A hydrogeomorphic classification of California for environmental flows applications

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UC DAVIS HYDROLOGIC SCIENCES

Introduction

Environmental flow targets are needed to support highly altered and degraded river ecosystems in California. However, defining flow targets for California is complicated by extreme hydrogeomorphic variability and an intensive water management legacy. Improved understanding of the diversity of natural flow regimes and geomorphic setting and their spatial arrangement across the state is needed **to develop effective flow targets at appropriate scales for river restoration applications with limited resource and data requirements.** This research develops (i) a spatially explicit reach-scale hydrologic classification for California and (ii) a coupled hydro-geomorphic classification of the Sacramento Basin. Seven natural flow classes are identified representing distinct flow sources, hydrologic characteristics, and catchment controls. The geomorphic sub-classification further distinguishes nine geomorphic settings across *low volume snow and rain dominated* reaches using a multivariate statistical analysis of reach-scale geomorphic attributes. From a river management perspective, this research provides the much needed **framework to assess the separate and combined influences of hydrologic and geomorphic settings on the maintenance or restoration of reach-scale river ecosystem functions in California.**

Objectives

HYDROLOGIC CLASSIFICATION

1) To characterize distinct natural streamflow patterns in streams and rivers throughout study regions
2) To determine key geographically-independent physical catchment and climatic controls over rainfall-runoff response
3) To assign natural flow classes to river reaches throughout study region based on geospatial controls

GEOMORPHIC CLASSIFICATION

1) To characterize distinct geomorphic reach types within each natural flow class
2) To determine key terrain indices distinguishing reach types
3) To assign reach types to stream reaches throughout each natural flow class based on terrain controls

Study Framework

Hydrologic classification

- **Physio-climatic catchment controls**: Topography; Climate; Soils and vegetation
- *Rainfall-runoff processes*
- **Reach-scale hydrologic setting**: Flow magnitude; Flow variability; Flow predictability

Geomorphic classification

- **Landscape setting**: Valley morphology; Relative basin position; Relief and curvature
- *Geomorphic processes*
- **Reach-scale geomorphic setting**: Cross-sectional morphology; Longitudinal morphology; Sediment composition

Ecosystem functions

- *Ecological, biogeochemical, and fluvial geomorphic processes*
- **Flow-driven ecosystem functions**: Resource/habitat for biota; Vector for connectivity and energy exchange; Agent of geomorphic change

Conclusions

- Distinct natural flow classes with specific hydrologic characteristics and physio-climatic controls can be distinguished for California using available hydrometric and geospatial data
- Hydrologic stratification improves ability to characterize regional geomorphic variability by reducing natural physio-climatic and geologic variability
- A stratified random sampling scheme based on geomorphic thresholds of contributing area and reach slope increases the range of variability distinguished by the geomorphic classification model
- 161 reaches described by 22 geomorphic variables can be grouped into nine reach types characterized by distinct variable ranges and combinations
- Six nondimensional geomorphic variables were found most signifiicant for distinguishing reach types for *low-volume snowmelt and rain* reaches: bankfull width and depth variance, slope, sinuosity, entrenchment ratio, and bankfull width-to-depth ratio

Hydrologic Classification

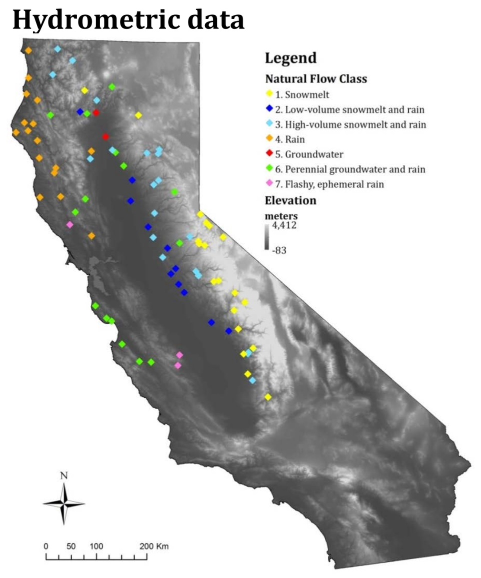
Methodology

Inputs	Step	Outputs	Goal
Hydrometric data: unimpaired daily streamflow time-series	Statistical analysis of streamflow data	*Uncorrelated hydrologic indices*	Characterize hydrologic response of reference gauge stations
	Cluster analysis	*Natural flow classes*	Distinguish dominant hydrologic responses across region
Geospatial data: genetic catchment attributes	CART classification	*Classification model*	Identify genetic catchment controls on dominant hydrologic responses
	CART prediction		Transfer natural flow classes to ungauged catchments

Reach-scale hydrologic classification of study region

Data

Hydrometric data

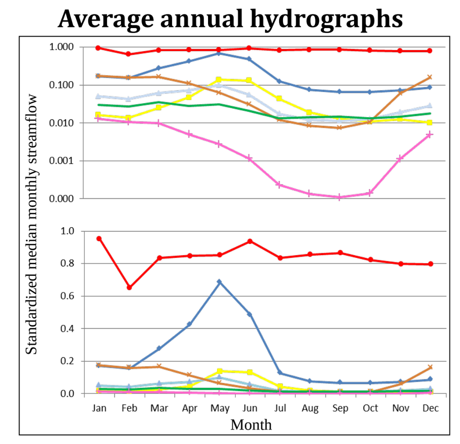


Geospatial data

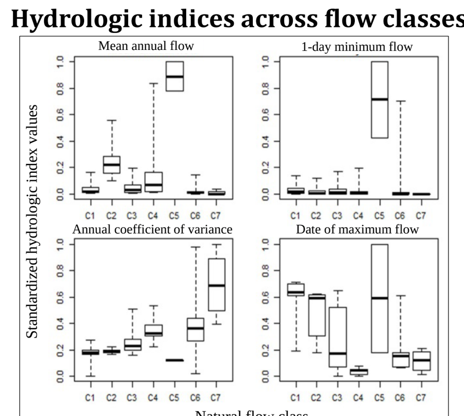
Topographic	Climatic
Elevation	Monthly temperature
Drainage area	Monthly precipitation
Slope	Annual temperature
Stream order	Annual precipitation
Stream density	Seasonality index
Basin compactness	**Geologic**
Relief	Dominant geology
Topographic wetness	Riparian soils
	Underlying aquifer

Analysis

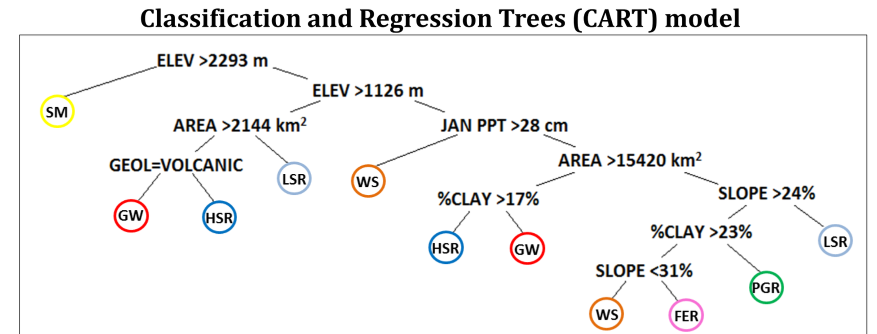
Average annual hydrographs



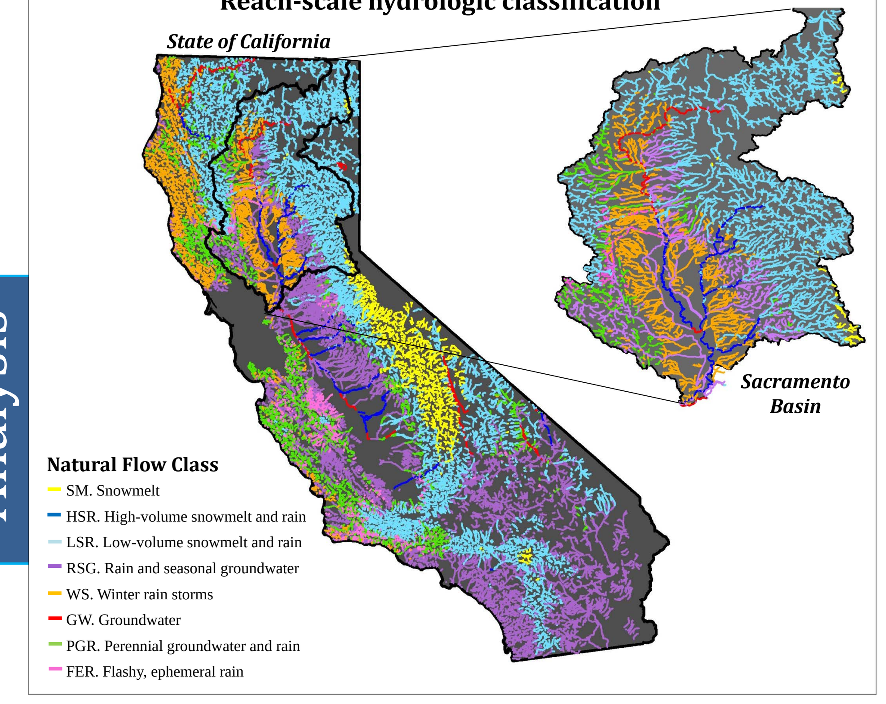
Hydrologic indices across flow classes



Classification and Regression Trees (CART) model



Reach-scale hydrologic classification



Results

Summary table of California natural flow classes

Class	Name	Hydrologic Characteristics	Physical and Climatic Catchment Controls
SM	Snowmelt	• Large spring snowmelt pulse (~May 24) • Very high seasonality index • Extreme low flows (<10th percentile) Sep-Feb	• High elevation catchments (>2,293 m), major snow influence
HSR	High-volume snowmelt and rain	• Spring snowmelt pulse (~May 4) • High seasonality but larger winter storm contributions • Retain high baseflow throughout summer low flow season • Bimodal snow - rain hydrograph	• Mid-elevation catchments (1,126 - 2,293 m), large contributing area (>2,144 km²) *not* underlain by volcanic geology [high stream density (>0.65 km/km²), mild winter temperatures (Jan temp >-5C°)] **OR** • Low elevation (<1,125 m) with very large contributing area (>15,420 km²) and high riparian soils clay content (>17% clay) [substantial winter precipitation (Jan precip 16-28 cm)]
LSR	Low-volume snowmelt and rain	• Transition between Classes 1 and 2 • Bimodal snow - rain hydrograph driven by spring snowmelt pulse and winter rain	• Mid-elevation catchments with limited area (<2,144 km²) [low winter temperatures (Jan temp <-5C°), high stream density (>0.65 km/km²)]
RSG	Rain and seasonal groundwater	• Bimodal hydrograph driven by winter rain pulse and percolating winter rain appearing as baseflow pulse later in year	• Low elevation catchments (<1,126 m) with limited winter precipitation (Jan precip <28 cm) and low slopes (<24%) • Underlain by igneous and metamorphic rock materials • Coastal catchments with small aquifers driving short residence times
WS	Rain	• 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 km²) underlain by volcanic (basaltic and andesitic) geology [low stream density (<0.65 km/km²)] **OR** • Low elevation catchments with limited winter precipitation, very large contributing area (>15,420 km²) with low riparian soils clay content (<17%) • Catchments underlain by igneous and metamorphic-rock aquifers
PGR	Perennial groundwater and rain	• Low seasonality • Low mean annual streamflow • Transition between Class 4 and 5, with winter rain contributions but generally stable flows	• Low elevation catchments with low riparian soils clay content (<23%) [low stream density (<1.1 km/km²)] • Catchments primarily underlain by residual sedimentary rock materials in western portion of California
FER	Ephemeral, flashy rain	• Lowest mean annual flows • Highest CV, lowest predictability • Longest extreme low flow duration • Highest flows in winter	• Low elevation catchments with high riparian soils clay content (>23%) and high slopes (>31%) [high stream density (>1.15 km/km²)]

Geomorphic Classification

Methodology

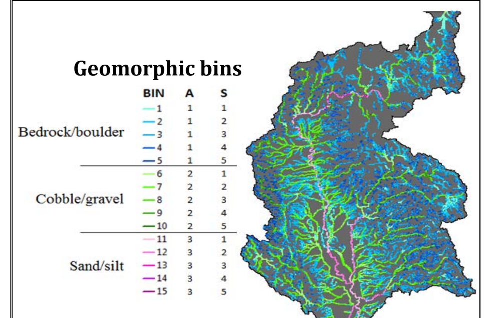
Inputs	Method	Outputs	Goal
Geomorphic data: geomorphic characteristics of reference reaches	Development of training datasets	*Geomorphic indices for reference reaches*	Characterization of unimpaired geomorphic reaches in flow class
	Cluster analysis	*Distinct HG settings*	Differentiation of distinct geomorphic settings
completed			
Geospatial data: topography	Terrain analysis	*Terrain indices*	Development of indices describing landscape spatial patterns
	Classification	*Multivariate predictive model*	Identification of landscape controls over geomorphic settings
next steps			
significant explanatory indices	Prediction		Application of model to non-reference reaches

Reach-scale hydrogeomorphic classification

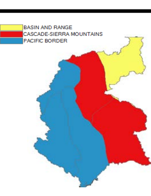
Reach-scale geomorphic stratification

Reach variable	BIN 1	2	3	4	5
Area (A) [km²]	bedrock/boulder	cobble/gravel	sand/silt	---	---
Slope (S) [%]	<0.1%	0.1 - 2%	2 - 4%	4 - 10%	>10%

Geomorphic bins



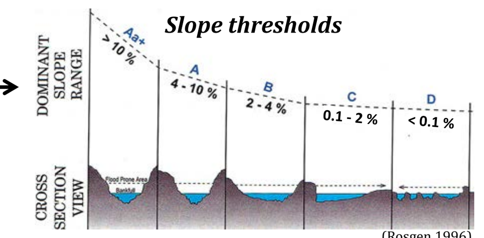
Contributing area thresholds



Physiographic province	Contributing area [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

(Montgomery and Buffington 1993; Gasparini et al. 2004)

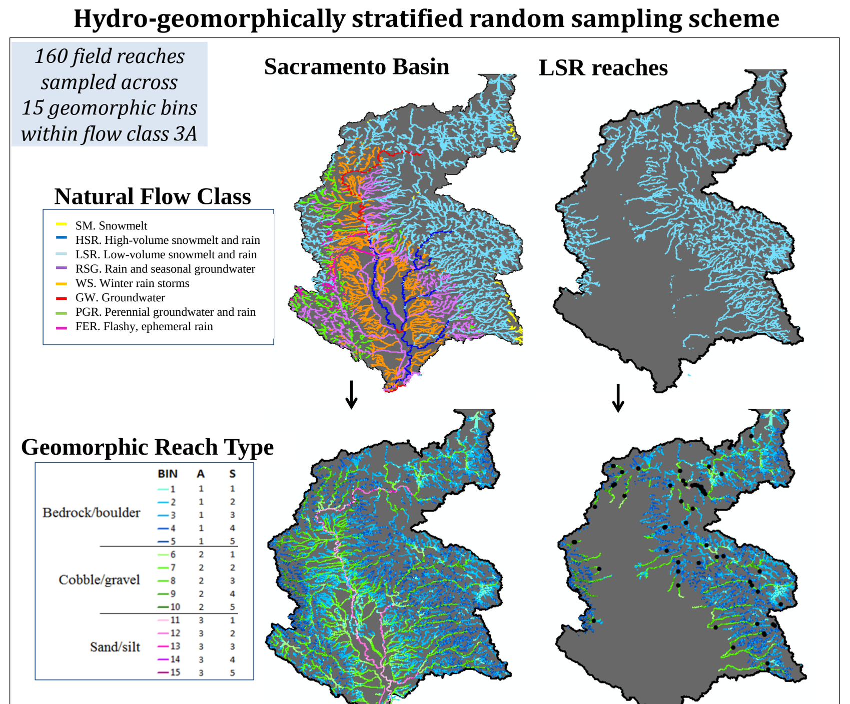
Slope thresholds



(Rosgen 1996)

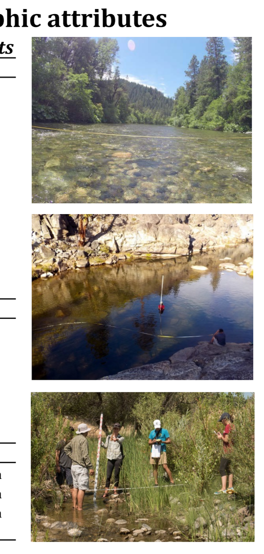
Data

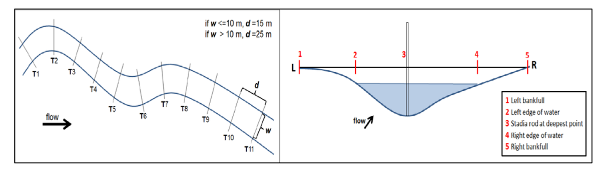
Hydro-geomorphically stratified random sampling scheme



Field-based geomorphic attributes

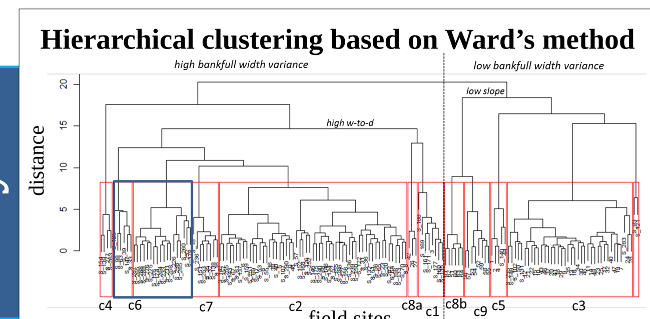
Geomorphic parameter	Code	Units
Cross-sectional morphology		
wetted depth	d	m
wetted width	w	m
wetted w/d	d.w	--
wetted depth/D50	d.D50	--
bankfull depth	bf.d	m
bankfull width	bf.w	m
bankfull w/d	bf.w.d	--
bf depth/D50	bf.d.D50	--
entrenchment ratio	e.ratio	--
shear stress	shearstress	Pa
shields stress	shield.stress	--
Longitudinal morphology		
slope	slope	%
sinuosity	sinuosity	--
channel depth variance	d.var	--
channel width variance	w.var	--
bankfull depth variance	bf.d.var	--
bankfull width variance	bf.w.var	--
Sediment composition		
D50	D50	mm
D84	D84	mm
Dmax	Dmax	mm
sediment variance	std.sed	--



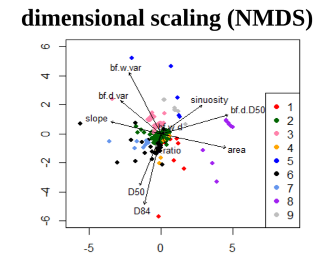


Analysis

Hierarchical clustering based on Ward's method



Nonmetric multi-dimensional scaling (NMDS)

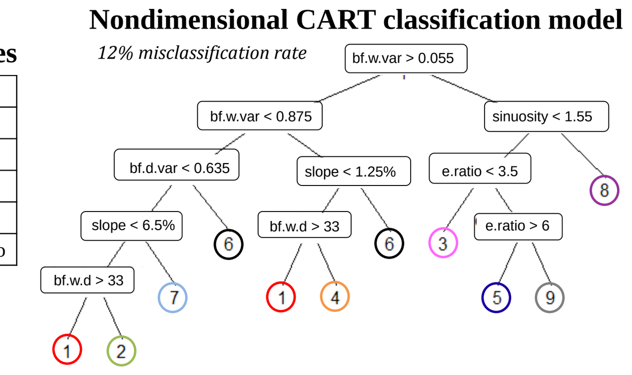


Explanatory geomorphic attributes

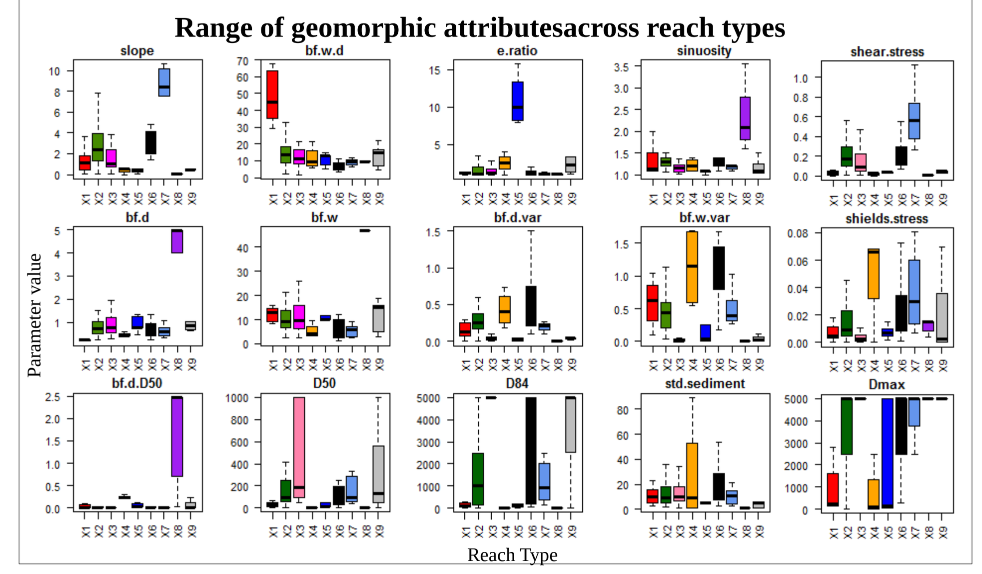
Bankfull width variance
sinuosity
slope
Bankfull depth variance
Entrenchment ratio
Bankfull width-to-depth ratio

Nondimensional CART classification model

12% misclassification rate



Range of geomorphic attributesacross reach types



Results

GEOMORPHIC REACH TYPE
1. LOW-ORDER WIDE VALLEY: 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 A_c
2. POOL-RIFFLE: Mid-slope, *mid* bf.w. and d. variance and sediment variance, small D50, variable D84
3. PLANE BED: Mid-slope, *very low* bf.w and d. variance, large D50, D84, Dmax, low shields stress
4. ANASTOMOSING CHANNEL: 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
5. UPLAND MEADOW: High e.ratio (low entrenchment), low slope, low bf.d. and w. variance, small D50 and D84, small A_c
6. CASCADE/STEP-POOL: 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
7. COLLUVIAL: Highest slope, high shear stress*, large D50 and D84, entrenched, low bf.w.d, low sinuosity, low bf.d.D50, very small A_c
8. LARGE UNIFORM SAND BED: 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 A_c
9. LARGE UNIFORM BOULDER BED: 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 A_c