Predicting natural channel patterns based on landscape and geomorphic controls in the Columbia River basin, USA

Tim Beechie[1] and Hiroo Imaki[1]

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[1] Based on known relationships of slope, discharge, valley confinement, sediment supply, and sediment caliber in controlling channel patterns, we developed multivariate models to predict natural channel patterns across the 674,500 km^2 Columbia River basin, USA. We used readily available geospatial data sets to calculate reach slopes, 2 year flood discharge, and valley confinement, as well as to develop hypothesized landscape-level surrogates for sediment load and caliber (relative slope, percent of drainage area in alpine terrain, and percent of drainage area in erosive fine-grained lithologies). Using a support vector machine (SVM) classifier, we found that the four channel patterns were best distinguished by a model including all variables except valley confinement (82% overall accuracy). We then used that model to predict channel pattern for the entire basin and found that the spatial distribution of straight, meandering, anabranching, and braided patterns were consistent with regional topography and geology. A simple slope-discharge model distinguished meandering channels from all other channel patterns, but did not clearly distinguish braided from straight channels (68% overall accuracy). Addition of one or more of the hypothesized sediment supply surrogates improved prediction accuracy by 4–14% over slope and discharge alone. Braided and straight channels were most clearly distinguished on an axis of relative slope, whereas braided and anabranching channels were most clearly distinguished by adding percent alpine area to the model.

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1. Introduction

[2] The identification of geomorphic and hydrologic thresholds that determine alluvial channel patterns (e.g., braided, meandering, and straight) has long been an important research focus in fluvial systems, and it is now well known that alluvial channel patterns are influenced by at least seven primary controlling variables: channel slope, discharge, valley confinement, sediment supply, sediment caliber, bank strength, and wood loading [*Leopold and Wolman*, 1957; *Parker*, 1976; *Desloges and Church*, 1989; *Fetherston et al.*, 1995; *Millar*, 2000; *Abbe and Montgomery*, 2002]. Many studies have also examined various derivatives of these variables, including stream power, dimensionless discharge, and relative bank strength [*Van den Berg*, 1995; *Bledsoe and Watson*, 2001; *Eaton et al.*, 2010]. *Leopold and Wolman* [1957] first noted that braided and meandering patterns were largely distinguished by channel slope and discharge, yet straight channels were not clearly separated from braided and meandering channels based on those two variables alone. Subsequent studies examined the role of sediment caliber in shifting the slope-discharge threshold between braided and meandering channels [*Van den Berg*, 1995; *Lewin and Brewer*, 2001; *Eaton et al.*, 2010], and several papers have conceptually examined the role of sediment supply in determining channel pattern [e.g., *Schumm*, 1985; *Church*, 2002]. More recently, the role of root strength has been shown to exert a strong control on the transition from meandering to braided channels [*Millar*, 2000], although the effect is mostly absent from larger channels because they are deep enough to erode banks beneath the rooting zone [*Beechie et al.*, 2006a; *Eaton and Giles*, 2009]. Wood abundance has also been suggested as a primary influence on channel form and dynamics in forested rivers [*O'Connor et al.*, 2003; *Latterell et al.*, 2006; *Sear et al.*, 2009].

[3] While the role of each these variables is generally understood, there have been few attempts to incorporate these variables into a predictive model of channel pattern [*Lewin and Brewer*, 2001; *Millar*, 2005; *Eaton et al.*, 2010]. A key challenge to building such models is that field measurements of variables such as sediment supply, grain size, bankfull discharge, and channel slope are not readily available at numerous suitable study sites, let alone over large geographic areas [*Beechie et al.*, 2006a; *Davies et al.*, 2007]. Hence, such analyses require some combination of modeled and surrogate variables that can serve as proxies for field measurements [*Van den Berg*, 1995], including development of stream channel metrics from

[1]Watershed Program, Fish Ecology Division, Northwest Fisheries Science Center, NOAA Fisheries, Seattle, Washington, USA.

Corresponding author: T. Beechie, Watershed Program, Fish Ecology Division, Northwest Fisheries Science Center, NOAA Fisheries, 2725 Montlake Blvd. E., Seattle, WA 98112, USA. (tim.beechie@noaa.gov)

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high resolution imagery, or of landscape and land cover variables that have indirect influences on channel morphology [*Marcus and Fonstad*, 2008; *Richards et al*., 1996]. The use of Geographic Information Systems for such purposes is widespread, and it is now common to estimate numerous channel parameters from readily available geospatial data sets [*Nardi et al*., 2006; *Davies et al*., 2007; *Clarke et al*., 2008]. Moreover, it is relatively easy to statistically analyze large and complex geospatial data sets, and to develop predictive models of channel patterns or ecological features of streams [*Lunetta et al*., 1997; *Wohl and Merritt*, 2005].

[4] In this paper, we develop a multivariate statistical model of geomorphic and landscape controls on channel pattern and map predicted channel patterns across a 674,500 km^2 river basin with diverse lithology, glacial history, and climate. The novel aspects of this study are that (1) we create a map of channel patterns that would be expected in the absence of land use or dams (to inform river conservation planning), and (2) we use knowledge of known controlling variables to create a model that predicts well-defined channel patterns with known dynamics and ecological functions. Because field measurements of the controlling variables (slope, discharge, valley confinement, sediment supply, sediment size) are not available for multiple sites of each channel pattern, we generate six geomorphic and landscape variables from five readily available geospatial data sets representing regional topography, precipitation, hydrography, geology, and land cover. We then construct statistical models to predict channel pattern using all possible variable combinations, use accuracy assessment to compare models and select the best model, and use an independent sample of randomly selected river reaches to test the accuracy of the model that best predicts channel patterns. We also examine how the statistical analysis informs an understanding of controls on channel pattern, discuss sources of error in predicting channel pattern, and describe how this model can inform conservation planning.

2. Study Area

[5] The Columbia River basin drains 674,500 km^2 in British Columbia, Canada, and seven states in the U.S. [*Quigley and Arbelbide*, 1997] (Figure 1). The region encompasses a wide range of physical and ecological conditions ranging from semiarid and desert regions in the

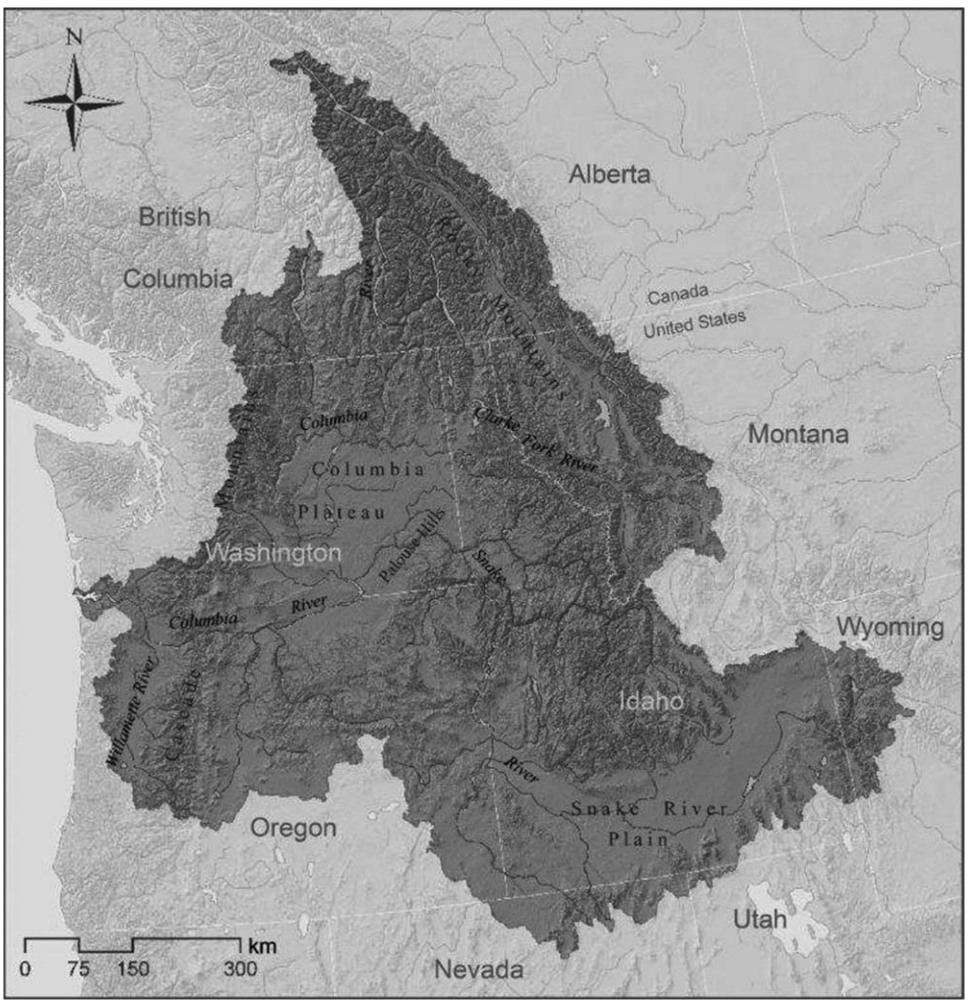

Figure 1. Study area map of the Columbia River basin indicating locations of major rivers and geographic features mentioned in the text.

central plateaus to relatively wet forests in the Cascade Mountains [*Omernik and Bailey*, 1997]. Mean annual precipitation ranges from <200 mm/yr in the central deserts to 3550 mm/yr in the Cascade Mountains at the western edge of the basin [*Daly et al.*, 2002]. Elevations range from sea level to over 3700 m in the Rocky Mountains.

[6] The Columbia basin is bordered by the Rocky Mountains to the east and north, the Cascade Mountains to the west, and several smaller mountain ranges to the south. Lithologies of these and interior mountain ranges include erosion resistant basalts in the Blue Mountains, easily weathered volcanic rocks in the south-central basin, and several granitic batholiths in the Rocky Mountains, Blue Mountains, and Cascade Mountains. Two basalt plateaus are located in the central Columbia and Snake River basins [*Lasmanis*, 1991], and deep loess deposits overly portions of the Columbia Plateau basalts [*Bretz*, 1929]. This wide range of lithologies contributes to high variation in sediment supply and caliber delivered to streams in the Columbia basin [*Mapes*, 1969; *Church and Slaymaker*, 1989].

[7] Most of the northern part of the basin was covered by the continental ice sheet during the last glacial maximum [*Booth et al.*, 2003], and ongoing river incision into valley fills (e.g., glacial till, outwash, and lacustrine deposits) produces relatively high sediment supply in glaciated areas in the Canadian portion of the basin [*Church and Slaymaker*, 1989]. During the last glaciation, the glacial Lake Missoula repeatedly formed east of the Rocky Mountains between 15,300 and 12,700 years BP when the continental ice sheet dammed what is today the Clark Fork River in northern Idaho [*Pardee*, 1910; *Waitt*, 1985]. Each failure of the ice dam (which formed every 30–70 years) released a catastrophic flood through the Columbia basin [*Bretz*, 1923; *Baker*, 1973; *Waitt*, 1985], scouring deep channels into the basalt, creating expansive areas of exposed bedrock, and leaving deep silt deposits in the backwater of flood flows near the mouths of the Walla Walla and Yakima Rivers [*Bretz*, 1923, 1925]. Unscoured loess "islands" of the Columbia Plateau are composed of deep, fine-grained sand and silt deposits, as is the Palouse Region of Washington State [*Bretz*, 1929; *Busacca and McDonald*, 1994]. As a result, the channeled scabland basalts contribute very little coarse sediment to channels and the unscoured loess deposits contribute extremely high volumes of very fine sediments [*Mapes*, 1969; *Beechie et al.*, 2008].

3. Methods

[8] We first provide a brief overview of the approach and methods to clarify the logic and steps involved in our analysis. We then follow with more detailed explanations of the data sets used, assignment of reach attributes to the stream data layer (including supporting logic), the channel typing and analysis procedures, and the error analyses.

3.1. Approach and Overview of Methods

[9] Our main objective in this study was to construct a predictive model of four alluvial channel patterns that encompass the dominant planforms observed in the Columbia River basin of Northwestern U.S.: straight, meandering, anabranching, and braided (Figure 2 and definitions in Table 1). These four patterns are based on the three pattern scheme of *Leopold and Wolman* [1957], but modified to include an intermediate anabranching pattern between meandering and braided [*Beechie et al.*, 2006a]. Here we use the term anabranching for multithread channels in which the channels are separated by islands [*Schumm*, 1985], although the terms island-braided [*Ward et al.*,

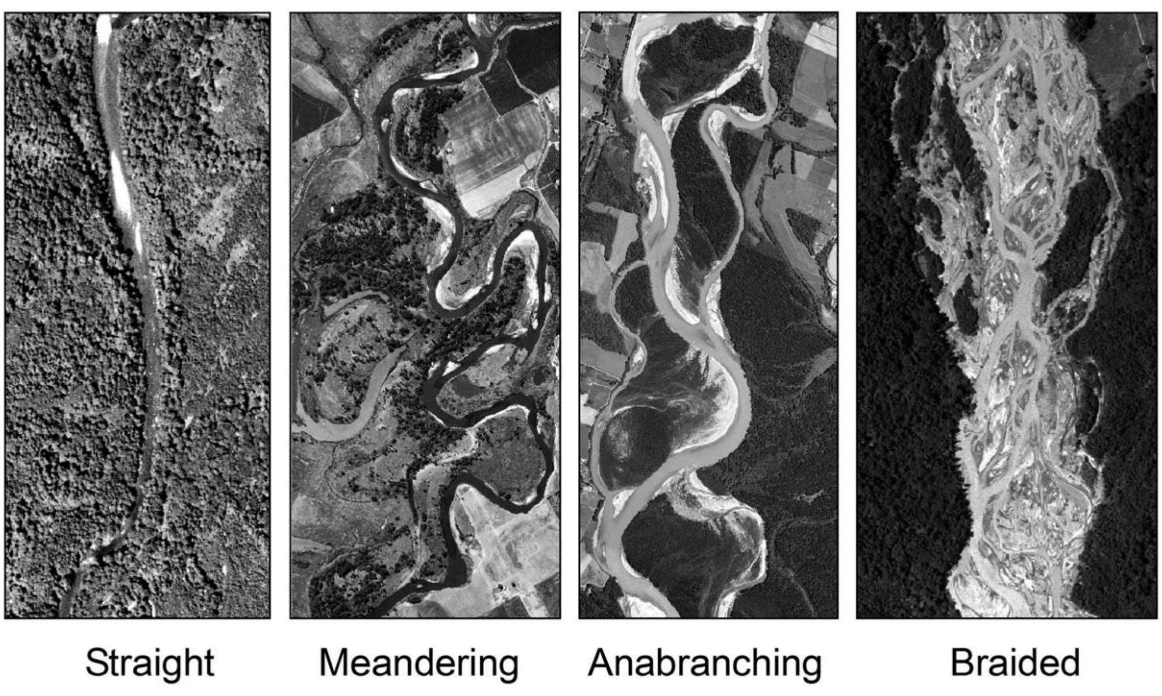

Figure 2. Illustration of the four channel patterns analyzed in this study. Definitions of each pattern are listed in Table 1.

Table 1. Summary of Channel Pattern Definitions Used in This Study [*Leopold and Wolman*, 1957; *Beechie et al*., 2006][a]

Channel Pattern	Definition
Straight	Primarily single thread channel, sinuosity <1.5
Meandering	Primarily single thread channel, sinuosity >1.5
Anabranching	Multiple channels, >50% of channels separated by vegetated islands
Braided	Multiple channels, >50% of channels separated by unvegetated gravel bars

[a]Neither small channels (<8 m wide) nor confined channels (confinement ratio <4) were included in the analysis because those channels are not able to form these patterns [*Hall et al*., 2007]. Hence, these definitions apply only to channels with bankfull width >8 m and confinement ratio >4.

2002; *Beechie et al*., 2006a] and wandering [*Carson*, 1984] have also been used to describe this channel pattern (see also *Beechie et al*. [2006a, Table 1], for discussion of overlapping and conflicting terms in channel pattern classification). We focus on these four channel patterns because they have distinctly different morphology and channel-floodplain dynamics, and they also differ ecologically [*Ward et al*., 2002; *Beechie et al*., 2006a; *Naiman et al*., 2010]. For example, lateral migration rates vary systematically among channel patterns, with the lowest migration rate in straight channels, highest rate in braided channels, and intermediate rates in meandering and anabranching channels [*Beechie et al*., 2006a]. The highest physical and ecological diversity is in channel patterns with intermediate disturbance regimes (i.e., intermediate migration rates), including high age diversity of floodplain surfaces, high riparian species diversity, and high aquatic species diversity [*Ward et al*., 2002; *Beechie et al*., 2006a; *Naiman et al*., 2010].

[10] We selected predictor variables for the model based on the following known controlling variables: channel slope, discharge, valley confinement, sediment supply, sediment caliber, bank strength, and wood abundance (Table 2). Of those variables we omitted bank strength and wood abundance because there are no regional data sets of bank material, natural riparian vegetation, or wood loading throughout the study area. Omitting root strength arguably has a small effect on the analysis because channels that develop the planforms are large enough to erode beneath the roots of riparian vegetation, so root strength has little effect on channel migration and channel pattern development [*Beechie et al*., 2006a; *Eaton and Giles*, 2009]. Omitting wood abundance may theoretically have more influence on channel pattern prediction [*Fetherston et al*., 1995; *O'Connor et al*., 2003], but it is currently not possible to characterize natural riparian vegetation or wood abundance at this scale. We ultimately focused on six channel and landscape variables, three of which we estimated directly from digital elevation data or models (channel slope, discharge, confinement) and three of which were hypothesized to be surrogates for sediment supply and caliber (relative reach slope, percent of basin in unvegetated alpine terrain, percent of basin in fine-grained erosive sediments). Detailed methods and logic for each of these variables are described in section 3.3.

[11] We first calculated and assigned reach attributes to each of more than 2,000,000 reaches in the study area based on available geospatial data. Once we had assigned parameter values to each reach, we aggregated adjacent reaches with similar characteristics to create geomorphically meaningful reaches, reduce the number of reaches for analysis, and reduce errors in parameter estimates. We then used a support vector machine (SVM) classifier to relate reach attributes to channel pattern using a training data set of 120 reaches, and created multiple models to predict channel pattern throughout the Columbia River basin using all possible combinations of the six predictor variables. We assessed model accuracy and uncertainty in three ways. First, the SVM classifier predicted channel pattern for each of the training reaches, and evaluated model accuracy by comparing predicted channel pattern to known channel

Table 2. Hypothesized Relationship Between Known Drivers of Channel Pattern, Predictor Variables Used in This Study, and Supporting Logic for Each Predictor Variable[a]

Driving Variable	Predictor Variable	Logic
Channel slope	DEM-derived reach slope	A key predictor of channel pattern; estimated from digital elevation data and digital hydrography
Discharge	2 year flood discharge	A key predictor of channel pattern; estimated from drainage area and precipitation
Valley confinement	Valley floor width divided by channel width	Confined channels do not have sufficient space to express significant meandering or multithread channel patterns
Sediment supply (1)	Relative channel slope	Channel slope of a reach minus channel slope of the adjacent upstream reach; negative values favor a transport-limited reach, positive values favor a supply limited reach
Sediment supply (2)	Percent of basin in alpine terrain	Braided channels are typically in areas with high sediment supply, and alpine areas typically have higher sediment supply than lower elevation forested areas
Sediment size	Percent of basin with lithologies producing fine-grained sediment	Sediment load in meandering channels is often dominated by suspended load; and fine grained lithologies favor dominance of suspended load
Bank strength	Not addressed	Historical or natural riparian vegetation data not available for the study area, and roots not likely to influence bank erosion in large rivers
Wood abundance	Not addressed	Historical or natural riparian vegetation data not available for the study area

[a]See text for additional explanation and supporting citations.

pattern for each reach in the training data set to calculate overall prediction accuracy. Second, we used the most accurate SVM model to predict channel pattern for all reaches in the study area, and then randomly selected 30 reaches of each pattern to independently assess model accuracy. Finally, we used bootstrapping (1000 model runs using 30 randomly selected reaches of each channel pattern) to create 1000 separate predictions of channel pattern for each reach, and use the consistency of predictions as an indicator of model uncertainty for each reach. These three error analyses provide complimentary insights into model performance.

3.2. Geospatial Data

[12] We used geospatial data from readily available sources representing topography, the stream network, discharge, precipitation, geology, and land use (Table 3). Since there were no seamless data sets covering the United States and Canada, we merged U.S. and Canadian data layers to create seamless coverages for each data set. Differences in resolution of source scales between U.S. and Canadian data sets sometimes dictated that we interpolate or downgrade one data set to match the scale or resolution of the other data set. For the digital elevation models (DEMs), the Canadian Digital Elevation Data (CDED, 20–90 m grid spacing) stored elevation values in integer form at 1 m vertical resolution, so we converted the vertical resolution of the U.S. National Elevation Dataset (NED, 10 m grid spacing) to integer values as well. We then interpolated the Canadian data to a 10 m grid spacing to match the 10 m grid spacing of the U.S. data. Finally, we merged NED and CDED and applied a 3 * 3 average filtering to reduce random elevation errors on floodplains and improve floodplain delineation. Gridded precipitation data obtained from PRISM [*Daly et al*., 2002] and ClimateBC [*Mitchell and Jones*, 2005] were also merged, and the Canadian data interpolated to create mean annual precipitation grid of consistent resolution (800 m grid cells).

[13] Our stream data were based on U.S. National Hydrography Dataset Plus (NHDplus, 1:100,000 scale) and the Canadian Watershed Atlas (1:50,000 scale). The Canadian data set shows more small channels than the U.S. data set due to its higher resolution. However, most differences in channel density between the data sets are in channels much smaller than our threshold size of 8 m, and differences in resolution have little effect on our analysis because we are modeling only channels with estimated bankfull width >8 m. Therefore, we did not attempt to reconcile the source resolutions between the two data sets. After merging the two data sources, we removed ditches and canals to reflect a more natural stream network, which left gaps in the stream network where ditches had replaced the natural channel. We then rejoined isolated natural streams using the minimum number of ditch or canal segments because it was not possible to retrace the missing natural channels at this scale.

[14] Geology data from state agencies in the U.S. and in British Columbia were merged and lithologies were categorized into (1) those that produce predominantly fine sediment, and (2) all other erosion categories. Fine sediment lithologies included sand and finer grained unconsolidated deposits such as alluvium or colluvium, as well as fine-grained and erosive volcanic and sedimentary rocks such as tuffs and mudstones. All remaining erodibility classes (coarser grained and/or erosion resistant) were grouped simply as "other" for this analysis. Details of the erodibility classification and the full geology data set are available at http://www.isemp.org/data.php?sub=12). We also created one land cover-based erosion category (alpine area), which is intended to map high-elevation areas that are naturally unvegetated and produce more sediment than non-alpine areas [e.g., *Church and Slaymaker*, 1989; *Hicks et al*., 1990; *Molina et al*., 2008]. Alpine areas were identified based on land cover data in the British Columbia Biogeoclimatic Subzone/Variant Data and U.S. National Land Cover Data, and included areas classified as barren, ice, or unvegetated that were above an elevation threshold of 2000 m (set by trial and error to remove land use related or non-alpine unvegetated areas).

3.3. Calculation of Stream Reach Attributes

[15] For each 200 m reach we first calculated five reach attributes: reach slope, 2 year flood discharge, confinement

Table 3. GIS Data Sources Used in This Study

	Canada	USA
DEM	The Canadian Digital Elevation Data (CDED; >20 m grid spacing)	National Elevation Dataset (NED; 10 m grid spacing)
	http://www.geobase.ca/	http://ned.usgs.gov/
Precipitation	ClimateBC (2 km grid spacing)	PRISM (800 m grid spacing)
	http://www.genetics.forestry.ubc.ca/cfcg/climate-models.html	http://www.prism.oregonstate.edu/
2 year flood discharge	University of Washington Climate Impacts Group (point data)	University of Washington Climate Impacts Group (point data)
Hydrography	The Watershed Atlas (source maps at 1:50,000 scale)	National Hydrography Dataset Plus (NHDplus) (source maps at 1:100,000 scale)
	http://www.env.gov.bc.ca/fish/watershed_atlas_maps/	http://www.horizon-systems.com/nhdplus/
Geology	Digital Geology Map of British Columbia (compiled at 1:250,000 scale)	Geological Survey from each state (compiled at 1:100,000 scale)
	http://www.em.gov.bc.ca/Mining/Geolsurv/Publications/catalog/bcgeolmap.htm	
Land use/land cover	British Columbia Biogeoclimatic Subzone/Variant Mapping (mapped by hand, source maps at 1:20,000 scale)	National Land Cover Data (NLCD; from satellite data; 30 m pixels)
	http://www.for.gov.bc.ca/HRE/becweb/	http://www.epa.gov/mrlc/

ratio, alpine sediment supply area, and fine-sediment supply area (Table 2). Intermediate variables that we estimated in order to calculate these attributes included drainage area, valley floor width, and bankfull width. We estimated reach slope by calculating the elevation difference between the start and end of a 200 m reach and dividing be the reach length. Because the stream line was sometimes on a hillslope or not in the valley bottom, we searched for the lowest elevation within 60 m of each reach endpoint using open source GIS programs [GDAL, *Open Source Geospatial Foundation*, 2008; StarSpan, *Rueda et al*., 2005] and used those elevations for the slope calculation. This was the most repeatable approach that removed the larger errors and produced reasonable slope estimates (see section 3.5, for accuracy assessment).

[16] We estimated the 2 year return interval flood for each reach by regressing the modeled 2 year return interval flood flow [from *Elsner et al*., 2010] against drainage area and precipitation at 277 sites. We used the modeled stream discharges representing unmodified flows because there are few unregulated gages with which to estimate natural stream flows. This allowed us to use a large number of sites in the regressions and to develop separate regressions for snowmelt-dominated, rainfall-dominated, and transitional hydrographs. Hydrologic regimes were classified using cluster analysis of the mean monthly flows [*Beechie et al*., 2006b, 2013a].

[17] We estimated channel confinement as the valley floor width divided by the bankfull channel width [*Beechie et al*., 2006a]. Bankfull channel width (w, m) was estimated for each reach after *Davies et al*. [2007] and *Hall et al*. [2007], based on drainage area (A, km^2) and mean annual precipitation (P, cm/yr) upstream of each reach [*Leopold et al*., 1964; *Richards*, 1982; *Knighton*, 1998]. We used 270 field measurements of channel width across the basin [*Oregon Department of Fish and Wildlife (ODFW)*, 1999; *WDOE*, 2004] to construct the bankfull width model and obtained the following equation:

$$w=0.177(A^{0.397})(P^{0.453}) \quad (R^2=0.844, P < 0.001)$$

[18] This estimate is based on measurements of single thread channels, which gives a more useful assessment of confinement than using the width of all channel patterns to estimate confinement. For example, using the width of a braided channel to estimate confinement would suggest that braided channels are confined when in fact they are not. Moreover, there is no way to determine channel pattern prior to estimating channel width.

[19] To estimate valley floor width we detrended the DEM by subtracting the global slope trend from the DEM, and then used a filling algorithm to create the valley floor polygon for each reach. Valley floor width for each reach was then estimated by averaging 10 width measurements at equally spaced transects across the valley floor. We evaluated a range of filling depths ranging from 1 to7 m above the channel and found that a filling depth of 5 m provided the most accurate estimate based on regression of measured versus estimated values ($n = 138$). While this 5 m fill height is clearly greater than one would expect from flood waters, lower search heights generated greater errors in the estimates because of inaccuracies in the DEMs. We also found that valley floor width can be overestimated when width measurements are perpendicular to the channel if the channel is sinuous, or when measurements are perpendicular to the valley axis if the valley is curved. Therefore, we estimated valley floor width using both methods and used the smaller of the two widths to minimize errors in the estimate.

[20] The three hypothesized sediment supply or caliber surrogate variables are relative slope, percent of basin in alpine terrain, and percent of basin in fine-grained erosive deposits or rock patterns. Relative slope is the slope of a reach minus the slope of its upstream neighbor. We use relative slope as indicator of the likely relative sediment supply, where relative sediment supply is the ratio of bed load transport capacity to bed load supply within a reach [*Dietrich et al*., 1989; *Knighton and Nanson*, 1993; *Yarnell et al*., 2006]. Positive relative slope values indicate that a reach is steeper than its upstream neighbor (usually forced by a geological control), and likely can transport more sediment than the upstream reach can deliver. That is, reaches with positive values of relative slope are more likely to have high transport capacity relative to the amount of bed load supplied (also termed supply-limited or undersupplied) [e.g., *Mertes et al*., 1996], and for a given slope and discharge will be narrower, deeper, and more armored or coarser grained [*Dietrich et al*., 1989; *Schumm*, 1985]. By contrast, negative values indicate that a reach is more likely to have low transport capacity relative to bed load supply (i.e., transport-limited or oversupplied), and will likely be wider, shallower, and less armored or finer grained. Because this variable does not account for potential changes in transport capacity at tributary junctions due to increasing discharge or stream depth, we also tested relative stream power and relative shear stress as potential surrogates and found that there was no improvement in classification accuracy. Therefore, we opted to use the simplest variable with the least potential error in parameter estimation (relative slope). We also note that we did not consider the potential influence of the slope of reaches farther upstream, which may also influence the amount of sediment delivered to a reach and therefore influence relative sediment supply.

[21] The second hypothesized sediment supply variable is percent of the drainage area upstream of each reach in unvegetated alpine terrain. We defined the drainage basin upstream of each reach from a 30 m resolution DEM using flow accumulation, and then averaged drainage area values for all cells intersecting a stream segment (~10 cells per segment) to assign a drainage area. We then calculated the percentage of the drainage area classified as alpine (using the classification of naturally unvegetated areas above 2000 m described in section 3.2). Alpine areas produce more sediment than forested areas [*Church and Slaymaker*, 1989; *Hicks et al*., 1990; *Molina et al*., 2008], and therefore reaches near alpine terrain are more likely to have high bed load supply. Local data support this contention, as sediment supply from basins in the Canadian Rockies with drainage areas <1000 km^2 have significantly higher sediment supply than non-alpine basins [*Church and Slaymaker*, 1989], and 92% of braided channels in our sample sets had drainage areas less than 1000 km^2 (average drainage area of braided channels = 362 km^2).

[22] Finally, as an indicator of sediment caliber, we estimated the proportion of the drainage basin upstream of each reach that likely produces fine sediments based on estimated drainage area as described above and the area of the basin in fine-grained deposits or rock types (described in section 3.2). We chose this variable based on the understanding that many meandering channels tend to be dominated by suspended load and have banks comprised largely of fine-grained sediment [*Schumm*, 1985; *Knighton and Nanson*, 1993; *Church*, 2002], and that basins producing mostly fine sediment are likely to create those conditions [*Beechie et al*., 2008]. Local data support the assertion that watersheds with fine grained sediments produce very high volumes of fine sediments [e.g., >1400 tonnes/km^2/yr in loess-dominated basins compared to 146 tonnes/km^2/yr in basalt basins, *Mapes*, 1969], and that floodplains and channel banks in those watersheds are composed predominantly of silt and fine sand [*Beechie et al*., 2008]. Hence, the requisite chain of cause-effect linkages between fine sediment sources and cohesive banks is plausible in the Columbia basin, although the utility of this predictor variable will depend in part on the proportion of meandering channels in the study area that are dominated by suspended load versus bed load.

[23] Once we had estimated all necessary attributes for each 200 m reach, we grouped segments into geomorphically meaningful reaches based on similarity of slope, bankfull width, and confinement. That is, beginning with the lower-most reach in each stream, we grouped successive upstream reaches into a single segment until we found a substantial change in any one of three attributes, defined arbitrarily as a 1% change in slope, a 10% change in channel width, or a change from confined to unconfined or vice versa. This process was repeated for all reaches greater than 8 m bankfull width to produce final set of geomorphic reaches for the Columbia River basin. Once the aggregated reaches were assembled, we averaged the segment attributes and assigned those values to the aggregated reach, and calculated the relative slope as the slope of the aggregated reach minus the slope of the next upstream aggregated reach. Ultimately, the majority of predicted braided, anabranching and meandering reaches were >1000 m long (66% of their total length), whereas the majority of straight and confined reaches were <1000 m long (82% of their total length).

3.4. Channel Typing and Analysis Procedures

[24] Our first step in the statistical analysis was to identify a population of river reaches that are capable of forming alluvial channel patterns. Prior studies indicate that channels less than 8 m wide are too small to erode vegetated banks and form complex patterns in the Columbia basin [*Hall et al*., 2007], and channels with narrow floodplains (valley width:channel width ratio <4) rarely exhibit evidence of past channel migration or express meandering or anabranching patterns [*Beechie et al*., 2006a; *Hall et al*., 2007]. Therefore, we eliminated small or confined reaches from our sample population. Hence our sample population includes reaches with confinement ratio >4 and bankfull width >8 m.

[25] From that pool of reaches, we located and typed a widely distributed sample of each of the four channel patterns (Figure 3) using Google Earth [*Google Inc*., 2009]. We visually typed channels based on the channel pattern criteria in Table 1. Because all classification systems separate the continuum of channel patterns into discrete classes, there is ambiguity in typing channels that are near thresholds. Therefore, we used simple rules to reduce observer bias. When sinuosity was near 1.5 we measured sinuosity to determine whether a single-thread channel should be classified as meandering or straight. For multithread channels, we classified a channel as braided if more than half of the channels were separated by gravel bars, and as anabranching if more than half of the channels were separated by vegetated islands. This procedure limited observer bias in channel pattern classification, and variation among observers was eliminated by having a single observer classify all channel patterns.

[26] Because there is no existing data base of channel patterns, we searched manually for at least 30 samples of each channel pattern and made every effort to assure that the sampled reaches of each pattern were widely spaced across the basin. Criteria that the determined suitability of a site for our analysis were (1) the image was clear enough to identify the channel pattern (i.e., not a low-resolution satellite image or poor quality photo), and (2) the natural channel pattern was not obscured by land uses or dams. This second criterion does not necessarily mean there were no land uses adjacent to a reach, but that land use influences were small and the natural channel pattern was still evident (e.g., see the meandering and anabranching examples in Figure 2). We located a total of 147 suitable sites for our training data set (34 braided, 48 anabranching, 34 meandering, and 31 straight).

[27] We used the SVM classifier to develop models that predict the four channel patterns using all 63 possible combinations of the six reach attributes: slope, 2 year flood discharge, valley confinement (if >4), relative slope, percentage of alpine sediment supply area, and percentage of fine sediment supply area. All SVM analyses were conducted using R [*R Development Core Team*, 2008] with the e1071 package [*Meyer et al*., 2012]. We used the bootstrapping procedure to predict channel pattern 1000 times for each reach, and then calculated the percentage of times each pattern was predicted (termed the "voting" distribution) as an indicator of the likelihood that each reach would exhibit a particular channel pattern. For example, if 80% of the predictions for a reach were "meandering," we considered that reach to have a high probability of having a meandering channel pattern. This voting distribution indicates the consistency or "stability" of a channel pattern prediction for an individual reach, where variation in predictions is created by randomly selecting a different set of 120 training reaches for each of the 1000 bootstrapped model runs. Finally, using the bootstrapped results of the most accurate model form, we produced maps of (1) the most likely channel pattern for each reach in the Columbia River basin, and (2) uncertainty in the channel pattern prediction.

3.5. Error Analysis

[28] We analyzed errors for individual parameter estimates if validation data were available or could be acquired, as well as overall classification accuracy of the 63 SVM models. For individual parameter estimates we

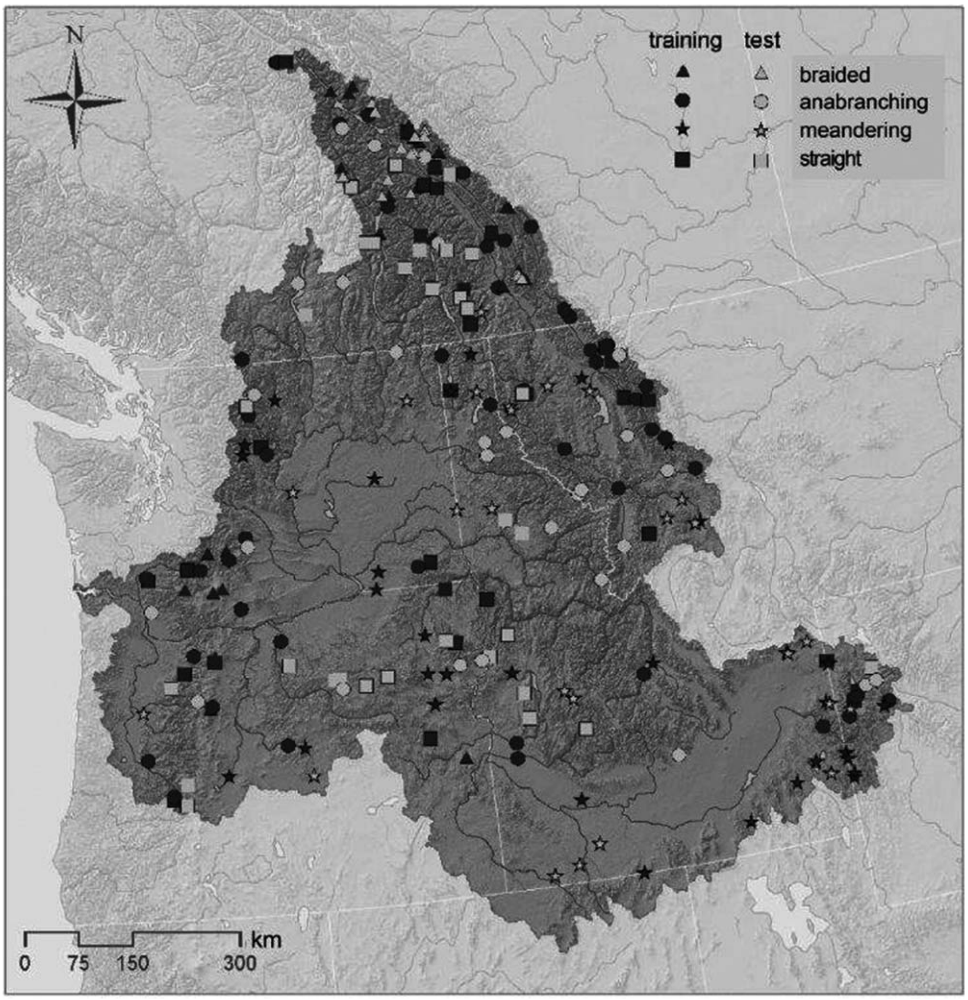

Figure 3. Map of the Columbia River basin showing reach locations by channel pattern. Dark symbols are sites used to develop the training data set and predictive model. Light symbols are sites that were randomly selected from the predicted channel patterns to test model accuracy.

compared our final estimates of slope, bankfull width, and valley floor width to field or photo-measured values using linear regression (Table 4). Perfect agreement is indicated by a slope of 1.0, an intercept of 0.0, and an R^2 of 1.0. Our most accurate estimates were for valley floor width (slope = 0.95, intercept = 94.7, R^2 of 0.77), and the intercept was not significantly different from zero indicating no bias in the estimates. Slope and bankfull width were slightly less accurate, and both were slightly biased at low values (i.e., we tended to overestimate the slope of low-gradient channels and the bankfull width of small channels). We did not conduct additional accuracy analysis for the 2 year discharge beyond the stratification by hydrologic regime and regression analysis shown earlier, which produced R^2 values of 0.73–0.92 (Figure 4). Nor did we have sufficient data to assess whether our surrogate variables accurately predicted either sediment supply or sediment caliber. However, we assessed overall accuracy of each of the SVM models, which incorporates the potential relationship of surrogate variables to sediment supply into the classification error analysis, as well as errors in model structure and parameter estimation.

Table 4. Summary of Linear Regressions of Observed Versus Estimated Reach Attributes for Channel Slope, Bankfull Width, and Floodplain Width[a]

Reach Attribute	*n*	Slope	Intercept	*P* Value	R^2
Slope	155	0.93	0.004	<0.001	0.73
Bankfull Width	270	0.90	4.34	<0.001	0.86
Floodplain Width	138	0.95	94.7	<0.001	0.77

[a]Regressions with slope near 1 and intercept near 0 are the most accurate predictions, and higher R^2 values indicate higher precision (n = sample size).

[29] We evaluated SVM model accuracies using a classification error matrix, and compared alternative SVM models using cross validation (accuracy assessment) because cross validation performs better than Akaike's Information Criterion (AIC) for model selection with discriminant analyses [*Biernacki and Govaert*, 1999]. We also compared predicted channel patterns from each model to actual patterns using the independent test data set, and evaluated model uncertainty using the bootstrapping procedure described earlier. Finally, we examined prediction accuracy for each channel pattern using matrices of classification

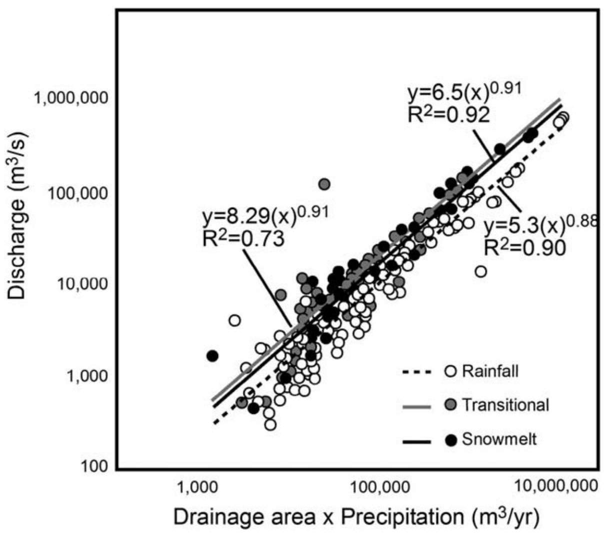

Figure 4. Regression equations for estimating 2 year flood discharge as a function of drainage area and mean annual precipitation, and stratified by hydrologic regime.

error for a subset of the models to examine the influence of different predictor variables on the classification accuracy of each channel pattern. We chose three models for this analysis: the most accurate five-variable model, the model with only slope and discharge, and the model that included slope, discharge, and relative slope. These error matrices highlight channel patterns that are predicted relatively accurately by each model, as well as channel patterns that are commonly misclassified.

[30] Examination of the bootstrapping results, influences of individual predictor variables on model accuracy, and error matrices helped identify which variables were the most important predictors of channel pattern. First, using the bootstrapping results we determined the frequency with which each variable occurred in the most accurate model, and interpreted those results as one indication of the importance of each variable as a predictor of channel pattern. Second, we estimated the effect of each variable on model accuracy by calculating the increase in accuracy when each variable was added to a model in which it was absent, and repeating this calculation for all possible models. For example, we calculated the change in overall accuracy when channel slope was added to each of the possible models that did not contain slope, and for each case we recorded whether accuracy was increased or decreased. We then calculated the average change in model accuracy across all 26 cases for each variable. Finally, we examined both bivariate plots and box and whiskers plots of the variables to visually assess which predictor variables appeared to best distinguish the various channel patterns.

4. Results

[31] Channel patterns predicted by the best model (Model 56 with five parameters, Table 5) exhibit a spatial distribution that is consistent with regional geology and topography. At the scale of the entire Columbia basin, braided channels are rare and are concentrated in the Canadian Rockies, with a few braided channels also predicted on high peaks in the Cascade Mountains or U.S. Rocky Mountains (Figure 5). Meandering channels are found mainly in long low-gradient valleys such as the Willamette Valley, as well as in the Columbia Plateau and the Snake River Plain. Straight channels are concentrated in the major mountain ranges, and anabranching channels are generally located in the valleys emerging from those ranges.

[32] At smaller regional scales, the arrangement of straight, meandering, and anabranching channels is largely consistent with patterns at the Columbia basin scale, but it is also evident that local geologic and topographic features interrupt that arrangement (Figure 6). Straight channels are found predominantly in the upstream alluvial valleys, anabranching channels are mostly where rivers emerge from mountain valleys (though they are sometimes lower in the network), and most meandering channels are in the lower valleys. However, alternating straight and anabranching reaches in some areas likely reflect geologically forced

Table 5. Ranking of SVM Models Based on Overall Accuracy Using the Training Data Set, Including the 10 Most Accurate Models and Selected Two-Variable Models[a]

Model ID	Model Rank	Slope	2 Year Discharge	Relative Slope	Valley Confinement	Fine Sediment	Alpine Sediment	Overall Accuracy (Training Data Set)	Overall Accuracy (Test Data Set)
56	1	X	X	X		X	X	82%	72%
48	2	X	X	X	X		X	81%	68%
64	3	X	X	X	X	X	X	79%	70%
40	4	X	X	X			X	79%	66%
32	5	X	X	X	X	X		77%	67%
24	6	X	X	X		X		77%	64%
52	7	X	X			X	X	75%	68%
54	8	X		X		X	X	75%	66%
47	9		X	X	X		X	75%	62%
8	10	X	X	X				74%	63%
22	27	X		X		X		69%	56%
4	32	X	X					68%	59%
6	41	X		X				64%	58%
10	56	X			X			57%	50%
18	49	X				X		62%	55%
34	44	X					X	63%	64%

[a]Overall accuracy using the test data set is also shown (right column). Accuracy percentages for the training data are averaged accuracies from 1000 bootstrapped model runs. Accuracies for the test data set compare the channel pattern from a single SVM model against actual channel patterns.

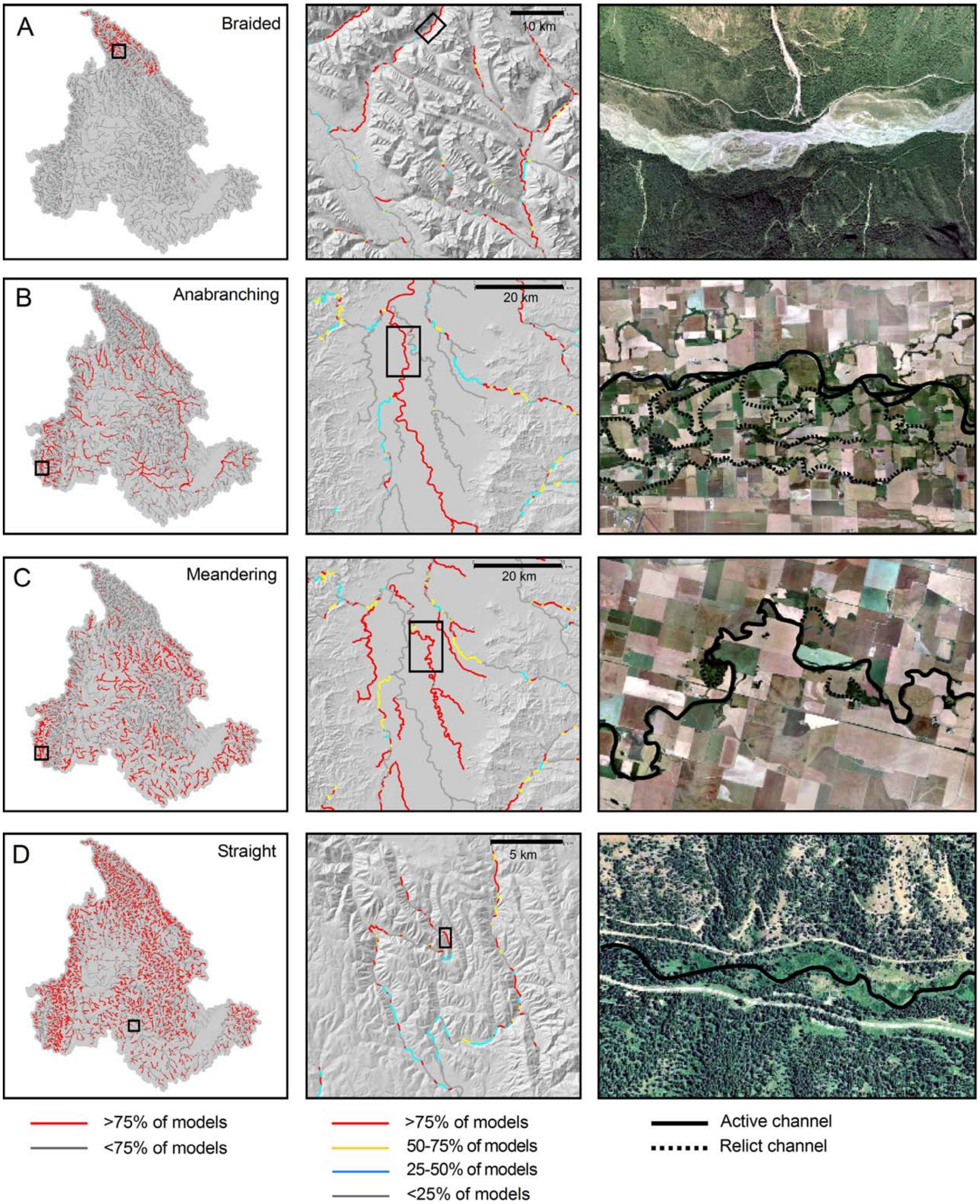

Figure 5. Illustrations of channel pattern distributions at the Columbia basin scale (left column), indicating reaches with more than 75% of boot strapped model runs predicting each channel pattern (a = braided, b = anabranching, c = meandering, d = straight). The second column illustrates close up views of voting distributions for the four channels patterns, and the third column shows aerial photographs of reaches for each channel pattern. Note that channels included in the model are in low-gradient alluvial valleys, and headwater tributaries are not shown.

changes in reach slope, which creates alternating positive and negative relative slopes. In other cases, geologic features create high-elevation depositional basins and force low-gradient meandering reaches high in the river network rather than in the lower valleys (e.g., the upper Grande Ronde River near the bottom of Figure 6). Finally, channels

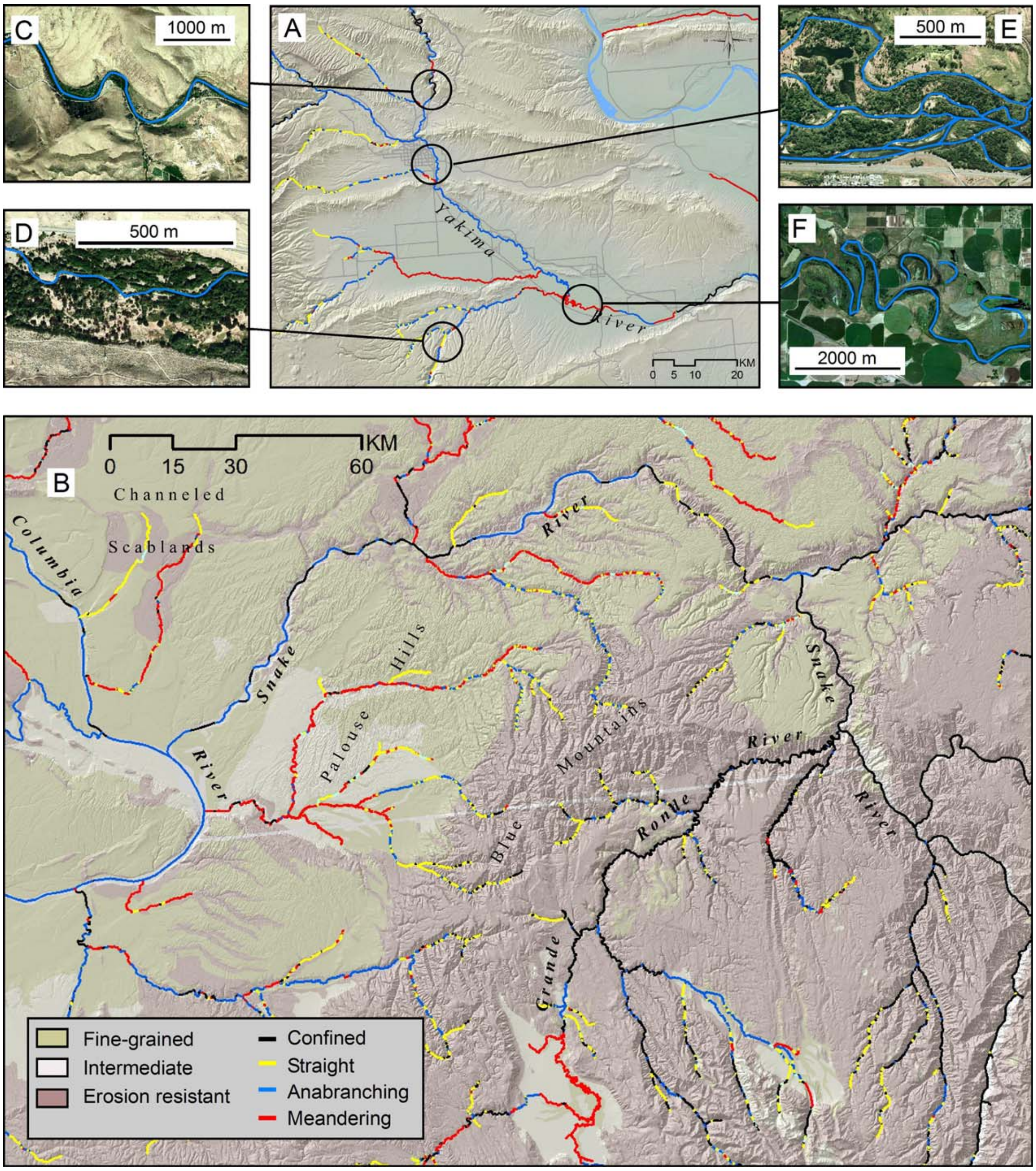

Figure 6. Illustrations of modeled channel pattern distributions at (a) the subbasin scale and (b) the subregion scale. At both scales, confined channels (c) tend to be located in canyons, straight reaches (d) are concentrated in small tributaries, anabranching reaches (e) are generally transitional between straight and meandering reaches, and meandering channels (f) are in low-gradient reaches low in the channel network. Note that the map only shows low-gradient alluvial valleys and canyons, and does not include headwater streams with bankfull width <8 m.

incised into resistant bedrock can create extensive networks of confined channels, preventing any of the channel patterns from being expressed regardless of position in the network (e.g., the lower Grande Ronde and Snake Rivers).

[33] A model including all parameters except confinement (Model 56) resulted in the highest overall prediction accuracy (Table 5, 82% accurate with the training data), and the traditional slope-discharge model was 68% accurate. Models with slope, discharge, and at least one of the hypothesized indicators of sediment supply increased accuracy by 4–14% over the model with slope and discharge alone. A three-parameter model with channel slope, relative slope, and percent of the basin producing fine sediment (Model 22) was 69% accurate, and was the most accurate

Table 6. Correlation Matrix of the Six Predictor Variables Used in Our Analysis[a]

	2 Year Flood Discharge	Relative Slope	Confinement	Fine Sediment	Alpine Sediment
Reach slope	**−0.48**	0.16	**−0.42**	−0.08	**0.40**
2 year flood discharge		0.21	0.22	−0.06	−0.18
Relative slope			−0.03	−0.04	−0.11
Confinement				0.07	−0.27
Fine sediment					**0.30**

[a]Values shown are R^2 values, and bold type indicates statistically significant correlations at $\alpha = 0.05$.

model with predictor variables that were uncorrelated (correlation matrix in Table 6). Accuracies with the test data set were typically about 10% less than accuracies with the training data set, although model 56 was still the most accurate (72% accuracy with the test data). Maps of the voting distributions for each channel pattern illustrate that, overall, 60% of the total reach length was predicted with relatively high confidence (Figure 5). That is, for 60% of the total reach length, more than 750 of the 1000 bootstrapped models agreed on the channel pattern prediction, indicating relatively high consistency among model runs even when using different training data sets.

[34] Seven of the top 10 models included slope, discharge, and relative slope. Adding more parameters generally resulted in higher model accuracy, with the exception of confinement which often decreased accuracy (Table 7). Pair-wise comparisons of 26 models that differed by a single variable showed that addition of slope, discharge or relative slope always increased prediction accuracy and on average improved overall accuracy by 6–9%. By contrast, addition of confinement decreased overall accuracy in 10 of 26 comparisons and on average increased overall accuracy by only 1%. In the bootstrapping analysis, discharge was included in the best model 98% of the time, followed by channel slope (97%), relative slope (95%), alpine sediment (93%), fine sediment (90%), and confinement (22%).

[35] Error matrices for selected models showed that the slope-discharge model performed well for distinguishing the meandering pattern from all other patterns, but did not clearly distinguish straight, braided and anabranching channels (Table 8). Adding relative slope, percent alpine, or percent fine sediment not only improved overall prediction accuracy, but also improved prediction accuracy of straight, braided, or anabranching patterns over the slope-discharge model. For example, the three-variable model including slope, discharge, and relative slope (Model 8), better distinguished braided and straight channels. While these channel patterns are partly distinguished on the axis of channel slope, they are more strongly separated on the axis of relative slope (Figure 7). Adding either percent of basin producing fine sediment or percent of basin in alpine terrain produced similar improvements in overall accuracy over the slope-discharge model. Notably, the six parameter model (all parameters) was not the most accurate model. Rather, the five-parameter model without confinement was most accurate overall, with low omission errors for all channel patterns (<25%) and the highest accuracy for predicting anabranching channels (77%).

Table 7. Changes in Overall Accuracy When Each Variable Was Added to the 26 Possible Models That Did Not Include It[a]

	Change in overall accuracy			
	Increase	No Change	Decrease	Average Increase in Accuracy
Slope	26	0	0	6%
2 year discharge	26	0	0	9%
Confinement	13	3	10	1%
Relative slope	26	0	0	6%
Fine sediment	22	1	3	4%
Alpine sediment	24	1	1	5%

[a]The "increase," "no change," and "decrease" columns indicate the number of models for which addition of the variable increased or decreased overall accuracy. Average increase in accuracy is the average percent increase in overall prediction accuracy across all 26 tests.

5. Discussion

[36] The primary aims of this study were to develop and test a predictive model of channel pattern for the Columbia River basin, and statistically evaluate the relative roles of slope, discharge, and landscape variables in controlling channel pattern. Here we discuss (1) geological and topographic controls on the spatial distribution of predicted channel patterns, (2) potential physical meanings of hypothesized indicators of sediment supply, (3) sources of model error, and (4) the management uses of predicted channel patterns.

5.1. Geologic and Topographic Controls on Channel Pattern

[37] The common downstream sequence of channel patterns described in other studies (from straight to anabranching to meandering) [*Church*, 2002; *Beechie et al.*, 2006a] is apparent in some basins within the study area, but there are also many departures from this idealized sequence. This downstream sequence is generally attributed to decreasing channel slope and a shift in the balance of sediment supply to transport capacity, as well as changes in grain size and bank strength [*Schumm*, 1985; *Church*, 2002]. However, it is also evident that geologic controls and tributary junctions locally interrupt this sequence [e.g., *Rice and Church*, 1998; *Benda et al.*, 2004]. Straight reaches in the Columbia basin tend to be steep (median slope ∼0.015, maximum slope 0.085), partially overlapping the slopes of sediment supply-limited reaches (meaning they transport more bed load than they receive; slope >0.03) [*Montgomery and Buffington*, 1997]. To the extent that our steeper straight reaches are similar to those studied by Montgomery and Buffington—which were also mountain streams, but smaller channels—this suggests that those

Table 8. Error Matrices of Three Selected SVM Models[a]

Model 4 (slope, 2 year discharge)
Overall accuracy = 63%, Kappa = 0.51

		Known Channel Pattern					
		Braided	Anabranching	Meandering	Straight	Total	Accuracy
Predicted channel pattern	Braided	20	14	4	6	44	45%
	Anabranching	0	16	0	0	16	100%
	Meandering	2	0	**25**	3	30	83%
	Straight	8	0	1	21	30	70%
	Total	30	30	30	30	120	
	Accuracy	67%	53%	83%	70%		

Model 8 (slope, 2 year discharge, relative slope)
Overall accuracy = 73%, Kappa = 0.69

		Braided	Anabranching	Meandering	Straight	Total	Accuracy
Predicted channel pattern	Braided	**25**	12	4	4	45	56%
	Anabranching	1	16	1	0	18	89%
	Meandering	2	1	**23**	2	28	82%
	Straight	2	1	2	**24**	29	83%
	Total	30	30	30	30	120	
	Accuracy	83%	53%	77%	80%		

Model 56 (slope, 2 year discharge, relative slope, % fine sediment, % alpine sediment)
Overall accuracy = 82%, Kappa = 0.79

		Braided	Anabranching	Meandering	Straight	Total	Accuracy
Predicted channel pattern	Braided	**23**	4	0	3	30	77%
	Anabranching	5	**23**	0	1	29	79%
	Meandering	0	0	**27**	1	28	96%
	Straight	2	3	3	**25**	33	76%
	Total	30	30	30	30	120	
	Accuracy	77%	77%	90%	83%		

[a]For each model, 30 sites of each channel pattern were selected from the training data set and compared to predicted channel pattern. Overall accuracy may differ from Table 5 because tests are based on a single model run rather than bootstrapping. Bold type indicate channel patterns with <25% omission error.

straight reaches are likely to have coarse-grained beds and banks relative to other channel patterns for a given discharge because they are commonly higher in the basin where sediment transport capacity typically exceeds sediment supply [*Montgomery and Buffington*, 1997; *Eaton and Church*, 2011]. The transition to anabranching reaches likely reflects a shift from supply-limited to transport-limited reaches (i.e., a shift to aggrading reaches), which facilitates bar and island formation necessary for the anabranching pattern to develop [*Desloges and Church*, 1989; *Church*, 2002]. Meandering reaches are generally lowest in the network where sediment supply tends to be dominated by suspended load rather than bed load [*Schumm*, 1985; *Church*, 2002], although some meandering reaches likely have gravel beds and significant bed load supply (discussed further in section 5.2). Notably, the largest rivers in our sample set are not the lowest gradient rivers as one might expect (see Figure 7), indicating that in some tributary

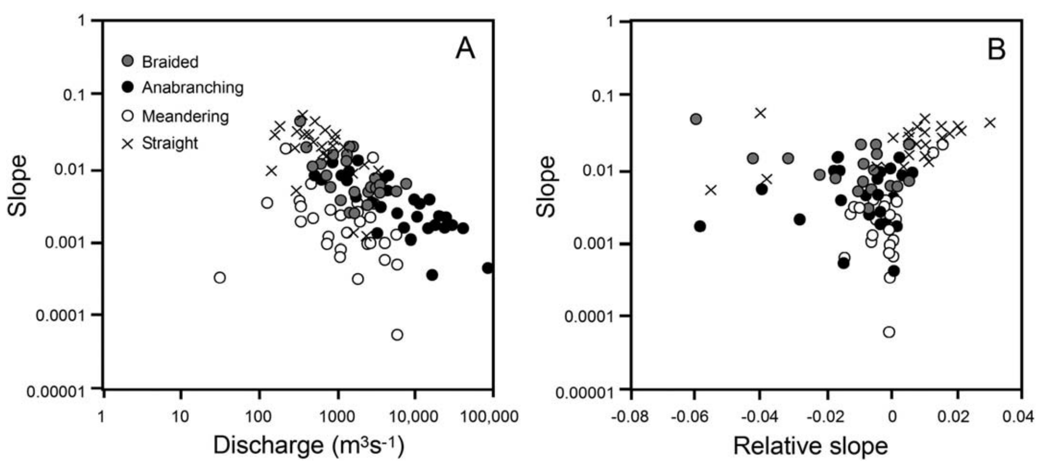

Figure 7. Bivariate plots of controls on channel pattern illustrating (a) the traditional slope-discharge form in which braided and straight channels overlap but meandering channels are somewhat distinct and (b) separation of braided and straight channels on an axis of relative slope.

basins the downstream-most reaches may exhibit the anabranching pattern rather than the expected meandering pattern. The braided pattern was the only pattern that was not widely distributed across the region. Rather, braided channels were concentrated in headwater basins of the Canadian Rocky Mountains where alpine and pro-glacial rivers have high bed load supply, much as observed in other studies of braided mountain rivers [e.g., *Fahnestock*, 1963].

[38] The idealized downstream sequence of channel patterns is rarely expressed without interruption in river networks, due to the influences of both geological controls and tributary junctions [*Ward et al*., 2002; *Benda et al*., 2004; *Brierley and Fryirs*, 2009]. Our model captures the main geological influences on channel characteristics because geologically forced changes in channel slope and valley width are directly reflected in our measures of channel slope, relative slope, and confinement. Geologically forced confined valleys prevent the formation of wide floodplains necessary for alluvial channel patterns to develop [*Beechie et al*., 2006a; *Hall et al*., 2007], and can create alternating confined and unconfined reaches with diverse physical and ecological attributes [*Ward et al*., 2002; *Brierley and Fryirs*, 2009]. While it is theoretically possible that some of these channel patterns could form where valley confinement is less than 4, a prior study in the Columbia basin statistically determined that the confinement threshold for channel pattern formation is 3.8 [*Hall et al*., 2007], indicating that these alluvial channel patterns are rare when valley width is less than approximately 4 times the channel width. Where valleys are unconfined, geologically controlled changes in slope may also force alternating straight and anabranching or meandering reaches, reflecting changes in boundary conditions (e.g., geologically forced changes in grain size that force a slope change, such as a river eroding through coarse-grained glacial deposits) or changes in relative sediment supply within a reach, which also influences bed and bank material size via the degree of armoring [*Dietrich et al*., 1989; *Benda et al*., 1992; *Yarnell et al*., 2006; *Phillips and Desloges*, 2012]. Tributary confluences can also locally alter the sequence of channel patterns by reducing channel slope upstream of confluences, or by increasing channel slope, discharge, or sediment supply downstream of confluences [*Benda et al*., 2004].

5.2. Influence of Predictor Variables on Channel Pattern, and Potential Physical Interpretations

[39] The relationship of channel pattern to the variables slope, discharge, sediment caliber, and confinement is well documented [e.g., *Leopold and Wolman*, 1957; *Van den Berg*, 1995; *Church*, 2002; *Beechie et al*., 2006a; *Eaton et al*., 2010]. However, the role of sediment supply, while generally agreed upon conceptually [*Schumm*, 1985; *Knighton and Nanson*, 1993; *Church* 2002], has not been well supported by quantitative analysis. In concept, the role of sediment supply in determining channel pattern is primarily in its influence on channel geometry and lateral migration rate, which is not entirely captured by slope and discharge [*Schumm*, 1985; *Marston et al*., 1995; *Kondolf*, 1997; *Liébault and Piégay*, 2001; *Church*, 2002; *Eaton et al*., 2010]. This concept is the basis of our idea that hypothesized sediment supply variables (relative slope and percent of basin in alpine terrain) would help distinguish wide, shallow patterns from narrow, deep patterns when they have similar slope and discharge (e.g., separating braided channels from straight or meandering channels). Our analysis then showed that channel pattern prediction was improved by inclusion of our hypothesized sediment supply variables. Hence, the improvement in channel pattern classification accuracy can be logically explained as a reflection of the influences of sediment supply, but there are no sediment supply data to verify that conclusion.

[40] The slope-discharge model performed reasonably well for separating the meandering pattern from all other patterns, suggesting that the hypothesized sediment supply variables were perhaps not necessary for predicting this channel pattern. Addition of the fine sediment variable to the slope-discharge model did not increase prediction accuracy for the meandering pattern as we expected (though overall accuracy increased slightly). This may be in part because the meandering channel pattern is a very broad class that encompasses a range of sediment textures from silt-dominated to gravel-dominated [*Schumm*, 1985; *Knighton and Nanson*, 1993; *Church*, 2002]. Where meandering channels are indeed characterized by low bed load and high suspended load, they tend to have fine-grained floodplain deposits, higher bank cohesion, and are narrow and deep with high sinuosity [*Schumm*, 1985; *Eaton et al*., 2004]. By contrast, gravel-bedded meandering channels are generally wider, less sinuous, and have higher lateral migration rates [*Hicken and Nanson*, 1975; *Schumm*, 1985]. While both may fit our definition of meandering channels (sinuosity >1.5), they have different sediment texture and channel geometry, making it difficult to identify landscape or remote sensing variables that will consistently help distinguish this pattern. Hence, the fine sediment variable may only improve prediction accuracy because it represents some unknown correlation with channel pattern, such as topographic position in the channel network.

[41] Past studies have found that straight channels are difficult to distinguish from other channel patterns based on slope and discharge alone [*Leopold and Wolman*, 1957; *Beechie et al*., 2006a], and even studies than include grain size do not clearly separate straight channels from meandering or braided channels [*Van den Berg*, 1995; *Lewin and Brewer*, 2001; *Eaton et al*., 2010]. In our analysis, straight and braided channels had considerable overlap in slope-discharge space and high classification error, and addition of the relative slope term improved prediction accuracy by reducing confusion between those two channel patterns. Assuming that the relative slope variable does indeed reflect differences in relative sediment supply, the likely mechanism underlying the improved accuracy is that, for a given channel slope and discharge, braided channels typically have high bed load supply relative to their transport capacity [*Schumm*, 1985; *Ferguson*, 1987; *Desloges and Church*, 1989; *Knighton and Nanson*, 1993], and therefore are shallow, wide, and have high lateral migration rates even though they are relatively steep [*Church*, 2002; *Beechie et al*., 2006a]. By contrast, straight channels tend to have low bed load supply relative to their transport capacity (i.e., they are unlikely to store sediment), and consequently are deeper and narrower with armored beds and low lateral migration rates [*Beechie et al*., 2006a;

Eaton et al., 2010]. Alternatively, the change in slope may result from a geologically forced change in bed material size. For example, for a given discharge, reaches eroding into coarse glacial deposits will tend to be steeper, have coarser beds, and have narrower and deeper channels compared to reaches eroding into finer grained material [e.g., *Benda et al*., 1992; *Phillips and Desloges*, 2012].

[42] Anabranching channels were most difficult to predict accurately with two or three-parameter models, but ultimately the five-parameter model predicted anabranching channels about as well as straight and braided channels. Addition of our hypothesized sediment supply surrogates clearly improved their prediction accuracy, most notably the percent alpine variable which helped reduce confusion between braided and anabranching channels. This may reflect a higher sediment supply to braided channels and somewhat lower sediment supply to anabranching channels, which has been considered a key parameter distinguishing these two channel patterns [*Desloges and Church*, 1989; *Nanson and Croke*, 1992; *Church*, 2002]. Another possible interpretation is that floodplain forests at higher elevations tend to consist of smaller trees, and wood supply may be lower in braided channels than in lower-elevation anabranching channels with larger trees on the floodplain, allowing higher lateral migration rates in braided channels [*Beechie et al*., 2006a]. However, the small trees along braided channels may also be a result of the high lateral migration rate rather than a cause of it, as rapid lateral migration erodes floodplain surfaces before large trees can develop [*Beechie et al*., 2006a].

[43] Our results are consistent with prior studies indicating that straight channels are coarser bedded than meandering ones [*Knighton*, 1998; *Eaton et al*., 2010] and also that single thread channels (both straight and meandering) are morphodynamically distinct from anabranching or braided channels [*Parker*, 1979; *Eaton et al*., 2010]. However, while *Eaton et al*. [2010] showed that straight and meandering channels are morphodynamically similar, other studies show that straight and meandering channels have distinctly different sinuosity, lateral migration rates, and ecology [*Leopold and Wolman*, 1957; *Beechie et al*., 2006a; *Naiman et al*., 2010]. Despite apparent differences among these studies, however, all are in general agreement that straight channels tend to have low sediment supply and coarser beds, braided channels have high sediment supply and finer beds, and anabranching channels are intermediate in terms of form and dynamics.

5.3. Sources of Model Error

[44] Errors in channel pattern prediction may arise from errors in model form, errors in parameter estimation, or errors in classifying channel pattern. Potential errors in model form include missing variables that might be important predictors of channel pattern, as well as the use of three predictor variables that are hypothesized indicators of sediment supply and caliber rather than direct measures. Root strength is not likely to be an important missing variable because (1) river channels in our study are large enough to erode beneath the rooting zone [*Beechie et al*., 2006a; *Hall et al*., 2007], and (2) all reaches in our data sets were bordered by relatively mature riparian vegetation, so there was little difference in root strength among sites. Of the missing variables, perhaps the most important is wood abundance (discussed previously), which has the potential to help create or reinforce both meandering and anabranching channel patterns [*Knighton and Nanson*, 1993; *Harwood and Brown*, 1993; *Millar and Quick*, 1993; *Abbe and Montgomery*, 2002]. The formation of stable islands is favored by persistent debris jams that establish erosion-resistant hard points, force channel switching, and push flood flows out on to the floodplain [*Abbe and Montgomery*, 1996; *Keller and Swanson*, 1979; *Fetherston et al*., 1995; *Abbe and Montgomery*, 2002; *Sear et al*., 2009], and this factor is not represented in our model.

[45] Physical changes at tributary junctions are partially captured in our analysis by our predictor variables slope and discharge, but changes in relative sediment supply at confluences may not be well represented. The relative slope variable ignores changes in channel size at tributary junctions, and therefore may mischaracterize changes in sediment transport capacity—especially where the tributary is large relative to the main channel—because it only considers the change in channel slope. While this may be important at certain tributary confluences, using relative stream power instead of relative slope did not improve classification accuracy, suggesting that this difference was not important for classifying channel patterns across a large area. Finally, our analysis does not consider local (within-reach) sediment sources, which may also influence relative sediment supply within a reach and have consequent effects on grain size, channel geometry, and therefore, channel pattern.

[46] The indirect indicators of sediment supply also likely produce some level of model error simply because they are potential correlates of known influences on channel pattern, and the correlations contain some unknown level of error. While we could not evaluate such model errors directly, the relatively high model accuracy and the predictive utility of the five main variables (slope, discharge, relative slope, percent alpine, and percent fine sediment) suggest that errors in model form were relatively small. Moreover, the five main variables were included in the most accurate model more than 90% of the time and the model containing all three of the hypothesized sediment supply indicators was the most accurate model, indicating that these variables have significant predictive utility despite the potential errors.

[47] Parameter error refers to the accuracy of estimated predictor variables for each reach, including channel slope, channel width, and valley floor width. Comparison of measured to estimated values for these variables showed that errors in estimation are statistically relatively small, but they are still large enough to result in prediction errors whenever reach characteristics are near model thresholds. For example, a relatively small overestimate of the channel slope for a meandering reach could easily result in misclassification as a braided reach if the reach slope is near the meandering-braided threshold and the overestimated slope places that reach in the braided channel domain. However, such errors are difficult to quantify precisely in multivariate models because the thresholds are not readily apparent, and it is therefore difficult to determine which variable caused a specific reach to be misclassified. Nonetheless, our analysis of which variables are the most important predictors of

channel pattern (Table 7), combined with accuracy of parameter estimation (Table 4), indicate the channel slope is an important and sensitive variable. That is, estimation of channel slope from the digital elevation model is both relatively imprecise ($R^2 = 0.73$) and included in the best model 97% of the time, suggesting that a significant number of errors in channel pattern prediction may be generated by relatively small errors in estimation of one of the most important driving variables. These same general points apply to the discharge and relative slope variables as well.

[48] Classification errors have two potential sources in our study: errors in classification by the observer, and potentially inaccurate thresholds separating channel patterns. We used a single observer for all classifications (both training and test data sets), so observer variation was eliminated. Moreover, where reaches were near classification thresholds, the channel pattern was assigned based on measurements of sinuosity or the relative abundance of bars or vegetated islands separating multiple channels (the two key classification criteria) to minimize observer error (see section 3.4). The more significant source of error is likely due to the relatively arbitrary sinuosity and bar/island thresholds adopted from previous studies, as these arbitrary thresholds may not be the best representation of thresholds in drivers, morphology, or dynamics. All classification systems attempt to place the continuum of channel patterns into discrete classes, and meaningful thresholds among channel patterns are not always obvious. For example, some classifications use a sinuosity threshold of 1.3 to separate straight and meandering channels [e.g., *Schumm*, 1985] whereas others use a threshold of 1.5 [e.g., *Leopold and Wolman*, 1957; *Van den Berg*, 1995]. While there is no evidence that one threshold is better or worse than another, the uncertainty in defining physically meaningful thresholds may contribute to prediction errors.

5.4. Conservation Applications

[49] For conservation planning, the most common use of large-scale analyses of potential habitat value is in identifying key areas for habitat protection or restoration [e.g., *Burnett et al*., 2007; *Whited et al*., 2012, 2013]. In our study area, most river restoration is driven by the listing of salmon (*Oncorynchus* spp.) under the U.S. Endangered Species Act, which motivates a need to identify conservation areas based on the spatial distribution of important habitats. For many species of salmon, floodplain channels have a disproportionately high habitat value [*Beechie et al*., 1994; *Bellmore et al*., 2012], and anabranching systems have the highest proportion of relatively stable floodplain channels among the four channel patterns [*Beechie et al*., 2006a]. Hence, an ability to map reaches with potential for anabranching is useful in large-scale conservation planning for salmon. Other studies have empirically demonstrated that geology, topography, and postglacial landscape evolution impose natural constraints on the spatial distribution of channel patterns via controls on valley slope and floodplain width [e.g., *Benda et al*., 1992; *Toivonen et al*., 2007; *Collins and Montgomery*, 2011], which also constrains the distribution of fish habitats across the landscape [e.g., *Beechie et al*., 2001; *Burnett et al*., 2007; *Whited et al*., 2013; *Davey and Lapointe*, 2007]. Together, these mechanistic linkages among landscape controls, channel pattern, and habitat value indicate that most salmon habitat is located in relatively low gradient streams and rivers with wide floodplains where the development of complex side-channel habitats favors persistence of the species [*Beechie et al*., 2001; *Burnett et al*., 2007; *Whited et al*., 2012].

[50] In a conservation context, our maps therefore help identify areas with high potential habitat value for salmon habitat protection or restoration. In areas with little human modification, common aims of conservation efforts might be to protect remaining high quality floodplain habitats or to restore salmon access to unimpacted habitats by removing obsolete dams [e.g., *Beechie et al*., 1994; *Pess et al*., 2008; *Whited et al*., 2012]. When combined with analysis of land cover or other landscape attributes, broadly defined restoration target areas can also be identified where significant land use impacts overlap reaches with high intrinsic potential to support salmon [e.g., *Beechie et al*., 1994; *Burnett et al*., 2007]. Not surprisingly, low elevation floodplains are the same areas in which modern settlers focused agricultural and urban development, resulting in large losses of salmon habitat over the last 150 years [*Beechie et al*., 2001; *Scheuerell et al*., 2006; *Burnett et al*., 2007; *Hall et al*., 2007]. Hence, it is not unusual to find that loss of floodplain habitats is one of the most critical habitat impairments to address through restoration efforts, and that restoration should to some degree target floodplain habitats because the large habitat gains needed to support salmon recovery are unlikely elsewhere (e.g., in confined or straight channels that have lower habitat restoration potential) [e.g., *Beechie et al*., 1994]. Where specific floodplains are targeted for restoration, three restoration approaches can be used: (1) fully restore natural processes where possible, (2) partially restore natural processes where some human constraints will not be removed, or (3) construct alternative habitat types where human constraints preclude restoration [e.g., *Cairns*, 1988; *Brown*, 2002; *Beechie et al*., 2010]. Specific restoration actions therefore might include extensive removal of river levees to reconnect floodplains, limited setback of levees to partially reconnect floodplains, or construction of artificial off-channel habitats where floodplain reconnection is not possible [e.g., *Buijse et al*., 2002; *Konrad et al*., 2008; *Beechie et al*., 2013b; *Roni et al*., 2013].

[51] Our general approach to predicting channel pattern should be portable to other river systems, although selection of input variables may vary depending upon landscape factors perceived to control channel patterns. Moreover, restoration goals may differ because the aims of legislation driving river restoration may focus on different objectives, including improvements to water quality, other species, or other measures of river health [*Beechie et al*., 2009, 2013a]. Hence, conservation priorities among channel patterns will vary depending upon ecological attributes that are valued as restoration objectives. While there is considerable debate in the scientific literature about how to set restoration targets for various objectives, there is also widespread agreement that a clearly articulated restoration goal or guiding vision is critical to successful restoration [*Kern*, 1992; *Sear*, 1994; *Palmer et al*., 2005; *Brierley and Fryirs*, 2009; *Beechie et al*., 2010]. Authors tend to disagree most strongly regarding the utility of historical references, which some consider useless based on assumptions

that (1) today's unmodified landscape would be significantly different from the historical one even in the absence of human modifications, and (2) human impacts are so ubiquitous or severe that return to the unmodified condition is impossible [e.g., *Dufour and Piégay*, 2009]. However, most also agree that contemporary reference sites are useful for identifying ranges of potential target conditions or restoration outcomes [e.g., *Palmer et al.*, 2005; *Dufour and Piégay*, 2009; *Brierly and Fryirs*, 2009; *Beechie et al.*, 2010]. In our study, we illustrated how contemporary reference sites can be used to develop a model to predict channel pattern, which can ultimately help identify key conservation areas and develop a landscape-scale guiding image for conservation of salmon habitats.

6. Conclusions

[52] We developed a model to predict channel pattern across the geologically diverse Columbia River basin using a SVM classifier, and produced maps of alluvial channel patterns expected in the absence of land use. Our maps identified both confined channels (valley floor width <4 times the channel width) where channel patterns generally do not form, and four alluvial channel patterns that develop where valley floors are >4 times channel width: straight, meandering, anabranching, and braided. Maps of predicted channel pattern accurately reflected the spatial distribution of these patterns in the Columbia basin, and overall prediction accuracy was high (82% with the training data set). We also used a bootstrapping procedure to assess uncertainty in the SVM model by mapping the probability of occurrence of each channel pattern in each river reach. These maps not only illustrate the spatial distribution of each channel pattern in the basin, but also the certainty with which the model predicts each channel pattern.

[53] Using the SVM-predicted channel patterns and an independent test data set, we found that a slope-discharge model distinguished meandering channels from all other channel patterns, but did not accurately identify braided, anabranching, and straight channels (59% overall accuracy with the test data set). The best model (72% overall accuracy with the test data set) included the variables slope, discharge, relative slope, percent of the basin producing fine-grained sediment, and percent of the basin in alpine terrain. These results suggest that while a traditional slope-discharge model can successfully distinguish the meandering pattern from other patterns, incorporating landscape variables that may indirectly represent sediment supply or sediment size are useful for distinguishing the remaining channel patterns and accurately predicting channel pattern across a geologically diverse landscape. Braided and straight channels were most clearly distinguished on an axis of relative slope, whereas braided and anabranching channels were best distinguished by percent alpine area.

[54] Prediction errors likely stem from use of surrogate variables for sediment supply or caliber, as well as from inaccuracies in variables calculated from digital elevation models (e.g., channel slope or valley width). The hypothesized sediment supply surrogates only indicate a likelihood of high or low sediment supply, and other factors such as local sediment sources or reach specific transport capacities may influence the actual relative sediment supply within a reach. Relatively small errors in key parameters such as channel slope can also have a strong influence on channel pattern prediction, but there is currently means of reducing this type of parameter error. Nevertheless, the relatively high prediction accuracies indicate that it is feasible to develop models to predict channel pattern across a geologically and climatically diverse landscape based on simple physical and landscape variables, and that such predictions can be used in conservation planning for river ecosystems.

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