing the disparity between class predictions and known physiographic and climatic patterns (NRCS 2015) as well as the large spatial footprint of LSR reaches compared to other natural flow classes, the LSR flow class was further split into two sub-classes. The classification tree indicated that two distinct groups of catchment attributes were capable of producing an LSR type hydrologic regime and that these functional groups could be distinguished on the basis of elevation. Thus LSR reaches were manually split into LSR and low-volume rain and seasonal groundwater (RGW), representing LSR reaches with average catchment elevations greater than and less than 1,126 m a.s.l., respectively.

Physical and climatic catchment controls on hydrologic regimes

Our classification model identified a combination of topographic, geologic, and climatic attributes as controls on the distinguished hydrologic response (Table 1-4). Specifically, the following six catchment attributes were found to be the predictor variables with the greatest explanatory power for the seven identified hydrologic regimes: mean catchment elevation, contributing area, mean upstream January precipitation, dominant rock type, percent clay content in riparian soils, and mean catchment slope (Fig. 1-6, Table 1-1). Mean catchment elevation was the primary splitting variable, distinguishing the SM sites (>2,293 m a.s.l.) from the other six flow classes (Fig. 1-6). Contributing area differentiated high-volume HSR and GW reaches from other reaches, and acted with elevation to define the transition from a highly seasonal snowmelt-dominated to a bimodal snow-rain regime. Climatic setting characterized by average winter precipitation distinguished WS reaches from other low-elevation reaches in California. Slope (and drainage density as a proxy variable) was identified as first-order control over the rate and duration of low-elevation catchment response to precipitation. The delayed response to winter storms characterized in the hydrograph as a long spring base flow pulse in LSR reaches can be distinguished from the large, rapid hydrograph response exhibited by FER reaches based on slope. The classification model also identified geologic rock type and soil permeability as major controls in distinguishing groundwater-dominated from snowmelt- and rain-dominated

hydrologic regimes. Underlying fractured volcanic bedrock distinguished high volume GW reaches from seasonal, high-volume HSR reaches, while high clay-content (low permeability) soils distinguished more stable flow PGR reaches from highly seasonal WS reaches in low-elevation catchments. In selecting natural flow classes (HSR, WS, GW), two alternative combinations of catchment attributes were capable of driving a similar hydrologic response. In these cases, Table 1-4 describes both potential catchment attribute combinations.
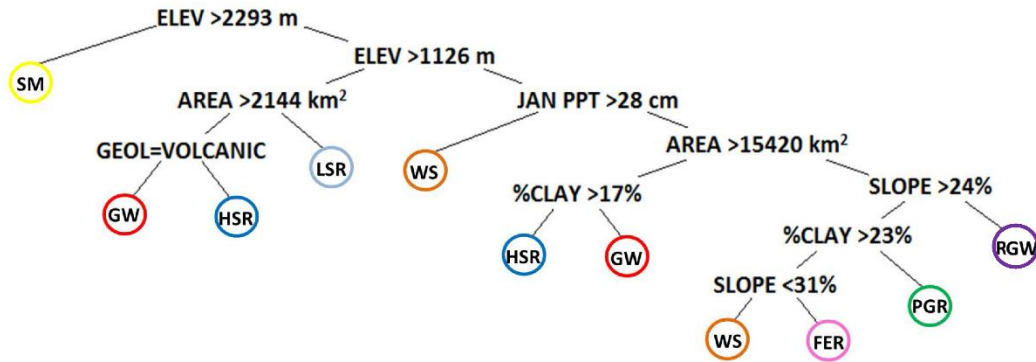
Figure 1-6. Classification tree model identifying the eight natural flow classes based on physical and climatic catchment attributes. If the stated condition is true, the left branch is followed, otherwise the right branch is followed (see Table 1-1 for variable definitions). Classes are defined as follows: SM, snowmelt; HSR, high-volume snowmelt and rain; LSR, low-volume snowmelt and rain; RGW, rain and seasonal groundwater; WS, winter storms; GW, groundwater; PGR, perennial groundwater and rain; FER, flashy ephemeral rain.

A fitted misclassification rate of 12% indicates that 80 of the 91 reference stations were correctly classified based on the six catchment attributes described above (Fig. 1-6) relative to their known hydrological regimes from statistical analysis. An out-of-bag error rate of 23% (Cohen's κ=0.66, Z=13.7, p<0.001; Landis and Koch 1977) indicates that natural flow classes were accurately predicted for 77% of the reference gauge stations. The model achieved highest classification accuracy for the most strongly seasonal annual hydrograph endmembers, WS (88%) and SM (82%), and the lowest accuracy for the classes with the least number of reference gauge stations, GW (50%, n=2) and FER (33%, n=4), which were primarily misclassified as HSR and PGR, respectively. The model misclassified at least one gauge into every natural flow class except GW, with the highest misclassification into LSR (n=8).

Final hydrologic classification

The predicted distribution of the eight natural flow classes across California stream reaches (Figs. 1-7 and 1-8) generally corresponds with expectations given known physio-climatic and

hydrologic patterns [see *Appendix A* for full description of each natural flow class]. Most mountain basins demonstrate a downstream progression from SM to LSR to HSR with decreasing elevation. WS reaches are generally located along the Pacific coast where the vast majority of the state's rainfall occurs or in small lowland basins lacking snowmelt influence, and GW reaches are generally underlain by fractured volcanic geologic settings expected to produce stable, high-volume hydrologic regimes.
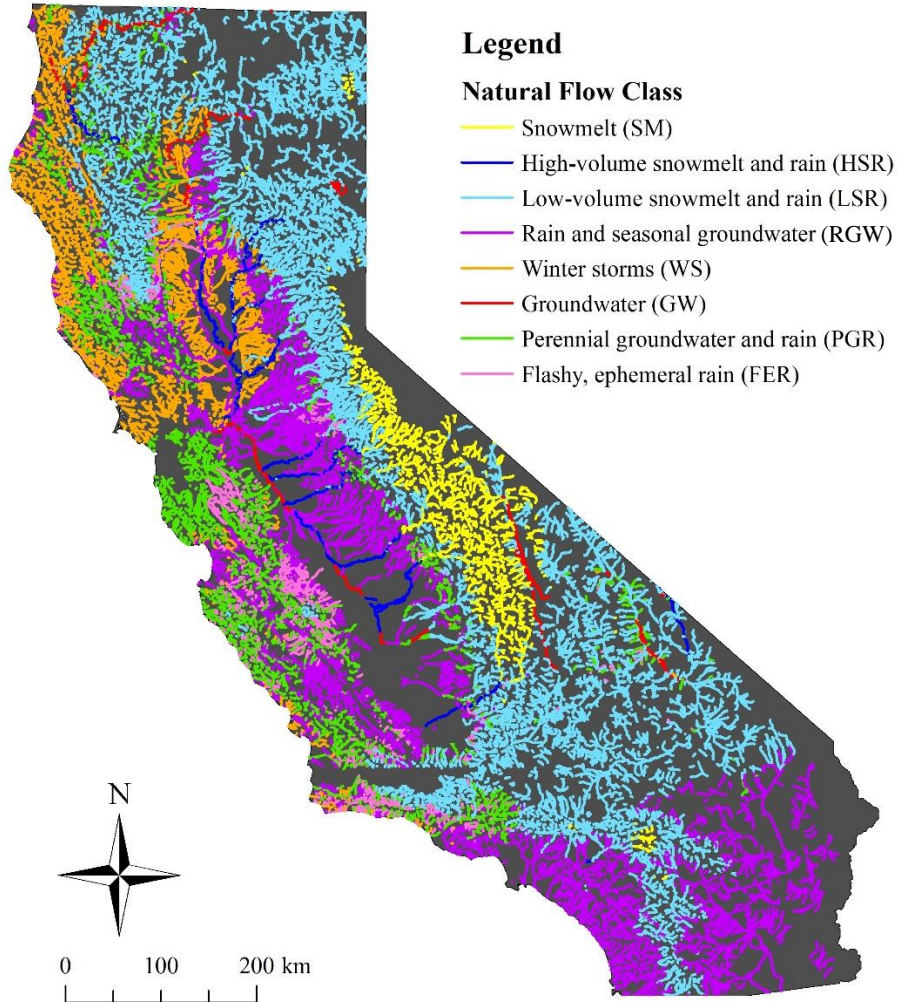
Figure 1-7. Map of reach-scale hydrologic classification of California NHD streamlines (excluding Strahler first order streams) resulting from the natural flow class transfer based on the classification tree model.
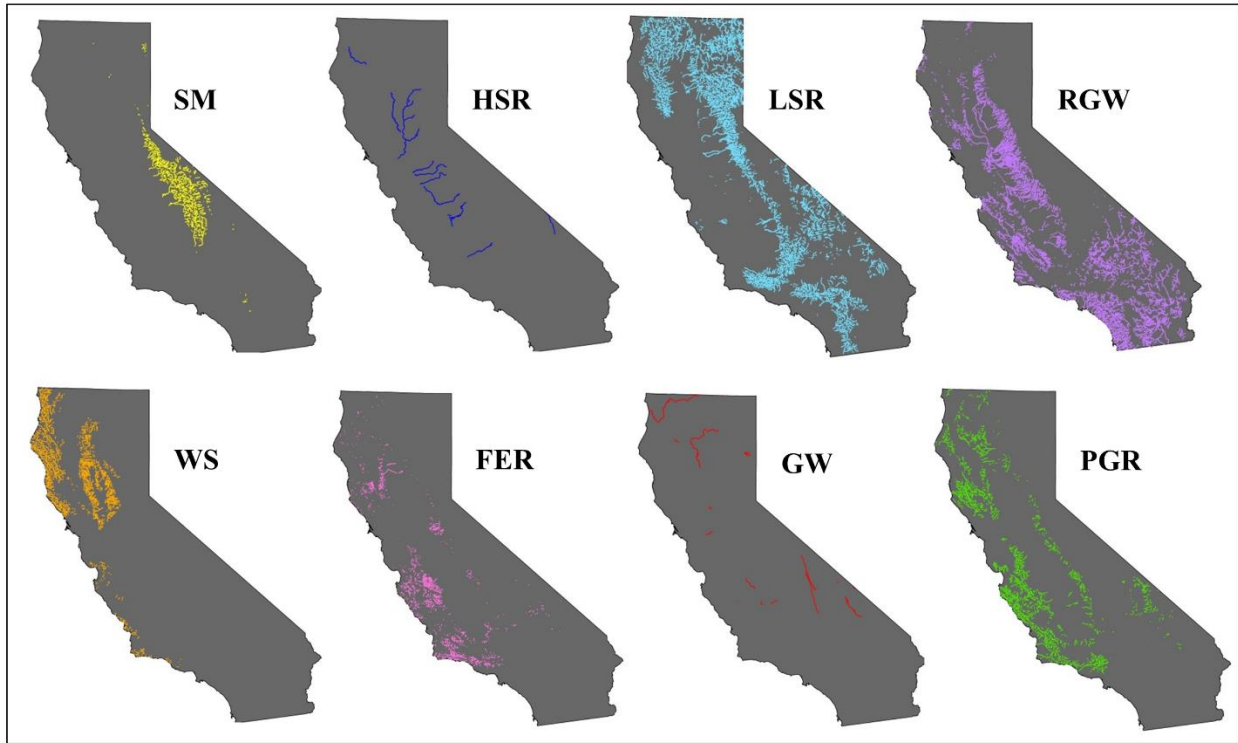
Figure 1-8. Spatial footprint of the final eight natural flow classes within California (excluding Strahler first-order streams and canals). Classes are defined as follows: SM, snowmelt; HSR, high-volume snowmelt and rain; LSR, low-volume snowmelt and rain; RGW, rain and seasonal groundwater; WS, winter storms; GW, groundwater; PGR, perennial groundwater and rain; FER, flashy ephemeral rain

1.4 Discussion

Can distinct hydrologic regimes be distinguished?

Study results indicate that our hydrologic classification is capable of distinguishing dominant hydrologic regimes and their physical and climatic catchment controls across California. Seven hydrologic regimes were identified, characterized by distinct combinations of snowmelt, rain, and groundwater flow sources and resulting streamflow patterns (Figs. 1-4 and 1-5). The high performance of the cluster analysis (DBI=1.45, CSI=0.71) and classification model (77% accuracy, κ =0.66) achieved in this study compared to other similar studies (e.g., Liermann et al. 2011; Snelder et al. 2009; Chinnayakanahalli et al. 2011; McManamay et al. 2014) is very encouraging. This provides some confidence that the identified dominant hydrologic regimes are derived from similarities in the hydrologic function of catchments characterized by similar catchment attributes. However, the focus on streamflow means that we are limited in the degree of detail regarding hydrologic function that can be extracted from such an integrated measure.

Despite overall high performance, limited FER and GW reference gauge stations and the lack of reference gauge stations in southern California somewhat constrain the classification's ability to accurately predict hydrologic regimes of these classes and parts of California. By considering gauge stations with both unimpaired (n=75) and naturalized (n=16) streamflow time-series, we were able to increase the number and distribution of reference gauge stations and reduce the systematic bias towards small, high elevation basins. However, the minimum record length required (> 15 years) and the choice of hydrologic impairment thresholds substantially limited reference gauge station availability, thus constraining classification performance (Olden et al. 2012). The final classification is therefore expected to better predict hydrologic regimes in the regions of the state with more reference gauge stations and should be applied with caution in regions with insufficient reference gauge stations. Future work could improve the performance of the classification by incorporating more gauges stations in these regions by loosening the minimum time series length and impairment threshold requirements.

Can identified explanatory catchment attributes help reveal the dominant processes distinguishing distinct hydrologic regimes?

The explanatory catchment attributes identified in our study showed wide agreement with existing hydrologic classification studies. For instance, elevation was also found by Singh et al. (2014) and Liermann et al. (2011) to be the primary control distinguishing snowmelt- from rain-dominated hydrologic regimes. Contributing area was found by Sawicz et al. (2011) and Belmar et al. (2011) to differentiate reaches of high versus low flow magnitudes, supporting its identification as the foremost control distinguishing HSR reaches from lower volume SM and LSR reaches in California. Sawicz et al. (2011) also found climate to exert a strong influence on catchment function and response in the eastern United States. Thus, although hydrology has not yet established a common catchment classification system (Wagener et al. 2007; Sawicz et al. 2011), the similarities in hydrologic regimes and catchment controls identified in our and the above studies suggest that a first-order classification of reaches based on upstream catchment attributes is warranted for California.

Only six of the 27 catchment attributes were found to be of significant explanatory value in predicting the seven natural flow classes with high accuracy. To our surprise, despite their known influence on catchment hydrologic response, the CART model did not select basin shape,

relief, and surficial geology as explanatory variables in the classification tree. Similarly, no climatic attributes (e.g., temperature, precipitation) other than January precipitation were recognized as explanatory variables. The significance of topography and geology in addition to climate for distinguishing flow regimes in California contrasts with findings of other classifications (e.g., Liermann et al. 2011; Chinnayakanahalli et al. 2011; Alba Solans and Poff 2013) that identified climate as the sole controlling attribute on hydrologic response. From a process perspective, this indicates that the dominant hydrologic regimes found in California are controlled by physical catchment attributes that influence runoff generation processes in addition to climate, highlighting the need to consider local controls (e.g., topography, soil, geology) in hydrologic classification that might act on the sub-catchment or reach-scale hydrology of a basin.

The inability of our classification to distinguish between LSR and RG hydrologic regimes highlights a significant limitation of the use of automatic, data-driven classifications for hydrologic analysis. While numerous clustering and regression algorithms have been applied in hydrologic classification, with the best algorithm depending primarily on the study objectives (Olden et al. 2012), we found an additional need for expert validation of the classification given external limitations on input data. Our approach of manually splitting a natural flow class because the classification model was incapable of resolving evident differences in catchment controls and hydrologic responses dramatically improved classification results in terms of the model's agreement with known physiographic and hydrologic patterns. Using the structure of the classification model in addition to regional expertise to define a splitting criterion (in our case elevation) increased the objectivity of the process and provided additional information regarding the differences in the driving catchment processes of the two sub-classes. Alternatively, adding other catchment attributes, such as glacial history or soil-to-bedrock ratio (Peterson et al. 2008), may further improve our classification's ability to capture distinct catchment processes and their effect on the hydrologic response of California catchments.

How do the identified dominant hydrologic regimes compare with those found in California field and modeling studies and in other hydrologic classifications?

Comparison with California field and modeling studies. In the absence of a statewide hydrologic classification, existing field and modeling studies can be used to evaluate our results for selected physiographic regions within California. Overall we found that the identified

hydrologic regimes and catchment controls were generally consistent with prior, local knowledge of rainfall-runoff processes in California (e.g., Mount 1995; Yarnell et al. 2010; Hunsaker et al. 2012). The transition from a highly seasonal SM regime to a high baseflow, bimodal HSR regime closely tracks the elevation gradient from the Sierra Nevada to the Central Valley. This is consistent with Hunsaker et al.'s (2012) finding that mixed rain-snow and snowmelt-dominated flow regimes could be differentiated solely on the basis of elevation for eight headwater catchments of the Kings River. Furthermore, their elevation threshold for distinguishing between these flow regimes (2,287 m a.s.l.) almost exactly matches the threshold identified by our classification model (2,293 m) for distinguishing SM from LSR reaches. Also similar to our study, annual discharge was found to increase with elevation over the eight catchments, indicative of a higher snow-rainfall ratio and a lesser role of evapotranspiration in snowmelt-dominated vs. mixed rain-snow catchments (Hunsaker et al. 2012). An estimate of water balance components along an elevation gradient in the American River basin suggests that runoff and evapotranspiration are about equal at 1,200 m a.s.l. (40% of total water balance each), whereas runoff increases to 68% at 2,100 m as the evapotranspiration effect decreases (Armstrong and Stidd 1967). These topographic controls over catchment function are profoundly similar to the two elevation thresholds identified in our study (1,126 and 2,293 m), indicating that the empirical classification model is in fact identifying similar catchment controls on rainfall-runoff response.

Relationships between natural flow classes and watershed-specific model parameters estimated for a hydrologic model of the western Sierra Nevada (Young et al. 2009) further corroborate the physical basis of our hydrologic classification. Of the 15 watersheds considered by Young et al. (2009), all but five are classified at their outlet as HSR by our hydrologic classification; four watersheds (Cosumnes, Calaveras, Kaweah, and Tule) are classified as LSR and one (Kern) as SM. The SM watershed exhibits much higher soil water storage capacity (1,181 mm) and lower hydraulic conductivity (30 mm/week) than the other watersheds based on model parameters; the LSR watersheds exhibit similar but less extreme trends. The high storage capacity and low hydraulic conductivity of SM and LSR watersheds implicate saturation overland flow as the dominant runoff process in these reaches, as infiltration rates far exceed precipitation intensities (Dunne and Black 1970; Dahlke et al. 2012).

Comparison with other regional hydrologic classifications. Our catchment classification model was highly accurate (77%) and exceeded the predictive capacities of classification models reported elsewhere (e.g., 75%, Liermann et al. 2011; 61%, Snelder et al. 2009; 70%, Chinnayakanahalli et al. 2011; 75% McManamay et al. 2014). We hypothesize that the high performance of our hydrologic classification may be attributable to the suggestion by Sawicz et al. (2011) that classification results are largely controlled by the particular gradients present and datasets analyzed in the study region. Sawicz et al. (2011) found that catchment attributes exhibiting steep gradients across regions tend to emerge as dominant controls over hydrologic response in regional hydrologic classifications, exerting a stronger control on separating the catchments into different classes than more spatially homogeneous attributes. Similar results were obtained by Sanborn and Bledsoe (2006) and Liermann et al. (2011) that identified climate as the only dominant control over hydrologic response in regions with steep climatic gradients, while topographic and geologic attributes exhibited minimal influence. The fact that California exhibits steep gradients across all three catchment variables representing primary controls on hydrologic behavior (Wolock et al. 2004) ensures that no single variable dominates the classification.

The significance of topographic (elevation, area, slope), geologic (rock type, soil type), and climatic (winter precipitation) attributes for explaining differences in identified hydrologic regimes corroborates the theory that watersheds should be grouped by similarity in topography, geology, and climate (Winter 2001; Wolock et al. 2004). Thus, the influence of dominant environmental gradients on hydrologic classification and the regionalization of hydrologic regimes need not necessarily discourage its application or require the splitting up of a region into smaller subregions, as suggested by Sawicz et al. (2011). Rather, it may indicate that hydrologic classification could provide a tool better suited for Mediterranean regions, which generally exhibit steep gradients across climate, topography, and geology (Peel et al. 2007), than regions with a single dominant environmental gradient.

Insights for environmental flows setting in California. Hydrologic classifications form the template for developing hypothetical relationships between hydrologic characteristics and ecological responses (Arthington 2012; Poff et al. 2010; McManamay et al. 2015). The significance of the natural flow regime for native river ecosystems (Richter et al. 1996; Poff et al.

1997) has generally been considered as appropriate for California rivers and streams (Marchetti and Moyle 2001; Brown and Bauer 2010). A recent ecological assessment of hydrologic alterations on large California rivers (Brown and Bauer 2010) indicated that changes to key components of the natural flow regime (e.g., spring high flows, summer low flows) had major implications for native and alien fish species assemblages. However, relating ecological measures to hydrologic regimes is currently limited in California because unimpaired streamflow records are unavailable for many locations of interest where biological data exists (e.g., Ode 2007; Santos et al. 2014). The spatial extent and reach scale of the proposed hydrologic classification are expected to substantially improve the coincidence of biological and hydrologic datasets statewide. Future comparisons of ecological patterns between natural and hydrologically altered streams within each of the eight natural flow class distinguished by our study are therefore expected to yield flow–ecological response relationships which can provide the basis for statewide environmental flow standards (see Poff et al. 2010).

The four flow components identified here as best capable of distinguishing natural hydrologic regimes (low flow characteristics, high flow characteristics, seasonality, and predictability, Table 1-3) highlight key characteristics of Mediterranean rivers [e.g., extreme high and low flows, high seasonality, and inter-annual variability (Gasith and Resh 1999)]. The hydrologic regimes distinguished in this study are therefore expected to be capturing ecologically significant distinctions rather than purely empirical groupings. Native Mediterranean biota have established life history traits providing resilience to the predictable and periodic extremes of these dynamic systems (Gasith and Resh 1999; Bonada et al. 2007), but these adaptations may make them particularly vulnerable to flow alterations (Lytle and Poff 2004). Improving understanding of the role of these key Mediterranean flow components in promoting natural ecosystem functions (Arthington 2012; Yarnell et al. 2015) in each of the distinguished natural flow classes would help to identify opportunities for environmental flow releases and link flow targets directly to driving ecosystem functions in stream reaches of each natural flow class. This would support the development of ecological performance metrics for regional adaptive management.

Stratification of California streams by natural flow class is expected to support the development of mechanistic associations between hydrologic classes and ecological characteristics and constrain the data and resource requirements of such efforts (Monk et al.,

2006; Chinnayakanahalli et al., 2011; Rolls and Arthington, 2014; McManamay et al. 2015). For example, based on the established ecological significance of dry-season low flow duration and magnitude for native species in LSR-dominated streams (Gasith and Resh 1999; Yarnell et al. 2015), the archetypal LSR low flow characteristics distinguished by our classification (Fig. 1-5; Table 1-3) could be used to develop preliminary flow targets for classified LSR reaches of interest for restoration. Flow targets could be based on expected ranges of unimpaired streamflow timing, magnitude, duration, frequency, and rate-of-change. For instance, the natural range of extreme low flow duration exhibited by unimpaired LSR rivers (Fig. 1-5) could be used as an initial flow threshold for water abstractions to support imperiled native biota over large areas in the absence of sufficient reach-specific data. In this manner, highly regulated LSR stream reaches in California could be targeted for recovery of these natural low flow characteristics or for a large-scale evaluation of the ecological impacts of removing this functional flow component (Brown and Bauer 2010).

The ultimate ecological value of the proposed classification lies in its ability to reduce natural hydrologic variability to a level at which functionally similar groups of stream reaches can be identified for future flow – ecology analysis. Future research that extends the organizational framework presented here by further stratifying natural flow classes based on ecologically relevant hydrologic distinctions will increase the predictive power of discriminant relationships between specific flow regime components and biotic and abiotic functions for each class. For example, further dividing streamflow records within a natural flow class based on season (e.g., fall vs. winter) or geomorphic setting (i.e., confined vs. unconfined) would allow for the separate analysis of streamflow patterns with respect to factors of known ecological significance not addressed here (Junk et al. 1989; Wohl et al. 2015; Yarnell et al. 2015). Stratifying biomonitoring campaigns with respect to natural flow classes and proposed sub-classes to obtain ecohydrologic information would support the development and testing of physically-based, statistically defensible relationships between hydrologic characteristics and flow-driven geomorphic and ecological functions.

1.5 Conclusions

This study presents a hydrologic classification for the State of California to meet the recognized need for improved broad-scale environmental management of the state's many

impaired streams. The classification evaluates the diversity and distribution of natural hydrologic regimes present in a large, heterogeneous Mediterranean region using available unimpaired streamflow and geospatial datasets. From a management perspective, the hydrologic classification provides a footprint of the locations of distinct dominant hydrologic regions across California. This classification, combined with ecological and geomorphic information, could be used to design functional flow targets that could then be incorporated with current human water management objectives through an adaptive management framework. The ultimate utility of this classification is demonstrated by its ability to distinguish distinct hydrologic regimes and characterize dominant physical and climatic catchment controls on hydrology with a strong physical basis and expected ecological relevance. Eight natural flow classes were distinguished for California and results were corroborated by high predictive accuracy and regional performance. Our analyses revealed that topographic, geologic, and climatic attributes all explained significant variation in these hydrologic regimes. This supports the view that spatial variation in hydrology is determined by interactions among these factors at multiple spatial and temporal scales (Snelder et al. 2005; Sanborn and Bledsoe 2006; Kennard et al. 2010) and the need to consider local hydrologic controls acting at the reach scale by means of a spatially-explicit hydrologic classification.

Supporting Information

Additional supporting information may be found in *Appendix A*, including a climate-based literature review of existing hydrologic classifications, a full description of the hydrologic time-series uncertainty analysis with gauge station specific results, and additional details on each of the identified natural flow classes.

Acknowledgements

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CHAPTER 2

THE ROLE OF TOPOGRAPHIC VARIABILITY IN RIVER CHANNEL CLASSIFICATION

Abstract

To date, subreach-scale variations in flow width and bed elevation have rarely been included in channel classifications. Variability in topographic features of rivers, however, in conjunction with sediment supply and discharge produces a mosaic of channel forms that provides unique habitats for sensitive aquatic species. In this study we investigated the utility of topographic variability attributes (TVAs) in distinguishing channel types and dominant channel formation and maintenance processes in montane and lowland streams of the Sacramento River basin, California USA. A stratified random survey of 161 stream sites was performed to ensure balanced sampling across groups of stream reaches with expected similar geomorphic settings. For each site surveyed, width and depth variability were measured at baseflow and bankfull stages, and then incorporated in a channel classification framework alongside traditional reach-averaged geomorphic attributes (e.g., channel slope, width-to-depth, confinement, and dominant substrate) to evaluate the significance of TVAs in differentiating channel types. In contrast to more traditional attributes such as slope and contributing area, which are often touted as the key indicators of hydrogeomorphic processes, bankfull width variance emerged as a first-order attribute for distinguishing channel types. A total of nine channel types were distinguished for the Sacramento Basin consisting of both previously identified and new channel types. These results indicate that incorporating TVAs in channel classification provides a quantitative basis for interpreting nonuniform as well as uniform geomorphic processes, which can improve our ability to distinguish linked channel forms and processes of geomorphic and ecological significance.

2.1 Introduction

Building on the classic premise of Davis (1909), Thornbury (1954) stated that geomorphic processes create a characteristic assemblage of landforms. Through judicious use of inverse reasoning, investigation of landforms can provide an understanding of linked geomorphic processes. Over the past century, studies have shown that ecological structure and function of rivers are strongly influenced by channel type (e.g., Hack and Goodlett, 1960; Smith et al., 1995; Vannote et al., 1980). As a result of these strong foundations, channel classification has come to the forefront of river science and management as a central feature of methods for understanding, protecting, and restoring rivers in North America (Rosgen 1994; Kondolf 1995; Buffington and Montgomery 2013), Europe (e.g., González del Tánago and García de Jalón 2004; Orr et al.

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2008), Australia (Brierley and Fryirs 2005), and South Africa (Rowntree and Wadeson 1998). Channel classification is of critical importance today for river management, because anthropogenic changes to flow regimes (Molles et al. 1998; Mailligan and Nislow 2005), sediment regimes (Graf 1980; Pitlick and Van Steeter 1998; Wohl et al. 2015), and the physical structure of rivers (Price et al. 2012) have led to widespread degradation of river ecosystems worldwide (Dynesius and Nilsson 1994; Arthington 2012).

Reach-scale geomorphic settings [e.g., pool-riffle, step-pool (Montgomery and Buffington 1997)] distinguished by attributes related to channel form and sediment transport and supply have been shown to influence ecosystem dynamics and biological diversity (Montgomery and Bolton 2003; Biggs et al. 2005; Meitzen et al. 2013; Milner et al. 2015), highlighting channel reach classification as a critical step in river ecosystem management. Geomorphic attributes used in channel classification are often chosen to describe relevant, persistent reach-scale characteristics that influence hydraulics and sediment dynamics and in turn aquatic and riparian ecosystem functioning (Birkeland 1996; Hupp and Osterkamp 1996; Merrit and Wohl 2003; Kasprak et al. 2016). Considerable recent efforts have been invested in developing geomorphic attributes for river characterization, particularly in Europe through the implementation of the Water Framework Directive (e.g., Raven et al. 1998; Orr et al. 2008; Sear et al. 2009; Polvi et al. 2014). Common attributes considered include uniform metrics such as reach-averaged channel slope, width-to-depth ratio, entrenchment ratio, valley confinement, sinuosity, stream power, and dominant channel substrate (Church 1992; Rosgen 1994; Montgomery and Buffington 1997; Knighton 1999; Brierley and Fryirs 2005; Kasprak et al. 2016).

However, nonuniform mechanisms not well characterized or indicated by reach-averaged uniform metrics have been identified as primary drivers of channel formation and maintenance in many channel settings (Lane and Carlson 1953; Dietrich and Smith 1983; Thompson 1986; Paustian et al. 1992; Wohl and Thompson 2000; Makaske 2001; Powell et al. 2005; Wilcox and Wohl 2006; White et al. 2010). For example, subreach-scale flow convergence routing has been shown to control riffle-pool formation and maintenance and the locations of sediment deposition and bar instability (MacWilliams et al. 2006). In meandering and alternate bar morphologies, nonuniformity is maintained primarily by the alternating converging and diverging secondary transverse flow cells in and between bends, respectively, which help to maintain sediment routing through the inside of meander bends (Thompson 1986).

Topographic variability attributes (TVAs), defined here as any measure of subreach-scale variability [i.e., departures from average conditions in channel bed elevation, bankfull width, curvature, and floodplain width], are closely tied to nonuniform channel processes and likely offer more appropriate metrics for characterizing and comparing dominant channel processes and habitat dynamics than their far more common uniform counterparts used in many channel morphologies. For example, measures of subreach-scale channel width and depth variance are expected to capture the frequency and magnitude distribution of flow expansions and contractions associated with flow convergence routing under a dynamic flow regime (MacWilliams et al. 2006). Furthermore, high within-reach topographic variability is often associated with heterogeneous habitat units available across a wider range of discharges that can support a variety of native biota and ecological functions (Murray et al. 2006; Scown et al. 2016), promoting high biodiversity (Poff and Ward 1990; Townsend and Hildrew 1994; Fausch et al. 2002) and ecological resilience (Elmqvist et al. 2003; McCluney et al. 2014).

Channel topographic variability exists naturally and is part of a dynamic equilibrium with other channel variables. At the valley scale, there are nested layers of topographic variability, including variations in the width of hillsides, terraces and floodplains along a corridor (e.g., Gangodagamage et al. 2007; White et al. 2010). When a flow of a set magnitude moves through a layered topographic boundary, it engages one or more of these controls and a specific scale of topographic steering is initiated. That specific type of steering then drives subreach variability in the hydraulic flow field that focuses erosion and deposition locally (Strom et al. 2016). This is analogous to blowing air through a wind instrument; depending on which holes are plugged with fingers, different notes are produced, and in the absence of any instrument, air makes no music at all. For a dynamic flow regime, topographic steering changes with flow and this results in a diversity of stage-dependent hydraulic patch behaviors (Scown et al. 2016; Strom et al. 2016), each with a different capability to promote erosion or deposition (Brown and Pasternack 2014; Grams et al. 2013).

As a result of these factors, rivers exhibit complex patterns of topographic change processes that promote strong longitudinal variation in width and depth (Wyrick and Pasternack 2015). Variability itself is expected to differ between reaches, because many geomorphic processes create variability, such as flow convergence, avulsion, turbulence-driven scour, and meander bend cut-off. One might conjecture that variability is indicated by reach-scale homogenous

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metrics like specific stream power, and thus not needed to define channel classes, but if the processes that control channel form are governed by variability, then the reverse should be taken as the dominant conjecture: reach-scale homogenous metrics are the outcome of the interplay between channel variability and flow, not the controls on it.

In spite of the established geomorphic (Thompson 1986; MacWilliams et al. 2006; White et al. 2010; Gostner et al. 2013a,b; Brown et al. 2014; 2015) and ecological (Murray et al. 2006; Scown et al. 2016; Elmqvist et al. 2003; McCluney et al. 2014) significance of subreach-scale topographic variability, very few existing channel classifications consider TVAs. While the Rosgen (1994) and Montgomery and Buffington (1997) classifications both consider the spacing of individual channel-unit types along a reach (e.g., non-dimensional pool spacing measured in channel widths) in their suite of geomorphic attributes, no direct measure of channel width or depth variability is included. The limited consideration of TVAs in past channel classifications may be due to the preference by practitioners to conduct rapid field surveys (sometimes at only one cross-section per reach) in order to maximize the number of channel reaches surveyed in lieu of performing more in-depth surveys across fewer reaches (Buffington and Montgomery 2013) given resource limitations. With the emergence of meter-scale remote sensing of rivers, datasets that support computing and analyzing TVAs will become more available, accurate, and useful (Gleason and Wang 2015; Gonzalez and Pasternack 2015). There has already been significant progress on the use of high resolution aerial imagery from drones to map river characteristics (e.g., Lejot et al. 2007; Rivas Casado et al. 2015).

A few exceptions include Trainor and Church (2003) and Jaeger (2015). Trainor and Church (2003) included channel depth and width variability as key geomorphic attributes in a channel comparison study, but the focus on quantifying dissimilarity between channel reach pairs precluded an evaluation of the relative significance of individual attributes for distinguishing channel types. Jaeger (2015) considered the standard deviation of channel bed elevation (a measure of depth variability) in their classification of headwater streams. However, the set-up of the study as an analysis of the geomorphic significance of mountaintop mining again precluded any evaluation of attribute significance. This major gap in the channel classification literature indicates a need to test the value of incorporating TVAs into the suite of potentially significant geomorphic attributes distinguishing ecologically relevant channel types. This must be done

before we can even begin to evaluate the geomorphic or ecological significance of these emerging attributes compared to the more traditional reach-averaged attributes described above.

The purpose of this study was to investigate how TVAs can be incorporated in a channel classification framework to improve the utility of morphological analysis to distinguish dominant channel processes and habitat dynamics along channel networks in varied landscapes. The specific study objectives were to test the use of TVAs in (i) distinguishing channel types across a landscape and (ii) characterizing dominant channel processes of interest. The utility and ecological implications of incorporating TVAs in a channel classification of montane and lowland streams of a Mediterranean basin are then discussed and evaluated in the context of the existing body of channel classification literature and current understanding of landscape form – process linkages.

2.2 Methodology

The Rosgen channel classification (Level II, Rosgen 1994), arguably the most commonly used channel classification system in North America and globally (Kasprak et al. 2016), was adopted and expanded on in this study to facilitate ease of application of the proposed methods in future channel classifications. The Rosgen channel classification is a stream-reach taxonomy that classifies channel types using field-collected geomorphic attributes (e.g., slope, entrenchment ratio, width-to-depth ratio, sinuosity, and median grain size). In an effort to support the incorporation of TVAs into field-based mapping for channel classification given the common constraint of resource limitations, the Rosgen channel classification procedure was extended in three ways: (1) the channel network was binned into hydro-geomorphically similar groups prior to field data collection using a stratified analysis of hydrologic and topographic data in a Geographic Information System (GIS); (2) four TVAs consisting of within-reach low flow and bankfull width and depth variance were measured in the field in addition to the traditional geomorphic attributes considered by Rosgen (1994); and (3) a heuristic refinement procedure was used to distinguish the most parsimonious set of physically interpretable channel types instead of associating the field-observed channel types with known Rosgen classes.

2.2.1 Study Region

The study was conducted in the Sacramento Basin of California, USA, encompassing the largest river in the State of California by discharge (producing ~ 30% of California's surface water runoff) and the second largest U.S. river draining into the Pacific Ocean (after the Columbia River) (Carter and Resh 2005). This 70,000-km^2 basin lies between the Sierra Nevada and Cascade Range to the east and the Coast Range and Klamath Mountains to the west. From its headwaters in the volcanic plateau of northern California (Upper Sacramento, McCloud, and Pit Rivers), the Sacramento River flows south for 715 km before reaching the Sacramento–San Joaquin River Delta and San Francisco Bay. The river has many small to moderate-sized tributaries (e.g., Clear, Cottonwood, Cow, Battle, Antelope, Mill, Deer, Stony, Big Chico, and Butte Creek) and two large tributaries, the Feather River and the American River. The basin primarily exhibits a Mediterranean climate with cold, wet winters (Oct - Apr) and warm, dry summers (May - Sep) (Leung et al. 2003).

The basin's diverse physiographic settings range from the glacially-carved Sierra Nevada mountains to lowland marshes and agricultural lands, with a total relief of about 4,300 m (USGS 2011). The Sacramento Basin is split into three overlying physiographic provinces: the Pacific Border, the Cascade-Sierra Mountains, and the Basin and Range provinces (Fenneman and Johnson 1946) (Fig. 2-1). These provinces exhibit distinct landscape units (*sensu* Brierley and Fryirs 2005) based on differential tectonic uplift, lithology, and climate (CGS 2002) and are therefore expected to account for major differences in geomorphic processes and resulting channel morphologies (Schmitt et al. 2007; Trainor and Church 2003). For instance, the Basin and Range province consists primarily of a thick accumulation of lava flows and tuff beds, supporting low slope meandering streams and large marshlands with low sediment transport capacity. The Cascade-Sierra Mountains province consists of a massive tilted fault block; the western slope descends in a series of undulating low-relief upland surfaces punctuated by deeply incised river canyons, driving high sediment transport rates (Stock et al. 2005). The Pacific Border province delineates an alluvial basin that acts as a depositional trough (CGS 2002). Relationships between contributing area and channel bed composition are expected to vary significantly between these provinces based on major differences in sediment regimes.

California's legacy of intensive and widespread hydrologic and geomorphic alteration for water supply, flood control, land use change, hydropower, and mining has left the Sacramento Basin's river ecosystems severely degraded (Healey et al. 2008; Hanak et al. 2011). The basin

simultaneously supports 2.8 million people and numerous federally endangered and threatened aquatic species [e.g., winter-run Chinook salmon (*oncorhynchus tschawytscha*), Sacramento splittail (*pogonichthys macrolepidotus*)] (Lindley et al. 2007; Moyle et al. 2011). Most of the Sacramento Basin valley is intensely cultivated, with over 8,100 km^2 of irrigated agriculture. Major reservoirs in the basin include Lake Shasta (5.6 km^3, upper Sacramento, McCloud and Pit Rivers), Lake Oroville (4.4 km^3, Feather River), Lake Folsom (1.2 km^3, American River), and New Bullards Bar Reservoir (1.2 km^3, Yuba River). In light of systemic anthropogenic alteration promoting channel homogenization and simplification (Arnold et al 1982; Booth and Jackson 1997; Walsh et al. 2005), one might expect that topographic variability would be suppressed. Therefore, if TVAs prove important here in the characterization of in-channel habitat dynamics, then they are likely even more important in undisturbed settings in which topographic variability is expected to be greater and thus influence habitat dynamics across a larger range of TVAs.

This study was constrained to one hydrologic regime found within the Sacramento Basin to help isolate factors that cause diverse hydrological and geomorphic effects. An existing regional hydrologic classification of California (Lane et al. 2016) was used to identify stream reaches exhibiting the low-volume snowmelt and rain (LSR) regime. The LSR hydrologic regime was chosen as it captures the transition from the montane snowmelt-driven to lowland rain-driven flow regime and has the largest spatial footprint of hydrologic regimes in the Sacramento Basin (47%); stream reaches in this hydrologic regime are expected to exhibit high geomorphic variability.

2.2.2. Channel network stratification

Given the large study domain with about 100,000 reaches and limited resources, the process of observing representative sites requires selecting a relatively small number of samples compared to the scope of the system. If sites were selected at random, then the odds are that different geomorphic settings would be observed in proportion to their frequency of occurrence, and that would bias the assessment of classification, especially if too few sites of rare yet important classes were sampled. Therefore, instead of random sampling, a stratified random approach was used to obtain an equal effort strategy mindful of process-based controls on river organization. Stratified random sampling and related variants using equal effort in each stratum have not been widely applied in channel classification studies to date to capture reach-scale

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geomorphic heterogeneity, but are well known in field ecology (Johnson 1980; Miller and Ambrose 2000; Manly and Alberto 2014; CHaMP 2016) and hydrology (Thomas and Lewis 1995; Yang and Woo 1999). Three landscape characteristics accounting for geologic structure, sediment availability, and sediment transport capacity were obtained from GIS data and analyses as described below and used to stratify the Sacramento Basin channel network into 15 subgroups or strata of potential distinct reach-scale geomorphic characteristics.

Geologic structure (i.e., tectonic uplift and lithology), derived from the overlying physiographic provinces (Fenneman and Johnson 1946; CGS 2002) (Fig. 2-1), was used in conjunction with sediment availability and transport capacity to distinguish 15 geomorphic strata. Sediment supply and transport capacity were represented using contributing area to a reach (A_c) and the channel bed slope of a reach (S). These were obtained through analysis of the National Hydrography Dataset (HUC 1802) (USGS 2013) in conjunction with a 10-m digital elevation model (DEM) of the study area (USGS 2009). A_c is a common topographically-derived surrogate for channel-forming discharge (e.g., Hack 1957; Schumm et al. 1984; Rosgen 1994) and S is consistently used in classifications to characterize local flow energy dissipation (e.g., Rosgen 1994; Montgomery and Buffington 1997; Gartner et al. 2015). The combination of the two variables is also prominent in hydrogeomorphic classification, as it is often conjectured that channel bed morphology arises as a function of reach-scale shear stress and/or specific stream power, which are determined by both unit discharge and channel slope (Flores et al. 2006). Indices combining A_c and S as a measure of stream power (Lane 1957; Leopold and Wolman 1957; Sklar and Dietrich 1998) and have been used to distinguish braided from meandering rivers (Carson 1984), to identify thresholds for channel incision (Schumm et al. 1984) and sediment transport capacity (Bledsoe et al. 2002), and in reach-scale channel classification (e.g., Schmitt et al. 2007).
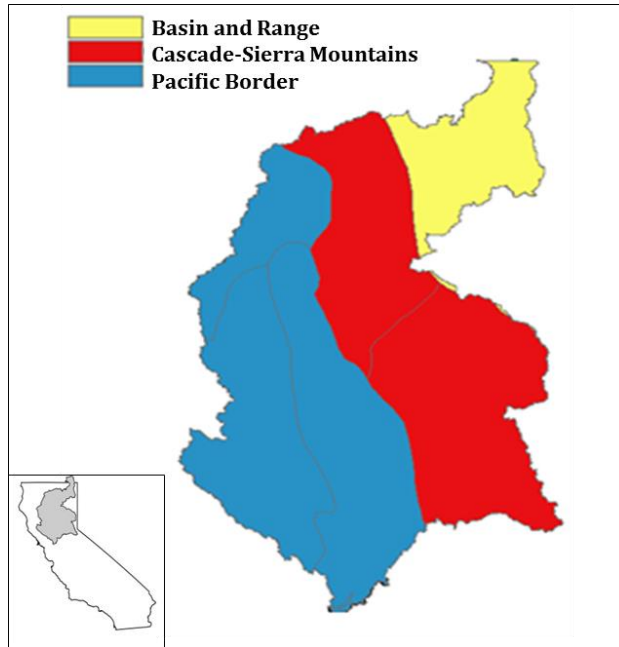
Figure 2-1. Sacramento Basin physiographic provinces used to refine contributing area (A_c) based sediment composition thresholds for channel network stratification.

The channel network was derived from the 10-m DEM and dissected into equidistant segments of 250 m length; S and A_c were subsequently derived from the DEM for each segment. Within each physiographic province, channel segments were binned according to GIS-derived S and A_c thresholds to aid with sampling – the results of the study are not sensitive to the exact number of bins or thresholds between bins, as long as the procedure aids with sampling the diversity in the system with equal effort. Five S bins were considered based on Rosgen's (1994) channel classification thresholds for ease of comparison: $< 0.1\%, 0.1 - 2\%, 2 - 4\%, 4 - 10\%,$ and $> 10\%$. Three A_c bins were established based on estimated A_c threshold transitions for prevalent sediment sizes: (1) bedrock/boulder, (2) cobble/gravel, and (3) sand/silt. The A_c thresholds assigned to distinguish channel bed composition classes were unique for each of the three physiographic provinces within the Sacramento Basin. This decision was based on the expected differences in A_c required to transition from boulder- to cobble- and from gravel- to sand-dominated channels arising from large-scale differences in geology, topography, and climate driving distinct sediment regimes. The physiographic provinces provide bounds on what channels are potentially comparable in terms of relations between drainage area and discharge, sediment supply, and substrate size (Montgomery and Buffington 1993). Within each province, A_c bin thresholds were estimated based on identified channel composition transition locations

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reported in available literature combined with expert knowledge relating A_c and sediment composition in the region (e.g., Montgomery and Buffington 1993; Gasparini et al. 2004) (Table 2-1). Fifteen geomorphic strata were then distinguished as all possible combinations of topographically-derived A_c and S bins (Fig. 2-2, top-left), and each stream segment in the channel network was assigned to a stratum based on its particular GIS-based A_c and S values (Fig. 2-2a).
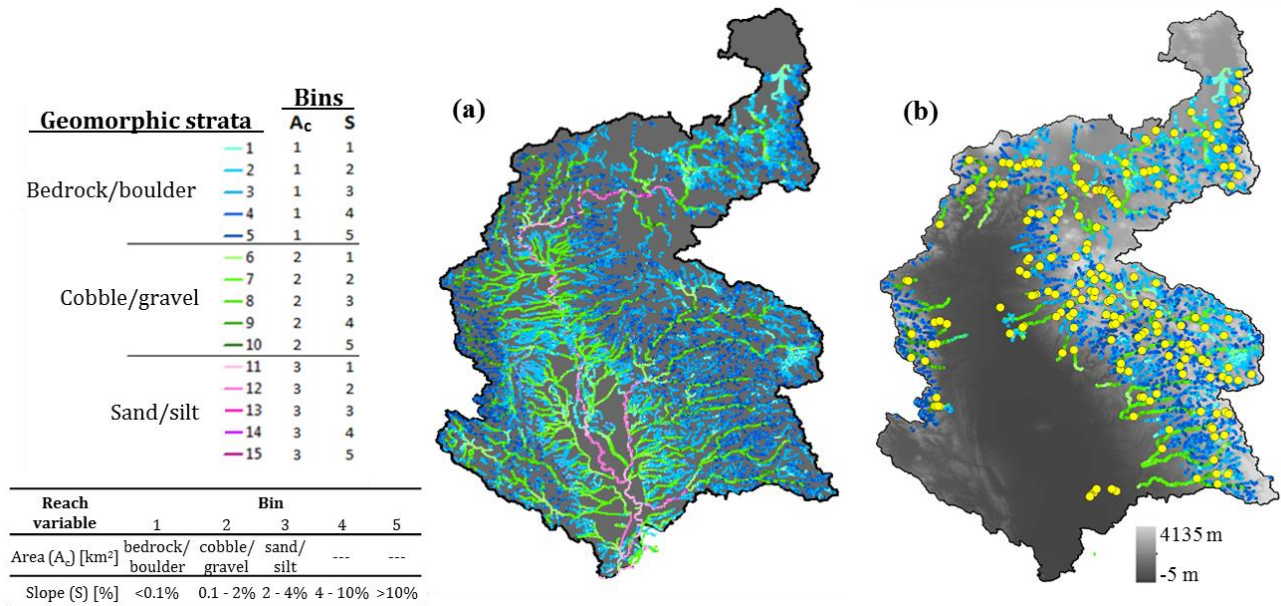
Figure 2-2. Map of geomorphic strata across (a) the entire Sacramento Basin and (b) only the low-volume snowmelt and rain (LSR) reaches. Black dots indicate the randomly chosen field survey locations across the 15 strata. The geomorphic strata are defined in the top-left table based on the combination of contributing area (A_c) and slope (S) bins, which are derived based on thresholds stated in the bottom-left table and Table 2-1.

Table 2-1. Contributing area (Ac) thresholds for channel composition distinctions across Sacramento Basin physiographic provinces (see Figure 2-1 for map of physiographic provinces).

Physiographic Province	Contributing Area Threshold (km²)	
	Bedrock/boulder to cobble/gravel	cobble/gravel to sand/silt
Pacific Border	50	5,000
Cascade-Sierra Mountains	300	9,000
Basin and Range	300	10,000

Of the 15 geomorphic strata distinguished across the Sacramento Basin by A_c and S combinations, 13 strata were exhibited by LSR reaches, indicating that LSR-dominated hydrologic regimes were 87% representative of the full range of geomorphic variability in the

Sacramento Basin as expressed with binned combinations of A_c and S. The two geomorphic strata not found within LSR reaches consisted of the combinations of the highest A_c bin and 4-10% or >10% slope bins. Based on reach accessibility and expected variability of geomorphic attributes, 10 to 12 field surveys were performed within each of the 13 geomorphic strata exhibited by LSR reaches for a total of 161 field survey reaches representing a large range of A_c – S combinations (Figs. 2-2b, 2-3). Note that DEM-derived S was not used further in this study, as it is not highly accurate at representing reach-scale channel slope.
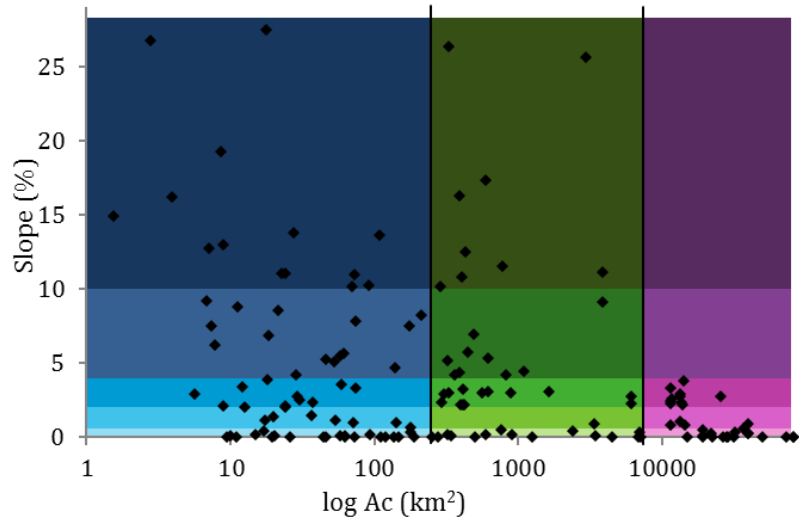
Figure 2-3. The stratified random field survey locations (n=161) represent a large range of GIS-based reach slopes (S) and contributing areas (A_c). Colors and shading indicate the distinct S and A_c bins that correspond to the geomorphic strata listed in Fig. 2 based on the Cascade – Sierra Mountains physiographic province A_c thresholds in Table 2-1.

2.2.3. Data-driven geomorphic channel classification

Field surveys. Geomorphic field surveys were performed for each study reach identified through the stratified random sampling scheme described above. Surveys of 64 reaches were conducted by the authors' crew and data from another 97 reaches were obtained from the Surface Water Ambient Monitoring Program (SWAMP) of the California State Water Resources Control Board. Both field campaigns used the same sampling protocols, outlined in Ode (2007) and briefly summarized below. Depending on whether the average wetted channel width was less than or greater than 10 m, a stream reach was surveyed over a length of 150 or 250 m, respectively (Ode 2007), corresponding to 10 - 100 bankfull widths. Eleven evenly spaced cross-sectional transects were surveyed along each stream reach to quantify variability in 22

geomorphic attributes listed in Table 2-2 (Ode 2007). These decisions were intended to balance geomorphic (Grant et al. 1990; Montgomery and Buffington 1997) and ecological (Frissell et al. 1986) relevance with the practical time and resource limitations of field surveying. The choice of reach length and transect spacing also enabled incorporation of the existing SWAMP geomorphic dataset for the study region that uses the same values. Channel morphology and reach characteristics for the 161 surveyed reaches were measured using a surveying level and stadia rod (Topcon AT-B, 0.01m). Longitudinal streambed profiles were surveyed at consecutive transects along the thalweg for the entire length of the reach. Wolman pebble counts (Wolman 1954) of 110 pebbles were performed at each reach such that ten pebbles were randomly selected from each of eleven transects to balance sampling precision and effort across a range of sediment material variability assuming normally distributed sediment size (Edwards and Glysson 1999; Bunte and Abt 2001).

Reach-scale geomorphic attributes. Twenty-two geomorphic attributes (Table 2-2) were chosen to describe relevant, persistent reach-scale geomorphic characteristics that influence hydraulics and sediment dynamics and in turn aquatic and riparian ecosystem functioning (Birkeland 1996; Hupp and Osterkamp 1996; Merrit and Wohl 2003). The field-measured and computed attributes included traditional reach-averaged diagnostic variables [e.g., slope ($\overline{slope}$), contributing area (A_c), sinuosity ($\overline{sin}$), entrenchment ($\overline{e.ratio}$), shear stress ($\overline{shear}$), relative roughness ($\overline{d.D}_{50}$), sediment composition (i.e., $\overline{D}_{50}$, $\overline{D}_{84}$, and $\overline{D}_{max}$) and base flow and bankfull depth ($\overline{d}$), width ($\overline{w}$), and width-to-depth ratio ($\overline{w.d}_{BF}$)] as well as four TVAs capturing within-reach variability in base flow and bankfull channel width (CV_w) and bed elevation (CV_d) (Table 2-2).

Table 2-2. Reach-scale geomorphic and topographic variability attributes considered in channel classification.

Geomorphic Attribute	Code	Description	Units
wetted depth	$\bar{d}$	average across 11 transects; 0 if dry channel	m
wetted width	$\bar{w}$	average across 11 transects; 0 if dry channel	m
wetted width-to-depth	$\overline{w.d}$	ratio of channel width to depth	--
wetted depth-to-D50	$\overline{d.D_{50}}$	low water roughness; channel depth standardized by median grain size	--
bankfull depth	$\overline{d_{BF}}$	average across 11 transects	m
bankfull width	$\overline{w_{BF}}$	average across 11 transects	m
bankfull width-to-depth	$\overline{w.d_{BF}}$	ratio of bankfull width to depth	--
bankfull depth-to-D50	$\overline{d_{BF}.D_{50}}$	roughness; bankfull depth standardized by median grain size	--
entrenchment ratio	$e.ratio$	floodprone width / average bankfull width; floodprone width manually estimated from high resolution aerial imagery (<1m)	--
shear stress	$\overline{shear}$	depth–slope product approximation	Pa
shields stress	$\overline{shields}$	non-dimensionalization of shear stress (Shields 1936)	--
contributing area	A_c	drainage area to downstream end of reach	km^2
slope	$\overline{slope}$	average water surface slope over 11 transects	%
sinuosity	$\overline{sin}$	straightline distance/actual channel distance along ~2000m of channel	--
sediment distribution variance	CV_{sed}	variance of transect sediment distribution (n=10) across 11 transects	--
D50	$\overline{D_{50}}$	median grain size across reach (n=110)	mm
D84	$\overline{D_{84}}$	84th percentile grain size across reach (n=110)	mm
Dmax	$\overline{D_{max}}$	maximum grain size across reach (n=110)	mm
† wetted depth variance	CV_d	std/mean across 11 transects; 0 if no water in channel	--
† wetted width variance	CV_w	std/mean across 11 transects; 0 if no water in channel	--
† bankfull depth variance	$CV_{d.BF}$	std/mean across 11 transects	--
† bankfull width variance	$CV_{w.BF}$	std/mean across 11 transects	--

† topographic variability attributes (TVAs)

Reach-scale estimates of geomorphic attributes were computed from field surveys by averaging values across the eleven surveyed cross-sections within each reach. Entrenchment was calculated as flood-prone width divided by bankfull width (Rosgen 1994), where flood-prone width was measured manually from sub-meter resolution aerial imagery. Sinuosity was calculated as the linear valley distance divided by the actual channel distance along 2 km of channel straddling the field site (Elliott et al. 2009). The coefficient of variation (CV) of base flow and bankfull width and depth was calculated among the eleven cross-sections of each survey reach as a measure of within-reach variability. CV is a nondimensional measure of standard deviation that provides a useful but not exclusive metric of variability (Schneider 1994) that is commonly used in spatial analysis of ecological patterns (Rossi et al. 1992; Simonson et al. 1994; Gubala et al. 1996; Palmer et al. 1997; Thoms 2006; Gostner et al. 2013a). A list of geomorphic attributes considered and their methods of measurement or calculation is provided in Table 2-2. When possible, these attributes were made non-dimensional for application in a range

of physiographic and climatic settings (Parker 1979; Parker et al. 2003). Given the dual aims of adapting the Rosgen classification to incorporate TVAs and comparability with existing field data for the study region, the present study omitted several potentially significant metrics [e.g., channel vegetation, bank material, dominant flow types (Raven et al. 1998), and stream power (Knighton 1999; Orr et al. 2008)] that could be considered in future studies.

Statistical analyses. The geomorphic attributes were initially re-scaled to range from 0 to 1 and examined for correlation to identify and remove highly correlated attributes (Pearson's correlation coefficient > 0.8) to meet the assumption of lack of multicollinearity. Five of the original 22 attributes were highly correlated ($\bar{d}$, $\bar{w}$, $\overline{d.D}_{50}$, $\bar{D}_{50}$, CV_{sed}), reducing the dataset to 17 geomorphic attributes (Table 2-2).

A hierarchical clustering analysis using Ward's algorithm (Ward 1963; Murtagh and Legendre 2013) was used to examine the clustering structure of the uncorrelated, standardized geomorphic attributes describing the 161 study reaches. The dataset also was analyzed by *k*-means cluster analysis stipulating 2 to 15 (*k*) clusters that maximize the between-group variation (Hartigan and Wong 1979; Kaufman and Rousseeuw 1990). Slope breaks in the *k*-means scree plot of the within-group sum of squares for each clustering solution were interpreted as numbers of clusters at which information content of the clustering process changed. Scree plot slope breaks and the Davies-Bouldin internal clustering index (DBI=0.91) indicated that 12 clusters created distinct groups of study reaches, similar to the hierarchical clustering results.

A combination of univariate and multivariate statistical methods was then applied to (i) examine the strength of variables for distinguishing identified channel types, (ii) test the hypothesis that channel types exhibit significantly different values of geomorphic attributes, (iii) examine the potential range of values for variables of interest between channel types, and (iv) validate the basis of the channel classification by predicting the channel type using geomorphic attributes. These statistical methods included nonmetric multidimensional scaling (NMDS) (Clarke 1993), one-way analysis of variance (ANOVA) with Tukey's honestly significant differences (HSD) test, nonparametric permutational multivariate analysis of variance (PerMANOVA) (Anderson 2001), and classification and regression trees (CART) (Breiman et al. 1984; De'ath and Fabricius 2000).

An exploratory NMDS analysis (Clarke 1993; Oksanen 2011) of the surveyed reaches based on the uncorrelated geomorphic attributes was performed to visually represent the structure of

the multivariate dataset and evaluate the relative significance and correlation of attributes. NMDS is common in ecological studies, including those identifying differences in biological communities based on geomorphic variables (e.g., Walters et al. 2003; Virtanen et al. 2010) and is increasingly included in dedicated geomorphic studies (e.g., Merriam et al. 2011; Sutfin et al. 2014; Varanka et al. 2014; Jaeger 2015). Histograms of each geomorphic attribute were also used to evaluate the density distributions of attribute values across the survey reaches and lend insight into the multivariate clustering structure.

Individual one-way ANOVAs were conducted to compare geomorphic attribute means between channel types. A post-hoc Tukey's HSD test at the 95% confidence level indicated the best attributes for distinguishing between channel types. A PerMANOVA analysis (Anderson 2001) [Euclidean distance, 9999 permutations (Oksanen 2011)] was performed to test the hypothesis that the channel types distinguished through clustering analysis exhibit significant differences ($p<0.01$) in geomorphic attributes.

Toward the primary goal of the study, CART (Breiman et al. 1984) was then used to identify the most explanatory geomorphic attributes distinguishing channel types and their threshold values. CART yields a binary decision tree where the response variable (study reach) is partitioned into groups (channel types) with minimized within-group variance (based on ten-fold cross-validation, Therneau et al. 2010) and increasing purity (based on the Gini index, De'ath and Fabricus 2000).

Heuristic refinement of inductive clustering solution.   The final number of clusters distinguished was determined heuristically based on a combination of statistical analysis interpretation and physical understanding of the region. First, potential splitting solutions were identified based on the structure of the hierarchical clustering and the shape of the scree-plots from the non-hierarchical *k*-means clustering. Each potential splitting solution was assessed iteratively from largest to smallest splitting distance (based on Ward's hierarchical clustering). Heuristic (dis)aggregation of clusters was subsequently performed based on the physical distinction and interpretability of the resulting clusters with the objective of minimizing the final number of physically interpretable channel types. For instance, if a particular splitting solution distinguished only some empirical clusters to a level of reasonable physical interpretability, the remaining clusters would be iteratively disaggregated based on the next potential splitting solutions until the minimal number of physically meaningful clusters was identified.

2.3 Results

2.3.1. Relative significance of geomorphic attributes

The two-dimensional NMDS ordination illustrated the significance of TVAs and the relative roles of geomorphic attributes in structuring the multivariate dataset. The NMDS minimized mean stress at 0.08 for 161 study reaches (Fig. 2-4); stress values of < 0.1 are considered to be a good ordination with little risk of drawing false inferences (McCune and Grace 2002). NMDS indicated that the first axis (NMDS1) is dominated by $CV_{d.BF}$, $CV_{w.BF}$, $\overline{slope}$, and A_c, while the second axis (NMDS2) is dominated by cross-sectional geomorphic attributes (e.g., $\overline{D}_{84}$, $\overline{D}_{50}$, $\overline{d_{BF}.D}_{50}$, $\overline{w.d}_{BF}$) as well as $CV_{w.BF}$. As these axes represent gradients of maximum variation, dominant attributes on each axis control the structure of the multivariate dataset.
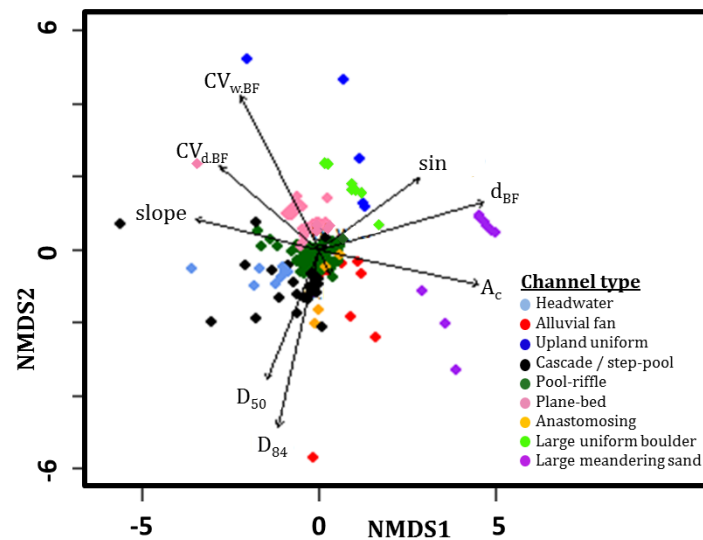
Figure 2-4. Nonmetric dimensional scaling (NMDS) for the first two axes with channel types of individual study reaches indicated. Vectors of attributes are plotted based on the strength of their correlation to the axis (e.g. longer vectors are more strongly correlated to an axis).

Histograms of rescaled geomorphic attributes lend insight into how the density distributions of geomorphic attribute values control the multivariate data structure (Fig. 2-5). If an attribute is normally distributed with a predominance of its values within a narrow band of its full range for most study reaches, then that attribute will likely yield a single grouping, so it cannot explain differences between those reaches; it may instead distinguish the few statistical outlier reaches.

In contrast, an attribute with a more uniform distribution will tend to produce more, equally weighted groupings and thus be a dominant factor explaining differences among many reaches. Upon visual assessment of the geomorphic attribute distributions, most attributes exhibited highly skewed distributions towards lower values (e.g., $\overline{sin}$, $\overline{e.ratio}$, and $\overline{w}_{BF}$). In contrast, the TVAs $(CV_{d.BF}$ and $CV_{w.BF})$ and $\overline{slope}$ exhibited more uniform distributions, helping to explain their dominant roles in structuring the multivariate dataset.
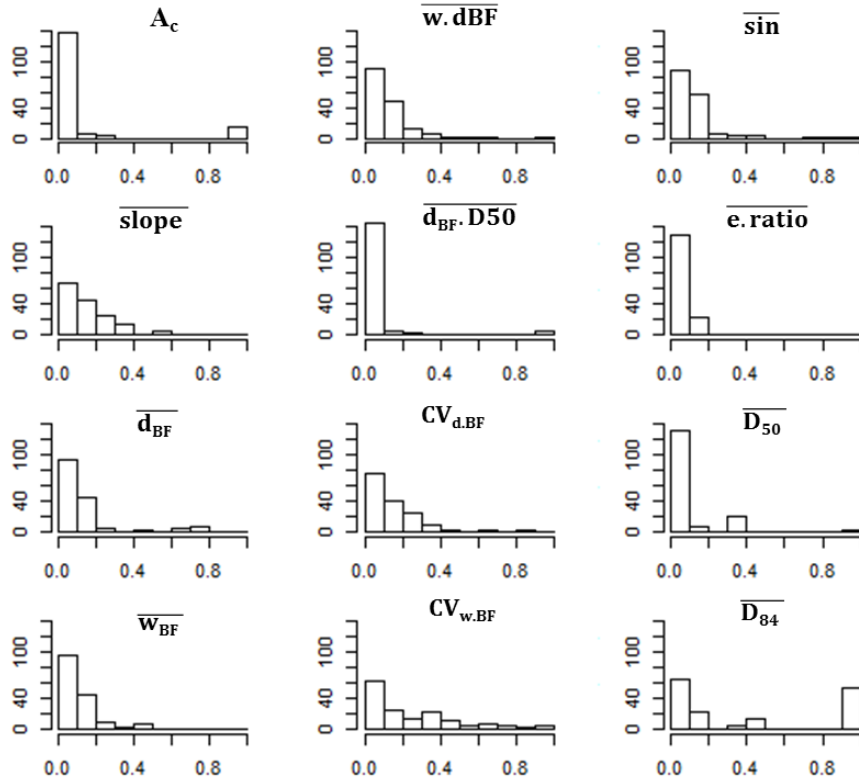
Figure 2-5. Histograms of geomorphic attributes (re-scaled from 0 to 1) across the 161 study reaches illustrate the distribution of each attribute. In contrast to the highly skewed distributions exhibited by most attributes about a small range of values, the TVAs ($CV_{d.BF}$ and $CV_{w.BF}$) and slope exhibit more uniform distributions.

2.3.2. Distinguishing channel types

Agglomerative hierarchical clustering with Ward's linkage (Ward 1963; Murtagh and Legendre 2013) illustrated the clustering structure of the 161 study reaches across the re-scaled uncorrelated geomorphic attributes (Fig. 2-6). The first split occurs at a distance of 20, distinguishing reaches of high (~0.2 – 1.7) and low (~0 – 0.2) bankfull width variance. Splitting groups at a distance of eight distinguished 12 groups that were then reduced to nine physically meaningful groups by applying the heuristic clustering refinement procedures explained in

Section 2.3.4. The nine resulting groups represented physically distinct channel types containing between 4 and 57 study reaches each (average of 18 reaches).
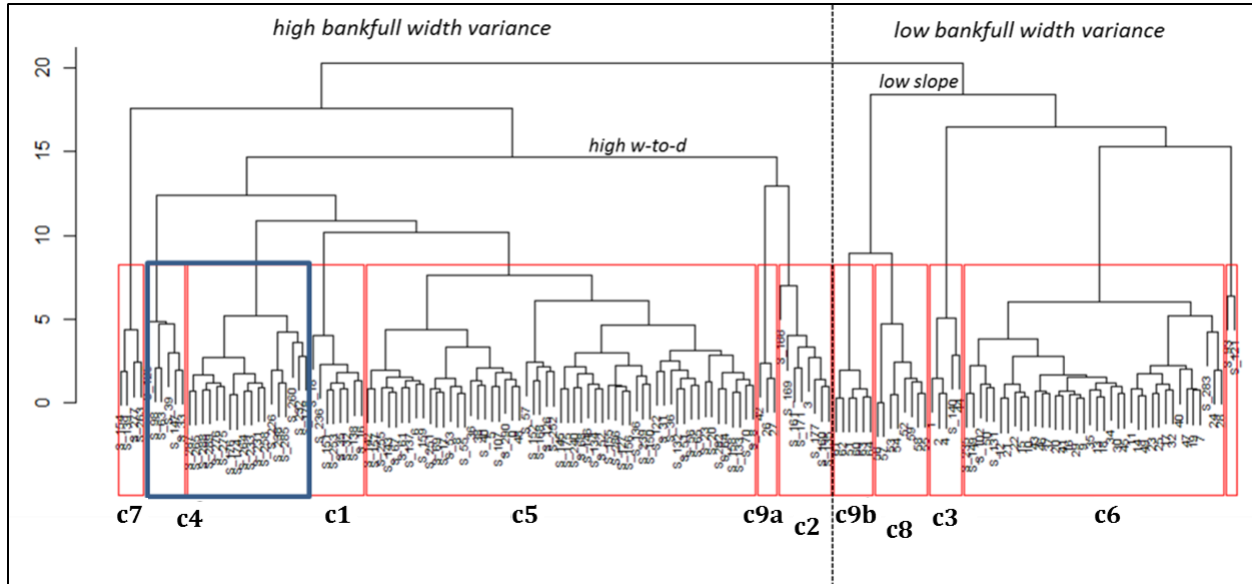
Figure 2-6. Hierarchical clustering of study reaches using Ward's method showing 12 distinct groups (boxed in red) representing nine physically distinct channel types following heuristic refinement.

Individual one-way ANOVA results indicated that group means of 12 of 17 geomorphic attributes varied significantly between the nine channel types ($p < 0.05$) (all attributes except $\overline{w}$, $\overline{d}$, $\overline{D}_{50}$, $\overline{D}_{\max}$, and $\overline{shields}$) (Table 2-3). Multiple comparisons of group means of each attribute using Tukey's HSD post-hoc test at the 95% confidence level indicated particularly significant channel types for specific attributes (Fig. 2-7). For example, $\overline{w.d}_{BF}$ is significantly higher for type 2 reaches than all other channel types. Conversely, $CV_{w.BF}$ differs significantly between channel types 4 and 7 and channel types 6, 8, and 9 while there is no significant difference in the attribute within those groups. Box-and-whisker plots illustrate relative differences in geomorphic attributes within and across the nine identified channel types (Fig. 2-7). Finally, a map of the spatial distribution of classified channel types across LSR-dominated reaches in the Sacramento Basin is provided in Figure 2-8.
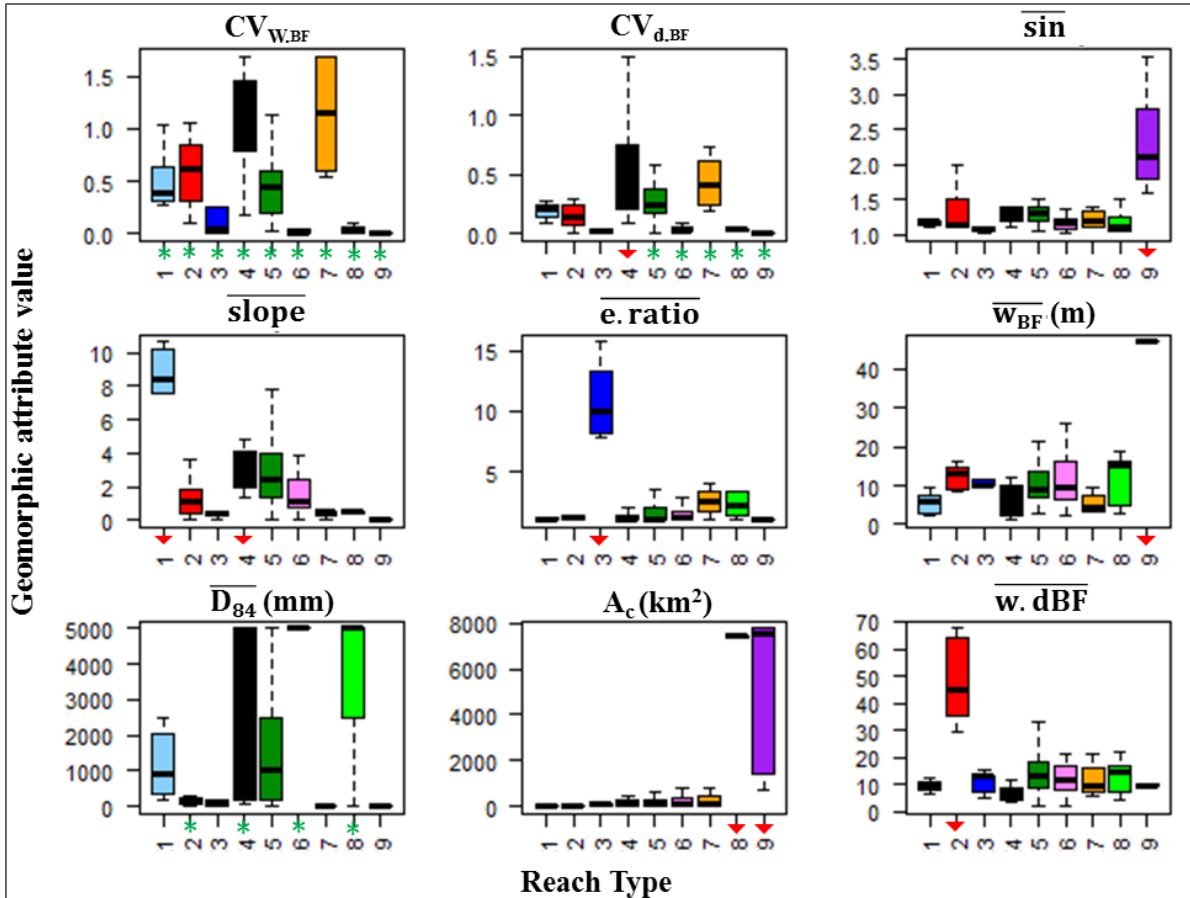
Figure 2-7. Box-and-whisker plots and Tukey's Honestly Significant Differences (HSD) test indicate differences in geomorphic and topographic variability attributes across the nine identified channel types: 1. confined headwater small boulder cascade, 2. partly-confined expansion pool - wide bar, 3. unconfined upland plateau large uniform, 4. confined cascade/step-pool, 5. partly-confined pool-riffle, 6. partly-confined large uniform, 7. unconfined anastomosing plateau small pool-riffle, 8. unconfined large uniform boulder, and 9. unconfined large meandering sand.
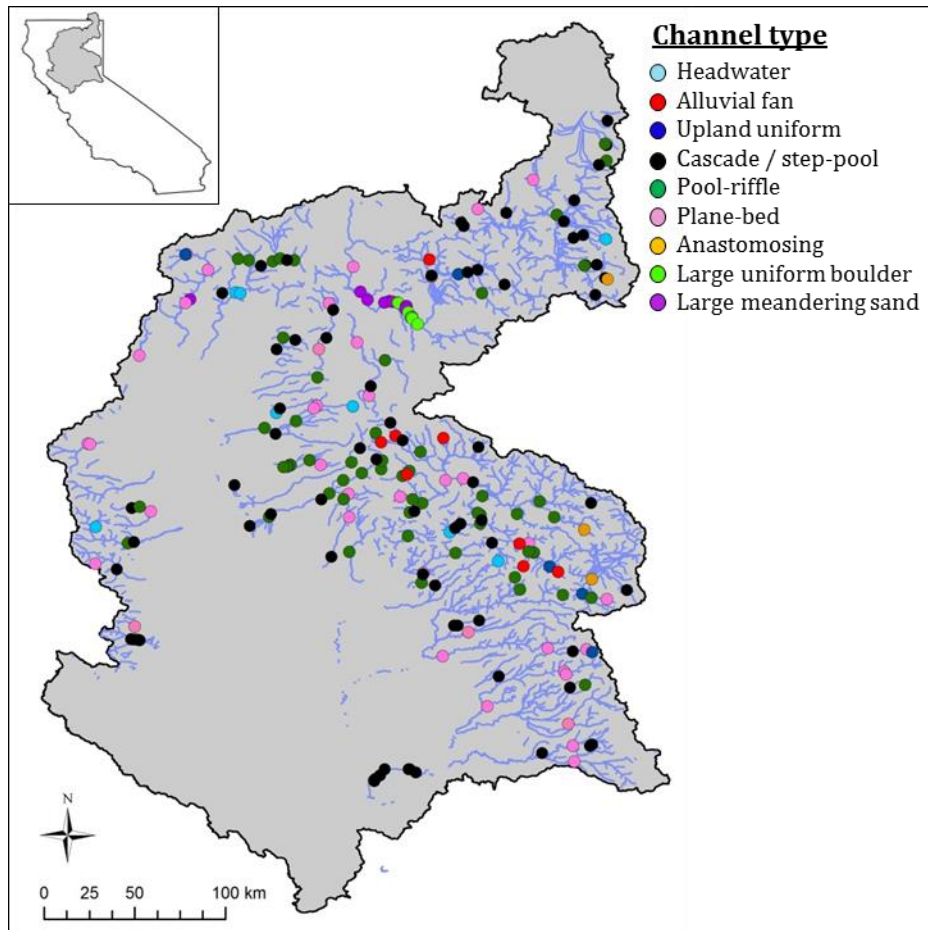
Figure 2-8. Map of the spatial distribution of field sites in the hydrological regime investigated and their classified channel types across low-volume snowmelt and rain dominated reaches (light blue lines) of the Sacramento Basin.

Table 2-3. ANOVA results show that mean geomorphic attribute values differ between the nine channel types. Statistically significant attributes ($p<0.05$) are indicated in bold.

Geomorphic attribute	Mean Square	F	p-value
$\overline{A_c}$	334.59	106.28	**0.00**
$\overline{d_{BF}D_{50}}$	121.09	26.96	**0.00**
$CV_{w.BF}$	0.25	19.90	**0.00**
$\overline{slope}$	37.06	18.63	**0.00**
$\overline{w.d_{BF}}$	76.26	15.98	**0.00**
$CV_{d.BF}$	0.24	15.90	**0.00**
$\overline{d_{BF}}$	59.50	12.20	**0.00**
$\overline{e.ratio}$	20.43	10.27	**0.00**
$\overline{w_{BF}}$	42.36	8.50	**0.00**
$\overline{sin}$	28.36	5.59	**0.02**
$\overline{D_{84}}$	9.86	4.96	**0.03**
$\overline{shear}$	9.28	4.66	**0.03**
Dmax	17.66	3.43	0.07
shields	0.74	0.14	0.71

Multivariate analyses revealed that the data-driven channel types identified exhibit significantly different geomorphic settings and identified the geomorphic attribute ranges across each channel type in the study basin. PerMANOVA results indicated that multivariate mean geomorphic setting is not equal for all nine channel types (p=0.0001; F-statistic=13), allowing for the rejection of the null hypothesis that channel types were identical. The CART analysis identified the most explanatory geomorphic attributes distinguishing channel types and their threshold values, providing potential ranges of attribute values expected for each channel type (Fig. 2-9). The classification tree model determined the relative strength of non-dimensional variables to be as follows: $CV_{w.BF}$, $\overline{sin}$, $\overline{slope}$, $\overline{e.ratio}$, $CV_{d.BF}$, $\overline{w.d}_{BF}$. This indicates that two of the six explanatory attributes identified by the model were TVAs (i.e., $CV_{w.BF}$, $CV_{d.BF}$), while slope played a lesser role. The non-dimensional classification tree correctly classified 85% of survey reaches based on their reach-averaged geomorphic attribute values (Fig. 2-9a). Alternatively, 93% of reaches could be correctly classified by the classification tree considering all attributes (Fig. 2-9b). When both dimensional and non-dimensional attributes were considered (n=17, Table 2-2), $\overline{D}_{84}$, A_c, and $\overline{w}_{BF}$ emerged as additional significant attributes for distinguishing channel types. Separate classification tree models using only the author's field sites (n=64) and using both the author's and SWAMP field sites (n=161) both identified $CV_{w.BF}$, $\overline{sin}$, and $\overline{slope}$ as the three primary attributes distinguishing channel types, emphasizing their persistent significance independent of individual field sites. Furthermore, $CV_{w.BF}$ emerged as a dominant attribute above traditional Rosgen (1994) geomorphic attributes in both models.
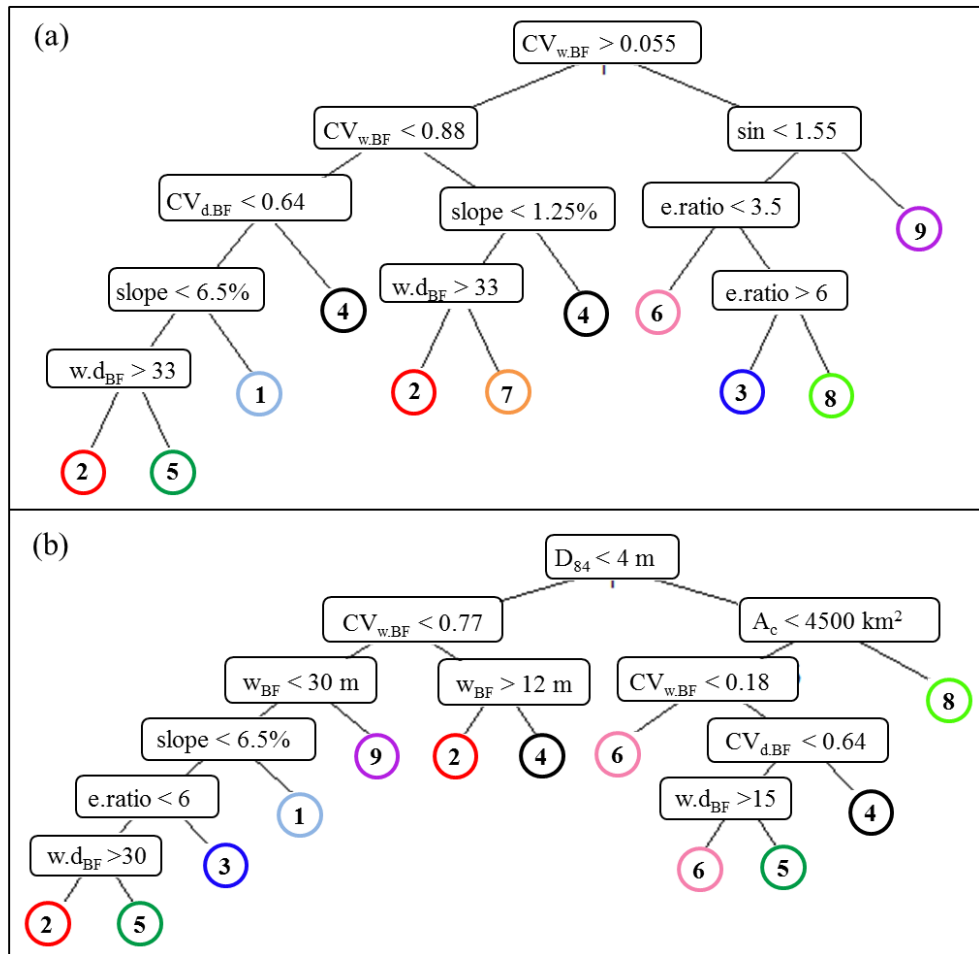
Figure 2-9. CART classification trees considering (a) non-dimensional and (b) all geomorphic attributes, indicating primary attributes and their threshold values distinguishing channel types. Geomorphic and topographic variability attributes are defined in Table 2-2 and circled numbers refer to channel types as defined in Table 2-4.

2.3.3. Physical interpretation of channel types

Physical interpretation of the above statistical analyses (summarized in Table 2-4) was used in combination with expert evaluation and existing channel classification literature to name the nine channel types based on their valley setting and distinguishing channel attributes (this nomenclature is used for the remainder of this study): 1. *confined headwater small boulder cascade*, 2. *partly-confined expansion pool - wide bar*, 3. *unconfined upland plateau large uniform*, 4. *confined cascade/step-pool*, 5. *partly-confined pool-riffle*, 6. *partly-confined large uniform*, 7. *unconfined anastomosing plateau small pool-riffle*, 8. *unconfined large uniform boulder*, and 9. *unconfined large meandering sand* (Fig. 2-10, Table 2-4).

1. CONFINED HEADWATER
SMALL BOULDER-CASCADE

2. PARTLY-CONFINED EXPANSION
POOL – WIDE BAR

3. UNCONFINED UPLAND PLATEAU
LARGE UNIFORM

4. CONFINED
CASCADE/STEP-POOL

5. PARTLY-CONFINED
POOL-RIFFLE
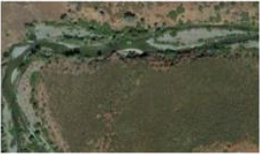
6. PARTLY-CONFINED
LARGE UNIFORM

7. UNCONFINED
ANASTOMOSING PLATEAU
SMALL POOL - RIFFLE

8. UNCONFINED
LARGE UNIFORM BOULDER

9. UNCONFINED
LARGE MEANDERING SAND BED

Figure 2-10. Example images of nine channel types distinguished in this study from field and Google Earth imagery.

Table 2-4. Descriptive names, literature analogs, key channel form characteristics, and physical process interpretation of identified channel types.

| Channel type	Descriptive name	Literature analog	Channel form characterization	Physical process interpretation
1	Headwater	Type A†	Highest slope*, high shear stress*, large D50 and D84, entrenched, low bf.w.d, low sinuosity, low bf.d.D50, very small Ac	Strong coupling between hillslope and channel; dominantly sediment evacuating system (Church 2002)
2	Fan	Type G4-5 †	High bf.w.d*, mid-slope, low shear stress, mid-sinuosity, small D50, D84, and Dmax, high sediment variance, mid bf.w and d. variance, very small Ac	Occurs at channel widening, often creating an alluvial fan; as a stream leaves a canyon, drainage becomes distributary; these wider, shallower, lower-gradient streams have limited transport capacity
3	Upland valley		High e.ratio (low entrenchment)*, low slope, low bf.d. and w. variance, small D50 and D84	Low energy alluvium filled valley; depositional environment
4	Cascade / Step-pool	Cascade or Step-pool‡; Type G1-2 or A †	High slope*, small D50 and variable D84, mid-sinuosity, high bf.d. and w. variance, low bf.d.D50, high shear stress, low bf.w.d	Valley confinement limits lateral adjustment capacity
5	Pool-riffle	Pool-Riffle ‡; Type C †	Mid-slope, mid bf.w. and d. variance and sediment variance, small D50, variable D84	Past threshold for dominantly un-coupled hillslope and channel (Church 2002); sinuous single thread channel formed and maintained by bank erosion and deposition on point bars; valley/floodplain controls on w and d drive heterogeneous conditions (topographic steering); substantial storage of episodically mobile bed material may occur in pool bottoms and on bars
6	Plane-bed	Plane-bed ‡; Type B †	Mid-slope, very low bf.w and d. variance, large D50, D84, Dmax, low shields stress	At time of transport the whole bed is moving as conveyor belt; no topographic steering control on where deposition or erosion take place drives uniform w and d
7	Anastomosing	Type DA †	Low slope, high e.ratio, small dimensions, small sediment, high bf.w and d variance and sediment variance, high shields stress, high bf.d.D50	Permanent multiple channels and mid-channel bars; channel width increases and depth decreases below a threshold for sediment transport and flow splits into deeper more narrow channels
8	Large uniform boulder		Low slope, large bf.d and w, high bf.w.d, small D50 and D84 but large Dmax, low bf.d. and w. variance and low sediment variance, very large Ac	Sinuous single thread channel
9	Large meandering sand		High sinuosity*, large bf.d and w*, very low bf.w. and d. variance, low slope, high bf.d.D50*, small D50 and D84 but large Dmax, low sediment variance, entrenched, low shear stress, very large Ac	Sinuous single thread channel; sediment fining and sorting has occurred; bed material is mobile over a wide range of flows and substantially the entire bed takes part in the sediment exchange with the flow (Leopold and Wolman 1957, Schumm 1963, Church 2002)

† Rosgen (1994)

‡ Montgomery and Buffington (1997)

The order of the identified channel types represents an idealized upstream to downstream progression in the landscape from montane to lowland streams, however some channel types are less predictable along such a progression (e.g., *partly-confined expansion pool - wide bar*, *unconfined upland plateau large uniform*). Four of the identified channel types (i.e., 2, 3, 6, and 8) were not commonly identified by previous classifications. The geomorphic characteristics of each channel type are described below, organized and interpreted with respect to presumed dominant channel processes and related to TVAs where applicable.

The *confined headwater small boulder-cascade* channel type (1) (*sensu* Sullivan 1986; Montgomery and Buffington 1997; Hassan et al. 2005) is characterized by the highest slopes and lowest A_c of any channel type. These channels exhibit high entrenchment, low width-to-depth, low sinuosity, and a boulder-dominated bed. High stream power combined with variable topography drive high sediment transport and high subreach-scale variability in scour and fill (Powell et al. 2005) indicated by high $CV_{d.BF}$. The *confined cascade/step-pool* channel type (4) is distinguished from the *boulder - cascade* by slightly lower slopes and larger A_c, as well as slightly increased channel dimensions and a reduction in $\overline{w.d}_{BF}$ and dominant sediment size. These changes are indicative of a downstream progression from hillslope- to channel-dominated processes. *Cascade/step-pool* channels are also characterized by the highest $CV_{d.BF}$ and $CV_{w.BF}$ of any channel type and generally negatively covarying bed and width undulations, indicating complex subreach-scale flow resistance dynamics. Flow resistance in these channels is hypothesized to be generated by the form drag of constricting step-forming roughness features and by tumbling flow regimes in which critical or supercritical flow over narrow step crests plunges into wider pools, abruptly decreasing velocity and generating substantial turbulence (Peterson and Mohanty 1960; Montgomery and Buffington 1997; Wohl and Thompson 2000; Wilcox and Wohl 2006; Wyrick and Pasternack 2008).

The *partly-confined pool-riffle* channel type (5) exhibits the next highest slopes and shear stress and slightly larger A_c than the *cascade/step-pool* channel. *Pool-riffle* channels are constrained by valley and floodplain topographic controls and characterized by positively covarying bed and width undulations that generate subreach-scale width and depth constrictions and expansions (indicated by high $CV_{w.BF}$ *and* $CV_{d.BF}$) which drive localized flow convergence. Topographically-driven convective accelerations have been shown to reinforce these nonuniform convergent and divergent flow patterns, and thus pool-riffle morphogenesis (Dietrich and Smith

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1983; Dietrich and Whiting 1989; Nelson and Smith 1989). The *pool-riffle* channel type is morphologically similar in many regards to the *partly-confined large uniform* channel type (6) except for significantly higher topographic variability and smaller sediment composition. This is interpreted as a difference in sediment transport mechanisms. In *pool-riffle* channels, topographic variability has been shown to control sediment transport through mechanisms such as topographic steering (Whiting and Dietrich 1991; MacWilliams et al. 2006), flow convergence (MacWilliams et al. 2006; Sawyer et al. 2010), and recirculating eddies (Lisle 1986; Rathburn and Wohl 2003; Woodsmith and Hassan 2005; Thompson and Wohl 2009). Alternatively, in *large uniform* channels largely devoid of any organized or rhythmic bedforms, at the time of transport the whole bed is expected to move as a conveyor belt (Lane and Carlson 1953; Montgomery and Buffington 1997). As there are no topographic steering controls on where deposition or erosion takes place in *large uniform* channels, the presumed result is maintenance of uniform width and depth with energy dissipation dominated by grain and bank roughness (Montgomery and Buffington 1997). The well-armored bed indicated by the large $\overline{D}_{50}$ and $\overline{D}_{84}$ suggest relative channel stability and a supply limited sediment transport regime (Dietrich et al. 1989).

Partly-confined expansion pool - wide bar channels (2) generally occur at abrupt valley widenings and exhibit very high $\overline{w.d}_{BF}$ and heterogeneous sediment composition (CV_{sed}). Alluvial fans develop by the accumulation of sediment where a channel exits an upland drainage area (Drew 1873). These lower-gradient Type 2channels running through alluvial fan style valley expansions likely have limited transport capacity due to reduced stream power and lateral flow divergence, driving rapid deposition of unsorted alluvial sediment (Paustian et al. 1992). These channels are distinguished by pool- wide bar morphology in which positively covarying bed and width variability combine with mobile sediment and limited lateral confinement to generate extremely wide, entrenched bars between constricted troughs.

The *unconfined upland plateau large uniform* channel type (3) exhibits very low entrenchment due to moderate-sized channels bordered by vast floodplains. The laterally unconfined upland plateau valleys through which these channels run are low-energy (low slope and A_c) depositional environments in which sediment supply is presumed to exceed transport capacity (Nagel et al. 2014). The uniform topography, low sinuosity, and homogenous sediment composition are indicative of uniform geomorphic processes [e.g., sediment transport as a

uniform sheet (Miller and Burnett 2008)]. The *unconfined anastomosing plateau small pool - riffle* channel type (7), also characterized by low entrenchment and a laterally unconfined valley setting, is distinguished from the large uniform channel type by much smaller channel dimensions and higher topographic variability and sinuosity. Similar to *partly-confined pool-riffle* channels, these channels are expected to maintain nonuniform morphology through nonuniform mechanisms such as topographic steering, flow convergence, and eddy recirculation. At the valley scale, these channels appear to connect to create multi-thread channels that diverge and converge around vegetated, rarely inundated islands cut from the floodplain (Knighton and Nanson 1993). The high channel depth variability that distinguishes this channel type from the *upland valley uniform* channel may be indicative of past avulsion triggered by rapid, heterogeneous channel deposition (Makaske 2001).

Finally, *unconfined large uniform boulder* (8) and *large meandering sand bed* channels (9) are characterized by very large A_c, large channel dimensions, low slopes, high sinuosity, and very low width and depth variability. *Large uniform boulder bed* channels are distinguished by boulder-dominated beds and lower bankfull depths, while the *large meandering sand bed* channels are sand-dominated and exhibit extremely high sinuosity and entrenchment typical of meandering morphologies (Hickin 1974). These differences likely indicate a difference in underlying geology and sediment supply constraining the formation of meanders by lateral migration and influencing channel bed composition. The *large meandering sand* channel type distinguished in this study appears similar to the meandering sand bed channel described by Lane (1957) and the labile channel distinguished by Church (2006). Meanders are hypothesized to be maintained primarily by the alternating converging and diverging secondary transverse flow cells in and between bends, respectively, which help to maintain sediment routing through the inside of meander bends (Thompson 1986). Mobile bedforms provide the primary hydraulic resistance in these channels (Kennedy 1975), driving "live bed" sediment transport (Henderson 1963).

2.4 Discussion

2.4.1. Lessons learned from channel classification modifications

Channel network stratification. The initial GIS-based stratification of the channel network based on catchment DEM-derived S and A_c proved effective at distinguishing underrepresented geomorphic settings in the landscape that would likely otherwise have been overlooked. While

some channel types (e.g., *pool-riffle*, *plane-bed*, *cascade/step-pool*) spanned many S-A_c bins, indicating their limited dependence on S or A_c, others were almost exclusively found in one bin (e.g., *pool - wide bar*, *large uniform boulder*, *large meandering sand*). Bins with the largest representation across the landscape unsurprisingly captured the largest number of channel types. Bins 2, 3, and 4 (Fig. 2-2) represented 28, 16, and 20% of the channel network in the study domain and contained 7, 6, and 5 channel types, respectively, compared with 3 channel types per bin on average. Geomorphic bins 1 – 5 with the smallest A_c accounted for 78% of LSR-dominated reaches in the Sacramento Basin while bins 11 – 13 with the largest A_c accounted for less than one percent of the study domain combined. However, field sites classified as *large uniform boulder* and *large meandering sand* channels fell almost exclusively in bins 11 – 13, emphasizing the value of stratified sampling for revealing naturally underrepresented channel types. Slope bins were more evenly distributed, but very low (<0.1%) and very high (>10%) slopes each accounted for less than 10% of the study domain. The identification of low slope dominated channel types by the classification (e.g., *anastomosing*, *large uniform boulder*, and *large meandering sand*) highlights the value of stratified sampling as these channel types would likely not have been sampled sufficiently to distinguish distinct classes in a uniform random sampling scheme given their limited representation in the basin.

The stratified sampling scheme enabled a large proportion of the full range of geomorphic variability present in the study domain to be captured by the field sites. For example, bankfull channel width across all surveyed sites ranged from 1.1 to 98.8 m. The smallest and largest channels evident in the system from visual inspection are 0.8 and 100 m, respectively, indicating that the sampling scheme captured 98% of the total range of bankfull widths. Similarly, the sampling scheme captured 78% of the total range of A_c and 65% of the total range of S. The maximum A_c for a surveyed site was 7,760 km^2 while the maximum A_c of any reach in the LSR channel network was closer to 10,000 km^2. The maximum surveyed S of 14.3% was substantially less than the estimated 22% maximum reach S. Overall, these results indicate that, while not entirely representative, stratifying field data collection by GIS-based landscape characteristics accounting for geologic structure, sediment availability, and sediment transport capacity enabled the resulting field sites to capture a large range of geomorphic variability. Splitting the channel network into further bins with more refined A_c and S requirements could increase the proportion of the total range of geomorphic variability captured by field surveys.

Alternatively, stratifying the network across other GIS-based characteristics such as bankfull width or adjusting the A_c and S thresholds for bin membership could potentially improve results.

Heuristic refinement of classification results. The nine channel types identified in this study capture a diverse range of reach-scale geomorphic settings including channel types previously identified by existing channel typologies and new, thus far unidentified, channel types. These findings emphasize the value of the *a posteriori* heuristic refinement of inductive classification results by suggesting that the resulting channel types retain a physical basis (deductive component) but are capable of capturing the unique context of the landscape under study (inductive component).

Identified channel types with strong analogs in the classification literature highlight the physical basis of the classification results achieved after heuristic classification refinement. For example, cascade channels as defined by Montgomery and Buffington (1997) generally occur on steep slopes, are narrowly confined by valley walls, and are characterized by longitudinally and laterally disorganized bed material typically consisting of cobbles and boulders. This channel type corresponds strongly to our identified *confined cascade/step-pool* channel, characterized by valley-confined channels with steep slopes, low width-to-depth, high bankfull width and depth variance, and cobble/boulder dominated sediment. Montgomery and Buffington (1993)'s plane-bed channel type refers to mid-slope planar gravel- and cobble- bed channels generally lacking discrete bars or in-channel features. This channel type is similar to our *partly-confined large uniform* channel, characterized by a moderate slope, cobble-dominated bed, and very low bankfull width and depth variance (indicating absence of bars and planar longitudinal morphology).

Some identified channel types have no analog in the Montgomery and Buffington classification designed for the mountains of the Pacific Northwest of the US, particularly those channel types associated with non-mountain environments. In these cases (e.g., *unconfined anastomosing plateau small pool-riffle*), the more descriptive Rosgen (1994) channel types may provide a better analog (Table 2-4).

Alternatively, the *large meandering sand bed* (9) channel type, while not present in the Montgomery and Buffington (1993) or Rosgen (1994) channel classifications, has been distinguished in numerous other channel classification frameworks (e.g., Lane 1957; Schumm 1963; Church 2006). The *partly-confined expansion pool – wide bar* channel type seems to only

have an analog in the moderate gradient alluvial fan channel as described by Paustian et al. (1992). This similarity of our results with the process-based channel types distinguished by Paustian et al. (1992) indicates that the classification framework as applied in this study is similarly capable of revealing distinct associations between channel morphology and processes.

Channel types with no clear analog in the literature were also identified (e.g., *unconfined upland plateau large uniform*, *unconfined large uniform boulder*), suggesting that the addition of TVAs to the classification framework combined with channel network stratification and heuristic refinement enabled the resulting channel classification to reveal the unique context of the landscape under study. For instance, *upland plateau large uniform* channels were distinguished from *anastomosing plateau small pool-riffle* channels primarily on the basis of topographic variability. Distinct geomorphic channel formation and maintenance processes and associated ecosystem functions were thus revealed from otherwise similar channel types and valley settings based on differences in subreach-scale topographic variability.

2.4.2. Value of topographic variability attributes

Distinguishing channel types. With respect to the first study objective, TVAs were found to play a major role in distinguishing channel types across the landscape. Numerous univariate and multivariate statistical analyses all identified bankfull width and depth variability as first-order predictors of geomorphic channel type. Even though S and A_c - frequently identified as dominant variables controlling channel form and geomorphic processes (Leopold and Maddock 1953; Dunne and Leopold 1978; Dietrich et al. 1992; Montgomery and Buffington 1997; Church 2002) - were used to stratify the channel network prior to random sampling, they were not identified as the primary attributes distinguishing geomorphic channel types, though they were significant attributes in CART. The hierarchical clustering structure (Fig. 2-6) and classification tree (Fig. 2-9) both identified $CV_{w.BF}$ as the primary splitting variable distinguishing channel types for LSR streams of the Sacramento Basin.

Unlike most geomorphic attributes, which had overlapping value ranges across all but one channel type (e.g., $\overline{w.d}_{BF}$, $\overline{e.ratio}$, $\overline{sin}$, $\overline{shear}$), $CV_{w.BF}$ and $CV_{d.BF}$ exhibited more uniform density distributions (Figure 5) and expressed a continuum of value ranges across all nine channel types (Fig. 2-7). Thus, TVAs were found to be very important because they show that some rivers have substantial channel bed and width variability and some do not– it is the

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variability in the variability that makes them powerful classifiers compared to A_c and many other reach-average metrics. For example, the channel classification distinguished four channel types with very low, one with moderate, and four with high topographic variability. Of the highly variable channel types, two exhibited primarily positive width and depth covariance, one exhibited primarily negative covariance, and one exhibited a mixture of both.

It may be possible that the significance of TVAs in this study is influenced by the specific positioning or frequency of cross-sections along each study reach. Topographic variability is often structured with quasi-periodic undulations, so how sample locations align with those structures is very important and probably should not be left to chance when designing observation protocols. Future studies with more cross-sections per reach or using near-census channel width measurements based on high-resolution remote sensing data would reduce the likelihood that the variability being measured is a function of the cross-section locations. However, the statistically distinct clustering solution and physical interpretability of results indicate that the significance of TVAs in the channel classification is fundamentally based on differences in subreach-scale channel forms and processes.

Furthermore, study results indicate that the history of land use and anthropogenic alterations in the Sacramento Basin are not artificially inflating the importance of TVAs in the landscape. If any reaches with small degrees of variability stood out given the simplified nature (e.g., dredged and straightened) of many parts of the basin, one would expect to see a highly skewed distribution of TVA values towards low variability. However, the uniform distributions exhibited by $CV_{w.BF}$ and $CV_{d.BF}$ (Fig. 2-5) negate this hypothesis, indicating instead a large, relatively evenly distributed range of width and depth variability across the landscape.

Characterizing dominant channel processes. With respect to the second study objective, TVAs were found to be extremely useful for characterizing dominant channel processes that have been reported extensively in the literature but which have been neglected from quantitative classification studies prior to this. Most studies only consider processes in terms of reach-average erosive potential, sometimes relative to sediment supply. They have no basis for describing channel types in terms of the actual specific processes that occur in reaches, such as knickpoint migration, bank erosion, and island formation. By incorporating TVAs in a channel classification framework, we were able to characterize and distinguish the type and magnitude of topographic variability within reaches. In doing so, this study provided a quantitative basis for interpreting

the resultant classes in terms of a diversity of mechanisms for fluvial landform formation and maintenance that rely on both nonuniform and uniform channel morphology (Lane and Carlson 1953; Dietrich and Smith 1983; Thompson 1986; Paustian et al. 1992; Wohl and Thompson 2000; Makaske 2001; Powell et al. 2005; Wilcox and Wohl 2006; White et al. 2010). As hypothesized, TVAs - closely tied to nonuniform processes - improved the ability to characterize and compare dominant channel processes in many channel types. For example, differences in TVAs and their covariance as distinguished by the channel classification appeared to be indicative of different sediment transport mechanisms in partly-confined pool – riffle and large uniform channels. Similarly, the high channel depth variance distinguishing unconfined plateau small pool-riffle channels from large uniform channels supported the interpretation of the dominant channel forming process as avulsion and the dominant channel maintenance processes as topographic steering, flow convergence, and eddy recirculation in spite of very similar valley settings and traditional geomorphic attributes (e.g., $\overline{slope}$, $\overline{w.d}_{BF}$, $\overline{e.ratio}$, $\overline{D}_{84}$). Alternatively, unconfined large uniform boulder and meandering sand bed channel types were differentiated on the basis of underlying geology rather than TVAs.

Ecological implications. The spatial variability or lack thereof of channel morphology and associated geomorphic processes as distinguished by TVAs has important ecological implications. For example, differences in spatial patterns of hyporheic exchange (Kasahara and Wondzell 2003; Tonina and Buffington 2009) drive differences in local biogeochemistry (Poole et al. 2008) and habitat dynamics (Geist 2000). Channels with high subreach topographic variability and associated heterogeneous sediment scour and deposition (e.g., our *pool-riffle* and *cascade/step-pool* channels) may exhibit highly localized hyporheic exchange (Kasahara and Wondzell 2003; Poole et al. 2006, 2008), creating local nutrient hotspots associated with algae or macrophyte growth (Fisher et al. 1998) and preferential spawning habitat (Geist 2000). In contrast, the uniform flow and sediment transport processes exhibited by very low topographic variability (e.g., *upland valley uniform* channels) are associated with long hyporheic flow paths that modify the reach's mean daily temperature (Poole et al. 2008) and biogeochemistry (Findlay 1995) from average channel conditions, in turn affecting habitat quality (Poole et al. 2008; Tonina and Buffington 2009) and salmonid population structure (e.g., Burnett et al. 2003) throughout the reach. Unconfined uniform channels with the propensity for these long hyporheic

flow paths have also been shown to provide low-velocity refugia for biota during periods of high flow (e.g., Wenger et al. 2011) and support wider riparian zones (Polvi et al. 2011).

Incorporating TVAs in channel classification is also expected to inform river restoration efforts. For example, riparian species richness has been shown to increase with subreach-scale bed elevation variability (Pollock et al. 1998), suggesting that characterizing TVAs in addition to more traditional geomorphic attributes may help predict the impact of disturbances on the biotic community across the channel network. Targeting high variability channel types (e.g., *cascade/step-pool*, *pool-riffle*) for riparian restoration efforts may increase the likelihood of success by increasing the range of hydrogeomorphic and thus ecological responses to disturbance. Alternatively, channel change associated with channel unit to reach scale (e.g., 10 – 100 channel widths) changes in TVAs may indicate changes in flow regimes, sediment regimes, or land use (Montgomery and Bolton 2003), indicating critical locations for larger-scale restoration efforts. For example, the conversion of fully forested riparian zones to grasslands has been associated with a significant reduction in within-reach width variability (Jackson et al. 2014). By identifying channels with rapidly changing $CV_{BF.W}$, practitioners may more easily define management objectives and prioritize restoration activities. Characteristic TVA values of ecologically functional reaches could provide practitioners with a baseline level of channel and floodplain variability to incorporate into restoration efforts for degraded reaches.

2.4.4. Future research

With the aim of characterizing dominant process regimes of distinct channel types as differentiated by TVAs, we speculated as to the physical processes associated with each identified channel type. We suggest direct measurement of these hypothesized dominant subreach-scale processes and their co-occurrence with distinct TVA settings as an important direction for future work. For instance, measurement of hydraulic flow fields, hyporheic exchange, or sediment transport rates across channel types would bolster physical understanding of the differences in processes regimes between distinct TVA settings.

With the emergence of meter-scale remote sensing of rivers, datasets that support computing and analyzing TVAs will become more available, accurate, and useful (Gleason and Wang 2015; Gonzalez and Pasternack 2015). In the meantime, by considering TVAs in addition to more traditional channel classification attributes, we hope to encourage future research into how a

stream reach is influenced by its surrounding landscape at various scales based on hierarchical topographic variability relationships. This could enable the application of increasingly available larger-scale topographic datasets to distinguishing differences in multi-scale process controls on channel morphology and predicting reach-scale geomorphic settings. Further understanding of relationships between TVAs and multi-scale geomorphic processes is critical to developing insight into sediment transport and formative processes in these diverse channel types.

2.5 Conclusion

This study found that measures of subreach-scale topographic variability provided improved information on river geomorphic landforms and processes in channel networks of varied landscapes. When incorporated in a channel classification framework among a suite of more traditional geomorphic attributes, TVAs improved the ability to distinguish dominant channel types and associated geomorphic processes in low-volume snowmelt and rain dominated streams of a Mediterranean region. Bankfull width variance was identified as the primary attribute distinguishing channel types over common attributes such as channel slope, width-to-depth ratio, confinement, sinuosity, and dominant substrate. The nine channel types distinguished for the Sacramento Basin included both channel types with strong analogs in existing geomorphic literature and novel channel types. By reenvisioning channel classification through the incorporation of TVAs, distinct channel landforms and processes were revealed from otherwise similar geomorphic settings with limited additional resource requirements. Results indicate that incorporating TVAs in channel classification may improve river restoration efforts by revealing ecologically-significant differences in channel form and function.

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CHAPTER 3

FLOW, FORM, AND FUNCTION: PREDICTING ECOHYDRAULIC PERFORMANCE WITH RELEVANCE BEYOND THE STREAM REACH

Abstract

The extent and timing of river ecosystem functions is largely controlled by the interplay of streamflow dynamics, or flow, and river corridor shape and structure, or form. However, most river restoration studies evaluate the role of either flow or form without regard for their dynamic interactions. This study represents a first attempt to apply synthetic channel archetypes to the evaluation of river flow-form-function linkages to inform process-driven river restoration efforts with limited data and financial resources. In an application to California's Mediterranean-montane streams, the interacting roles of channel morphology, water year type, and hydrologic impairment were evaluated with respect to a suite of river ecosystem functions related to hydrogeomorphic processes, aquatic habitat utilization, and riparian habitat recruitment dynamics. Channel form acted as the dominant control on overall hydraulic diversity and the occurrence of flow convergence routing, while water year type controlled salmonid bed occupation and preparation functions. Streamflow alteration for hydropower increased redd dewatering risk and altered aquatic habitat availability and riparian recruitment dynamics. Study results highlight critical tradeoffs in ecosystem function performance and emphasize the significance of spatiotemporal diversity of flow and form at multiple scales for maintaining river ecosystem integrity. The approach is broadly applicable and extensible to other systems and ecosystem functions, where findings can be used to characterize complex controls on river ecosystems, assess impacts of proposed flow and form alterations, and inform river restoration strategies.

3.1 Introduction

Rivers are highly complex, dynamic systems. Streamflow, for example, provides ecosystem functions by transporting sediment, modulating biogeochemical processes, regulating disturbances, and supplying habitat for aquatic species (Doyle et al., 2005). The extent and timing of these functions is largely controlled by the interplay of streamflow dynamics, or *flow*, described by streamflow magnitude, timing, duration, frequency, and rate-of-change (Poff, 1997), and the shape and structure of the river channel, or *form*, described by channel slope, planform and cross-sectional geometry, sediment composition, etc. (Small et al., 2008;

Pasternack et al., 2008; Worthington et al., 2014; Wohl et al., 2015; Yarnell et al., 2015; Vanzo et al., 2016).

Alluvial rivers are generally thought to adjust their morphology and bed substrate regimes to their flow regime (Wolman and Miller, 1960; Leopold et al., 1964; Poff, 1997). Under these circumstances, reinstating the natural flow regime would be expected to promote natural geomorphic processes and dependent ecosystem functions. However, this notion is often inaccurate for intensively altered river systems (Jacobson and Galat, 2006; Wohl et al., 2015). Channel form and bed substrate regimes are often partially or entirely uncoupled from flow in such systems, limiting the efficacy of considering the flow regime alone in river restoration studies (Brown and Pasternack, 2008). In spite of this, many studies evaluate the effects of flow on a particular species or life-stage without regard for the role of channel form in modulating ecosystem response (Stalnaker et al., 1995; Tharme, 2003; Poff et al., 2010; Wohl et al., 2015).

The few studies that have effectively examined the interacting roles of flow and form in the performance of river ecosystem functions (or flow-form-function linkages) highlight the scientific and management value of such analyses. For instance, by evaluating the potential for shallow water habitat in the historic and current lower Missouri River corridors under various dynamic flow regimes based on hydraulic model outputs, Jacobson and Galat (2006) informed restoration priorities for the Missouri River. Such studies distinguish stream reaches that are flow- or form-limited for future management efforts and guide ecologically functional river management. However, this and similar studies (Brown and Pasternack, 2008; Price et al., 2013; Gostner et al., 2013b) are site specific, limiting their applicability to the range of flow and form settings that may be exhibited by a given hydroscape, as evidenced by existing hydrologic and geomorphic classifications (e.g., Lane et al., 2017a, 2017b), each combination supporting a distinct set of ecosystem functions. Vanzo et al. (2016) offer a valuable exception in their evaluation of the ecohydraulic response to hydropeaking over a spectrum of flows and forms and the ecological trade-offs between various combinations.

Utilizing archetypal channel forms and streamflows in lieu of detailed, site-specific datasets allows for the evaluation of a larger range of flow-form settings exhibited by a hydroscape with limited data and financial resources, thus improving basic understanding of the interacting roles of river flow and form with respect to ecohydrology and ecohydraulic response, respectively. In this study, an archetype refers to a simple, standard example exhibiting typical qualities of a

particular group without the full local variability distinguishing members of the same group (Cullum et al., 2017). An archetypal approach was employed by Escobar-Arias and Pasternack (2011) in an ecohydraulic analysis of sediment mobility dynamics under a set of representative 'at-a-station' cross-sections and streamflow times series from distinct water year types. An emerging technique for synthesizing digital terrain models (DTMs) of river corridors using simple mathematical functions (Brown et al., 2014) provides an opportunity to expand on the work of Escobar-Arias and Pasternack (2011) to evaluate 2D ecohydraulic response to flow-form interactions for channel and floodplain morphologies of interest without a dramatic increase in data requirements.

The application of synthetic DTMs to the evaluation of ecohydraulic performance bypasses data constraints of previous studies through the ability to directly generate representations of historic, existing, or proposed morphologies with user-defined geomorphic attributes. These synthetic river corridors have been used to test the occurrence of the hydrogeomorphic mechanism known as flow convergence routing across a range of archetypal morphologies (Brown et al., 2015), but have not yet been applied to the development of ecohydraulic design criteria. At the rapid rate of river ecosystem degradation (Magilligan and Nislow, 2005), the ability to design and compare the ecohydraulic performance of distinct morphologies with relevance beyond an individual study site to an entire watershed or physioclimatic setting would offer a powerful tool to support the design of functional large-scale river rehabilitation measures (Brown et al., 2015).

3.1.1. Flow-form-function conceptualization

The performance of a given ecosystem function depends on a nested set of physical controls. At the largest spatial and temporal scale, climate and geology act as independent controls on the range of possible reach-scale flow and form settings through their influence on factors such as topography, vegetation, and sediment supply and composition. Ecological and geomorphic studies frequently focus on the reach scale largely because variables of interest remain relatively homogeneous within a reach several channel widths in length (Montgomery and Buffington, 1997). In response to these controls, the flow and form settings of a given stream reach are characterized by specific attributes. Ecologically relevant attributes of *flow* include the magnitude, frequency, duration, timing, rate of change, interannual variability, and sequencing of

flows (Poff, 1997). Classifications of flow regimes have identified distinct patterns of flow at the watershed to global scale based on these attributes (Richter, 1996; Poff et al., 2010; Reidy Liermann et al., 2012; Olden et al., 2012). Similarly *form*, defined herein as the morphology and composition of the river corridor, can be characterized and classified by reach-scale topographic attributes including slope, channel dimensions, planform and cross-sectional geometry (Rosgen, 1994; Montgomery and Buffington, 1997; Thomson et al., 2001; Kasprak et al., 2016), and sediment composition, as well as subreach-scale topographic landform variability and patterning (i.e., departures from reach-averaged bed elevation, bankfull width, curvature, and floodplain width) (White et al., 2010; Brown and Pasternack, 2014; Lane et al., 2017b).

Different combinations of these flow and form attributes, as distinguished by hydrologic and channel classifications, are generally hypothesized to generate different hydraulic patterns of depth and velocity in the river corridor, in turn supporting different ecosystem functions or varying performance of the same function. River ecosystem functions can be grouped into three functional categories: hydrogeomorphic processes, aquatic habitat, and riparian habitat (Table 3-1Table 3-1). Hydrogeomorphic processes play key roles in creating, modifying, or destroying aquatic and riparian habitat and act as ecological disturbances that shape ecosystem characteristics and dynamics (Montgomery, 2003). Example ecosystem functions categorized as hydrogeomorphic processes include flow convergence routing, salmonid bed preparation, and hydraulic diversity, each controlled by a distinct combination of flow and form attributes, as indicated in Table 3-1Table 3-1. Aquatic habitat functions consist of utilization indicators such as salmonid bed occupation suitability and redd dewatering risk. Riparian habitat functions characterize riparian recruitment and growth dynamics.

Table 3-1. Key flow and form attributes and their interacting controls on example river ecosystem functions related to hydrogeomorphic processes, aquatic habitat, and riparian habitat.

Ecosystem function category	Hydrogeomorphic processes			Aquatic habitat		Riparian habitat
Example functions	flow convergence routing	salmonid bed preparation	hydraulic diversity	redd dewatering	salmonid bed occupation	riparian recruitment
Flow						
timing		X		X	X	X
magnitude	X	X	X	X	X	X
duration		X		X	X	X
frequency						X
rate of change						X
Form						
slope	X	X		X	X	
channel dimensions	X	X	X	X	X	X
topographic variability	X	X	X	X	X	X
geomorphic covariance	X	X	X	X	X	
sediment composition		X			X	X

3.1.2. Study objectives

This study represents a first attempt to apply synthetic DTMs of archetypal river morphologies to the evaluation of flow-form-function linkages to understand how river corridor configurations interact with hydrologic dynamics to influence ecological and geomorphic processes. The authors investigate the common notions of flow-process and form-process linkages, in which different flow regimes and morphologies, respectively, are assumed to support distinct hydrogeomorphic processes (Montgomery, 1997; Poff, 1997; Kasprak et al., 2016), by examining the performance of a suite of ecosystem functions across alternative flow-form scenarios. The overall goal of the study is to test whether archetypal combinations of flow and form attributes generate spatiotemporal hydraulic patterns that support distinct ecosystem functions.

The study objectives are to (1) generate synthetic digital terrain models of distinct channel morphology archetypes, (2) evaluate the spatiotemporal patterns of fundamental hydraulic variables across alternative morphologies, and (3) quantify the performance of a suite of river ecosystem functions across alternative flow-form test cases. The specific scientific questions addressed through these objectives are as follows: (i) Do archetypal channel morphologies

support distinct hydrogeomorphic processes and dependent ecosystem functions or is more or different local variation within archetypes needed? (ii) What is the significance of subreach-scale topographic variability in river ecosystem functioning? (iii) What are the separate and combined roles of water year type, hydrologic impairment, and channel morphology in the performance of critical Mediterranean-montane ecosystem functions? (iv) What performance tradeoffs can be identified with relevance for environmental water management?

3.1.3. Case study: Mediterranean-montane rivers

Mediterranean-montane river systems provide a useful case study for evaluating the interacting roles of hydrologic and geomorphic dynamics in ecosystem functioning. In the Mediterranean-montane Sierra Nevada of California, with extreme seasonality and interannual variability, native river biota are highly adapted to the natural biotic and abiotic stresses associated with hydrogeomorphic variability (Gasith and Resh, 1999). Many ecosystem functions critical to riverine biota in Mediterranean systems depend on the performance of ecosystem functions that vary with both flow and form. Salmonid eggs, for example, require sufficient inundation depths and intragravel flows in certain channel locations during biologically significant periods to survive (Service, 2010a). In a geomorphic example, flow convergence routing, considered a key sediment transport mechanism for maintaining topographic variability and associated biological diversity in mountain streams, depends on the migration of peak shear stress and spatially convergent flow from topographic highs (riffles) to troughs (pools) from low to high discharge, respectively (Wheaton et al., 2010). The hydraulic parameters associated with these functions (e.g., depth, velocity, shear stress) depend on sufficient flow magnitudes and durations over appropriate channel and floodplain morphologies.

The rivers of the Sierra Nevada are highly altered by dams and reservoir operations for water supply, flood control, and hydropower (Hanak et al., 2011). In general, these activities have led to increasing channel simplification, armoring, and entrenchment (Yarnell et al., 2015). Simultaneously, anthropogenic activities have driven intensive regulation of the highly seasonal and predictable flow regimes to which native Mediterranean biota are adapted (Gasith and Resh, 1999). For example, the natural recession of the spring snowmelt regime is often dampened for flood control or ramped down more rapidly for hydropeaking, driving dramatic declines in native salmonid and amphibian populations (Yarnell et al., 2016).

3.2 Methods

The methodology for addressing the scientific aims of this study can be summarized by three steps (Fig. 3-1). First, a set of hydrologic scenarios is selected for evaluation and a set of DTMs is generated to synthesize archetypal river corridor morphologies. Next, a 2D hydrodynamic model [SRH-2D (Lai, 2008)] is used to simulate ecologically relevant hydraulic parameters [ERHPs, *sensu* Vanzo et al. (2016)] for each flow-form test case. Finally, spatiotemporal ERHP patterns are used to evaluate the performance or occurrence of a suite of ecosystem functions in each test case.
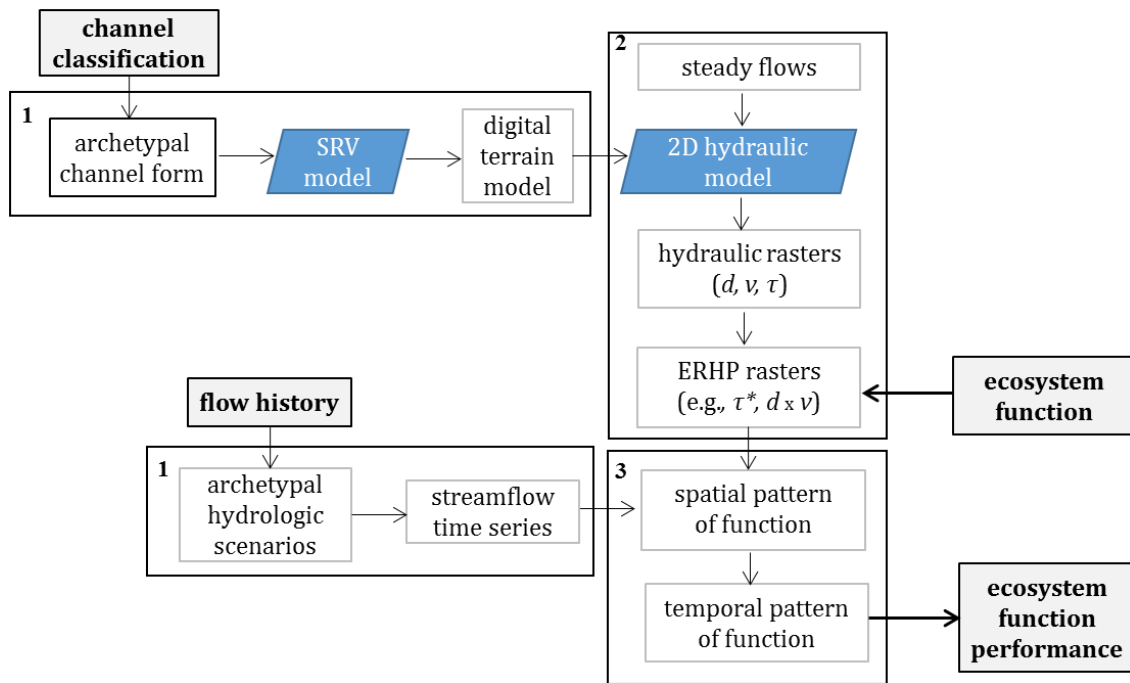
Figure 3-1. Major steps used to quantify ecosystem function performance across archetypal channel forms and hydrologic scenarios. Key inputs and outputs are bolded and modeling tools are blue parallelograms, including the Synthetic River Valley (SRV) model for generating digital terrain models from archetypal channel forms.

In the second step (Fig. 3-1), select archetypal streamflow time series and digital terrain models generated in step one from flow history and channel classification inputs, respectively, are input to a 2D hydraulic model to produce a continuum of hydraulic rasters [i.e., depth (d), velocity (v), shear stress (τ)] for a modeled river corridor at each modeled flow stage. For each model run, a set of ERHP rasters is calculated [e.g., Shield's stress (τ^*), $d \times v$] from fundamental hydraulic raster outputs. In step three, spatial and temporal statistics characterizing ERHP outputs are used first to evaluate hydraulic model results in terms of fundamental hydraulic

parameters (water depth and flow velocity) at base, bankfull, and 50% exceedance flows, and then to quantify the performance of distinct ecosystem functions.

Spatial statistics (e.g., proportion of wetted area, location, average value) are used to quantify the patterns of ERHPs for each flow stage based on the specific spatial extent (e.g., bankfull channel or floodplain) and hydraulic thresholds associated with each ecosystem function (e.g., shear stress > gravel entrainment threshold). Temporal dynamics of these patterns are then evaluated by integrating flow-based ERHP statistics over each hydrologic scenario. Using simple look-up tables, each day in an annual time series is associated with an ERHP spatial statistic value for a given channel morphology. The resulting time series represent the temporal pattern of 2D ecohydraulic response in a given morphological configuration under a single hydrologic scenario. These time series can then be analyzed to quantify the performance of ecosystem functions of interest based on ecologically relevant temporal requirements related to timing, frequency, duration, or rate-of-change of ecohydraulic response.

As applied to this specific study, the experimental design involved a series of 16 numerical runs of a 2D hydrodynamic model under steady flow conditions, simulating two channel morphologies across eight discharges spanning baseflow (0.2 times bankfull) to twice bankfull flow stages. These eight discharges discretized the daily flow regimes of four annual hydrologic scenarios. All simulated combinations were designed to reproduce realistic archetypal flow and form conditions in Mediterranean-montane river systems for two classes of interest (Lane et al., 2017b). A rigorous scaling approach to compare the full range of possible configurations was outside the scope of the current study. The following sections describe the flow regimes, river corridor morphologies, hydraulic modeling approach, and ecosystem functions considered.

3.2.1. Channel morphologies

Two morphological configurations were considered in this study, semi-confined plane bed and pool-riffle morphologies. These morphologies were selected for their common occurrence in mid-elevation montane environments and similar dimensions and slopes contrasted by their major differences in subreach-scale topographic variability (Fig. 3-2). An existing channel classification for the Sacramento Basin (Lane et al., 2017b) provided the parameter values needed to synthesize the two archetypes, quantified as the median field-surveyed values for each channel type.
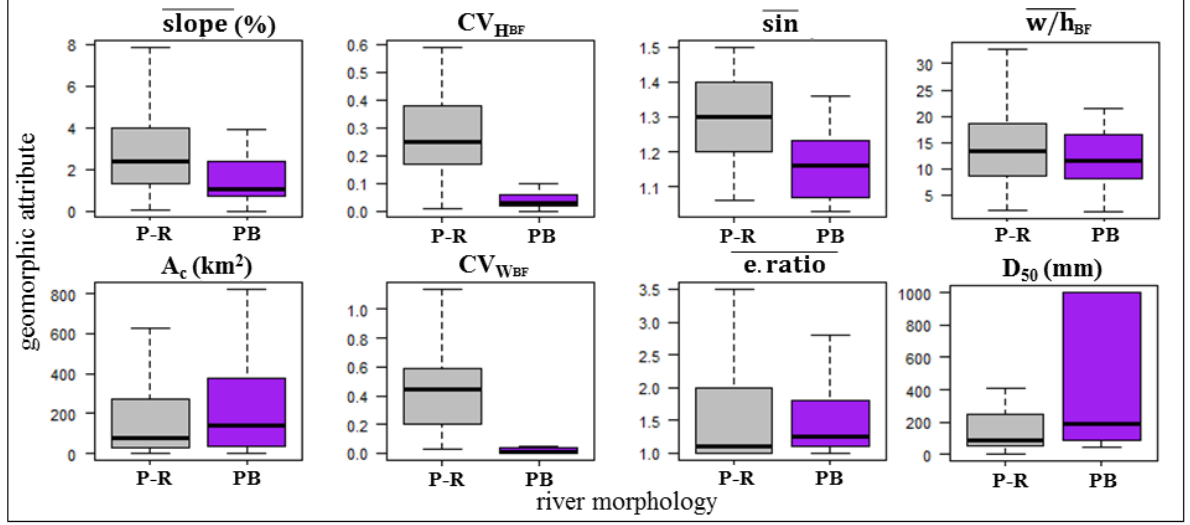
Figure 3-2. Box plots comparing field-based geomorphic attributes (range, interquartile range, and median) between pool-riffle (P-R) and plane bed (PB) morphologies, including contributing area (A_c), sinuosity (sin), entrenchment ratio (e.ratio), and median sediment size (D_{50}) from Lane et al. (2017b).

DTMs of the investigated channel types were generated using the synthetic river valley framework of Brown et al. (2014), with the parameter values taken from a real-world channel dataset (Fig. 3-2). Herein only the equations vital to understanding the DTMs created in this study are provided. The goal of the design process is to capture the essential organized features of each channel type so that their functionalities can be evaluated in a reductionist approach without the random details of real river corridors that cause highly localized effects- those features can also be studied, but they are not the focus of the current study.

Reach-average parameters

The synthetic river valley approach first creates a reach-averaged channel that is scaled by the bankfull width and depth, with reach-averaged bankfull width (w_{BF}), median sediment size (D_{50}), and slope (S) as input variables, and bankfull depth (h_{BF}) determined from these variables by setting it equal to critical depth for incipient motion so that the geometry reflects a quasi-equilibrium state. This first step draws on the common understanding of rivers as having representative reach-scale typologies, as widely published in many river classification systems (Kasprak et al., 2016). Assuming h_{BF} can be approximated by the hydraulic radius, the depth at incipient motion was used to determine h_{BF} as follows

$$h_{BF} = \frac{(\gamma_s - \gamma_w) D_{50} \tau_c^*}{\gamma_w S} \qquad [3.1]$$

where y_s and y_w are the specific weight of sediment and water, respectively and τ_c^* is the reach-averaged critical Shields stress for sediment entrainment (Miller et al., 1977). For each channel scenario, there were 140 longitudinal nodes spaced at 1 m (~1/10 bankfull channel widths) with a total length of 140 m. The user-defined channel (w_{BF}, S, D_{50}) and floodplain (width, lateral slope) attributes were set with the aim of designing DTMs to reflect the channel classification-derived values for reach-averaged geomorphic attributes.

Channel variability functions

Next, this approach adds on subreach-scale topographic variability, because many geomorphic processes and ecological functions depend on high topographic variability and associated heterogeneous habitat (MacWilliams et al., 2006; Poff and Ward, 1990; Scown et al., 2015). Synthetic sub-reach variables can be used to mimic more local scale conditions with minimal field data. The local bankfull width at each location x_i along the channel $w_{BF}(x_i)$ is given by the following equation as a function of reach-averaged bankfull width w_{BF} and a variability control function $f(x_i)$, with a similar equation used to characterize the depth profile that incorporates S and vertical channel undulations

$$w_{BF}(x_i) = w_{BF} * f(x_i) + w_{BF} \qquad [3.2]$$

There are many available mathematical and statistical control functions that may be used to describe archetypal river variability (Brown and Pasternack, 2016). For example, the sinoidal function could be a good choice to capture riffle-pool bed undulations with sharp transitions and long, flat troughs and crests. Autoregressive statistical functions could capture sinuosity well. For the experimental purpose of this study, the variability of w_{BF} and h_{BF} about the reach-averaged values was determined by a sinusoidal function, as

$$f(x_i) = a_s \sin(b_s x_r + h_s) \qquad [3.3]$$

where a_s, b_s, and h_s are the amplitude, angular frequency, and phase shift parameters for the sinusoidal component, respectively, and x_r is the Cartesian stationing in radians. The Cartesian stationing was scaled by w_{BF} so that the actual distance was given by $x_i = x_r * w_{BF}$. The sinusoidal function alignment parameters describing undulations in planform, bankfull width, channel bed elevation, and floodplain width were adjusted through an iterative process to achieve desired values for h_{BF}, width-to-depth ratio (w/h_{BF}), sinuosity, and the coefficient of variation (CV) of w_{BF} and h_{BF} based on channel classification archetypes for plane bed and pool-riffle

morphologies (Lane et al., 2017b). Geomorphic covariance structure (GCS) refers to the longitudinal profile of covarying bed and width fluctuations, which can covary positively (narrow troughs and wide riffles) or negatively (narrow riffles and wide troughs). Floodplain confinement, the ratio of bankfull width to floodplain width, was used to set valley width.

Because river classification datasets traditionally aim to capture the central tendency at the reach scale, they contain little to no information on subreach-scale variability and landform patterning. This study used a new classification methodology that included statistical characterization of subreach-scale variability using the metric of coefficient of variation (Lane et al., 2017b). However, there were numerous possible landform patterning permutations using the control function parameters of Eq. 3.3 that could yield those statistical values, many with profoundly different processes. To choose the correct permutation of parameters, expert judgment was used based on field experience and understanding of how to interpret the processes associated with different patterns of topographic variability. Over time, more datasets focusing on geomorphic variability will be published enabling more confident parameterizations (Brown and Pasternack, 2017). Similarly, some attributes required to generate the synthetic topographies, such as floodplain width variability and floodplain lateral slope, were not available in the channel classification of Lane et al. (2017b). In these cases, field experience and judgment informed design of topographies capable of supporting the dominant geomorphic processes of each channel type as outlined in this classification study. The ability to design synthetic topographies from channel classification archetypes to exhibit distinct hydrogeomorphic processes of ecological relevance based on this methodology is explored further in the discussion section.

3.2.2. Flow regimes

Four hydrologic scenarios were evaluated, characteristic of the mixed snowmelt and rain hydrologic regime (Lane et al., 2017a) typical of Mediterranean-montane systems: unimpaired and altered annual hydrographs under wet and dry water year conditions. Daily streamflow time series for two mid-elevation gauge stations in the western slope of the Sierra Nevada, California, were chosen to represent this archetypal hydrologic regime under unimpaired (North Yuba River below Goodyears Bar) and highly altered (New Colgate Powerhouse) conditions (Fig. 3-3). These gauges lie within similar physioclimatic and geologic settings and provide daily

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streamflow time-series for both an extremely wet (2010; >75th percentile annual streamflow) and an extremely dry (2014; <25th percentile annual streamflow) water year.
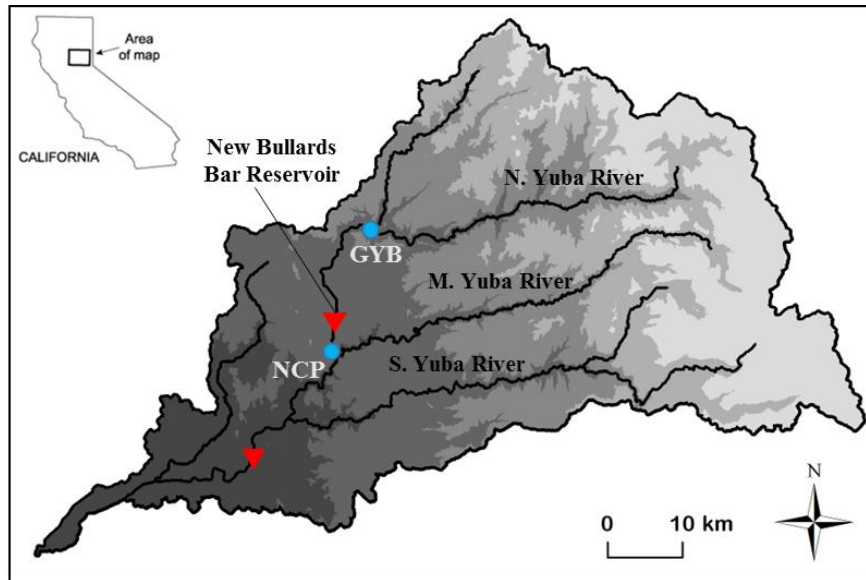
Figure 3-3. Map of the Yuba River watershed, indicating North Fork Yuba River unimpaired (Goodyears Bar, GYB) and altered (New Colgate Powerhouse, NCP) gages considered in this study (blue dots) and major dams (red triangles).

The four hydrologic scenarios are illustrated in Figure 3-4. The unimpaired Goodyears Bar gage (USGS stream gage 11413000) is at an elevation of 748 m and drains the upper 647 km^2 of the North Yuba watershed. Peak flows occur in winter, driven by large storms, and spring, driven by snowmelt, and streamflow recedes throughout the summer and fall during the dry season. New Colgate (USGS gage 11413510) is an aboveground powerhouse just downstream of New Bullards Bar reservoir with a combined capacity of 340 megawatts under a design head of 398 m and a maximum release rate of 97 m^3/s. New Colgate operates as a combined peaking and ancillary services facility. Under peaking operations, releases are concentrated to hours of peak electricity demanded when power prices are higher. Under ancillary services operations, flows may be changed on a sub-daily basis to respond to power system load changes (Service, 2010b). These alterations capture hydrologic impairment patterns typical of mid-elevation Mediterranean-montane regions. The 50% exceedance flows for each annual hydrologic regime are 23.3, 5.0, 19.2, and 18.5 m^3/s for wet unimpaired, dry unimpaired, wet altered, and dry altered conditions, respectively.
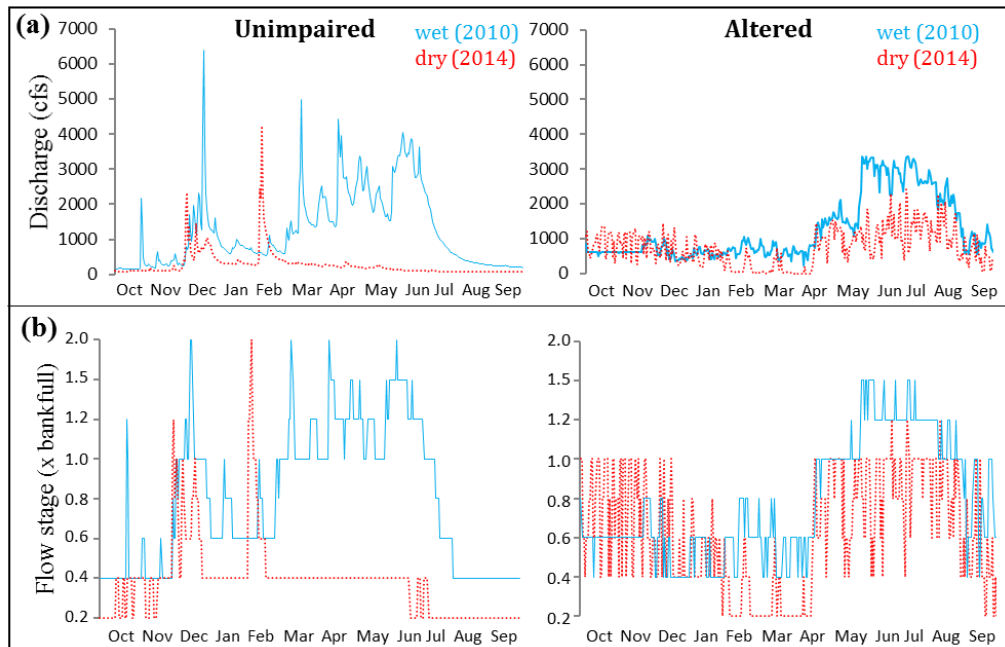
Figure 3-4. Four hydrologic scenarios were considered: unimpaired wet, unimpaired dry, altered wet, and altered dry. Graphs illustrate daily time series of (a) streamflow and (b) discretized bankfull flow stage based on stage-discharge thresholds from Table 3-2~~Table 3-2~~.

3.2.3. Hydraulic modeling

The surface-water modeling system (SMS; Aquaveo, LLC, Provo, UT) user interface and Sedimentation and River Hydraulics- Two Dimensional (SRH-2D) algorithm (Lai, 2008) were used to produce hydrodynamic models for each test case. SRH-2D is a finite-volume numerical model that solves the Saint Venant equations for the spatial distribution of water surface elevation, water depth, velocity, and bed shear stress at each computational node. It can handle wetting/drying and supercritical flows, among other features. The parametric eddy viscosity equation was used for turbulence closure in this study, and a coefficient value of 0.1 was used in that equation. A computational mesh with internodal mesh spacing of 1 m (relative to a channel width of 10 m) was generated for each synthetic DTM.

Because this study was purely exploratory, using numerical models of theoretical river archetypes, no calibration of bed roughness or the eddy viscosity coefficient was possible. Similarly, no validation of model results was possible. However, 2D models including SRH-2D have been used with similar parameter values and validated in similar settings (Brown and Pasternack, 2008; Jowett and Duncan, 2012; Abu-Aly et al., 2014). Also, several exploratory 2D

modeling studies of unvalidated channel morphology scenarios have been published in a similar manner to this study (Pasternack et al., 2004; Jackson et al., 2015; Brown et al., 2015).

The model requires hydrological inputs of discharge and downstream stage as well as boundary conditions of bed topography and roughness. Eight model runs for each morphology capture the discharge range of 0.2 – 2.0 x bankfull flow stage (Table 3-2Table 3-2), where bankfull flow stage is where flows begin to engage the floodplain. The specific simulated discharge values associated with these flow stages were estimated for each archetypal morphology using Manning's equation based on representative cross-sections of the synthetic DTMs. Bankfull stage and wetted perimeter were determined manually from the cross-sections, and cross-sectional area was calculated using the trapezoidal approximation. Manning's n was set at 0.04 to represent a typical unvegetated gravel/cobble surface roughness (Abu-Aly et al., 2014).

Table 3-2. Simulated channel archetype discharge values for 0.2 - 2.0 times bankfull flow stage calculated from Manning's equation, and associated stage - discharge threshold estimates for the North Yuba River.

	Simulated discharge		N. Yuba River discharge
Fraction of bankfull flow	**Plane Bed** (m^3/s)	**Pool-Riffle** (m^3/s)	**Stage - discharge threshold** (m^3/s)
0.2	1.3	1.2	2.8
0.4	6.8	4.5	14.2
0.6	17.7	9.7	22.7
0.8	28.7	17.8	28.3
1.0	58.2	27.7	56.6
1.2	95.5	64.3	85.0
1.5	164.4	139.9	113.3
2.0	310.3	338.1	141.6

Scaling

One additional step is required when utilizing synthetic DTMs in lieu of real river bathymetry: Either the forms must be scaled to the flows or the flows must be scaled to the forms. To simplify the novel process of synthetic DTM generation, we chose the latter option. In order to scale the real Yuba River streamflow time-series to the synthetic DTMs, stage - discharge relationships were needed to associate each of the eight flow stages simulated in the hydraulic model (Table 3-2Table 3-2) with the actual discharge required to fill the North Fork Yuba River corridor to that flow stage. In the absence of local stage-discharge relationships,

these eight thresholds were instead estimated manually (Table 3-2Table 3-2, final column) with the aim of retaining archetypal hydrologic characteristics of wet and dry years for the Yuba River. Specifically, stage - discharge thresholds were chosen such that, in the wet year, the flow stage time series remained at or above bankfull during winter storms and throughout the spring snowmelt recession while, in the dry year, flow stage only exceeded bankfull twice and spent the majority of summer at base flow. The estimated stage-discharge thresholds were validated by the ability of the flow stage discretized time-series to retain these hydrologic patterns (Fig. 3-4b).

A major assumption of this approach is that the flow stage discretization captures all significant spatial hydraulic patterns in the river corridor relative to the functions under consideration in this study. This is likely to be the case if hydraulic patterns scale linearly between flow stages. An example of non-linear scaling would be if backwater zones or shear stress reversals emerged and disappeared between two consecutive flow stages simulated in the hydraulic model. Due to the simplistic nature of the DTMs developed in this study, we expect that hydraulic patterns indeed scale linearly with flow and that this methodology is therefore capable of capturing all significant changes in hydraulic patterns. However, we emphasize that the bankfull stage flow exceedance thresholds are estimates and should not be considered as ultimate targets to inform river management but rather as a proof-of-concept.

3.2.4. River ecosystem functions

Six Mediterranean-montane ecosystem functions were considered in this study (Table 3-3Table 3-3), associated with three major components of river ecosystem integrity: hydrogeomorphic processes, aquatic habitat, and riparian habitat. These functions were all used to answer the specific scientific questions outlined in the study objectives. The performance of these functions was tested based on the following criteria: (1) a longitudinal shift in the location of peak shear stress at high flows from topographic highs to topographic lows was used to test the occurrence of flow convergence routing, a dominant geomorphic formation and maintenance process in certain channels (MacWilliams et al., 2006); (2) a measure of hydraulic variability was used to quantify overall habitat heterogeneity in the river corridor (Gostner et al., 2013a); shear stress thresholds were used to quantify the performance of salmonid (3) bed preparation and (4) bed occupation functions during biologically relevant periods (Escobar-Arias and Pasternack, 2010); (5) depth and velocity thresholds delimited the proportion of salmonid

spawning habitat at risk for redd dewatering during bed occupation; and (6) a combination of winter floodplain scour, spring floodplain stage recession rate, and summer low flow stage was used to assess riparian recruitment dynamics.

Table 3-3. Six ecosystem functions evaluated and their associated ecologically relevant hydraulic parameters (ERHPs), biologically relevant periods, and spatial extents.

Ecosystem Function	ERHP(s)	Biological Period	Spatial Extent	Citations
Hydrogeomorphic processes				
Flow convergence routing	shear stress	--	bankfull channel	MacWilliams et al. 2006
Hydrogeomorphic diversity	velocity, depth	--	river corridor	Gostner et al. 2013a
Salmonid bed preparation	shear stress	Oct. – Mar.	bankfull channel	Escobar-Arias and Pasternack 2010
Aquatic habitat				
Salmonid bed occupation	shear stress	Apr. - Sep.	bankfull channel	Escobar-Arias and Pasternack 2010
Redd dewatering	velocity, depth	Oct. - Mar.	bankfull channel	USFWS, 2010b
Riparian habitat				
Riparian recruitment	shear stress	Dec. – Mar	floodplain	Buffington and Montgomery, 1997
	stage rate of change	Apr. – Jun.	floodplain	Rood et al. 2003
	depth	Jul. – Sep.	floodplain	Rood et al. 2003

Flow convergence routing mechanism

A large body of research into riffle-pool formation and maintenance suggests that the longitudinal profile of covarying bed and width fluctuations (i.e, geomorphic covariance structures) needed to maintain pool-riffle units requires positively covarying bed elevation and bankfull width oscillations (MacWilliams et al., 2006; White et al., 2010; Brown et al., 2015). Caamaño et al. (2009) propose that width and depth variations are both controls on whether a flow reversal occurs and on the riffle depth needed to engender a reversal. Specifically, for a uniform roughness and assuming equal head losses, the Caamaño criterion requires width variations to be greater than depth variations for a reversal to occur such that

$$\frac{w_r}{w_p} = 1 + \frac{h_{res}}{h_r} \qquad [3.4]$$

where h_r is the flow depth over the riffle, h_{res} is the residual pool depth, w_r is the width of the riffle, and w_p is the bankfull width of the pool.

In the current study, the Caamaño criterion indicated the minimum riffle depth needed for the peak shear over a pool to exceed that over a riffle at bankfull discharge in each archetypal

channel morphology. This mechanism was further evaluated by assessing the presence of a shift in peak shear stress from topographic wide-highs (riffles) to narrow-lows (pools), which would indicate that the locations of scour and deposition are periodically shifted in the channel to maintain the relief between riffles and pools (Brown and Pasternack, 2014).

Hydrogeomorphic diversity

The hydro-morphological index of diversity (HMID) (Gostner et al., 2013a) was used to quantify overall physical heterogeneity of a river corridor based on the spatial or temporal variability of water depth and velocity. HMID is calculated as follows, where the coefficient of variation (CV) is the standard deviation of the hydraulic parameter divided by its mean

$$HMID_{reach} = (1 + CV_v)^2 * (1 + CV_d)^2 \qquad [3.5]$$

This index has been shown to accurately represent the hydraulic variability of actual stream reaches (Gostner et al., 2013b), commonly recognized as a major component of ecosystem integrity (Elosegi et al., 2010). Higher hydraulic diversity does not necessarily equate to higher ecological performance, but rather differences in hydraulic diversity along a stream network are expected to influence the longitudinal distribution and assemblages of aquatic and riparian species. However, hydraulic heterogeneity is an important feature of salmonid spawning habitat at the subreach scale (Wheaton et al., 2004).

Three tiers of spatial hydraulic diversity were delineated as follows (Gostner et al., 2013b): HMID<5 indicates simple uniform or channelized reaches; 5 < HMID < 9 indicates a transitional range from relatively uniform to relatively variable morphology; HMID > 9 indicates morphologically complex reaches. To date, no studies have applied this index or tiered rating system to archetypal terrains lacking local random variability, so this is a novel application of this metric to further understand its value in characterizing ecological functionality of stream reaches. Percent exceedance curves of HMID were then used to graphically represent differences in the temporal patterns of hydraulic diversity under alternative flow-form scenarios

Redd dewatering

Hydropeaking (daily fluctuations in stage) for hydropower generation is a dominant form of hydrologic alteration in Mediterranean-montane rivers, with potentially severe ecosystem impacts for fish communities (Vehanen et al., 2005; Young et al., 2011) and macroinvertebrates (Céréghino et al., 2004; Bruno et al., 2013). Among these impacts, salmonid redd dewatering is a

major concern in Sacramento Basin streams managed for hydropower (Service, 2010b). Reductions in flow stage exposing the tailspill and reductions in velocity diminishing intragravel flow through the redd have been associated with dramatic reductions in the survival of salmonid eggs and pre-emergent fry (Healey, 1991; Service, 2010b).

This study focused specifically on fall-run Chinook salmon (*Oncorhynchus tshawytscha*), the most widely distributed salmon run in the Sacramento Basin (Moyle, 2002), with regards to aquatic habitat. Historically spawning in low- to mid-elevation streams (<300 m above sea level), fall-run Chinook have been heavily impacted by spawning habitat reductions and are currently federally listed as a species of special concern (Myers et al., 1998). Redd dewatering risk was measured as the areal proportion of viable spawning habitat in which depth fell below 0.15 m and/or velocity fell below 0.09 m/s during the incubation and emergence period (Dec. – Mar.), in accordance with biological survey results (Service, 2010b). Viable spawning habitat was defined as the portion of the bankfull channel with velocity from 0.1 – 1.6 m/s and depth from 0.1 – 1.3 m at 0.4x bankfull stage, the most common stage experienced under unimpaired conditions during the spawning period (Oct. – Dec.) (Service, 2010a).

Salmonid bed occupation and preparation

Different channel morphologies may behave differently in terms of their hydraulics and sediment transport regimes, causing differences in ecological functionality. With regard to salmonids, ecosystem functions related to hydraulic habitat conditions can be split into bed occupation functions, which occur in occupation periods when the fish interact with the river bed (i.e. spawning, incubation and emergence), and (2) bed preparation functions that occur in times when high flows modify river bed surface conditions for the next spawning season (Escobar-Arias and Pasternack, 2011). For fall-run Chinook in particular, bed occupation occurs generally from October through March and bed preparation occurs from April through September (Fig. 3-5). A stable bed indicated by low shear stress ($\tau_o < \tau_{c\,50}$) is needed to minimize scour during bed occupation, while high shear stress capable of mobilizing the active layer $\tau_o < \tau_{c\,50}$ is necessary to rejuvenate the sediment while the bed is not occupied (Soulsby et al., 2001; Konrad et al., 2002) (Fig. 3-5).
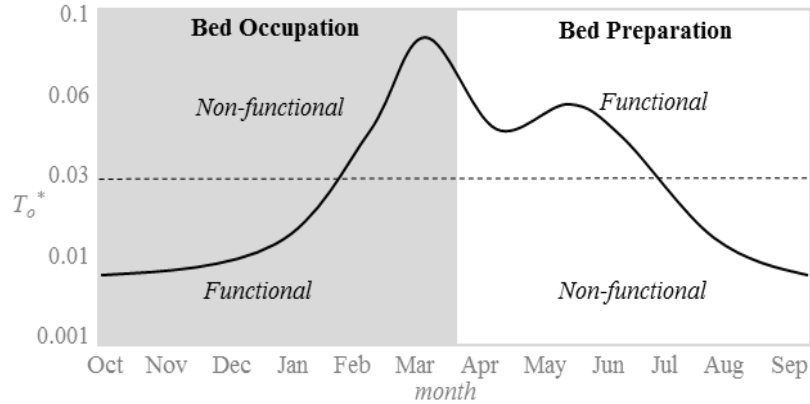
Figure 3-5. Fall-run Chinook bed occupation and preparation functions quantified by biologically relevant periods and sediment mobility thresholds based on nondimensional boundary shear stress (τ_o^*) requirements.

Bed mobility transport stages delimited by nondimensional boundary shear stress (τ_o^*) thresholds were used to quantify these bed occupation and preparation functions according to the following equation

$$\tau_o^* = \frac{\rho g h S}{g(\rho_s - \rho)D_{50}}$$ [6]

where shear stress varies with discharge for a given channel with slope S and median grain size D_{50}, assuming uniform and steady flow. For the present application to Mediterranean-montane streams, a stable bed is assumed when $\tau_o < 0.01$, intermittent transport when $0.01 < \tau_o < 0.03$, partial transport when $0.03 < \tau_o < 0.06$ and full mobility when $0.06 < \tau_o < 0.10$ (Buffington and Montgomery, 1997) (Figure 3-5Figure 5). The resulting temporal pattern of bed mobility under alternative channel morphologies and hydrologic scenarios represents geomorphic dynamics relevant to fall-run Chinook salmon life stages. The performance of bed occupation and preparation ecosystem functions can then be quantified as the cumulative proportion of the channel providing functional bed mobility conditions during biologically relevant periods. Results are then binned such that low, mid, and high performances are associated with 0-25%, 25-75%, and 75-100% performance values.

Riparian recruitment dynamics

Riparian zones support a disproportionately high diversity of wildlife and aquatic species and provide critical river ecosystem functions including habitat heterogeneity, nutrients and woody debris inputs, and biogeochemical processing (Gregory et al., 1991; Naiman and Decamps,

1997). Riparian zones are dominated by fast growing pioneer species that colonize the floodplains, such as willows and cottonwoods in Mediterranean systems. The life history traits of these riparian species are specialized to exploit the dynamic, disturbance-driven river ecosystem (Scott and Auble, 2002). As such, riparian recruitment is largely controlled by abiotic processes resulting from the interplay of the flow regime and channel morphology (Rivaes et al., 2016). The 'recruitment box' conceptual model (Mahoney and Rood, 1998; Amlin and Rood, 2002) outlines specific seasonal hydraulic requirements for successful establishment of riparian seedlings, or riparian recruitment, timed to correspond with seedling physiology.

Based on the 'recruitment box' model and available literature for mid-elevation Sierra Nevada streams, the potential for riparian recruitment was evaluated based on the following three consecutive hydraulic objectives: (i) winter high flows that drive full mobility of some fraction of the floodplain to create open, moist substrate for germination; (ii) a gradual daily floodplain stage recession in the spring to minimize desiccation-induced seedling mortality; and (iii) summer low flows that do not inundate the floodplain to minimize seedling scour/deposition. All three objectives must be met for riparian recruitment to be considered successful under a given flow-form scenario.

The first objective required a minimum of seven days of full sediment mobility (τ_o>0.06) over at least 35% of the floodplain. These temporal requirements are based on the Floodplain Activation Flood criteria previously defined to meet the needs of native fish and riparian species in Sierra Nevada rivers (Opperman, 2006). The exact hydraulic requirements depend on a combination of sediment load, type and age of pre-existing vegetation, and flow history as well as discharge (Scott et al., 1996), which could be incorporated into future applications. The second objective was quantified by estimating the average daily floodplain stage recession rate from a linear trend line (r^2>0.9) during the biologically relevant spring snowmelt recession period from May 15 – Aug. 15 (Yarnell et al., 2016). This approach was intended to capture a representative daily recession rate given the limitation that the hydraulic model outputs do not necessarily change daily with flow as they are associated with flow stage thresholds that may remain static over several days as flows recede until flows drop below a particular discharge threshold (Table 3-2Table 3-2). Thirdly, recession rate performance was evaluated such that 2 – 5 cm/day was considered optimal, 5-10 cm/day was at risk, and >10 was lethal for riparian seedlings (Rood et al., 2003). All three objectives must be met for a flow-form scenario to be

considered successful for riparian recruitment. This workflow was implemented using a Python script that enabled rapid evaluation of hydraulic model raster outputs over the spatial and temporal constraints above.

3.3 Results

The synthetic DTMs are shown to meet study objective one, and the hydraulic modeling results based on these DTMs are discussed first in terms of fundamental hydraulic parameters, and then used to interpret the performance of six ecosystem functions (Table 3-3~~Table 3-3~~) across alternative flow-form test cases as defined by the second and third study objectives.

3.3.1. Synthetic digital terrain models

Two synthetic DTMs were generated representing archetypal morphological configurations of semi-confined pool-riffle and plane bed morphologies. These DTMs exhibited distinct reach-averaged attributes (e.g., S, w/h_{BF}, and D_{50}), subreach-scale topographic variability (e.g., CV), and proportions of the river corridor exhibiting positive and negative GCSs (Table 3-4~~Table 3-4~~a). The control function alignment parameters used to generate the synthetic DTMs based on the SRV model are listed in Table 3-4b. The resulting DTMs exhibited major differences in subreach-scale topographic variability as illustrated by the planform and longitudinal topographic patterns in Figure 3-6

Table 3-4. (a) Channel and floodplain geomorphic attributes and (b) control function alignment parameters used in the design of synthetic DTMs of plane bed and pool-riffle channel morphologies.

(a) *Geomorphic Attributes*			(b) *Alignment Parameters*		
	Plane Bed	Pool - Riffle		Plane Bed	Pool Riffle
Channel			**Planform**		
w_{BF} (m)	10	10	phase shift	0.00	0.00
h_{BF} (m)	1	1	amplitude	0.80	0.00
S (%)	1	2	frequency	2.00	2.00
w/h_{BF}	10	14	**Bankfull Width**		
D_{50} (m)	0.2	0.1	phase shift	$\pi/2$	π
sinuosity	1.1	1.1	amplitude	0.01	0.50
CVw_{BF}	0.01	0.35	frequency	2.00	3.00
CVH_{BF}	0.03	0.18	**Bed Elevation**		
+ **GCS** (%)	55	86	phase shift	0.00	2.70
- **GCS** (%)	45	14	amplitude	0.04	0.35
Floodplain			frequency	2.00	3.00
confinement	0.5	0.5	**Floodplain Outline**		
lateral slope	0.8%	0.8%	phase shift	0.00	0.00
width (m)	16	16	amplitude	0.00	0.50
			frequency	1.50	1.50
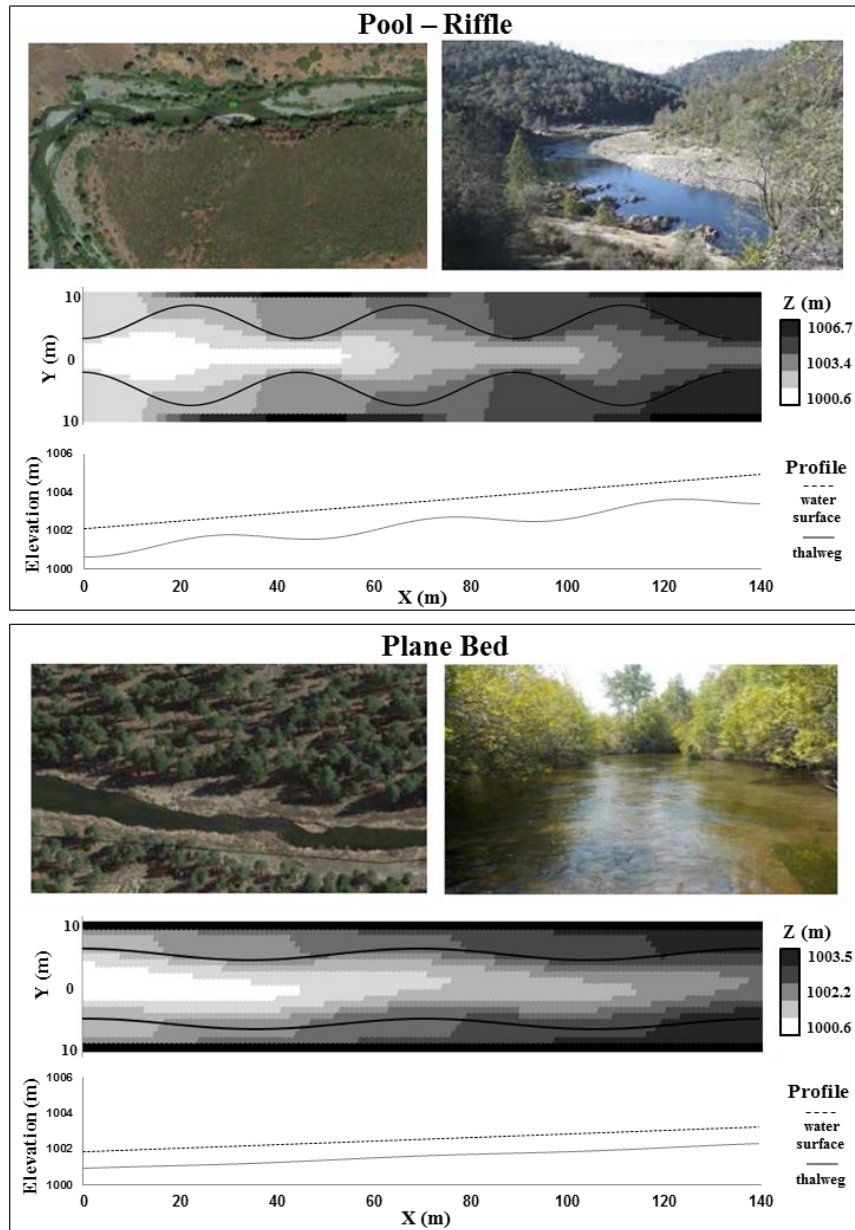
Figure 3-6. Example images, synthetic DTMs overlaid by bankfull channel boundaries, and longitudinal profiles of the two archetypal morphological configurations.

3.3.2. Spatial and temporal distribution of hydraulic variables

The base, bankfull, and 50% exceedance flows that were used to analyze spatial variability in depth and velocity showed that the values were within the typical range for gravel-bed montane streams (Table 3-5), which supports the archetypal specifications used in this study (Richards, 1976; Jowett, 1993). Water depths ranged from 0.0 to 2.4 m, with higher average depths in the plane bed than the pool-riffle channel across all three flow levels and the largest relative

difference in depths at base flow. The pool-riffle morphology had lower minimum depths and higher maximum depths across all flow levels, resulting in larger depth ranges and higher CVs. Flow velocities ranged from 0.0 to 7.2 m/s. Flow velocities exhibited a similar pattern to depth between archetypes, with higher average and minimum velocities in the plane bed channel across all three flows. In contrast with depth, at bankfull flow, maximum velocity was substantially higher in the plane bed than the pool-riffle morphology, resulting in a higher velocity CV. The HMID was substantially higher at baseflow than higher flows, and was more than twice as high in the pool-riffle as the plane bed at baseflow.
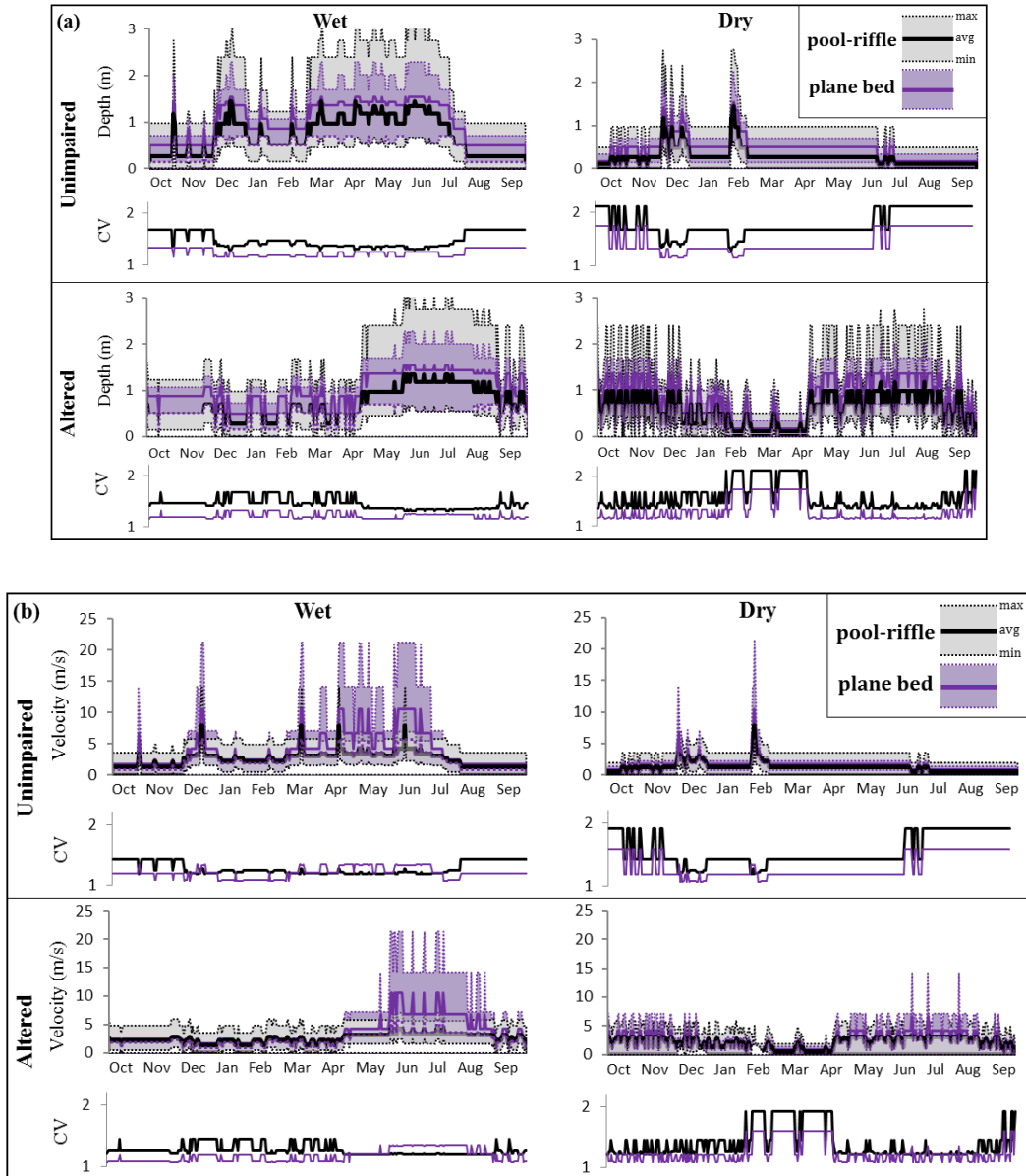
Table 3-5. Spatial summary statistics of depth and velocity at baseflow, 50% exceedance flow and bankfull flow.

Channel	Pool-Riffle			Plane Bed		
Flow	base	50%	bankfull	base	50%	bankfull
Water depth (m)						
min	0.0	0.2	0.5	0.0	0.5	0.7
mean	0.1	0.5	1.0	0.2	0.9	1.4
max	0.5	1.2	2.4	0.3	1.1	1.7
CV	2.1	1.5	1.4	1.7	1.2	1.2
Flow velocity (m/s)						
min	0.0	0.5	1.6	0.0	1.8	3.1
mean	0.5	2.2	3.0	0.8	2.4	4.2
max	1.8	4.8	5.7	1.4	2.9	7.2
CV	1.9	1.2	1.2	1.6	1.1	1.4
HMID	16.3	3.3	2.7	7.8	1.7	2.0

Time series plots of hydraulic variable summary statistics illustrate the daily temporal variability of depth and velocity over the annual hydrographs (Fig. 3-7). A reversal in the maximum CV of velocity from the pool-riffle to the plane bed channel is evident in the spring snowmelt season in the wet unimpaired scenario and the summer in the wet altered scenario, corresponding with very high maximum velocity in the plane bed channel (22.5 m/s). The remainder of seasons and water year types exhibit higher hydraulic variability in the pool-riffle channel, with the largest differences in CV occurring at low flows.

Figure 3-7. Annual time series plots of maximum, average, minimum, and CV of (a) depth and (b) velocity in plane bed and pool-riffle morphologies over four hydrologic scenarios.

Water depth was more sensitive to low flow variations in terms of rate of change, while velocity was more sensitive to changes in high flows (Fig. 3-8). This likely occurs because, in parabolic channel geometries, the channel fills rapidly from low to bankfull flow, whereas, once the bankfull channel is overtopped, a larger flow increase is required to engender the same increase in water depth over the wider floodplain so high flow changes translate more directly to velocity. With regards to channel type, the pool-riffle morphology demonstrated an approximately linear increase in depth with flow, while the plane bed morphology demonstrated

a rapid increase in depth from low flow to 0.8x bankfull and a reduced rate of increase at higher flows (Fig. 3-8). Conversely, velocity in both morphologies increased at a slow linear rate from low flow to 0.8x bankfull flow and then increased much more rapidly in the plane bed at higher flows. Only at high flows (>1.5x bankfull) did pool-riffle velocity exhibit a strong sensitivity to flow variability. These findings demonstrate that changes in the hydraulic environment due to variations in discharge were stronger in the plane bed than the pool-riffle, indicating that pool-riffle hydraulics are less sensitive to changes in flow on average but instead exhibit more complex spatial patterns.
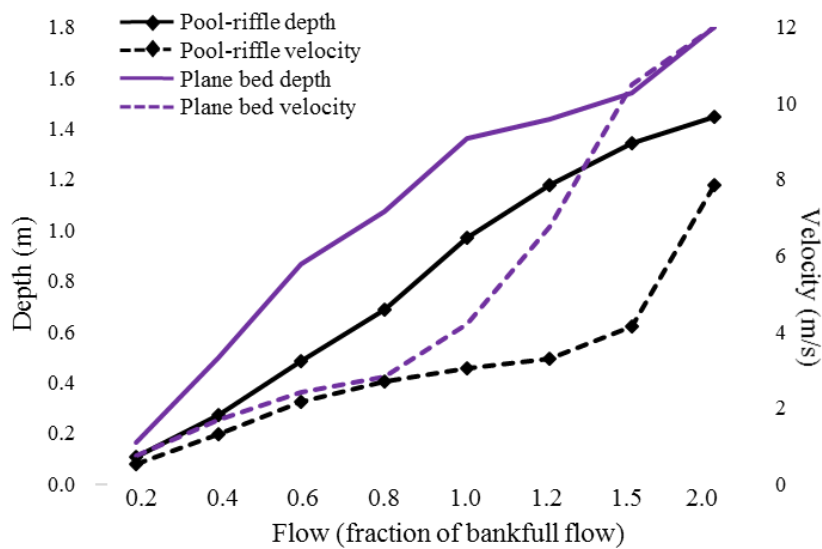
Figure 3-8. Curves illustrate the change in reach-averaged depth (solid line) and velocity (dashed line) in the plane bed (no markers) and pool-riffle (diamond markers) channels from 0.2 – 2.0x bankfull flow.

3.3.3. Summary of ecosystem function performance

All six Mediterranean-montane river ecosystem functions were found to be controlled by both flow and form attributes to varying extents, as illustrated in Figure 3-9.
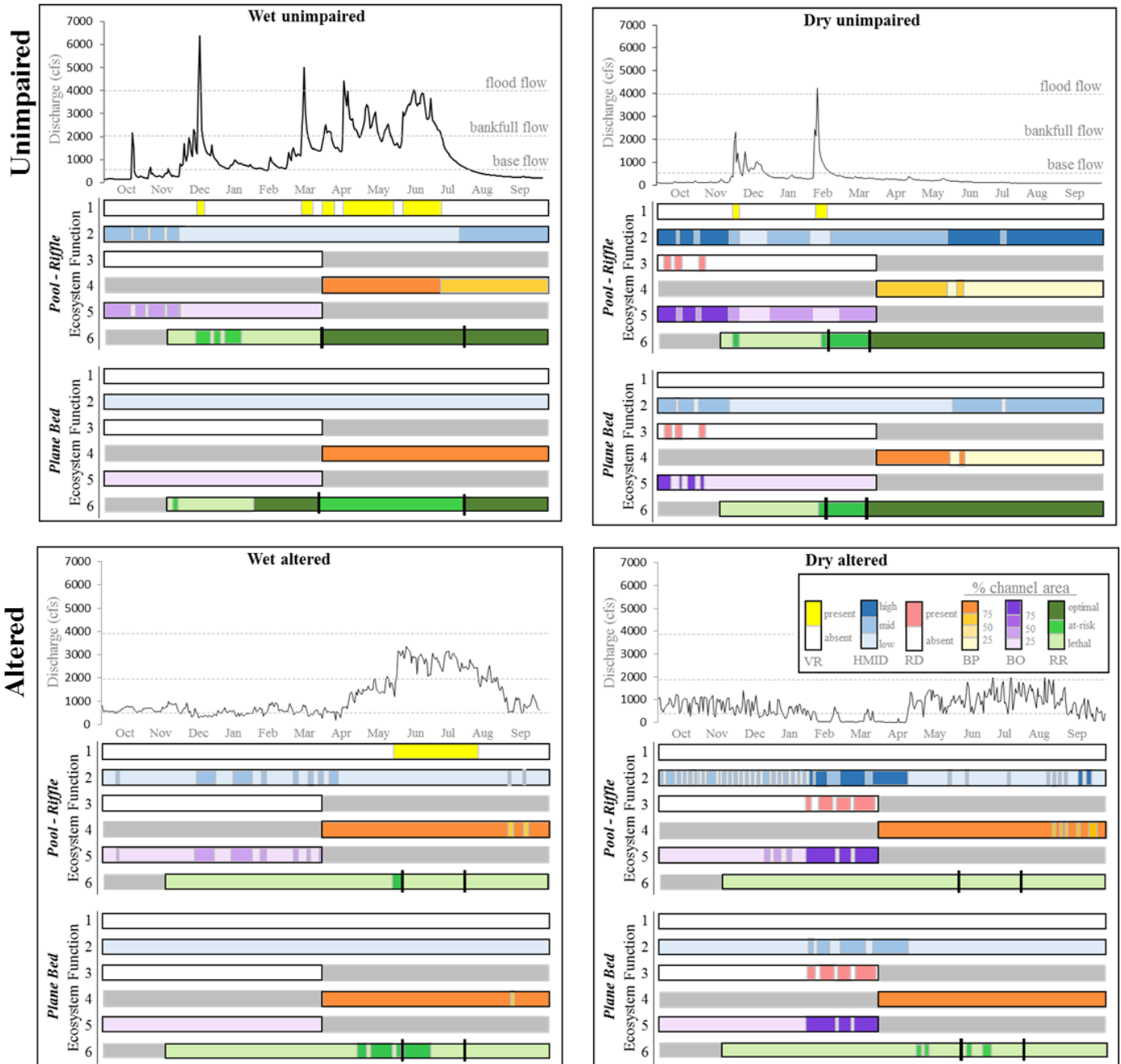
Figure 3-9. Summary of annual ecosystem function performance across eight flow-form scenarios with respect to: 1. flow convergence routing (VR), 2. hydrogeomorphic diversity (HMID), 3. redd dewatering risk (RD), salmonid bed 4. preparation (BP) and 5. occupation (BO); and 6. riparian recruitment (RR). Tiered performance is indicated in key by increasingly dark color shades and bimodal performance (VR and RD) is either colored or empty. Greyed regions indicate periods of the year that functions are not biologically relevant. The black bars in RR split up the function performance into three objectives (winter, spring, summer) as described in the text. Base flow = 0.2x, bankfull flow = 1.0x, and flood flow = 1.5x bankfull flow as defined in Table 3-2Table 3-2.

Flow convergence routing mechanism

The pool-riffle morphology demonstrated a shear stress reversal from low to high flow, as indicated by a Caamaño criterion riffle depth threshold for reversal of 0.21 m (approximately 0.4x bankfull stage) and a shift in the location of peak shear stress from the riffle to the pool (Fig. 3-10). This shift was further illustrated by the longitudinal relationships between cross-sectional area (A) and average velocity (V), derived from 2D hydraulic model outputs, through interspersed pools and riffles along the channel at (a) base and (b) bankfull flow conditions (Fig. 3-10). While A was also influenced by a stepped water surface elevation driven by strong width constrictions in the pool-riffle channel that offset peak V slightly downstream from the riffle crest, the inverted relationship between A and V and the shift in minimum A and maximum V from the riffle to the pool are evident. The existence of a dominant flow convergence routing mechanism is further indicated by 86% of the pool-riffle morphology exhibiting a positive geomorphic covariance structure (i.e., a channel consisting of primarily wide shallow riffles and narrow deep pools) [*sensu* Brown et al. (2015)]. Alternatively, the plane bed morphology did not exhibit a shear stress reversal based on either the Caamaño criterion or a peak shear stress location shift, and 55% of the river corridor exhibited positive geomorphic covariance (not shown).
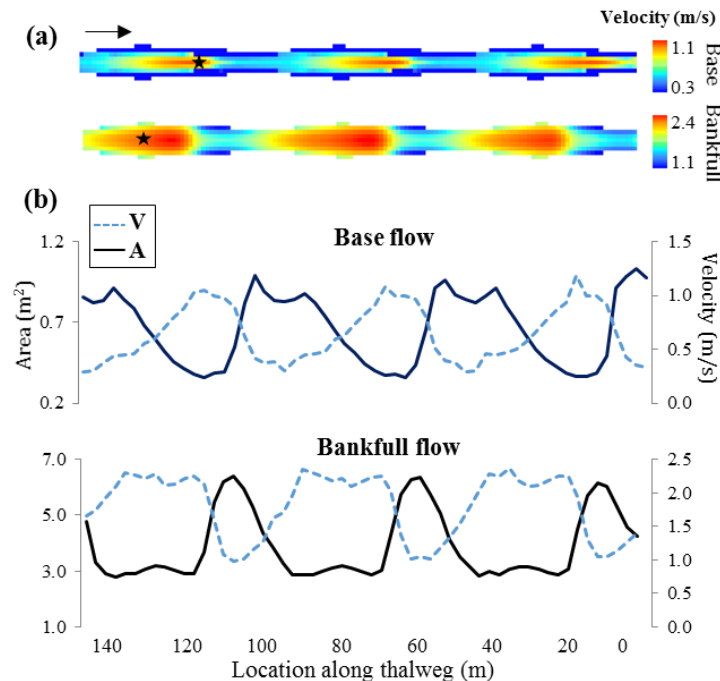

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Figure 3-10. (a) Velocity rasters and (b) plots of cross-sectional area and average velocity along the pool-riffle channel at base and bankfull flow. The stars indicate the location of peak shear stress at each flow and the arrow indicates the direction of flow.

Hydrogeomorphic diversity (HMID)

A comparison of HMID in the plane bed and pool-riffle morphologies indicated that spatial hydraulic diversity is higher in pool-riffle channels at flows up to 1.2x bankfull flow, beyond which they are nearly equivalent (Fig. 3-11). That is, for a given annual hydrograph, cumulative hydraulic diversity over the year is higher in the pool-riffle. The highest HMID values and the greatest difference in hydraulic diversity between the two forms occurred at the lowest flow stage (0.2x bankfull discharge), during which HMID was twice as high in pool-riffle channels (Fig. 3-11). The rapid decrease in HMID in both channel types as discharge increases from base flow illustrates the limited temporal persistence of high diversity hydraulic habitats in all but the lowest flow conditions. Further, the similarity in HMID at flood flows can be attributed to the simple floodplain archetypes in both morphologies that need refinement in future work.
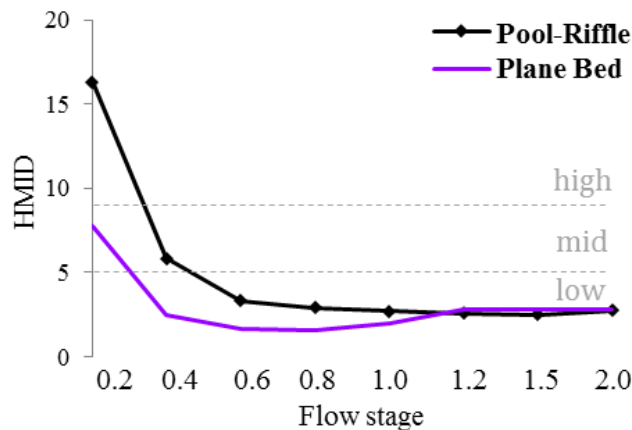
Figure 3-11. Hydromorphic index of diversity (HMID) values from 0.2 - 2.0x bankfull flow stage in the plane bed and pool-riffle morphologies. Dotted lines delineate thresholds for low, medium, and high diversity

As low flows produce higher HMID values in general, it is unsurprising that in dry years all channels experience high hydraulic diversity for more of the year (Fig. 3-12). Within dry years, the unimpaired flow regime provided approximately twice as many days with high diversity in both channel types. Under hydrologic impairment for hydropower, hydraulic diversity was slightly greater under the wet pool-riffle scenario than the dry plane bed scenario for all flows with greater than 17% exceedance.
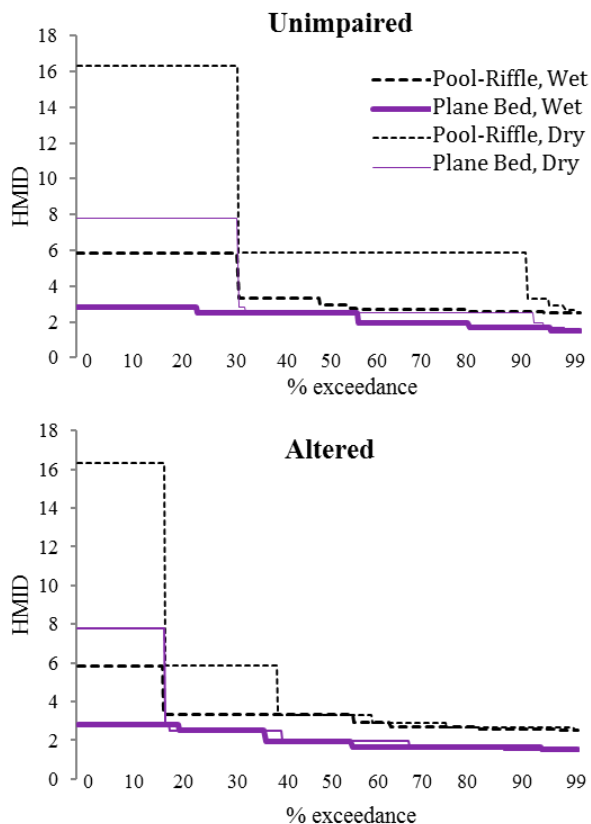
Figure 3-12. HMID exceedance curves for (a) unimpaired and (b) altered flow regimes under different channel morphologies (pool-riffle and plane bed) and water year types (wet and dry).

The HMID values for the 50% exceedance flow in each of the hydrologic scenarios, indicated in Table 3-6, refer to single observations in time representative of most of the discharges that occur throughout a year except for the extreme ends of the flow - duration curve. The highest hydraulic diversity was exhibited by the pool-riffle under dry unimpaired conditions (HMID=5.9), presumably due to the combination of topographic variability and extended summer low flows. At the 50% exceedance flow, hydraulic diversity was more sensitive to water year type than hydrologic impairment, and appeared to be most influenced by channel morphology (Table 3-6). Alternatively, at the 10% exceedance flow, water year type plays a more significant role, with dry years exhibiting much higher HMID values than wet years across both morphologies and unimpaired and altered conditions (Fig. 3-12). However, the dry unimpaired conditions exhibit high HMID during a large portion of the fall-run Chinook salmonid bed occupation period while the dry altered conditions exhibit high HMID while salmonids are not present, which is less biologically functional (Figs. 3-9, 3-13).

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Table 3-6. Hydromorphic index of diversity (HMID) values for the 50% exceedance flows of each of the four hydrologic scenarios.

Hydrologic Impairment	WYT	Flow (cms)	HMID	
			Plane Bed	*Pool-Riffle*
unimpaired	wet	23	1.5	2.9
	dry	5	2.5	5.9
altered	wet	19	1.7	3.3
	dry	18.5	1.7	3.3
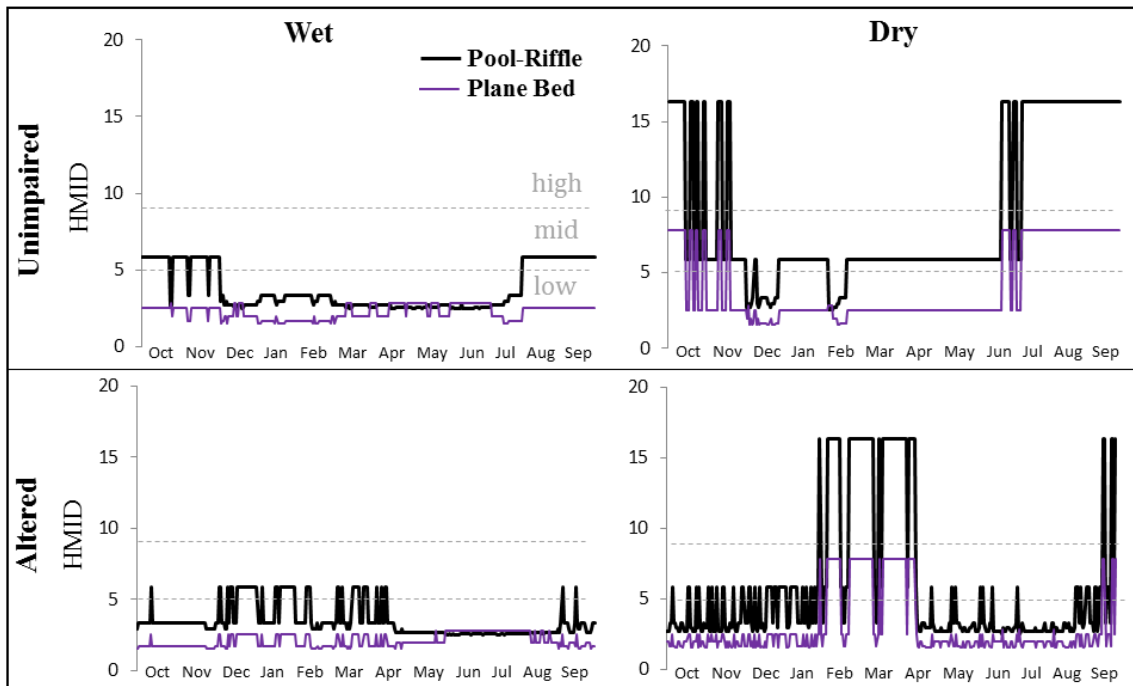
Figure 3-13. Time series of HMID across all four hydrologic scenarios illustrate periods of low, medium, and high diversity over the year based on thresholds determined by Gostner et al. (2013b).

Redd dewatering risk

Redd dewatering risk, quantified as the proportion of viable spawning habitat exhibiting excessively low depth and/or velocity conditions, varied significantly across flow-form scenarios. In the pool-riffle, 49% or 428 of the 868 m^2 bankfull channel provided viable spawning habitat while, in the plane bed, only 31% or 328 of the 1,041 m^2 bankfull channel was viable. Pool-riffle spawning habitat was extensive and patchy, excluding only excessively high velocity zones on the riffle crests. Alternatively, spawning habitat only occurred in the plane bed channel in one to two meter bands along the wetted channel margins with sufficiently low

velocity. Fall-run Chinook redd dewatering risk was greater in the plane bed than the pool-riffle morphology at base flow (100% vs. 57% of spawning habitat) but dewatering risk was maintained across a greater range of flows (0.2-0.4x bankfull flow) in the pool-riffle. This is because the pool-riffle archetype has more gradual side slopes and the total available spawning habitat is greater. High dewatering risk (>30% of spawning habitat experiencing low depth and/or velocity conditions) occurred only in dry altered conditions in which very low flows occur throughout the redd incubation and emergence period (Fig. 3-14).
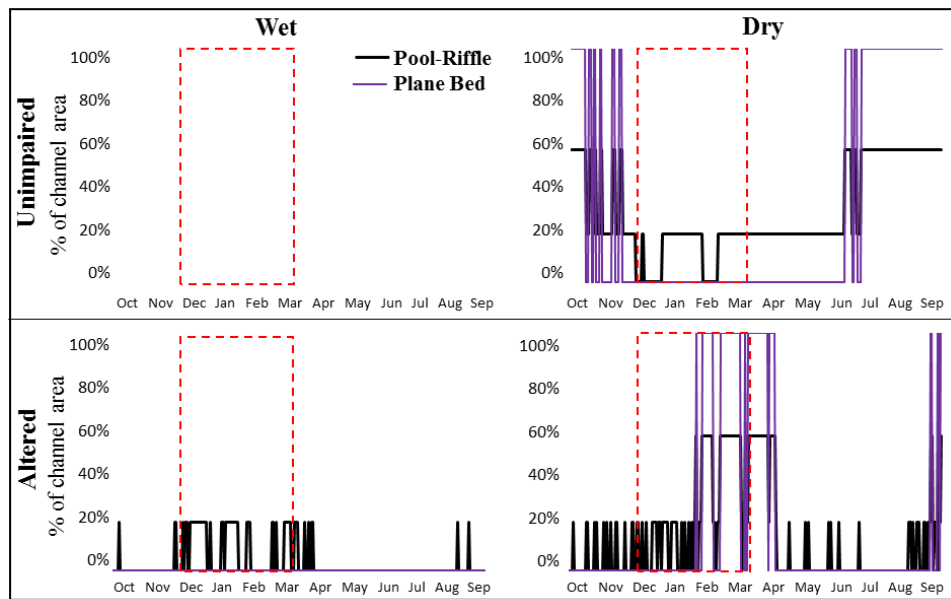
Figure 3-14. Daily time series indicate proportion of spawning habitat exhibiting salmonid redd dewatering risk over each of the eight flow-form scenarios. The red boxes indicate biologically significant periods for fall-run Chinook redd dewatering.

Salmonid bed preparation and occupation

Shear stress based sediment mobility patterns varied across flow-form scenarios, driving significant differences in salmonid bed preparation and occupation function performances under different hydrologic conditions and channel morphologies (Fig. 3-9). Under unimpaired conditions, the wet year exhibited high bed preparation performance and low bed occupation performance while the dry year exhibited mid performance in both functions with reduced bed preparation but increased bed occupation performance (Table 3-7). Under streamflow alteration, bed preparation performed well across water year types while bed occupation performed poorly

across water year types and morphologies due to increased sediment mobility under elevated low flows during the occupation period. Spatially, in the pool-riffle channel, higher sediment mobility occurred over the riffle crests while the pools remained less mobile at all but twice bankfull flood flows. Conversely, sediment mobility was nearly uniform in the plane bed channel across all flows. While not incorporated into performance metrics, these distinct spatial patterns of sediment mobility likely also influence biological suitability of the river corridor for bed occupation that could be incorporated into future performance metrics. The timing of changes in the spatial pattern and areal proportion of different bed mobility stages varies substantially within the bed occupation and preparation periods across flow-form scenarios (Fig. 3-15), but this temporal variability is not captured within the performance metrics. More information about the temporal and spatial bed mobility requirements for particular aquatic species and life-stages would allow for refined performance estimates within the proposed framework.

Table 3-7. Performance of bed occupation and preparation functions for fall-run Chinook salmon, based on the cumulative proportion of the channel exhibiting low (no/low) and high (partial/full) sediment mobility, respectively, during biologically significant periods under (a) unimpaired and (b) altered hydrologic regimes. Red = low, yellow = mid, and green = high performance.

(a) Function	Bed Occupation				Bed Preparation			
Flow	wet		dry		wet		dry	
Form	P-R	PB	P-R	PB	P-R	PB	P-R	PB
Performance	57%	75%	2%	0%	70%	72%	90%	93%

(b) Function	Bed Occupation				Bed Preparation			
Flow	wet		dry		wet		dry	
Form	P-R	PB	P-R	PB	P-R	PB	P-R	PB
Performance	60%	82%	45%	49%	74%	81%	78%	83%
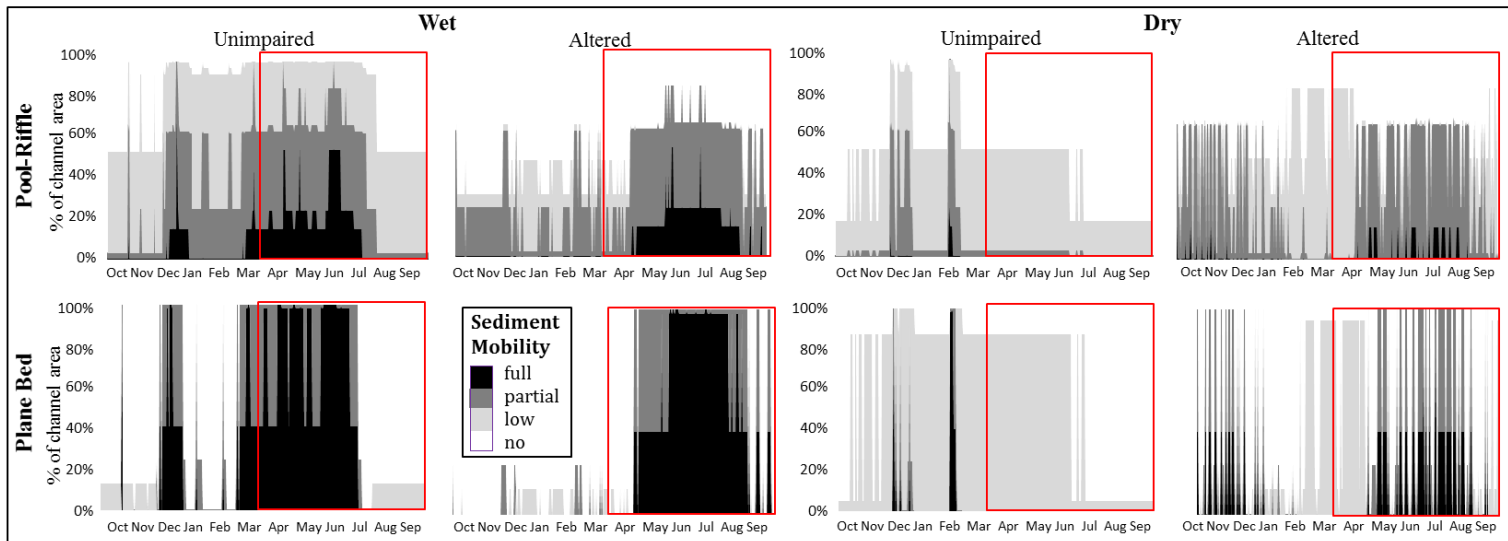
Figure 3-15. Daily time series plots of the proportion of the bankfull channel exhibiting different tiers of sediment mobility illustrate the performance of salmonid bed preparation (boxed, partial/high mobility from Apr-Sep) and occupation (no/low mobility from Oct-Mar) functions.

Riparian recruitment dynamics

Combining the results for the three riparian recruitment objectives over all eight flow-form scenarios, only the wet unimpaired pool-riffle channel met all three requirements for successful riparian recruitment (Table 3-8, Fig. 3-9). The wet unimpaired plane bed scenario met the first and third objectives, but the high streamflow recession rate put seedlings at risk of desiccation. The dry unimpaired scenarios lacked the winter scouring flows to create substrate for germination and were at-risk for seedling desiccation, while the wet altered scenarios had sufficient winter scouring flows but receded too rapidly and exposed the remaining seedlings to scour and deposition. Finally, the dry altered scenarios did not exhibit streamflow recessions at all, and thus offered no chance of riparian recruitment.

Table 3-8. Performance of riparian recruitment based on three ecohydraulic objectives (i. winter floodplain scour, ii. gradual spring streamflow recession, and iii. no subsequent summer flooding) across eight flow-form scenarios. An "X" indicates that an objective was met for a given flow-form scenario while a blank cell indicates unmet objectives.

		Flow – Form Scenario							
Flow		Unimpaired				Impaired			
		Wet		Dry		Wet		Dry	
Form		P–R	PB	P–R	PB	P–R	PB	P–R	PB
Obj. i (Winter)		X	X			X	X		X
Obj. ii (Spring)		optimal	at-risk	at-risk	at-risk	lethal	lethal	N/A	N/A
Obj. iii (Summer)		X	X	X	X				

With regards to the first objective for riparian recruitment, both unimpaired and altered wet years exhibited > 7 consecutive days with full sediment mobility on > 35% of the floodplain during winter high flows. Full sediment mobility occurred over a longer duration and larger proportion of the floodplain in the plane bed than the pool-riffle morphology across all hydrologic scenarios. In dry years, temporal requirements for winter high flows were not met. Under dry unimpaired conditions, hydraulic requirements were met for 7 and 4 days in the plane bed and pool-riffle, respectively. Under dry altered conditions, the plane bed channel met the spatial hydraulic requirements for 6 days, while insufficient winter floodplain scour occurred in the pool-riffle to fully mobilize >35% of the floodplain (Fig. 3-16).
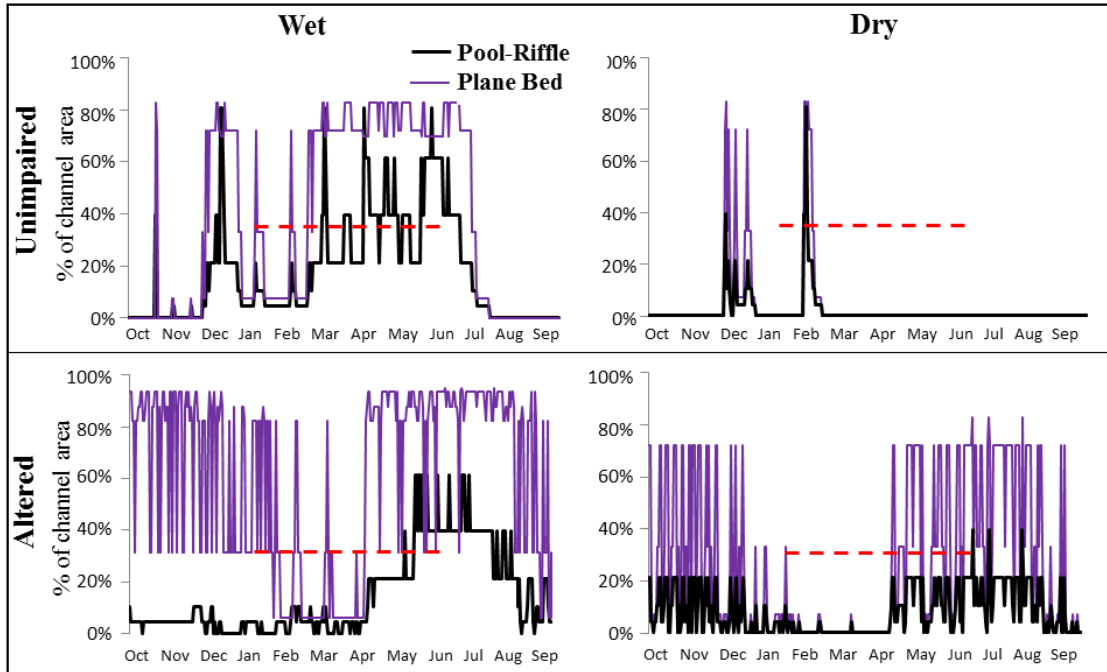
Figure 3-16. Daily time series plots of the proportion of the floodplain exhibiting full sediment mobility under each of the eight flow-form scenarios. The dashed red line indicates the minimum floodplain proportion (35%) required to be fully mobilized during winter (Jan. – Jun.) for > 7 days for riparian seedling recruitment (obj. 1). Function performance also required no floodplain re-inundation after winter following successful recruitment (obj. 3).

With regards to the second objective, maintaining a gradual spring streamflow recession, the dry altered hydrologic scenario did not exhibit a streamflow recession at all, as defined by >7 days of consecutively lower flows culminating in baseflow. Under the wet unimpaired scenario, the spring snowmelt recession (Jun. 17 – Aug. 4) was associated with average daily floodplain stage recessions of 3.75 and 5.7 cm/day in pool-riffle (r^2=0.97) and plane bed (r^2=0.90) morphologies, respectively. Under dry unimpaired conditions, the only true streamflow recession (Feb. 9 - 26) receded from the floodplain at rates of 5.2 and 5.8 cm/day in pool-riffle (r^2=0.92) and plane bed (r^2=0.92) morphologies, respectively. The wet altered scenario had low fit linear trend lines for both the pool-riffle (r^2=0.34) and plane bed (r^2=0.47), indicating a highly variable and steep (>10 cm/day) recession limb likely to cause seedling mortality. Therefore, the only flow-form scenario to exhibit an optimal streamflow recession rate for riparian seedling recruitment was the pool-riffle morphology under wet unimpaired conditions, while the other three unimpaired scenarios put seedlings at risk of desiccation-induced mortality and the four altered scenarios all resulted in seedling mortality.

The third recruitment objective, no floodplain re-inundation after the spring streamflow recession, was only met under unimpaired hydrologic scenarios. The wet and dry unimpaired hydrographs both exhibited extended low flow conditions throughout the summer. The highly variable and aseasonal altered hydrographs drove periodic summer floodplain inundation up to 0.17 and 0.62 m in the pool-riffle and plane bed, respectively (Fig. 3-16).

3.4 Discussion

3.4.1. The utility of synthetic digital terrain models

Successful application of synthetic morphologies to serve as scientifically transparent, repeatable, and adjustable archetypes in support of flow-form-function inquiry was demonstrated here by the ability to synthesize DTMs from channel classification archetypes exhibiting distinct hydrogeomorphic attributes and processes of ecological relevance. Specific geomorphic attribute values were accurately captured by the synthetic morphologies, including channel dimensions, cross-sectional geometry, depth and width variability, sinuosity, and slope. The flow convergence routing mechanism was shown to occur in the pool-riffle but not in the plane bed channel, confirming that the two morphologies were capturing distinct geomorphic maintenance processes as distinguished by the Sacramento Basin channel classification (Lane et al., 2017b). Synthesizing datasets dramatically reduced resource requirements from those of similar analyses, including topographic surveying and 2D hydraulic modeling calibration for two distinct river corridors. This approach therefore liberates future research to explore and isolate a larger range of flow and form characteristics than those considered in the present study.

3.4.2. Ecological significance of specific patterns of topographic variability

The spatial and temporal distributions of fundamental hydraulic variables indicate that the specific pool-riffle hydraulics associated with a positive GCS between bed elevation and width are less sensitive to temporal changes in flow but are more spatially variable, exhibiting a larger range and CV of depth and velocity values for a given discharge. Linked narrow pools and wide riffles also exhibited shallower depths and lower velocities than the plane bed morphology on average. These findings correspond with a recent study by Gostner et al. (2013b), who found that hydraulics in natural, more topographically diverse sites (corresponding to the pool-riffle channel

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in our study) were less sensitive to flow and exhibited larger and more skewed hydraulic variable distributions than simplified, channelized sites (corresponding to the plane bed channel). They also found that the topographically diverse sites generally had lower average depths and velocities than their channelized counterparts. Results in this study also support emerging scientific understanding that many geomorphic and ecological functions are controlled by subreach-scale topographic variability (Lane et al., 2017b) by demonstrating the occurrence of distinct ecosystem functions in reaches of high versus low topographic variability. Most importantly, it is not enough to just obtain random variability or any arbitrary coherent permutation of variability, but rather the pattern of organized variability must meet the requirements of the appropriate geomorphic covariance structure for that channel archetype (Brown and Pasternack, 2014; Brown et al., 2015).

3.4.3. Flow and form controls on ecosystem functioning

Six Mediterranean-montane river ecosystem functions related to geomorphic variability, aquatic habitat, and riparian habitat were evaluated in the context of interacting flow (i.e., water year type and hydrologic impairment) and form (i.e., morphology type) controls on ecohydraulic response. The occurrence of flow convergence routing was controlled primarily by channel form, with only the pool-riffle morphology exhibiting that mechanism. However, sufficiently high flows were also needed for a shear stress reversal to occur in support of the mechanism. Hydrogeomorphic diversity was controlled primarily by river form, and specifically topographic variability, as expected. More surprisingly, HMID was also influenced by flow attributes, with water year type, hydrologic impairment, and morphology type all playing significant and interacting roles in the ecohydraulic response. The duration and timing of redd dewatering risk were controlled by water year type and hydrologic impairment, while the magnitude of dewatering risk, based on the proportion of spawning habitat exhibiting sufficiently low depth or velocity, was controlled solely by channel form. Salmonid bed preparation and occupation functions illustrate trade-offs in all three controlling variables, with bed preparation performing best in the wet, altered, plane bed scenario while bed occupation performed best in the dry, unimpaired pool-riffle morphology. Finally, only the wet unimpaired pool-riffle scenario met all three ecohydraulic requirements for riparian recruitment, indicating that all three variables were critical to this outcome. These results emphasize the complex interacting flow and form controls

on key ecosystem functions and the differences in dominant controls between ecosystem functions.

Hydrogeomorphic diversity performance tradeoffs in particular provided insight for environmental water management, given its established significance. The highest HMID was exhibited by the pool-riffle under dry unimpaired conditions. However, under hydrologic impairment, HMID was higher under the wet pool-riffle than the dry plane bed scenario for all but the lowest flows. This finding indicates a tradeoff between flow and form with respect to diversity whereby either increasing topographic variability (i.e., plane bed to pool-riffle) or increasing the number of low flow days in the flow regime (i.e., wet to dry water year type) was capable of increasing overall spatiotemporal diversity. In such instances, knowledge of flow - form interactions could be used to provide more nuanced, targeted river management to enhance positive and dampen negative ecosystem impacts.

In general, bed occupation performed poorly across all flow and form scenarios. This finding may be attributed to the coarse bankfull stage discretizations used in the study (eight discharges from 0.2 – 2x bankfull stage, Table 3-2~~Table 3-2~~), allowing lower daily discharge values to be associated with higher sediment mobility than occurs in reality. Performance results such as these can inform future studies by encouraging iterative modification of decisions such as the number of bankfull stage discretizations and the range of discharges considered to improve representation of ecosystem functions within the proposed methodology.

3.4.4. Implications for environmental water management

Channel <u>form and bed substrate regimes</u> are often partially or entirely uncoupled from flow in ecologically degraded river systems, limiting the efficacy of restoring the flow regime alone. This study corroborates the hypothesis that <u>flow and form</u> archetypes <u>work in concert to support distinct ecosystem functions</u> in Mediterranean-montane river systems, and most likely in many other river systems. Results highlight critical tradeoffs in ecosystem function performance, emphasizing the <u>significance of spatiotemporal diversity of flow and form at multiple scales for maintaining river ecosystem integrity</u>. These findings support the emerging recognition of spatial and temporal heterogeneity as fundamental characteristics of fluvial systems and the need for a flexible framework within which natural processes, such as sediment transport and nutrient dynamics, can occur (Clarke et al., 2003).

With respect to geomorphic diversity, high subreach-scale topographic variability pool-riffle reaches supported flow convergence routing and promoted high hydraulic diversity, salmonid bed occupation, and riparian recruitment, while plane bed reaches provided habitats of reduced stress for salmonid redds during dry years. Thus, restoring or designing a stream network to provide interspersed plane bed reaches within a pool-riffle dominated system may support higher overall ecosystem integrity by promoting distinct and complementary functions in different locations during biologically significant periods.

Regarding hydrologic variability, only wet years supported riparian recruitment, high performance of salmonid bed preparation, and a shear stress reversal, while dry years significantly increased spatiotemporal hydraulic diversity in the river corridor, and increased availability of fall-run Chinook spawning habitat. These results indicate that a range of wet to dry years is required to support the full suite of river ecosystem functions considered herein. Thus, inter-annual flow variability also plays a key role (in concert with spatial variability of form and bed substrate) for maintaining river ecosystem integrity. This finding also indicates the potential for changes or losses in ecosystem functionality under a changing climate in which the spectrum or the ratio of wet to dry years is significantly altered from that to which native riverine species are adapted (Null and Viers, 2013). For example, fewer sufficiently wet years to generate a shear stress reversal in pool-riffle reaches may compromise their ability to maintain high topographic variability, thus shifting the suite of ecosystem functions supported in these reaches towards those already supported by plane bed reaches. This would reduce ecological variability and thus overall ecological resilience of the stream network.

This first successful application of synthetic datasets to flow-form-function inquiry also provides a foundation for transitioning from expressing ecosystem impacts and responses in terms of fixed flow or form features to spatiotemporally varying hydrogeomorphic dynamics along a spectrum of alterations of the synthetic datasets. The simple, process-based framework proposed here for examining flow-form-function interactions in diverse physioclimatic settings is expected to elucidate key processes underlying spatial and temporal dynamics of river ecosystems through future applications. For instance, through iterative generation and evaluation of numerous synthetic channel forms, the functional role and alteration thresholds of individual geomorphic attributes (e.g., confinement, channel bed undulations) could be isolated. This

information would improve understanding of ecosystem resilience and the potential for rehabilitation projects under current and future hydrogeomorphic alterations.

3.5 Conclusion

The study objectives and scientific questions investigated here advance basic understanding of hydrogeomorphic processes and ecohydraulic patterns in complex river ecosystems. Specifically, this study tackled key questions regarding the utility of synthetic DTMs for ecohydraulic analysis, the ecological significance of topographic variability, how to evaluate the ecological performance of different flow-form settings or types of river restoration efforts, and whether (re)instatement of key flow or form features will restore ecological processes (Council, 2007). The application and development of simple, quantitative ecosystem performance metrics, such as those proposed for salmonid bed preparation and riparian recruitment, enabled evaluation of the ecohydraulic response to changes in flow and/or form settings typical of Mediterranean-montane river restoration efforts. By comparing these performance metrics across individual and combined changes to hydrologic and geomorphic attributes, this study was able to predict ecosystem performance under natural or anthropogenic changes to water year type, hydrologic impairment, and channel morphology. More importantly, this research demonstrates the significance of the spatiotemporal diversity of *flow* (seasonally and inter-annually) and *form* (channel form and bed substrate regimes), both of them working in concert to support distinct ecosystem *functions* for maintaining river ecosystem integrity.

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APPENDIX A

Climate-based review of regional hydrologic classifications

The Köppen climate classification (Köppen and Geiger 1930), which organizes regions into five major climate zones and further distinguishes classes based on precipitation and temperature characteristics, provides a framework for evaluating the climatic distribution of existing regional hydrologic classifications. Figure A-1 illustrates the global distribution of the Köppen Mediterranean climate (Köppen climate classes Csa and Csb). A literature review indicated that, of 50 regional hydrologic classifications developed in the past 40 years, only 10% fell within dominantly Mediterranean regions (Köppen climate classes Csa and Csb) (Fig. A-2a) (Turkey, Kahya et al. 2008; Spain, Baeza and Jalon 2005; Washington State; Liermann et al. 2011; Oregon State, Wigington et al. 2012). Furthermore, 71% of studies were based in fully humid regions while only 10% fell within seasonally dry climates (Fig. A-2b).
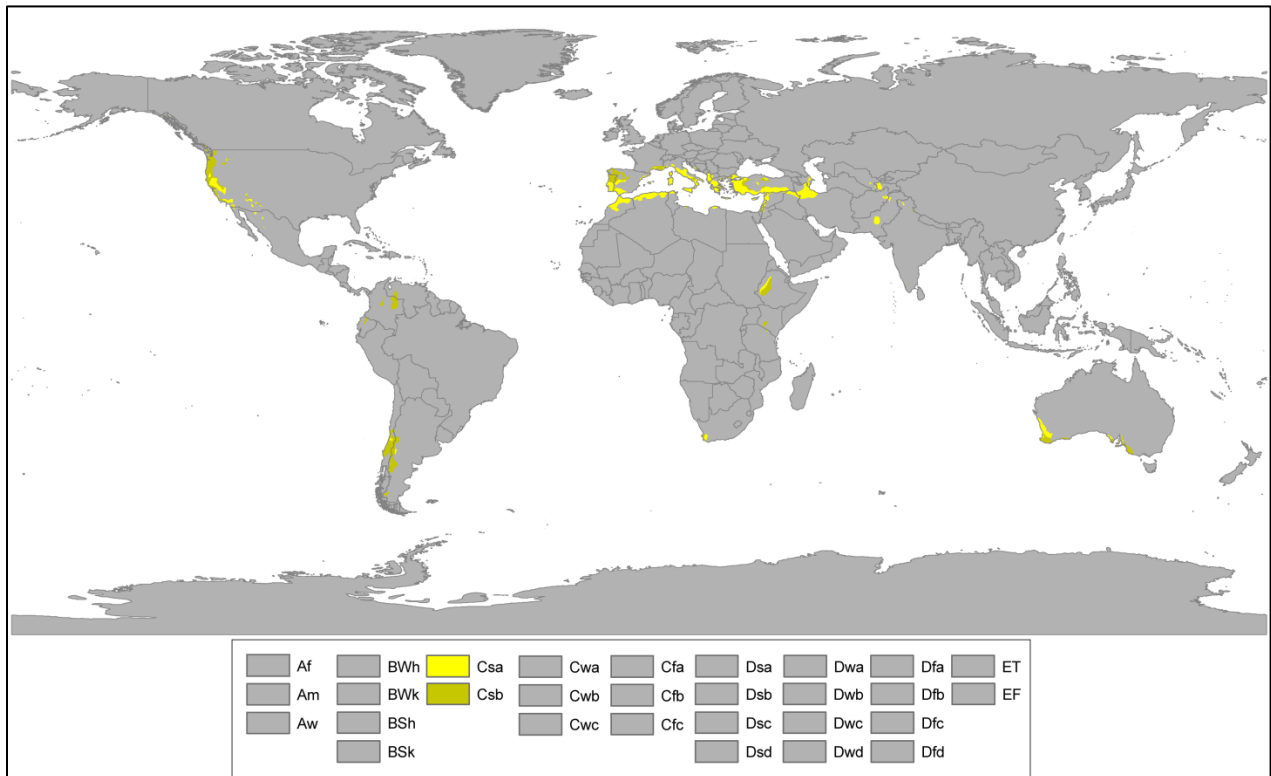

Figure A-0-1. Global distribution of Mediterranean climate (Köppen climate classes Csa and Csb) (adapted from Peel et al. 2007)
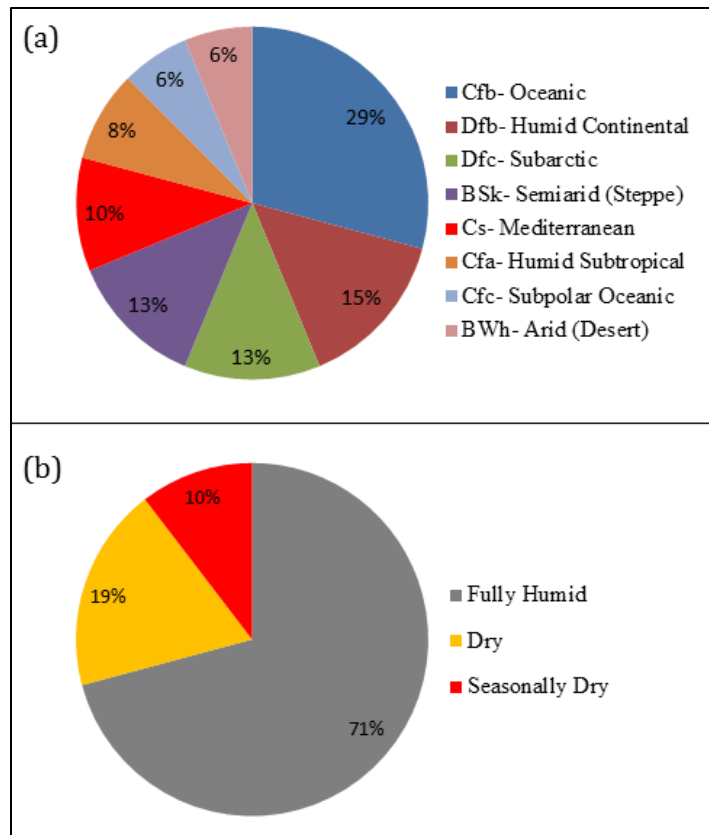
Figure A-0-2. Distribution of existing hydrologic classifications (n=50) across (a) Köppen climate classes based on regional precipitation and temperature and (b) secondary Köppen climate classes based on seasonality of precipitation.

Uncertainty Analysis

In order to assess potential climate non-stationarity in the streamflow records used to calculate hydrologic indices due to long-term shifts in climate, the non-parametric Mann-Kendall (MK) trend test (Kendall 1975) and generalized least squares (GLS) regression were used. Trends in the long-term median monthly streamflow time-series (Fig. A-3a) were assessed for a subset of reference gauge stations (Table 1) representing a range of physical and climatic characteristics. The six gauge stations considered had a minimum and maximum period of record of 53 years (1961-2014) and 81 years (1928-2014), respectively. The MK trend test indicated whether a time series exhibited a significant monotonic trend using a 15-year moving window approach by fitting a GLS regression to the median monthly streamflow values versus the hydrologic year over the period of record. Autocorrelation in the time-varying, moving window median monthly streamflow values was also estimated using the Durbin-Watson (DW) test

(Durbin and Watson, 1950). The results of the MK and DW trend tests indicate minimal monotonic climate trends and autocorrelation in the streamflow data from the time period considered (1952-2015) (Table A-1). While the PDO shift was apparent when comparing average hydrograph trends over time, all influences of climate non-stationarity fell within the 95th percentile confidence bounds of the MK trend test over the entire period of record (Fig. A-3b). The majority of DW values with $p<0.05$ were close to 2, and DW values below 1 were exclusively lags expected to be correlated for seasonal time-series (e.g., 6 and 12 months) (Durbin and Watson, 1950). These results support the use of the selected streamflow records for the calculation of the hydrologic indices and subsequent classification development.
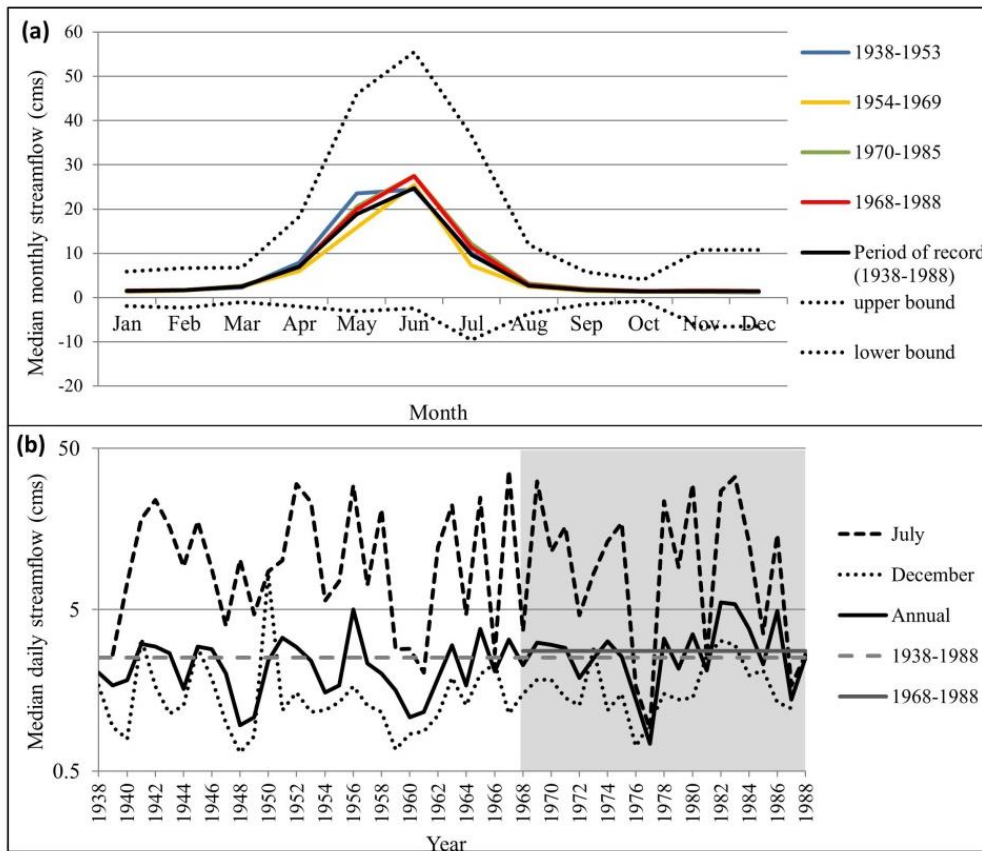
Figure A-3. (a) Monthly median streamflow values estimated for selected 15-year moving window periods and over period of record (1938-1988) for a low-elevation Sierra Nevada gauge station. 95% confidence bounds of MK trend test illustrate relative climate insensitivity of time period selection. (b) Median July, December, and annual daily streamflow over period of record indicate lack of monotonic trend. Median daily streamflow over period of record and over 20-year window used for calculation of majority of hydrologic indices are indicated.

Table A-0-1. Summary of the Mann-Kendall (MK) and Durbin-Watson (DW) test statistics of monthly streamflow records for one long-term unimpaired gauge station example for each available natural flow class. MK and DW tests significant at the α = 5% significance level are highlighted in bold. DW index values between 1 and 2 indicate non-autocorrelation (Durbin and Watson 1950).

USGS Gauge Station	Natural Flow Class	Start Year	End Year	Total # of years	MK *tau*	2-sided *p*-value	DW Index	DW trend test 2-sided *p*-value
10308200	1	1961	2014	53	**-0.066**	**0.012**	1.6	0.25
11522500	2	1928	2015	77	0.005	0.802	**1.9**	**0.01**
11315000	3	1928	2014	81	0.021	0.310	1.6	0.30
11478500	4	1951	2015	64	**-0.049**	**0.042**	1.6	0.20
11162500	6	1952	2015	63	-0.033	0.178	1.8	0.31
11224500	7	1946	2015	69	0.010	0.685	1.8	0.51

Final hydrologic classification of California

Based on the cluster and CART analyses, seven natural flow classes distinguished by six explanatory catchment attributes could be identified within the State of California. Below we summarize the dominant rainfall-runoff responses for the seven identified natural flow classes together with their catchment controls (Table 1-4 in Chapter 1):

Snowmelt (SM): Reaches with catchments above 2,293 m a.s.l. are characterized by a highly seasonal snowmelt-dominated hydrologic regime (Fig. 1-4) with spring snowmelt (Mar-Jul) contributing 75% of annual streamflow. These reaches are characterized by high flows in late spring (median June streamflow 91 to 3,695 cfs), a predictable snowmelt recession curve (Yarnell et al. 2010), and very low flows (<10th percentile) throughout the remainder of the year (median December streamflow 4 to 283 cfs).

High-volume snowmelt and rain (HSR): These reaches are characterized by large mean annual streamflow volumes (average 2,386 cfs; range of 891 to 5,456 cfs). They have significant spring snowmelt contributions (70% of annual streamflow occurs Mar. - Jul.), with highly seasonal flow patterns similar to those observed in SM and LSR reaches (Fig. 1-4) (because they are generally located downstream of SM and LSR reaches) but with larger winter storm contributions (15% of annual streamflow Dec. – Feb.) because precipitation inputs occur as a mix of rain and snow; the highest flows occur mainly in spring (median May flow 1,775 to 7,003 cfs), and the lowest in summer (median October flow 40 to 1,281 cfs). HSR catchments have well developed channel

networks (stream density >0.65 km/km^2) and reaches therefore tend to retain higher summer base flow contributions than their SM and LSR counterparts (median May streamflow of 5.6 to 254 cfs and 31 to 2,320 cfs, respectively). The combination of large (>2,144 km^2) mid-elevation (1,126 to 2,293 m) drainage basins with high stream density restricts HSR reaches almost exclusively to the Central Valley draining the western Sierra Nevada.

In order to improve understanding of catchment function and first-order controls on hydrologic response in the low-*volume snowmelt and rain* natural flow class, we distinguish here between LSR and *rain and seasonal groundwater* (RGW), representing LSR reaches greater than and less than 1,126 m a.s.l., respectively, as differentiated by the CART analysis (Fig. 1-6).

Low-volume snowmelt and rain (LSR) reaches demonstrate hydrologic characteristics of both SM and HSR in that they display strong seasonal snowmelt signatures (78% of annual streamflow Mar. - Jun.) like SM hydrographs but receive sufficient summer precipitation (26% of annual streamflow Jul. - Sep.) and larger winter rain inputs (25% of annual streamflow Dec. - Feb.) to create bimodal snowmelt- and rainfall-dominated hydrographs (Fig. 1-4). These mid-elevation (1,126 to 2,293 m) reaches are located such that on average the snowmelt pulse peaks prior to SM reaches (May 24) but later than HSR reaches (May 4). They are characterized by steeper slopes than SM reaches (>20%) and lower winter temperatures than HSR reaches (Jan. temp <-5C^o).

The lower elevation rain and seasonal groundwater (RGW) reaches cover the largest spatial footprint of any natural flow class (Fig. 1-8) and are therefore expected to capture a range of physical processes combining rain and groundwater contributions. Annual hydrographs are winter rain dominated (peak in March, average median flow 171 cfs), but they do not get as much rain in winter as WS reaches (60% of annual streamflow Dec. - Mar.); instead storms are more spread out over winter and spring. These catchments generally overlay coastal basin aquifers, which are primarily recharged by deep percolation of winter precipitation runoff from the surrounding mountains (Hanson 2003). As there is very little vertical flow through the layered aquifer systems in coastal regions of California, these catchments often have very short residence times (Hanson 2003). Rain percolating into the shallow, laterally connected aquifers of these regions is therefore expected to appear as a lagged base flow pulse in the stream

hydrograph, which would explain the bimodal signature of this natural flow class in the absence of snowmelt influence.

Winter storm (WS): These highly seasonal winter rain driven reaches are found in low-elevation (<1,126 m) regions of the California coastal range and central valley underlain by unconsolidated sand and gravel aquifers covered in alluvial sediments. Characteristic winter storms (68% of annual streamflow Dec. - Mar.) drive the earliest maximum flows of any class (January, median flow 81 to 7,220 cfs) while dry summers promote extreme low flow conditions [average median Sep. streamflow 33 cfs; average base flow index 0.01 (Poff and Ward 1989)]. Upstream catchments are characterized by substantial winter precipitation (Jan. precipitation >28 cm) and high riparian soils clay content (>23%). High clay content is often associated with higher soil water content during storm events, reflecting perched water table dynamics associated with clay-rich soils (Swarowsky et al. 2011). Higher soil water content during storm events is expected to contribute to the large winter storm flows characteristic of WS reaches.

Groundwater (GW): These reaches are characterized by significantly higher streamflows year-round than reaches of any other flow class (average mean annual flow 8,729 cfs) and very stable flows (average CV 1.07). Their upstream catchments are characterized by low stream density, low precipitation inputs (Jan. precipitation <16 cm), and large upslope contributing areas (see Fig. 1-6), indicating streams receive large contributions from groundwater. This is corroborated by the occurrence of relatively permeable, unconsolidated deposits of alluvial or volcanic origin underlying GW catchments (USGS 2014), which according to Planert and Williams (1995) provide a significant groundwater source due to their fractured volcanic geologic setting. These reaches therefore dominate the northernmost Sierra Nevada and the Basin and Range Province region, which consists of a broad, young volcanic platform of high elevation and low relief, reflecting recent constructional volcanism rather than erosional forms. Rock type is dominated by low gradient basaltic and andesitic lava flows (Fig. 1-6), and the young age of the surficial deposits results in poor soil development. Surface and subsurface hydraulic conductivities in young volcanic deposits are exceptionally high due to highly porous and permeable volcanic layers (Tague and Grant 2004), and this geologic setting promotes deeper percolation of surface water and greater groundwater contributions to streamflow (average 7-day minimum flow 3,203 cfs; average base flow index 0.37) (Freeze and Cherry 1979). Many areas of northeastern

California appear to lack surface drainage systems altogether, and drainage densities in GW catchments are significantly lower than the rest of the state (<0.65 km/km^2) despite very large drainage areas (2,144 km^2). Large, high volume springs in the headwaters of these reaches further indicate the existence of extensive, well-developed subsurface drainage systems.

Perennial groundwater and rain (PGR): These reaches combine the stable, base flow-driven conditions of GW reaches (average base flow index 0.12) with the winter rain-dominated conditions of WS reaches (36% of annual streamflow Jan. - Mar.) in catchments with low mean annual streamflow (average 258 cfs). PGR reaches are found in low-elevation, low stream density (<1.1 km/km^2) catchments characterized by low riparian soils clay content ($<23\%$). They are prevalent in the southern coastal region, presumably due to the high hydraulic connectivity of the underlying unconsolidated coastal basin sediments and aquifers (USGS 2014).

Flashy, ephemeral rain (FER): These reaches are characterized by a high coefficient of interannual CV (average CV 4.93), extended extreme low flows (<10th percentile) (average duration 98 days per year) and large floods ($<$ 10-year return period), and the lowest average annual daily streamflows of any class (105 cfs). The high CV indicates a high ratio of streamflow variance to average daily streamflow and corresponds to low predictability. These FER reaches drain steep ($>31\%$), low elevation and high stream density (>1.1 km/km^2) catchments dominated by riparian soils with high clay content ($>23\%$) in which runoff responds quickly to precipitation events. In such low-order streams with small channel capacities and minimal surface water - groundwater interactions (average base flow index 0), saturation-excess overland flow is the dominant runoff process (Fryirs and Brierley 2012), leading to more extreme low flow (1% of annual streamflow Jul. - Oct; average 7-day minimum flow 0 cfs) and flood conditions (68% of annual streamflow Jan. - Mar) than streams with substantial surface water – groundwater interactions such as GW and PGR reaches. FER reaches are mainly located along the southern coast of California and the inland face of the coastal range.

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