Basin-scale availability of salmonid spawning gravel as influenced by channel type and hydraulic roughness in mountain catchments

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Abstract: A general framework is presented for examining the effects of channel type and associated hydraulic roughness on salmonid spawning-gravel availability in mountain catchments. Digital elevation models are coupled with grain-size predictions to provide basin-scale assessments of the potential extent and spatial pattern of spawning gravels. To demonstrate both the model and the significance of hydraulic roughness, we present a scenario for optimizing the spatial extent of spawning gravels as a function of channel type in Pacific Northwest catchments. Predictions indicate that hydraulic roughness could control more than 65% of the potential available spawning habitat at our study sites. Results further indicate that bar roughness can be important for maintaining spawning gravels in lower mainstem reaches, while wood roughness may be required for spawning-gravel maintenance in steeper, upper mainstem channels. Our analysis indicates that wood loss and consequent textural coarsening could deplete up to one third of the potentially usable spawning area at our study sites.

Résumé : Nous présentons ici un cadre général pour l'examen des effets du type de chenal et de la rugosité hydraulique associée sur la disponibilité de graviers pour la fraye des saumons dans les bassins versants de montagne. Le couplage de modèles digitaux d'altitude et de prédictions des tailles des particules fournit une évaluation à l'échelle du bassin versant de l'étendue potentielle et de la répartition spatiale des graviers de fraye. Comme illustration du fonctionnement du modèle et de l'importance de la rugosité hydraulique, nous présentons un scénario pour l'optimisation de l'étendue spatiale des graviers de fraye en fonction du type de chenal dans les bassins versants de la région pacifique du nord-ouest. Les prédictions indiquent que la rugosité hydraulique peut contrôler plus de 65 % des habitats de fraye potentiellement disponibles dans nos sites d'étude. Les résultats indiquent de plus que la rugosité due aux seuils peut être importante pour le maintien des graviers de fraye dans les sections d'aval du cours principal, alors que la rugosité due au bois est nécessaire pour le maintien des graviers de fraye dans les cours principaux d'amont à pente plus forte. Notre analyse montre que la perte du bois et la texture plus grossière qui en résulterait pourraient éliminer jusqu'à un tiers de la surface utilisable potentielle de fraye dans nos sites d'étude.

[Traduit par la Rédaction]

Introduction

Channel characteristics such as temperature, depth, velocity, percent fines, and intragravel flow affect selection of salmonid spawning sites (Bjornn and Reiser 1991), but perhaps the most important characteristic is the size of sediment in which an adult salmonid can excavate a redd. As a family, salmonids prefer to spawn in sediments ranging in size from small gravel to cobble (Kondolf and Wolman 1993). The availability of sediment suitable for spawning depends on two geomorphic factors: (*i*) channel hydraulics and (*ii*) sediment supply. Channel hydraulics control the shear stress and competence of the river (largest size of sediment that the channel can carry) and are modified by channel type and associated hydraulic roughness (Buffington and Montgomery 1999*a*). Sediment supply controls the size and volume of material available to be transported and hydraulically sorted into suitable spawning habitats. In this paper, we assess the influence of hydraulic roughness on sediment size and spawning habitat availability.

Theory

The following theoretical development is an extension and modification of concepts originally proposed by Dietrich et al. (1996) and Montgomery et al. (1998).

Surface grain size in gravel- and cobble-bed rivers is strongly controlled by channel hydraulics and the consequent

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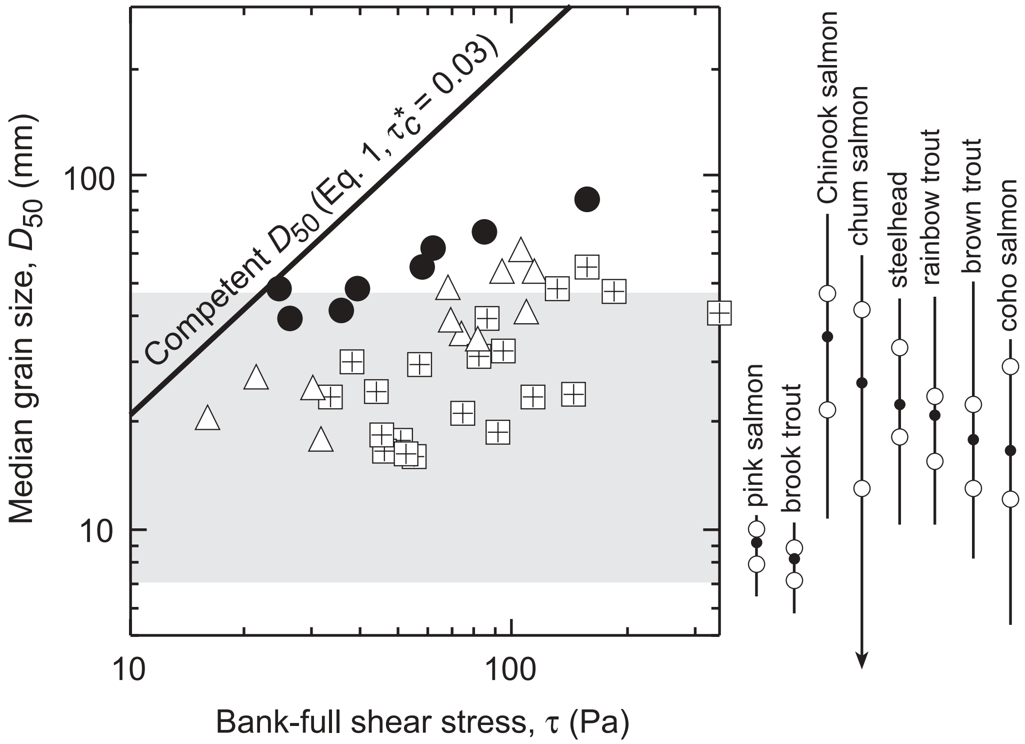
Fig. 1. Reach-average median surface grain size (D_{50}) as a function of total bank-full shear stress (τ) and channel type (modified from Buffington and Montgomery 1999*a*). Circles represent plane-bed channels, triangles represent wood-poor pool–riffle channels, and squares represent wood-forced pool–riffle channels. Right side of figure shows D_{50} ranges preferred by different salmonid species (Kondolf and Wolman 1993), with solid circles indicating median values and open circles indicating inner and outer quartiles of each distribution. Gray area defines typical range of suitable D_{50} values based on overall range of quartiles.



boundary shear stress that is imparted to the streambed (Buffington and Montgomery 1999*a*). In particular, the bank-full flow is the dominant discharge influencing sediment transport, surface grain size, and channel morphology in many alluvial rivers (e.g., Wolman and Miller 1960; Parker 1978; Andrews 1984; Andrews and Nankervis 1995). The median surface grain size (D_{50}) that can be mobilized by the bank-full flow can be predicted from the Shields (1936) equation

$$(1) \qquad D_{50} = \frac{\tau}{(\rho_s - \rho) g \tau_c^*} = \frac{\rho h S}{(\rho_s - \rho) \tau_c^*}$$

where τ is the total bank-full shear stress defined from the depth–slope product ($\rho g h S$), ρ_s and ρ are sediment and fluid densities, respectively, g is gravitational acceleration, h is bank-full depth, S is channel slope, and τ_c^* is the critical Shields stress for movement of D_{50} (see review by Buffington and Montgomery 1997). All values in eq. 1 are reach-average quantities.

Equation 1 is a theoretical prediction of competence (largest mobile D_{50}), assuming that particle size is not limited by local sediment supply. Although surface grain size can be modified by local sediment supply (Dietrich et al. 1989; Buffington and Montgomery 1999*b*), particle abrasion (Dietrich and Dunne 1978; Parker 1991), and chemical decomposition (Bradley 1970), downstream variations in substrate size in mountain rivers are principally driven by spatial changes in shear stress and channel competence (Constantine et al. 2003; Brummer and Montgomery 2003; Mueller and Pitlick 2005). That is to say, rivers hydraulically sort the sediment that is supplied to them. However, the supply of sediment in mountain basins can be punctuated in both space and time. In particular, local point sources of sediment from tributaries and hillslope mass wasting can interrupt and reset downstream fining trends (Rice 1998; Cui and Parker 2005) and may have significant influences on faunal distributions (Rice et al. 2001*a*, 2001*b*). Wood jams and other flow obstructions can also dam sediment, forcing textural changes that disrupt or modify larger-scale downstream fining trends (Rice and Church 1996).

Equation 1 predicts the competent D_{50} as a function of the total boundary shear stress (τ). However, rivers contain a variety of roughness elements (such as bars, wood, and bank irregularities) that extract momentum from the flow and reduce the reach-average shear stress acting on the streambed. Consequently, it is expected that channels with greater hydraulic roughness will have relatively smaller substrate sizes. Field data from forest gravel-bed rivers in western Washington and southeastern Alaska support this hypothesis (Fig. 1). For a given τ, observed values of D_{50} systematically decrease as one moves from plane-bed to pool–riffle to wood-forced pool–riffle channel types (morphologic definitions of Montgomery and Buffington 1997, 1998; Buffington et al. 2003). The observed decrease in surface grain size is due to a systematic increase in hydraulic roughness and a consequent reduction of channel competence (Buffington and Montgomery 1999*a*). Plane-bed channels generally have the least amount of roughness, with resistance primarily due to bank irregularities, bed-surface grains, and occasional pieces of wood debris. Wood-poor pool–riffle channels have an additional source of roughness because of topographic form drag (bars). Wood-forced pool–riffle channels have the greatest roughness because of the addition of abundant wood debris and the combined effects of grain, bank, bar, and wood resistance.

Because these data come from forest rivers, wood debris is present in each of the channel types. Although the sites were selected to minimize wood abundance in the plane-bed and pool–riffle channels, there is a systematic increase in wood loading from plane-bed to pool–riffle to wood-forced pool–riffle sites. The increase in wood loading across the sites forces a higher frequency of bed and bank scour, causing greater bank and bed topography and a systematic increase in form drag that reduces channel competence and surface grain size (see Buffington and Montgomery 1999*a* for further detail). Systematic increases in roughness due to greater particle form drag (lower relative submergence) and lower channel width–depth ratios at steeper slopes are also incorporated in each data set (see Buffington and Montgomery 2001).

Figure 1 demonstrates that channel type and associated hydraulic roughness alter channel competence and observed substrate size relative to that predicted by eq. 1. Moreover, comparison of the range of roughness effects to the size of salmonid spawning gravels shows that these effects may have important implications for the availability of salmonid spawning habitat in mountain catchments. The right side of Fig. 1 shows ranges of median grain sizes preferred by different salmonid species for spawning (Kondolf and Wolman 1993). Comparison of observed median grain sizes with those preferred by spawning salmonids suggests that bar and wood roughness can produce suitable substrate in channels that might otherwise be too coarse. We explore this issue by coupling the above theory and observations with digital elevation models (DEMs) to predict the potential spatial distribution of salmonid spawning gravels as a function of channel type and hydraulic roughness in mountain catchments. Our intent is to provide a general framework for assessing spawning habitat availability, which can be modified, as needed, for basin-specific and species-specific concerns.

Analysis framework

Here, we describe the general procedure for evaluating parameters in eq. 1 and for assessing potential spawning-gravel availability at basin scales. We then present an application of our analysis framework that systematically examines the potential influence of channel type and hydraulic roughness.

Assuming that sediment and water densities are known (typically 2650 and 1000 $\mathrm{kg\cdot m^{-3}\cdot s^{-1}}$, respectively), the only remaining unknown parameters for predicting D_{50} from eq. 1 are channel slope (S), bank-full depth (h), and critical Shields stress (τ_c^*); all reach-average quantities. We obtain S from DEMs, predict h from local hydraulic geometry relationships, and predict τ_c^* as an empirical function of channel type and associated roughness.

Bank-full depth can be predicted from region-specific hydraulic geometry relationships (Leopold et al. 1964; Dunne and Leopold 1978). In these relationships, bank-full depth is expressed as a power function of drainage area (a surrogate for bank-full discharge)

$$h = \alpha A^{\beta} \tag{2}$$

where A is drainage area, and α and β are empirical values representing local physiography (geology, topography, and climate), basin hydrology, and sediment supply.

To evaluate the Shields stress, we assume a bank-full threshold for significant sediment transport (e.g., Henderson 1963; Parker 1978; Buffington and Montgomery 1999*a*), such that the critical Shields stress can be approximated by the mean bank-full value ($\tau_c^* \approx \tau_{bf}^* = \tau/[(\rho_s - \rho)gD_{50}]$). This is a reasonable assumption for coarse-grained channels typically used by salmonids. In particular, many authors have shown that gravel- and cobble-bed rivers have a near bank-full threshold for sediment transport (e.g., Leopold et al. 1964; Parker 1978; Andrews 1984) and that the bank-full flow is the dominant discharge (that which controls channel morphology and transports the most sediment in the long term) (e.g., Carling 1988; Andrews and Nankervis 1995; Emmett and Wolman 2001). A bank-full threshold for significant sediment transport assumes a low bed load supply (Buffington and Montgomery 1999*a*). As bed load supply increases, surface grain sizes fine, reducing the threshold for sediment transport to values less than bank-full (e.g., Dietrich et al. 1989; Buffington and Montgomery 1999*b*; Lisle et al. 2000). The assumption of a low bed load supply may not be valid for areas that have been recently disturbed by fire or logging or areas with chronically high sediment inputs (e.g., weak lithologies or persistent mass wasting).

Using field data, we express τ_{bf}^* as a power function of mean bank-full shear stress (τ), with separate functions for different channel types (Fig. 2). Although τ appears in both variables of the plot (τ_{bf}^* is calculated from τ (eq. 1)), it is nonetheless useful to express τ_{bf}^* as a function of τ as part of our model development. The stratification of these data represents channel response to hydraulic roughness similar to that of Fig. 1 (Buffington and Montgomery 2001). Hence, we use τ_{bf}^* as a roughness correction factor (i.e., τ_{bf}^* is an apparent value of τ_c^* that incorporates channel roughness; greater roughness reduces channel competence and observed bed-surface grain size, resulting in apparently larger values of τ_{bf}^*). Textural response to local bed load supply (as discussed above) is also implicitly included in τ_{bf}^*.

The relationships shown in Fig. 2 can be mathematically represented as

$$\tau_{bf}^* = k\,\tau^n = k(\rho g h S)^n \tag{3}$$

where k and n are empirical values that vary with channel type and local catchment conditions.

Channel type and selection of appropriate values for k and n are predicted from stream gradient (Fig. 3). Previous studies demonstrate that different reach-scale channel types preferentially occur over different ranges of channel gradient (Montgomery and Buffington 1997, 1998; Buffington et al. 2003). Although the observed gradient ranges of different channel types overlap, they nonetheless have nonoverlapping central tendencies (25th–75th percentiles of slope) that allow first-order prediction of channel type based on reach-average channel gradient. A continuous range of slopes is developed

Fig. 2. Bank-full Shields stress (τ^*_{bf}) as a function of total bank-full shear stress (τ) and channel type in Pacific Northwest rivers (morphologic definitions of Montgomery and Buffington 1997, 1998; Buffington et al. 2003). PR, pool–riffle (circles); PB, plane-bed (open triangles); wfPR, wood-forced pool–riffle (squares); SP, step–pool (diamonds); CA, cascade (solid triangles). PR, PB, and wfPR data are from Buffington and Montgomery (1999*a*, 2001); SP and CA data are from Montgomery and Buffington (1997).

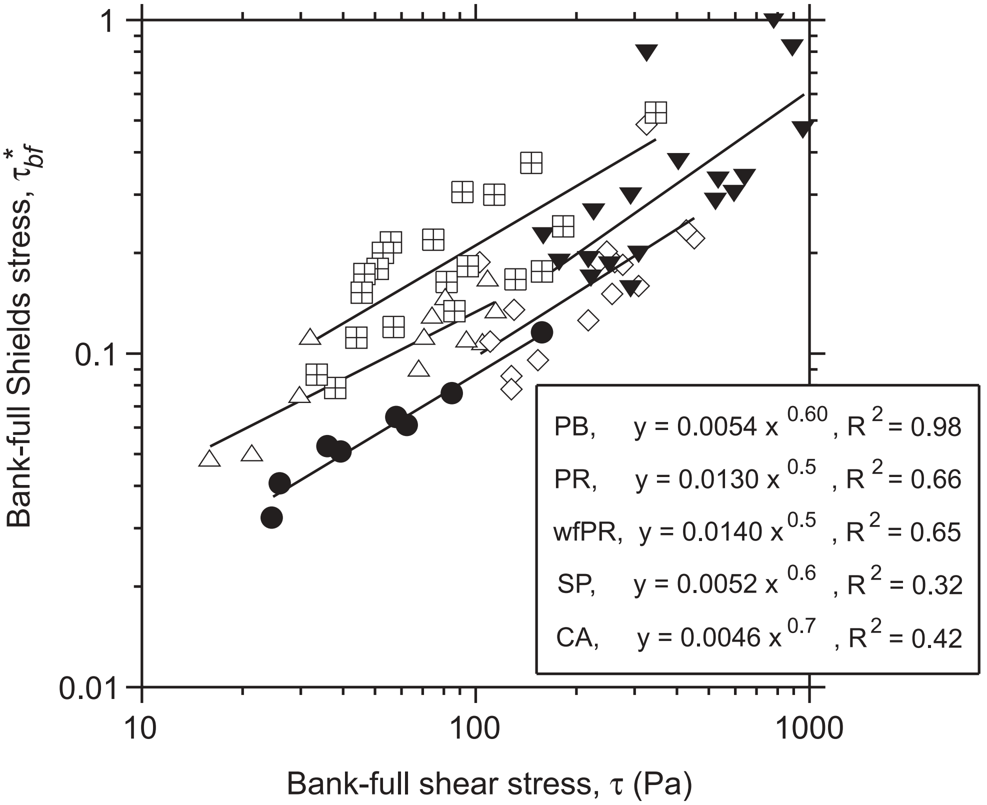
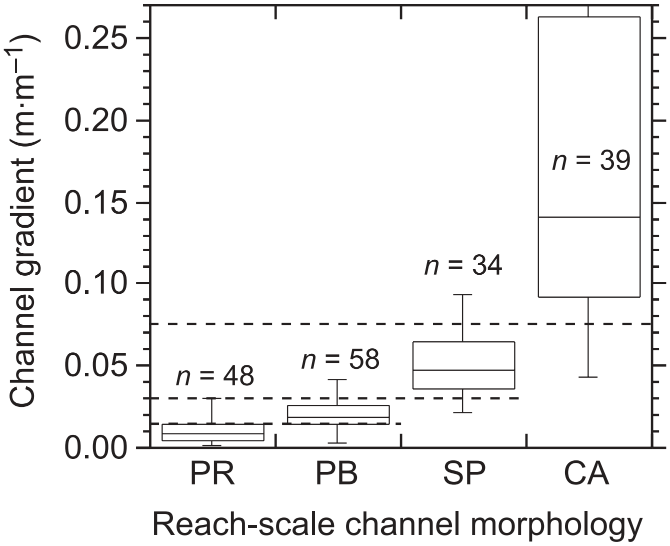


Fig. 3. Box plots of channel gradient for different reach-scale channel types. The horizontal line within each box indicates the median value, box ends are quartiles, and whiskers are tenths. PR, pool–riffle; PB, plane-bed; wfPR, wood-forced pool–riffle; SP, step–pool; CA, cascade. See Buffington et al. (2002, 2003) for data sources. Broken lines define typical slope ranges for each channel type.



for predicting channel type by selecting range boundaries as the approximate midpoint between successive box ends. The resulting characteristic slope ranges are as follows: <1.5% for pool–riffle channels, >1.5%–3% for plane-bed channels, >3%–7.5% for step–pool channels, and >7.5% for cascade channels (Fig. 3). Characteristic slopes for each channel type are statistically different for both their central tendencies (box ranges) and the above continuous ranges (*t* test, $p < 0.05$, Bonferroni correction). However, channel morphologies different from those expected for a given slope range can occur, particularly where due to external forcing. For example, in forested basins wood debris can force a pool–riffle or step–pool morphology in channels that might otherwise have a plane-bed morphology (Montgomery et al. 1995; Montgomery and Buffington 1998). Moreover, reach-scale channel morphology can be influenced by the local sediment supply. Channels with high transport capacities and low sediment supplies may scour to bedrock and not produce the alluvial channel type expected from the above channel gradient ranges. In some settings with relatively uniform sediment supplies, the occurrence of bedrock versus alluvial channel types can be predicted by considering drainage area (a surrogate for both discharge and basin sediment supply) in addition to channel slope (Montgomery et al. 1996*a*; Massong and Montgomery 2000). Finally, recent debris-flow scour or deposition also can alter the expected channel type.

In general, alluvial channel type can be predicted from slope and combined with empirical τ^*_{bf} functions to correct grain-size predictions for channel type and associated roughness. However, predictions of channel type based on stream gradient should be viewed as first-order approximations that require field validation and empirical adjustment for local catchment conditions.

Inserting eqs. 2 and 3, eq. 1 can be rewritten as

$$(4)\qquad D_{50} = \frac{(\rho \alpha A^{\beta} S)^{1-n}}{(\rho_s - \rho) k g^{n}}$$

Equation (4) indicates that for a given channel type and for a given physiographic region (i.e., for specific values of k, n, α, and β), surface grain size can be predicted as a function of drainage area and slope, values readily determined from a DEM. Reach-average values of D_{50} predicted from eq. 4 are then compared with preferred spawning-gravel sizes (e.g., Kondolf and Wolman 1993) to assess the availability and spatial distribution of suitable spawning reaches. To demonstrate the model and explore the significance of hydraulic roughness, we present a sample application using data from Pacific Northwest catchments and channel types.

Methods

Study sites and analysis

We examined three mountain catchments in western Washington, USA (Fig. 4). The Boulder River (a tributary to the North Fork Stillaguamish River) and Finney Creek (a tributary to the Skagit River) are located in the Northern Cascades north of Seattle. The Willapa River is located along the Pacific coast south of Seattle. The drainage networks of the Boulder River and Finney Creek basins are characterized by a variety of alluvial channel types, ranging from low-gradient plane-bed and pool–riffle channels to steep-gradient step–pool and cascade channels (morphologic definitions of Montgomery and Buffington 1997, 1998; Buffington et al. 2003). In contrast, the channels of the Willapa basin are a mixture of alluvial and bedrock reaches, with many of the alluvial channels forced by large wood jams on slopes that otherwise would not support alluvial deposits (Massong and Montgomery 2000).

These three basins were chosen because of the availability of hydraulic geometry data and because the basins represent a broad range of lithology, geologic history, and physical size. The Boulder River and Finney Creek are underlain by Cretaceous metamorphic rocks (folded and foliated phyllite, greenschist, and argillitic mélanges) and glacial sediments derived from Pleistocene ice-sheet advances (Tabor et al. 2002). In contrast, the Willapa River is incised into Tertiary marine sediments (sandstones, siltstones, and mudstones) and Eocene marine basalts (Massong and Montgomery 2000). The glacial histories of the basins also differ. Both the Boulder River catchment and the Finney Creek basin contain abundant ice-sheet deposits from Pleistocene glaciation, while the Willapa basin escaped glaciation because of its position south of the Pleistocene ice-sheet advance. The physical size of the study basins also differs. The drainage area of the Boulder River catchment (63 km^2) is roughly half the size the Finney Creek basin (128 km^2), which is in turn about one-fifth the size of the Willapa River basin (680 km^2).

Ten-metre DEMs (based on 40-ft contour lines; 1 foot = 0.3048 m) were used for each study basin. For the Finney Creek basin, the drainage network was determined from the DEM in terms of critical values of slope and drainage area needed to support channel incision and maintenance of a stream network (Montgomery and Dietrich 1992). Following the approach suggested by Montgomery and Foufoula-Georgiou (1993), cells were classified as streams if the product of drainage area and slope squared exceeded 50 000 m^2 (a value the produces good agreement between predicted and observed stream networks in the study area). For both the Boulder and Willapa catchments, the drainage networks were defined from the Washington State Department of Natural Resources hydrology coverage, which is based on channels occurring on the US Geological Survey 7.5′ topographic maps and supplementary interpretation of aerial photographs. For all basins, individual channel segments were defined between the intersection of blue lines and 40-ft contours depicted on 7.5′ quadrangles. These segments were further divided at tributary confluences that occurred between contour intervals.

Hydraulic geometry relationships for predicting bank-full depth were obtained from field studies (Fig. 5). τ^*_{bf} values were predicted as a function of channel type (from Figs. 2 and 3). Based on salmonid preference for gravel- and cobble-bed rivers (Montgomery et al. 1999), we focused our analysis on channels with slopes <3% (typical of plane-bed, pool–riffle, and forced pool–riffle morphologies having gravel–cobble beds (Montgomery and Buffington 1998; Buffington et al. 2003). In contrast, alluvial channels with slopes greater than 3% tend to be composed of boulder-sized substrate (step–pool and cascade morphologies) that are generally inhospitable for spawning salmonids. Although salmonids (particularly resident species) do spawn in gravel and cobble patches that occur in local backwater areas and low shear-stress environments in these steep channels (Kondolf et al. 1991), salmonids typically prefer lower-gradient, plane-bed and pool–riffle channels (Inoue et al. 1997; Montgomery et al. 1999).

We conducted three sets of analyses to illustrate our approach and to systematically evaluate the potential effects of hydraulic roughness on spawning-gravel availability in channels with gradients <3%. Scenario 1 examines an idealized case in which all channels have a plane-bed morphology. This is an end-member case, representing low hydraulic roughness (Montgomery et al. 1998; Buffington and Montgomery 1999*a*). Scenario 2 predicts spawning-gravel availability in a network composed of both plane-bed and pool–riffle channels. This case represents the addition of bar roughness and predicts channel type based on characteristic gradients (i.e., <1.5% for pool–riffle, >1.5%–3% for plane-bed; Fig. 3). Hence, this scenario describes the effects of self-formed plane-bed and pool–riffle morphologies and their associated roughness. Scenario 3 adds wood roughness and optimizes the occurrence of plane-bed, pool–riffle, and wood-forced pool–riffle channels to maximize spawning-gravel availability. Where surface grain size is predicted to be too coarse for spawning with a plane-bed morphology, a pool–riffle morphology is selected to add bar roughness and reduce substrate size. If the predicted grain size is still too coarse to be suitable for spawning, a wood-forced pool–riffle morphology is selected

Fig. 4. Study site locations in Washington, USA.

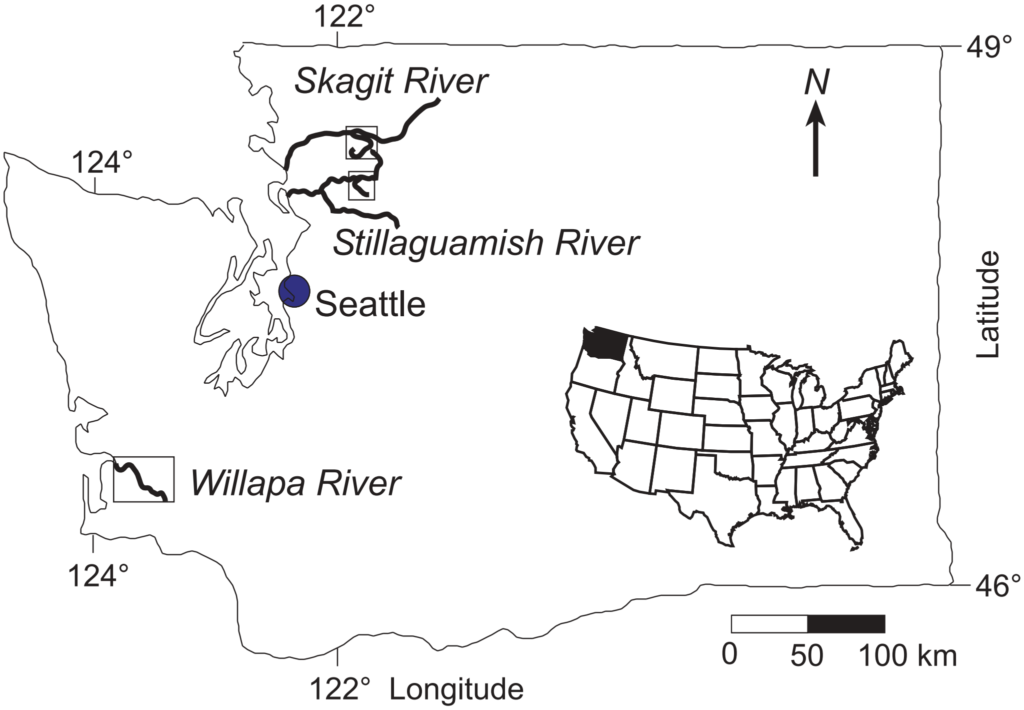
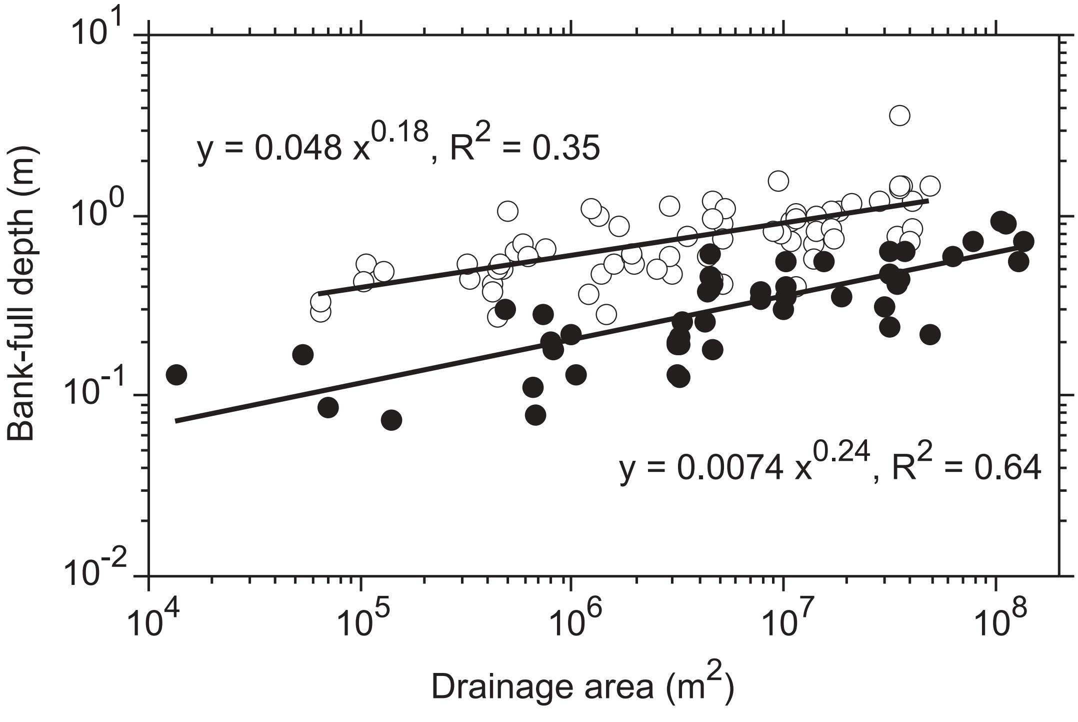


Fig. 5. Bank-full depth (*h*) versus drainage area (*A*) for the Willapa River (open circles; data from Massong and Montgomery 2000) and the Boulder River and Finney Creek (solid circles; data from Montgomery et al. 1998).



to add wood roughness and further reduce bed-surface grain size. Consequently, bar and wood roughness is added wherever the shear stress is otherwise too great to permit sufficiently fine gravel for spawning (i.e., in areas designated as too coarse plane-bed or pool–riffle under Scenario 2). Scenario 3 is intended to be a "what-if" scenario for assessing potential watershed productivity as a function of spawning-gravel availability (one of several limiting factors affecting potential productivity of a region).

Finally, we compare reach-average values of D_{50} predicted from eq. 4 to preferred spawning-gravel sizes to assess the availability of suitable spawning reaches. A general range of suitable spawning substrate is defined from Kondolf and Wolman's (1993) data as D_{50} = 7–47 mm (Fig. 1). This range of values is based on the quartile ranges (25th and 75th percentiles) of their reported median grain-size distributions (see Fig. 1). Although salmonids can spawn in both smaller and larger median grain sizes than the selected range, these values represent a central tendency of sizes used by salmonids as a whole.

Results

In these mountain drainage basins, the largest proportion of channel segments is those with slopes greater than 3% (Figs. 6–8). These steep segments comprise almost 90% of the total stream length in each basin and are generally inhospitable to spawning salmonids because of boulder-bed channel morphologies (Table 1). These results are the same for each scenario, with differences between scenarios occurring within channel segments with slopes <3%.

Scenario 1: minimal roughness (plane-bed channels)

Predicted reach-average D_{50} values are divided into three categories in channel segments with slopes <3%: <7 mm (too small for spawning), 7–47 mm (just right), and >47 mm (too coarse). Results indicate that 21%–34% of the stream length with slopes <3% could host suitable spawning gravels with minimal roughness and a plane-bed morphology (Figs. 6*a*–8*a*; Table 1). However, most of the stream length with slopes <3% would have substrate too coarse for salmonid spawning if characterized by a plane-bed morphology and minimal hydraulic roughness; predictions indicate that 66%–79% of this stream length would be unsuitable for spawning.

Scenario 2: self-formed roughness (plane-bed and pool–riffle channels)

When we include the potential occurrence of pool–riffle channels and consequent textural fining due to bar form drag, the predicted availability of spawning sites increases (Figs. 6*b*–8*b*). Suitable pool–riffle channels are predicted to comprise 43%–64% of the stream length with slopes <3% (Table 1), and they make up 86%–100% of the total available spawning habitat. This represents a 27%–32% increase in spawning-gravel availability over the plane-bed case (Scenario 1). Moreover, our results indicate that plane-bed channels with suitable spawning gravels are relatively rare (no more than 7% of the stream length with slopes <3%).

Scenario 3: optimal conditions

By optimizing channel type and hydraulic roughness, 98%–100% of the stream length with slopes <3% is potentially available for salmonid spawning (Figs. 6*c*–8*c*). 21%–34% of the stream length is predicted to require minimal hydraulic roughness (plane-bed morphology), 39%–51% of the stream length would require textural fining due to bar roughness (pool–riffle morphology), and 15%–31% of the stream length would require the combined effects of bar and wood roughness (wood-forced pool–riffle morphology) to produce suitable spawning gravels (Table 1). In these steep basins, no more than 2% of the stream length with slopes <3% is predicted to have grain sizes too small for spawning.

This scenario highlights potential effects on grain size and spawning habitat caused by differences in channel roughness

Fig. 6. Maps showing the predicted extent and distribution of salmonid spawning gravels for (*a*) Scenario 1, (*b*) Scenario 2, and (*c*) Scenario 3 in the Boulder River basin. PR, pool–riffle, PB, plane-bed; wfPR, wood-forced pool–riffle; SP, step–pool; CA, cascade.

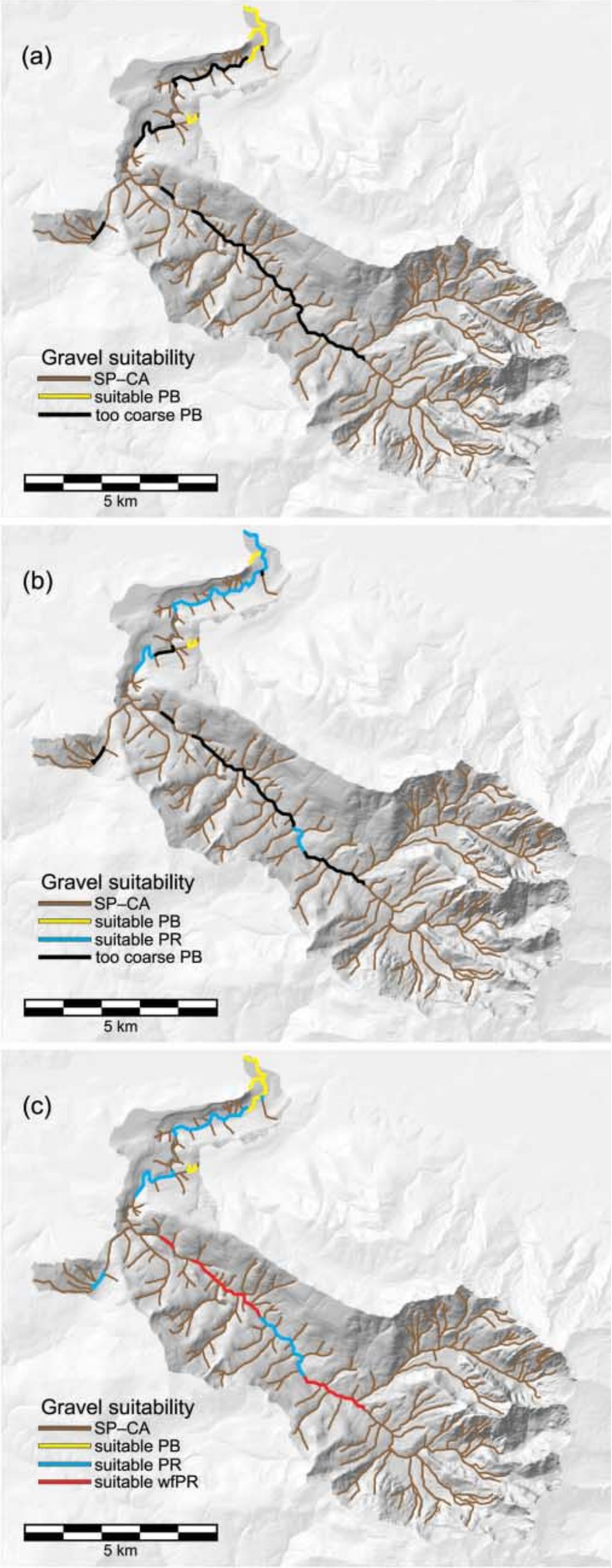


Fig. 7. Maps showing the predicted extent and distribution of salmonid spawning gravels for (*a*) Scenario 1, (*b*) Scenario 2, and (*c*) Scenario 3 in the Finney Creek basin. PR, pool–riffle, PB, plane-bed; wfPR, wood-forced pool–riffle; SP, step–pool; CA, cascade.

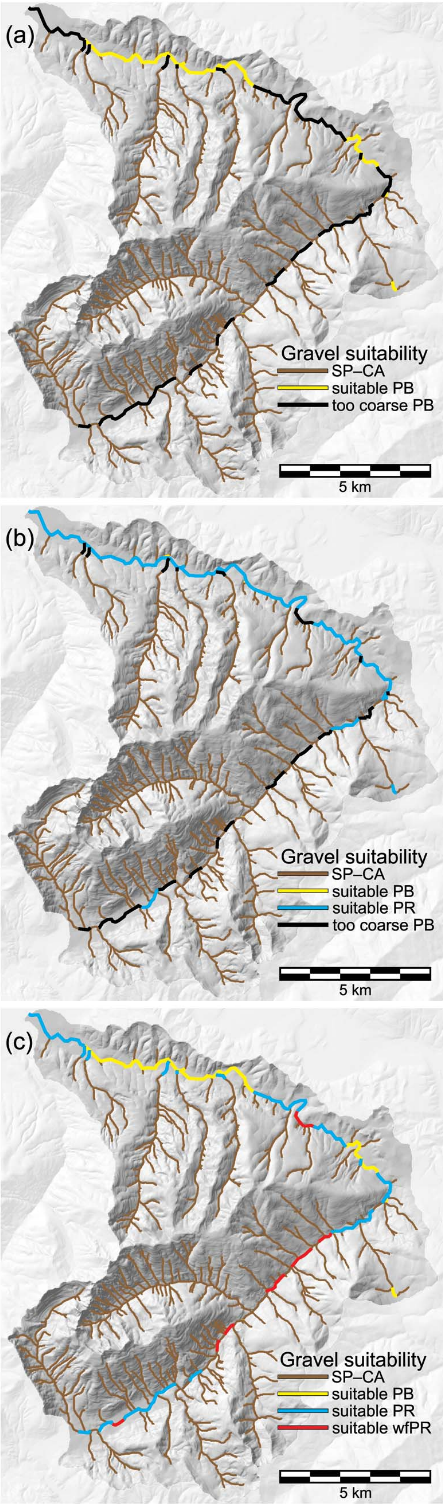
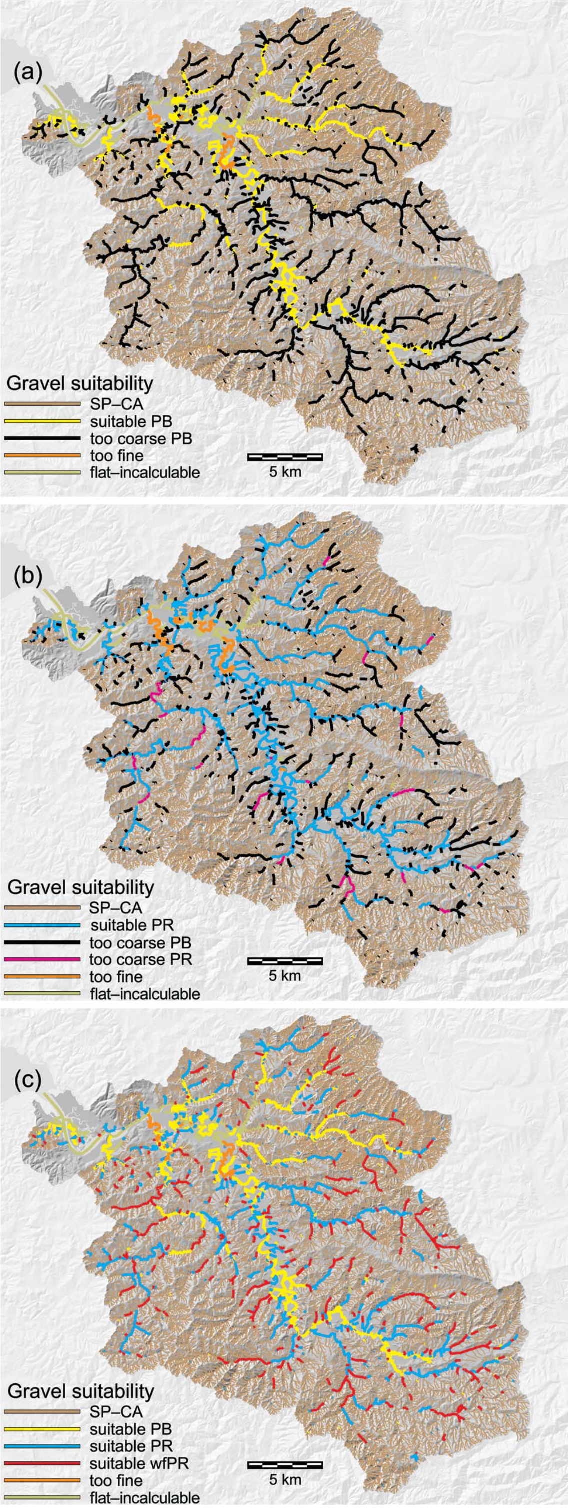


Fig. 8. Maps showing the predicted extent and distribution of salmonid spawning gravels for (*a*) Scenario 1, (*b*) Scenario 2, and (*c*) Scenario 3 in the Willapa River basin. PR, pool–riffle, PB, plane-bed; wfPR, wood-forced pool–riffle; SP, step–pool; CA, cascade.



(changing k and n values in eq. 4), rather than slope-related changes in typical channel type and competence (Scenario 2). In particular, wood loading is an external factor that forces changes in roughness and channel morphology independent of channel gradient (Montgomery et al. 1995; Montgomery and Buffington 1998; Buffington and Montgomery 1999*a*). For example, slopes of wood-forced pool–riffle channels commonly span those of pool–riffle and plane-bed

Table 1. Stream-segment statistics by D_{50} class (mm).

Segment types		Boulder			Finney			Willapa		
Slope	Morphology	<7	7–47*	>47	<7	7–47*	>47	<7	7–47*	>47
% of total stream length										
>3%	Step–pool, cascade	—	—	89	—	—	87	—	—	87
% of stream length with S <3%										
Scenario 1: minimal roughness										
<3%	Plane-bed	0	21	79	0	34	66	2	29	69
Scenario 2: self-formed roughness										
>1.5%–3%	Plane-bed	0	7	50	0	2	34	0	0	36
<1.5%	Pool–riffle	0	43	0	0	64	0	4	56	4
Scenario 3: optimal roughness										
<3%	Plane-bed	0	21	0	0	34	0	2	29	0
<3%	Pool–riffle	0	48	0	0	51	0	0	39	0
<3%	Wood-forced pool–riffle	0	31	0	0	15	0	0	30	0

*Suitable spawning reaches (D_{50} = 7–47 mm). D_{50}, median surface grain size.

channels (Montgomery et al. 1995; Montgomery and Buffington 1997).

Discussion

The results obtained for each catchment are strikingly similar, despite differences in basin lithology, geomorphic history, and physical size. In each basin, nearly 90% of the total stream length is predicted to be unsuitable for spawning because of steep slopes (>3%) and associated boulder-bed morphologies (step–pool and cascade channels). Moreover, in each catchment hydraulic roughness due to bars and wood could potentially control more than 65% of the available spawning habitat (Scenario 1 vs. 3). Although 35% of the potential spawning habitat requires only minimal roughness (plane-bed morphology) (Scenarios 1 and 3), the occurrence of suitable plane-bed reaches is likely rare (no more than 7% of the stream length with slopes <3%; Scenario 2).

The predicted locations of each channel type also are quite similar within each basin. Channel segments with suitable spawning gravels tend to be confined to mainstem reaches within each basin, with bar roughness important for spawning-gravel maintenance in lower-mainstem reaches and wood roughness important for maintaining spawning gravels in the steeper, upper-mainstem channels (Scenario 3).

However, it is important to note that our predictions are based on region-specific functions. While these functions are appropriate for the basins used in our sample predictions, they may not apply to other locations. Consequently, we recommend construction of local relationships for bank-full depth, channel type, and roughness before applying our analysis framework to other catchments.

In particular, channel type and hydraulic roughness may depend on a variety of site-specific characteristics, such as (*i*) the size, frequency, and effectiveness of roughness elements, (*ii*) the size and volume of sediment supplied to a channel, (*iii*) valley confinement (and its effect on channel width and depth), and (*iv*) the local basin physiography, hydrologic regime, and geomorphic processes. For example, plane-bed channels are rare in many forest environments because of the preponderance of in-channel wood debris that forces pool-and-bar morphology (Montgomery et al. 1995; Buffington et al. 2002). Moreover, differences in either the tree species or the style and rate of wood input to channels may cause differences in the effectiveness of wood, despite similar wood loadings (Buffington et al. 2003). Similarly, other types of flow obstructions (e.g., bedrock projections and boulders, rather than bars and wood) may create different relationships among roughness, channel type, and grain size.

We also recommend that predictions be ground-truthed (i.e., field verification of predicted values of channel slope, channel type, reach-average grain size, etc.). For example, channel gradients obtained from DEMs may differ substantially from observed field values (Massong and Montgomery 2000), causing errors to cascade through predictions of channel type, roughness correction, and surface grain size (eq. 4). High bed load supply can also cause observed surface grain sizes to be finer than predicted (as discussed in the Analysis framework section). Consequently, the predicted grain size could be used as a reference value against which to explore departures due to sediment supply and other geomorphic processes not specified in the analysis (e.g., Dietrich et al. 1996; Montgomery et al. 1998; Buffington and Montgomery 1999*a*, 1999*b*). However, empirical τ^*_{bf} functions will include regional sediment-supply effects, which may preclude this reference state approach.

Although we focus on the potential availability of salmonid spawning sites as influenced by hydraulic roughness, the rate and caliber of sediment supply also is an important control on surface grain size (Buffington and Montgomery 1999*b*). In particular, increased sediment supply can cause textural fining through size-selective deposition of fine-grained particles. While supply-related textural fining has the potential to increase spawning-gravel extent in channels that otherwise would be too coarse, it may induce higher embryo mortality, offsetting any potential gains in spawning-habitat availability. Increased sediment supply can cause bed mobility at stages lower than bank-full and thus more frequent scour and a higher probability of egg excavation (Montgomery et al. 1996*b*). Furthermore, increased sediment loading may lead to greater interstitial filling of bed material, resulting in reduced intragravel flow of oxygen to buried salmonid embryos, as well as creating a physical barrier to emergence (Everest et al. 1987; Chapman 1988; Bjornn and Reiser 1991).

Sediment inputs typically are neither uniform nor random, but rather are structured by basin topology, geology, and associated geomorphic processes. For example, the style, magnitude, and frequency of sediment inputs can exhibit systematic downstream variations in mountain basins as one moves from steep, confined headwater regions to low-gradient alluvial valleys (Benda and Dunne 1997*a*, 1997*b*; Montgomery 1999; Buffington et al. 2003). Moreover, network structure and the location of tributary inputs can influence the spatial distribution of sediment size, quantity, and consequent aquatic habitat (Rice et al. 2001*a*, 2001*b*; Martin et al. 2004). Thus, broad-scale geomorphic controls on sediment supply should be considered in addition to channel type and competence.

Results of our analyses indicate that textural fining due to bar and wood resistance has the potential to dramatically affect the extent of salmonid spawning habitat in mountain drainage basins. In particular, wood roughness can be a first-order control on the availability of spawning gravel in steep, upper-mainstem reaches (slopes of <1.5%–3%).

Land management practices of splash damming, riparian clear-cutting, and stream cleaning have decreased the amount of wood debris in many channels throughout North America. Our results suggest that consequent textural coarsening in response to wood loss decreased salmonid spawning habitat availability and may be a factor in historic declines of fish populations (Nehlsen et al. 1991; Montgomery 2003). The impact of wood loss can range from significant textural coarsening that may destroy spawning habitat for salmonids in general to less severe changes in grain size that may alter the species-specific appeal of a given channel reach (i.e., textural coarsening may stimulate a shift in the type of salmonids that use a given portion of the channel network). Wood loss can further compound impacts on fish populations by decreasing pool frequency and area and thus the availability of potential rearing habitat (Montgomery et al. 1995, 1999; Buffington et al. 2002).

Our analysis is intended to predict potential availability of spawning habitat based on general hydraulic controls on surface grain size. It is a first-order assessment of basin conditions that is not species specific. Nor does our analysis consider catchment-specific controls on access to various portions of the drainage network. For example, both the Boulder River and Finney Creek have waterfalls that limit anadromous fish to the lower reaches of each basin. However, because our analysis is purposefully general, basin-specific or species-specific issues can be overlain on our approach. For example, our current analysis could be tailored to spawning-gravel availability for a particular species of concern, such as coho salmon habitat in coastal basins of the Pacific Northwest.

Our analysis has several potential land management applications. It allows rapid prediction of the extent and distribution of potential salmonid spawning sites at basin scales. It can also be used to identify unrealized spawning sites (i.e., suitable locations that are not currently used but are part of the potential habitat range). Moreover, the approach can be used to prioritize locations for salmonid habitat conservation or restoration. Finally, our approach can be used to explore what-if scenarios for assessing potential habitat response to natural or anthropogenic disturbances. For example, the analyses presented in this paper could be used as part of a proactive land management plan for optimizing spawning habitat availability by managing channel type in locations where spawning gravels are limited. Based on model results of this sort and field verification, one might plan riparian growth that would supply wood debris and associated roughness where shear stresses and grain sizes are too large. Similarly, channel dimensions (width and depth) might be altered to encourage development of pool–riffle versus plane-bed morphologies (Buffington et al. 2003).

However, it is important to note that our approach is not a dynamic process–response model. Our analysis does not include specific predictions of channel response and is not intended for that use. While our predictions can be used to identify potential locations that might benefit from altered roughness (such as the addition of wood debris), a channel may respond in many different ways to this change in roughness. For example, addition of roughness elements may cause changes in channel width, depth, or slope in addition to, or in place of, the intended effect of textural fining (Buffington and Montgomery 2001).

Because our analysis focuses on reach-scale predictions of surface grain size, it should be viewed as a coarse-level quantification of potential spawning habitat. In particular, subreach-scale grain size patches and textural variability are not captured by this analysis, but may be important factors in spawning-site selection and overall reach suitability (Buffington and Montgomery 1999*a*). Nevertheless, there is a general association between reach-level channel types and textural-patch complexity. Both the number and frequency of textural patches within a reach increase across plane-bed, pool–riffle, and wood-forced pool–riffle channel types because of increasing spatial variability of shear stress and sediment supply forced by subreach-scale roughness elements (Buffington and Montgomery 1999*a*). Consequently, reach-level predictions provide a first-order assessment of habitat quality that has implications for subreach usage. Inoue et al. (1997) found that reach-scale channel morphology provides a dominant control on subreach habitat availability and is a better predictor of salmonid abundance than that obtained from reach-specific channel-unit characteristics.

The results presented here illustrate our analysis framework and demonstrate the potential effects of channel type and hydraulic roughness. Companion investigations comparing predicted versus observed spawning locations are currently being conducted.

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