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Title:

A Hydrogeomorphic Dynamics Approach to Assess In-Stream Ecological Functionality Using the Functional Flows Model, Part 1 – Model Characteristics

Running Head: Functional Flows Model Characteristics

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Abstract

The functional flows model integrates hydrogeomorphic processes and ecological functions for stream physical habitat evaluations. Functional flows are discharge values that serve ecological uses. Assessment of functional flows is based on evaluation of shear stress dynamics. As an example, the model was tuned for fall-run Chinook salmon spawning. Ecological functions studied were bed occupation (spawning, incubation, and emergence) and bed preparation (river bed reworking periods)- both reliant on shear stress dynamics. The analysis is based on the occurrence of sediment transport regimes defined by threshold values of Shields stress estimated from discharge (Q), a parameter (f) governing depth response to incremental discharge changes, water surface slope (S), and median grain size (D_{50}). A numerical experiment and sensitivity analysis using a wide range of realistic values of input variables indicated the effect of each variable on flow functionality. Combinations of S=0.001, 0.005, and 0.01, D_{50}=0.02, 0.05, 0.1 m, f=0.2, 0.3, 0.4, 0.5, and four sediment transport stages produced 144 scenarios. Ranges of functional flows were greater for scenarios with low f (0.2), low slope (0.001,0.05), for high f (0.5) with small grain size (0.02 m), and for intermediate low f (0.3) with coarse grain size (0.1 m). The functional flows model incorporates in-stream habitat processes by including metrics of hydrologic, hydraulic, geomorphic, and ecologic dynamics. Model uncertainties related to input data, calculation algorithms, and model structure are analyzed. Functional flows analysis can be useful in studying water management alternatives to improve habitat conditions for target species and lifestages.

Keywords: aquatic habitat evaluation, ecological functions, functional flows, instream flow, spawning habitat, sediment transport stages, stream ecology

1 Introduction

Habitat units in rivers, also known as physical habitat, are defined as zones with characteristic physical attributes where organisms perform ecological functions, defined as the ways in which organisms interact with each other and their environment (Knighton, 1998; Marcot and Heyden, 2001; Moyle and Check, 2004). In this paper, habitat functions are defined as the subset of ecological functions that relate to habitat units. The attributes of physical habitat in rivers stem from the interaction among hydrologic, hydraulic, and geomorphic processes (Poff *et al.*, 1997; Brierley and Fryirs, 2000; Wheaton, 2003). These watershed and stream processes determine measurable habitat conditions for the natural occurrence of transient ecologic functions such as salmon spawning (Maddock, 1999; Marcot and Heyden, 2001). A considerable amount of physical habitat characterization methodologies (i.e. more than 200 according to Tharme, 2002) (Tharme, 2003) have been developed in the context of in-stream flow requirements. Still, reviews of the methods identify additional research needed to improve the understanding of the fundamental associations between aquatic ecosystems and physical factors (Payne, 2004). From the perspective of assessing freshwater ecosystem services, approaches that relate ecological functions and physical processes help evaluate how hydrologic processes contribute in the creation and maintenance of habitats required by in-stream organisms (DeGroot *et al.*, 2002; Moir and Pasternack, 2008).

A sample of the most commonly used approaches for characterizing physical habitat were reviewed from the perspective of their emphasis on some key parameters over others (Fig. 1; Table 1). This review stresses that existent approaches may be useful to produce detailed characterizations of parameters representing one or two habitat functions, however they do not incorporate key parameters of the omitted habitat functions lacking the capacity to represent hydraulic, geomorphic, and ecologic interactions of physical habitat (Maddock, 1999; Clarke *et al.*, 2003). Also, methods using detailed characterizations require detailed input data at small spatial scales, such as the hydraulic-unit (10^{-1}-10^{0} channel widths) and geomorphic-unit (10^{0}-10^{1} channel widths) scales, making applications at the larger reach scale (> 10^{2} channel widths) time consuming due to data input requirements and computer model set up (Maddock, 1999; Kondolf, 2000).

The overall goal of this study was to develop a simple model to determine ecological functionality for a reach at the habitat-unit scale, with each unit represented by a characteristic cross section. The model is called the "Functional Flows Model", because it identifies ranges of streamflow that interact with river bed morphology through hydraulic processes serving ecological functions. To understand why this new model is useful, the next subsections will describe existing approaches; and then present a brief description of the new model.

1.1 Functional Flows Model (FFM)

A great number of methods for evaluating physical habitat exist; many of them have been developed within the context of environmental flow assessment. Also, many reviews of instream flow methods exist. For instance, the review by Tharme (2003), identifies more than 200 approaches (Tharme, 2003). After classifying a selection of habitat evaluation methods based on the inclusion of hydrologic/hydraulic, geomorphic and ecologic processes (Fig. 1.; Table 1) it is clear that existent approaches lack the integration of necessary physical and ecological processes, which constitutes the conceptual foundation of the new functional flows model presented in this paper (Rosgen, 1994; Montgomery and Buffington, 1997; Poff *et al.*, 1997; Bovee *et al.*, 1998;

Moyle and Randall, 1998; Thorne, 1998; Guay *et al.*, 2000; Lamouroux and Cattaneo, 2006)(Moyle and Randall, 1998; Rosgen, 1994; Montgomery and Buffington, 1997; Poff *et al.*, 1997, Thorne, 1998; Lamouroux *et al.*, 2006; Bovee *et al.*, 1998, Guay *et al.*, 2000). It is important to recognize that all methods included in the classification represent significant scientific contributions, but inevitably it is important to identify pros and cons to identify future opportunities for improvement. Even the new model herein has limitations that could be improved upon in the future, too.

Based on this lack of integration of physical and ecological processes of exiting methods, a need for integration of physical processes and aquatic ecosystems to improve the understanding the links between flow and habitat quality has been identified (Payne, 2004). One approach previously not attempted is to link streamflow and channel conditions to assess the status of geomorphic dynamics necessary to promote ecological functionality in rivers (Hardy, 1998). The new model presented in this paper does this by combining a stream's discharge record and channel data to estimate the temporal pattern of shear stress, which is the key factor preparing physical habitat for several ecological functions. Functional flows are defined as discharge values that interact with the river bed morphology through hydraulic processes providing shear stress conditions that serve ecological purposes.

To classify ranges of flows that are functional, the initial step is to identify ecologic functions and their dependence on hydraulic and geomorphic processes of the river bed. The next step is to select key parameters to characterize hydraulic and geomorphic processes. Key parameters selected are discharge time series, cross-section geometry, water surface slope, and grain size distribution, which are used as input data to calculate temporal patterns of shear stress. Thresholds of non-dimensional shear stress define bed mobility stages that provide favorable conditions for ecological functions, and are used to classify functional flows. The algorithm for functional flows analysis integrates key relations between shear stress and ecological functions that have already been investigated.

1.2 Study Objectives

The FFM constitutes a robust conceptual framework to identify ecological functions and their relation to physical processes. It also provides an approach to assess functionality of habitat units. It could be applied to any situation in which ecological functions are linked to hydrologic regime and geomorphic channel change.

To provide a concrete illustration that exemplifies the response and sensitivity of the FFM, this study focused on structuring the model to assess the instream physical habitat typically used during the spawning stage of fall-run Chinook salmon (*Oncorhynchus tschawytscha*), an endangered species of the Pacific northwest of the USA (Augerot *et al.*, 2005). The freshwater lifestage of a key salmon species was chosen because the status of these species is an indicator of ecosystem functionality (Merz *et al.*, 2004; Merz and Chan, 2005) and it affects the fate of major dam re-licensing efforts on-going in the U.S. Pacific region.

The goals of our research program have been to 1) develop a detailed FFM for the freshwater lifestage of fall-run Chinook salmon and to explore the range of its capabilities through sensitivity analysis to glean general principles about instream ecological functionality. (presented in this article, labeled as Part 1), and 2) perform an application of the example FFM to specific rivers experiencing temporal changes in geomorphic dynamics due to river rehabilitation as well as due to natural flooding (presented in the accompanying article, labeled as Part 2). The exploration of complex linkages among hydraulic, geomorphic, and ecologic variables through numerical experimentation and sensitivity analysis constitutes the new scientific advancement of the work reported in this article.

The specific objectives of this article were to 1) present a conceptual framework of relevant hydraulic and sediment transport processes that determine in-stream habitat conditions (Section 2. Conceptual Model); 2) generate algorithms based on the conceptual model to yield quantitative predictions of ecological functionality (Section 3. Analytical Model); and 3) investigate the non-linear dynamism of the proposed algorithms to explore the range of functional conditions and to determine combinations of key parameters that yield functional flows for fall-run Chinook salmon spawning habitat (Section 4. Numerical Experiment). The study concludes with a discussion of model results and uncertainties, and implications of the use of the model for resources management (Section 5. Discussion).

2 Conceptual Model of Functional Flows for Salmon in Gravel Bed Rivers

2.1 Salmon Freshwater Lifestage

Salmon are a family of fish species that live in the North Pacific and the North Atlantic Oceans and migrate to lay their eggs in cold water streams of North America and Eurasia (Augerot *et al.*, 2005). In their freshwater lifestage, salmon depend on stream physical habitat, defined here as local depth, velocity, and river-bed substrate, of the locations where they are commonly found (Reiser and Bjornn, 1979; Groot and Margolis, 1991; Lisle and Lewis, 1992; DeVries, 1997; Jager *et al.*, 1997; Gallagher and Gard, 1999; Montgomery *et al.*, 1999; Soulsby *et al.*, 2001; Malcolm *et al.*, 2003; Meyer, 2003). Salmon populations of the west coast of North

America have declined due to loss of stream physical habitat caused by watershed degradation, dam construction, and manufactured flows (Allan and Flecker, 1993; Moyle, 1994; Augerot *et al.*, 2005). As a consequence, the Pacific runs of Chinook, Coho, Chum, and Sockeye salmon species have been listed as endangered or threatened (Fisher, 1994; Moyle, 1995).

During the freshwater life stage, salmon perform several ecological functions, defined as the ways in which they interact with and use their physical habitat (Marcot and Heyden, 2001). These freshwater ecological functions are upstream migration of adults, spawning, embryo incubation, fry emergence, and juvenile rearing. Salmon migrate to upstream reaches to spawn in foothill and mountain cold water streams (Reiser and Bjornn, 1979). They search for low depth-high velocity portions of the river found in pool-riffle sequences, which are vertical undulations of the bed in phase with horizontal meandering (Keller, 1971; Keller and Mellhorn, 1978; Wilkinson *et al.*, 2004). Pools are the topographic lows and riffles are the topographic highs. Riffle entrances and lateral bars with swift water are typical spawning locations where females search for clean gravel (Montgomery *et al.*, 1999; Lapointe *et al.*, 2000; Meyer, 2003; Moir *et al.*, 2004; Moyle and Check, 2004). They initiate the construction of the nest, called a redd, by digging a hole to depths that vary depending on the size classes of the females for each species (DeVries, 1997; Montgomery *et al.*, 1999). After females lay their eggs and males fertilize them, the females finish redd construction by covering embryos with gravel (Groot and Margolis, 1991; DeVries, 1997). During incubation, embryos remain buried within the gravel. After a period that ranges between 2 - 8 months, the just-hatched fish, called fry, emerge through the gravel to begin their juvenile life in freshwater (Groot and Margolis, 1991; Merz *et al.*, 2004; Augerot *et al.*, 2005).

Variables such as streamflow and in-channel sediment affect stream physical habitat throughout the freshwater lifestage (Fig. 2). Minimum streamflow values within perennial channels and on seasonally inundated floodplains provide minimum depths and velocities during upstream adult migration (Reiser and Bjornn, 1979; Jager *et al.*, 1997). Channels free of fish passage barriers such as dams, road crossings, and culverts allow migrating fish access to spawning grounds (Reiser and Bjornn, 1979). After migration, calm waters of pools and side channels provide holding habitat for adult fish to save energy for reproduction (Groot and Margolis, 1991; Nielsen *et al.*, 1994). Riparian vegetation and other channel cover elements such as logs and undercut banks provide shade and protection from predation (Reiser and Bjornn, 1979; Augerot *et al.*, 2005). Preferred spawning habitat units are areas with low water depths, moderate velocities, and gravel that fish can move for redd construction (Lisle and Lewis, 1992; Kondolf and Wolman, 1993; DeVries, 1997; Gallagher and Gard, 1999; Lapointe *et al.*, 2000). During the embryo incubation and emergence periods, the depth and velocity of the water in contact with the river bed must provide sufficient shear, preventing fine sediment from depositing within the gravel to maintain porosity for well oxygenated intragravel water flow, and preventing fine sediment from depositing on top of the redds to permit unobstructed fry emergence without exceeding shear thresholds that would scour gravel exposing or stranding the embryos (Petts, 1984; Lisle and Lewis, 1992; Kondolf and Wolman, 1993; DeVries, 1997; Soulsby *et al.*, 2001; Malcolm *et al.*, 2003; Meyer, 2003; Greig *et al.*, 2005).

2.2 Fluvial Hydrogeomorphology

The physical habitat conditions described above for the freshwater lifestage of salmon result from interactions between hydrologic and geomorphic processes. Watershed hydrologic processes such as climate change, landscape evolution, natural floods, storms, and earthquakes determine the amount of rainfall turned into streamflow. Hydrologic variation over time yields a flow regime, defined as flow magnitude, frequency of occurrence of high and low flows, flow duration, flow timing, and rate of change between flow magnitudes (Poff *et al.*, 1997; Ward, 2000), which is the driving force of riverine ecosystems (Richter *et al.*, 1997).

Geomorphic processes at the basin scale such as landsliding, gullying, and sheet wash erode sediment off the land and into streams. In addition, bank and bed erosion contribute sediment to downstream reaches. These sources provide the river's sediment supply. Sediment can be moved in the form of suspended load composed of particles that move in the fluid supported by turbulence (Knighton, 1998) or bed load composed of material entrained from the bed that rolls, skips, and hops along the bed (Nelson *et al.*, 1995).

Streamflow variability controls bedload transport processes (Lisle *et al.*, 2000; Parker *et al.*, 2003) (Table 2, Column 1). Frequent entrainment of particles into the flow takes place when the shear stress provided by the flow, τ_o, is larger than the critical shear stress required to move a particle of size *i* of interest, τ_{ci} (Paintal, 1971). Of particular relevance is the critical shear stress of the median grain size, τ_{c50}, which is representative of the critical shear stress of a non-uniform mix of grain sizes (Buffington and Montgomery, 1997). Shields (1936) proposed a function to relate non dimensional shear stress (see Eq. 6) to particle Reynolds number (D/δo, where δo is the thickness of the laminar sublayer) (Knighton, 1998). The resultant curve defines a threshold for motion above which there is motion and below which there is no motion, and defines zones of suspension and bed movement along the abscissa. In hydraulically rough beds such as gravel bed rivers the threshold for movement tends to be constant at around 0.06 (Knighton, 1998).

Bed load transport capacity can be expressed as a function of the relative excess between τ_o and τ_{c50}. At low discharges bed load transport approaches zero allowing the accumulation of organic and inorganic fines within gravel interstices (Marks and Rutt, 1997; Soulsby *et al.*, 2001). At a given discharge the onset of fines entrainment removes superficial fines deposited on the surface of the bed. Shear stress just below the shear stress that moves gravel ($\tau_o < \tau_{c50}$) is enough to entrain superficial fines (Ashworth and Ferguson, 1989; Wilcock *et al.*, 1996a). At a higher discharge, entrainment of the median grain size releases interstitial fines trapped in pores between larger size gravel of the active layer. Shear stress that entrains the gravel itself ($\tau_o = \tau_{c50}$) is required to remove interstitial fines and to maintain gravel looseness (Kondolf and Wilcock, 1996; Wilcock *et al.*, 1996b). At an even higher discharge full mobility rejuvenates the gravel of the active layer and may transport and redeposit fine sediment. Shear stress that moves the active layer ($\tau_o > \tau_{c50}$) is necessary to rejuvenate the gravel of the active layer (Soulsby *et al.*, 2001; Konrad *et al.*, 2002). The proper combinations of these flow processes keep the gravel sorted, loose, and free from fines. Floods that dramatically re-arrange the ordering and structure of riffles and pools are also important for long-term channel self-maintenance (Keller, 1971; Lisle, 1979; Parker *et al.*, 2003; MacWilliams *et al.*, 2006).

2.3 Functional Flows Theory

A functional flow is defined as a discharge that interacts with river bed morphology through hydraulic processes providing a shear stress value that serves an ecological function. Depending on the specificity of a given ecological function, a functional flow may occur over a range of discharges. For the specific example of spawning habitat, in this study it is proposed that key functions can be classified into 1) hydrogeomorphic functions that support bed occupation ecological functions, which are those that interact directly with the river bed, namely spawning, incubation, and emergence; and 2) hydrogeomorphic functions that support bed preparation ecological functions, which include the preparation of the ground in periods where no interaction with the active layer occurs but reworking of the ground conditions the bed for the next spawning cycle (Groot and Margolis, 1991) (Table 2; Fig. 3A). Ecological functions may be defined differently depending on the criteria of the researcher, the lifestages studied, and the target species. The model is not specific to fish, but can be adapted for any instream organism affected by sediment transport and channel change. For the salmon spawning lifestage, during bed occupation periods functional flows are moderate low flows that provide a stable surface layer during redd construction and flush fines from the bed surface during embryo incubation (Montgomery *et al.*, 1983; Kondolf and Wilcock, 1996). Non-functional flows are high flows that cause stranded fish or egg-pocket scour that kills embryos (Montgomery *et al.*, 1999). During bed preparation periods between emergence and spawning, functional flows include high flows that induce full mobility of sediment on the stream bed, and moderately high flows that sort gravels to maintain high porosity (Kondolf and Wilcock, 1996). Non-functional flows are low flows that allow the accumulation of sand and organic mud within the gravel (Soulsby *et al.*, 2001) (Fig. 3B). This characterization of functional flows represents hydrogeomorphic dynamics by evaluating conditions at each location independently of other locations. A more sophisticated definition that could be implemented in the future would analyze the spatial sequencing of shear stress to identify functional flows that assist pool-riffle sequence self-maintenance and other dynamics governed by channel non-uniformity (Lisle and Lewis, 1992; MacWilliams *et al.*, 2006). Another improvement would be to characterize sediment supply effects and recognize that sediment-laden tributary inflows that cause sand to smother over egg-pockets thereby limiting fry emergence are non-functional flows (Lapointe *et al.*, 2000).

Functional flows for spawning habitat occur at specific locations of hydraulic and sediment transport processes (Groot and Margolis, 1991). For instance, flow, bed topography, and sediment sorting at the pool tail provide the bed form and water depth and velocity that salmon seek to carry out their reproductive lifestage (Emery *et al.*, 2003). Consequently, the pool tail/riffle entrance is one preferred location for spawning (Montgomery *et al.*, 1999; Coulombe-Pontbriand and LaPointe, 2004; Moir *et al.*, 2004; Moyle and Check, 2004). Other locations include side channels and lateral bars (Webb *et al.*, 2001; Moir *et al.*, 2004; Morley *et al.*, 2005). Also, functional flows occur at specific timing of flow intensity and transport processes. For instance, in California, extended periods of base flows and stable beds that allow the accumulation of fines and algae in the gravel interstices precede spawning. After spawning, the peak flows of the winter might produce positive effects removing superficial and interstitial fines, or, if too high, might produce negative effects stranding embryos and scouring the river bed. After emergence, spring snowmelt reworks the river bed that will serve for the next spawning cycle (Fisher, 1994; Soulsby *et al.*, 2001) (Fig. 3A, B).

Physical habitat delimiters like flow depth, velocity, and Froude number are typically used to assess hydraulic habitat functionality (Moir *et al.*, 2002; Clifford *et al.*, 2006). Shear stress is also an appropriate delimiter for habitat units that are highly dependent on sediment transport regimes because it represents the force available to scour the bed (Montgomery *et al.*, 1999). Consequently, bed mobility stages delimited by boundary shear stress thresholds are appropriate to classify functional flows for spawning habitat units (Brown and Pasternack, 2008b). Functional flows can be classified by the relative difference between boundary shear stress and the critical shear stress to entrain the median grain size (τ_o vs τ_{c50}) (Table 2, Column 2A). Functional flows can also be expressed in terms of absolute values of non-dimensional shear stress τ_o*, which allows for a more generalized definition (Fig. 4) (Table 2, Column 2B). This is the approach used in this paper and will be explained in the analytical model development section.

3 Analytical Model Development

Given the above conceptual understanding of hydrology, ecology, and geomorphology governing salmon spawning, the next step is to obtain algorithms that characterize the key processes related to functional flows. This section presents algorithms representing associations between hydraulics and channel features that serve as spawning habitat units (Clifford *et al.*, 2006) (Fig. 2). The relation between streamflow and channel geometry determines velocity and water depth and can be represented by a power function (Leopold and Maddock, 1953). In turn, hydraulic principles of mass and momentum conservation determine the magnitude of the shear stress acting on the river bed which controls sediment transport and gravel sorting (Parker, 1979; Knighton, 1998). Non-dimensional shear stress is estimated using equations that integrate non-linear interactions among discharge, median grain size, slope, and channel geometry. Functional flows estimations result from classifications of discharge ranges delimited by thresholds of non-dimensional shear stress (Table 2).

3.1 Equations for Fluvial Physical Processes

The first step in the evaluation of functional flows is to select an algorithm to evaluate shear stress. Ideally a 2D or 3D hydrodynamic model would be used to accurately estimate shear stress at the redd scale (10^{-1}-10^{0} channel widths). Such models and the necessary field methods and environmental informatics are advancing rapidly, but are still limited to <10-km stream reaches with highly detailed site information (e.g. bed facies maps and a topographic resolution of 1 m^2 or better) (Pasternack *et al.*, 2006; Pasternack, 2008). The costs to obtain detailed input data, perform modeling, and analyze model output as of yet makes it impracticable to apply such detailed methods to model large river reaches (> 10^2 channel widths). For most rivers the necessary field data do not exist and the high level of complexity of the problem require simpler representations than 3D and 2D models produce. Thus, a 1D analytical procedure was selected for incorporation into the FFM at this stage of development to estimate boundary shear stress in the downstream direction of habitat units represented by a characteristic cross-section. It is acknowledged that 1D analytical models do not account for convective accelerations common in gravel bed rivers (Brown and Pasternack, 2008a; Pasternack *et al.*, 2008), and this is a limitation of the current implementation of the FFM. In general, this 1D approach would be valid for conditions of uniform channel configuration where the main depth and velocity vectors occur in the downstream direction. However, under conditions of non-uniform channel configurations, depth and velocity vectors occur in the downstream and cross-stream directions because channel elements such as bed undulations and larger grains in the substrate force streamlines to clump and expand irregularly. In these cases, flow non-uniformity is better represented by 2D/3D hydrodynamic models (Escobar-Arias, 2008).

Boundary shear stress, τ_o, for unsteady, non-uniform flow derived from the 1D Saint

Venant momentum equation is

$$\tau_0 = \rho g R\left(S - \frac{\partial h}{\partial x} - \frac{U}{g}\frac{\partial U}{\partial x} - \frac{1}{g}\frac{\partial U}{\partial t} \right) \quad (1)$$

where ρ is the water density, g is gravity, R is the hydraulic radius (wetted area/ wetted perimeter). The first term in the brackets, S, is the bed surface slope at the control volume being analyzed (i.e. slope of river bed) and $\rho g R S$ represent the steady component of the shear stress due to gravity forces acting on the fluid mass. The second term, $\partial h / \partial x$, is the change in depth, and the third term, $U \partial U / g \partial x$, is the cross section averaged velocity of the control volume multiplied by the change in cross section averaged velocity; these two terms represent the non-uniformity of the control volume. The fourth term in the brackets, $\partial U / g \partial t$, is the change in velocity between two timesteps divided by gravity, and represents the temporal change of the shear stress.

In addition to the 1D Saint Venant equation for non-steady non-uniform flow, at least nine other methods can be used to estimate boundary shear stress from field measurements as summarized in Table 1 of Dietrich and Whiting (1989). Any of the methods summarized in Dietrich and Whiting (1989) could be used to estimate boundary shear stress for functional flows analysis. For the application presented in this study, the simplified depth-slope product was selected to calculate boundary shear stress

$$\tau_0 = \rho g R S \quad (2)$$

For wide channels, R can be approximated to the average depth of the cross section,

$$\tau_0 = \rho g \bar{h} S \quad (3)$$

which is called the "depth-slope product". The simplified definition of shear stress in Eq. 3 allows keeping focus on the exploration of the interactions among physical processes and ecological functions without deviating on calculating shear stress with detail, which is a valuable effort that has been the focus of several studies (Booker, 2003; Rodriguez *et al.*, 2004; Wilson *et al.*, 2006). The depth-slope product has been used as a first order assessment in landscape evolution models to understand erosion processes at scales ranging from the geomorphic unit to the watershed (Dietrich *et al.*, 1993). Eq. 3 is an approximation to estimate total boundary shear stress in short reaches that presents constraints and advantages (Dietrich and Whiting, 1989). For instance, it neglects convective accelerations that are important in controlling sediment transport processes in pool-riffle morphologies (MacWilliams *et al.*, 2006; Brown and Pasternack, 2008a; Pasternack *et al.*, 2008). However, it is a robust and simple calculation of the momentum available to determine sediment transport stages. At the smallest scale of interest, defined by the size of the redds (10^{-1}-10^{0} m), the use of cross section average-depth to calculate boundary shear stress produces a unique average value that may overestimate local shear stress for most of the channel side and underestimate local shear stress for the thalweg of the cross section (Brown and Pasternack, 2008a). However, at higher scales defined by the length of the spawning reach (>10^{2} channel widths), Eq. 3 can be used to obtain results at several sites providing an index of spatial distribution of bed load transport capacity (Konrad *et al.*, 2002; Buffington *et al.*, 2004). Eq. 3 represents the total force on the wetted boundary of bed and banks without partitioning the portion of the force that drives the entrainment of the grains, called grain roughness or skin friction, from the portion of the force that acts on other elements of the channel such as wood and bends, called form drag or bed form resistance (Dietrich and Whiting, 1989; Dade, 2000). In rivers with surface beds in the gravel (2-64 mm) and cobble (64-256 mm) size, grain roughness is generally the main component of resistance (Knighton, 1998).

"At-a-station" cross-section geometry relations for depth can be used for the evaluation of depth for a range of discharge values

$$h = cQ^f \quad (4)$$

where c and f are empirical values that control the water depth response to discharge increments at the cross section (Leopold and Maddock, 1953). Replacing Eq.4 in Eq. 3, the shear stress becomes

$$\tau_0 = \rho g (cQ^f) S \quad (5)$$

The coefficient c and exponent f are site specific and need to be determined for each cross section in question. An analysis of these exponents for mountain streams is provided by Wyrick and Pasternack (2008). A non-dimensional τ_o can be defined as

$$\tau_0{}^* = \frac{\tau_0}{g(\rho_s - \rho) D_{50}} \quad (6)$$

where ρ_s is the sediment density and D_{50} is the median grain size. Non-dimensional boundary shear stress can be compared to values of τ_o* that represent the critical magnitude necessary to entrain gravel of a given size, τ_{crit}*, or Shields parameter (Buffington and Montgomery, 1997; Wheaton *et al.*, 2004). Of particular interest is the Shields parameter for D_{50}

$$\tau_{c50}{}^* = \frac{\tau_{c50}}{g(\rho_s - \rho) D_{50}} \quad (7)$$

where τ_{c50}^*, or mobility number, is an indicator of the initiation of motion in a non-uniform mix of grain sizes. Comparing τ_o* vs τ_{c50}^* provides and indication of the degree of mobility of the river bed. On hydraulically rough beds, which is the common condition in gravel bed streams, the Shields parameter τ_{c50}^* ranges from ~0.03 to ~0.06 (Andrews, 1984; Knighton, 1998). However, values of τ_{c50}^* reported in the literature present variability. Buffington and Montgomery (1997) report ranges of 0.030-0.086 for incipient motion in their compilation of data from eight decades of studies. In addition, other thresholds for degrees of river bed mobility have been identified. Konrad et al. (2002), uses Eq. 6, and reports that no entrainment of a bar occurs at $\tau_o^*<0.01$, 50% of entrainment occurs at $\tau_o^*=0.085$, and 100% of entrainment occurs at $\tau_o^*=0.12$. In addition, Lisle et al. (2000), also using Eq. 6, assumes that partial transport occurs for $0.03< \tau_o^*<0.06$, full mobility happens at $\tau_o^*>0.06$, and reports that intensive bed load transport occurs at $\tau_o^*> 0.15$. Sediment transport stages can be defined as conditions of river bed mobility that are a function of bed load transport processes that are delimited by Shields values (Knighton, 1998). Despite the variability of specific values, thresholds of τ_{c50}^* are often used to determine ranges of τ_o* for river bed mobility stages (Knighton, 1998) which in turn can be used to determine ecological purposes of hydrogeomorphic processes.

3.2 Functional Flows Analysis

The analytical framework proposed in this study for the evaluation of functional flows is structured in a table of functionality using τ_o^* delimiters and ecological functions timing (Table 2). Categories of flow range intensity and associated sediment transport stages are determined: high flow/full mobility (FM), intermediate high flow/interstitial fines mobility (IFM), intermediate low flow/ superficial fines mobility (SFM), and low flow/stable bed (SB) (Table 2, Column 1) (Kondolf and Wilcock, 1996; Lisle *et al.*, 2000). Values of dimensionless critical shear stress values are used to delimit bed mobility stages for gravel-bed rivers according to values found in the literature (Column 2B). For functional flows analysis, a stable bed is assumed when $\tau_o^*<0.01$, intermittent transport when $0.01< \tau_o^*<0.03$, partial transport when $0.03<\tau_o^*<0.06$, and full mobility when $0.06<\tau_o*<0.10$ (Buffington and Montgomery, 1997; Lisle *et al.*, 2000). The upper threshold for full mobility is set at 0.10 assuming that beyond this point there is intensive bed load transport that is non-functional to support spawning ecological functions (Lisle *et al.*, 2000). The proposed thresholds constitute an uncertainty of the model because of their variability (van Asselt and Rotmans, 2002). Sources of variability include the looseness of the bed material which cause lower thresholds, and armoring of the river bed which cause higher thresholds (Vericat *et al.*, 2006). In addition, variability in thresholds values comes from the random nature of sediment transport and conflicting evidence of different thresholds reported in the literature (Buffington and Montgomery, 1997; van Asselt and Rotmans, 2002). For instance, depending on whether the bed is loose or compacted, the Shields parameter may vary by one order of magnitude for grains >8 mm (Knighton, 1998). Consequently, the proposed thresholds may not always hold.

The table of functionality includes assumptions about the functionality of flow ranges and associated sediment transport stages (Table 2, Columns 3, 4, 5 and 6). “Functional” refers to streamflow ranges associated with mobility stages that favor the lifestage. “Non-functional” refers to streamflow ranges associated with mobility stages that hinder the lifestage. In the determination of functionality, it is assumed 1) that there are sediment inputs into the channel from a variety of sources, including tributaries, organic growth, direct runoff, bank erosion, etc.; and 2) that surface flow controls hyporheic flow through gravel, so the latter is not considered explicitly (Tonina and Buffington, 2007). Stable bed is assumed functional for spawning and emergence that benefit from low disturbance of the substrate, and non-functional for embryo incubation because some removal of fines from the surface of the active layer is necessary to maintain circulation of the oxygenated water through the interstices. Superficial fines mobility is assumed functional for bed occupation because removal of superficial fines favors redds construction, oxygenated water flow, and surface cleaning for fry emergence (Montgomery *et al.*, 1983; Kondolf and Wilcock, 1996). Interstitial fines mobility and full mobility are assumed non-functional during bed occupation because spawning may be halted by gravel entrainment, incubating embryos may be exposed or entrained, and emerging fry may be stranded or may be blocked by new sediment deposited (Montgomery *et al.*, 1999; Lapointe *et al.*, 2000). Stable bed and superficial fines mobility are assumed non-functional during the bed preparation periods because armored and compacted grounds are unfavorable for spawning (Soulsby *et al.*, 2001), while interstitial fines mobility is assumed functional because gravel free of fines is beneficial for subsequent spawning (Kondolf and Wilcock, 1996) and full mobility is assumed functional because rejuvenation of the gravel and maintenance of pool-riffles create new spawning grounds that are necessary for spawning (Lisle and Lewis, 1992; MacWilliams *et al.*, 2006).

Estimating τ_o* as a function of discharge time series, it is possible to use the table of functionality (Table 2) to determine functional flows serving ecological functions. Substituting Eq. 3 and 5 into Eq. 6, a new form of τ_o* is obtained:

$$\tau_0{}^* = \frac{\rho g h S}{g(\rho_s - \rho)D_{50}} = \frac{\rho(cQ^f)S}{(\rho_s - \rho)D_{50}} \tag{8}$$

that can be used to evaluate τ_o* for discharges time series and for a given cross section with a specific median grain size. The temporal pattern of shear stress represents geomorphic dynamics that are relevant for fall-run Chinook salmon (Fig. 4). This calculation procedure helps determine the timing in which a section of the river is functional. Assumptions of steady and uniform flow need to be checked for applications of Eq. 8 to determine functional flows. If these assumptions are inappropriate for specific applications, the numerator in Eq. 8 needs to be calculated from Eq. 1 or from other methods outlined in section 3.1. In addition, for non-steady discharge conditions the slope changes with time so the assumption of using a constant slope would not be appropriate.

In addition to temporal changes in bed mobility stages represented by Eq. 8, it is possible to observe the dependence of the geomorphic dynamics on streamflow. This can be achieved having Q as the independent variable and τ_o* as the dependent variable. Q can be non-dimensionalized by a combination of variables with length and time dimensions (i.e. $L^{-3}T^{1}$). Parker et al. (1979) proposed

$$Q^* = \frac{Q}{\sqrt{gD_{50}}\,D_{50}{}^2} \tag{9}$$

Eqs. 8 and 9 can be used to produce curves of τ_o* vs. Q* to observe shear stress as function of streamflow (Fig. 5). Curves of non-dimensional quantities allow comparison of channels with a wide range of characteristics and have been used to group and observe trends in data of rivers from different geographic regions (Parker *et al.*, 2003). In this study, the resultant curve τ_o* vs. Q*, where τ_o* is function of S, D_{50}, c and f; and Q* is function of Q and D_{50}, depicts the variation in bed mobility stages for a cross section with a particular slope, median grain size, and geometry for a range of discharges. Each portion of the curve within thresholds of τ_{c50}^* (0.01, 0.03, 0.06, and 0.1) is considered a scenario that can be categorized as functional or non-functional. The flowchart in Fig. 6 is a summary of the procedure to assess functional flows. A full set of uncertainties of the analytical model related to the selection of parameters and model structure will be presented in the discussion section.

4 Numerical Experiment

A numerical experiment was designed as a sensitivity analysis to analyze model results for a system of scenarios generated for potential combinations of streamflow and channel variables found in spawning habitat units used by fall-run Chinook salmon. The model was used for identifying the effect of combinations of hydrogeomorphic variables on spawning habitat functionality. Although the FFM is structured to track temporal patterns of shear stress which occur based on ranges of flows available at different times, this preliminary assessment assumes that a full range of flows is available on these rivers and does not incorporate any temporal consideration. An example of how FFM assesses temporal patterns of shear stress is presented in the accompanying paper Part 2. Fundamental research questions addressed using fall-run Chinook salmon spawning habitat ecological functions as an example are: 1) what is the effect the variable f, which represents depth response to discharge increments, on functionality?, 2) what is the effect of grain size on functionality?, 3) what is the effect of slope on functionality?, and 4) what is the combined effect of slope and grain size on functionality?.

4.1 Methods

Typical riffle crest slopes, grain sizes, and c and f exponents were identified from values found in the literature. Slopes of <1.5% (0.015 $m.m^{-1}$) are likely to have a pool-riffle configuration (Montgomery and Buffington, 1997, 1998). Spawning gravel median grain size, D_{50}, typically range from 0.011 m and 0.078 m for Chinook salmon (Kondolf and Wolman, 1993; Elkins *et al.*, 2007). The coefficient c typically ranges from 0.25 to 0.49 m, while the exponent f ranges from 0.33 to 0.42 in gravel bed rivers (Leopold and Maddock, 1953; Knighton, 1998). Based on this assessment, values of S equal to 0.001, 0.005, and 0.01 were chosen to represent low, moderate, and high slope for pool-riffle units, respectively. Similarly, D_{50} values of 0.02, 0.05, and 0.1 m were chosen to represent the median grain size of fine, intermediate, and coarse spawning gravel, respectively. Considering the low relative importance of c as a multiplier variable in comparison to the exponent f when calculating τ_o* from Eq. 8, then a constant value of c=0.5 and four values of f representing channels that respond with short depth increments to flow increases (i.e. wide/shallow), channels that respond with intermediate depth increases to flow increases, and channels that respond becoming deeper to flow increases (i.e. narrow/deep) were selected (f=0.2, 0.3, 0.4, 0.5). The analytical model was programmed into Mathematica, Version 5.0, Champaign, IL (Wolfram Research, 2003) to produce lists of τ_o* vs Q* for each combination of variables, which were then plotted in a graphing program. Nine τ_o* vs Q* graphs resulted from the nine possible combinations of S and D_{50} (Fig. 7). The curves in the τ_o* vs Q* space were the solution to Eqs. 8 and 9 for each of the four geometries selected intersecting the four bed mobility stages (SB, SFM, IFM, FM).

To observe a wide range of significant discharges, Q was varied between 1 m^3s^{-1} (~35 cfs) and 10,000 m^3s^{-1} (~350,000 cfs). For instance, in Figs. 7A,D, and F, the low and high limits of the x-axes were $Q^*=5.6x10^3$ and $5.6x10^7$ which were the maximum and minimum Q^* for D_{50}=0.02 m. The y-axes were also graphed in logarithmic scale and were divided into four sections that define bed mobility stages according to the upper limits of stable bed ($\tau_o^*=0.01$), superficial fines mobility ($\tau_o^*=0.03$), and interstitial fines mobility ($\tau_o^*=0.06$). For $\tau_o^*>0.06$ the active layer was expected to be at full mobility, and the upper limits of the y-axes were set to a value of $\tau_o^*=0.1$, according to the table of functionality definitions.

The range of functional flows (range of Q*) within a transport regime category for each bed occupation and bed preparation scenario was calculated based on the table of functionality (Table 2). In order to simplify the analysis, spawning, embryo incubation, and emergence were analyzed together as bed occupation ecological functions; consequently, the stable bed transport regime was considered non-functional for the whole bed occupation period since it is non-functional for embryo incubation, even though it is considered functional for spawning and emergence. The functionality of scenario corresponds to its range of Q*. For example, a cross section with the characteristics of the scenario: $S=0.001/D_{50}=0.02m/f=0.2$ from Fig 7A., would be functional for periods of bed occupation within the superficial fines mobility stage, so the correspondent range of functional flows is $5.6x10^3<Q^*<1.5x10^5$, for range of $Q^*=1.4x10^5$, and would be functional for periods of bed preparation within the interstitial fines mobility stage for $1.5x10^5<Q^*<4.7x10^6$, for a range of $Q^*=4.6x10^6$. Consequently, this cross section would be more functional for bed preparation than for bed occupation. A group of scenarios fell outside the categories of functional or not-functional for bed occupation or bed preparation either because they were truncated by the lowest and the highest limit of Q*, or by the thresholds of transport regimes (SB, SFM, IFM, or FM), consequently those scenarios were considered non-functional. For the remaining scenarios, which classified as functional for bed occupation or bed preparation their range of Q* was calculated. The numerical experiment produced values of ranges of functional flows for typical spawning habitat conditions. This information was useful to address the research questions about combinations of key hydrogeomorphic parameters that provide ecological functionality for spawning habitat geomorphic units.

4.2 Results

Of a total of 144 possible scenarios 76 were functional (Table 3). A total of 29 were functional for bed preparation within the full mobility stage, 23 were functional for bed preparation within the interstitial fines mobility stage, for a total of 52 functional scenarios for bed preparation; 16 scenarios were functional for bed occupation within the superficial fines mobility stage, and 8 were functional for spawning and emergence only within the stable bed stage. Functional scenarios for bed preparation were given by all the combinations of slope and grain size, except for the high slope, fine sediment, and all geometries scenarios which were off-scale (Fig. 7G: S=0.01/ D_{50}=0.02/ f=0.2,0.3,0.4,0.5). Functional scenarios for bed occupation were given within the superficial fines mobility stage by low slope and fine to coarse grain size for all geometries (Figs. 7A, 5B, 5C: S=0.001/ D_{50}=0.02,0.05,0.1/ f=0.2,0.3,0.4,0.5), and moderate slope and coarse grain size for all geometries (Fig. 7F: S=0.005/ D_{50}=0.1/ f=0.2,0.3,0.4,0.5). Functional scenarios for spawning and emergence only were given within the stable bed stage by low slopes and median to coarse grain size (Figs. 7B, C: S=0.005/ D_{50}=0.05,0.1/ f=0.2,0.3,0.4,0.5).

A considerable proportion of the scenarios studied, 68 out of 144, were non-functional. Four of these scenarios were non-functional because they were truncated by the upper limit of Q* (Table 3). Eight of these scenarios were non-functional because the curves initiated in superficial fines mobility, and were given by low slope and fine sediment (Fig. 7A: S=0.001, D_{50}=0.02), and intermediate slope and coarse sediment (Fig. 7F: S=0.005, D_{50}=0.01). In sixteen of the non-functional scenarios, the curves began in interstitial fines mobility and were given by intermediate slope and intermediate grain size (Fig. 7E: S=0.005, D_{50}=0.05) and high slope and coarse grain size (Fig. 7I: S=0.01, D_{50}=0.1). The extra 40 non-functional scenarios were given by moderate and high slopes and fine and intermediate grain size (Figs. 7D, G, H).

5 Discussion

The numerical experiment allows linking hydrogeomorphic processes and ecological functions to identify values of parameters that are favorable for spawning habitat ecological functions, hence answering the research questions proposed in section 5. The next two sections present model effects of variables involved, identify model uncertainties, and consider implications for spawning habitat management.

5.1 Research Questions

Model results can be analyzed by observing the effect of each variable in non-dimensional shear stress values to answer the research questions. Eq. 8 is rewritten in terms of Q* to observe each controlling term individually

$$\tau_0 * = \frac{\rho}{(\rho_s - \rho)} \frac{S}{D_{50}} c(g^{1/2} D_{50}{}^{5/2} Q*)^f \qquad (9)$$

The exponent f determines the slope of the curve τ_o* vs. Q* and the effect of D_{50} on τ_o*. S is linearly related to τ_o*.

Curves τ_o* vs. Q* for geometries with low f have a lower slope than those of geometries with high f (Fig. 7). The consequence of this effect is that low-f curves present longer spans within each sediment transport stage and larger ranges of Q* than high-f curves. A comparison of scenarios according to their f value shows the effect of f on functionality. In all cases low-f scenarios present larger functional flows for bed preparation and bed occupation than high-f scenarios (Table 3; Fig. 8 and Fig. 9). This effect is also observed in the least and most functional combinations of hydrogoemorphic variables for spawning habitat ecological functions (Table 3). The most functional scenarios for bed preparation (S=0.001/D_{50}=0.02/f=0.2) and bed occupation (S=0.001/D_{50}=0.05/f=0.2) have low-f values. One such example of a river located in California supporting fall-run Chinook salmon spawning that almost matches these scenarios is the rehabilitated Mokelumne River in the1,500 m reach downstream of Camanche Reservoir. On the other hand, the least functional scenarios for bed preparation (S=0.01/D_{50}=0.1/f=0.5) and bed occupation (S=0.005/D_{50}=0.1/f=0.5) have high-f values. The Timbuctoo Bend of the Yuba River downstream of Englebright dam is an example that almost matches these scenarios. This preliminary assessment assumes that a full range of flows is available on these rivers. These two river reaches are briefly compared here in general terms, but are evaluated in detail in the accompanying article (Part 2) relative to specific scientific questions. As it turns out, the flow regime of the Mokelumne is highly regulated, while that of the Yuba is relatively natural. Thus, it is necessary to consider potential functionality and actual conditions.

The effect of grain size on functionality is to localize the y-intercept of the τ_o* vs. Q* curves at a lower τ_o* for higher D_{50}. As a consequence, some curves span partially in the domain of the sediment transport stage where they intercept the y-axes (Fig. 7A, B, C, and F) while at the same time the ranges of flow are smaller for higher grain sizes (i.e. smaller span of x-axes for higher grain size). D_{50} also controls the upper and lower thresholds of Q* axes (Fig. 7). As a consequence curves with fine grain size reach full mobility before the lower threshold, while some curves are truncated by the upper limit of Q* (i.e. Fig. 7C, f=0.2 and f=0.3, also shown in Table 3). The combined effects of D_{50} drive a trend in functionality for bed preparation and bed occupation, as observed in scenarios with the same slope and f-exponent (Fig. 8). For high f, functionality is greater for finer grain size (f=0.5 in Fig. 8). For intermediate-high f, functionality is almost always independent of the grain size (f=0.4 in Fig. 8). For intermediate-low f, functionality is greater for coarser grain size (f=0.3 in Fig. 8). For low f, functionality is greater for an intermediate grain size (f=0.2 in Fig. 8). These results corroborate the controlling effect of the exponent f, which represents depth response to discharge increments, since the effect of the median grain size depends on the value of f.

The effect of slope on functionality is to localize the y-intercept of the τ_o* vs. Q* curves at a lower τ_o* for lower slopes (Fig. 7). Consequently, curves with lower slopes span over greater ranges of flows for each sediment transport stage. This effect of slope drives a trend in functionality, as observed in the analysis of scenarios with the same grain size and f-exponent (Fig. 9). For all the bed mobility stages, functionality is improved with a lower slope. Since functional flows are a measure of ecological response, this result corresponds with the findings of Montgomery and Buffington (1999) that the response of spawning fish as measured by densities of redds is greater in pool-riffles with slopes between 0.008 and 0.002, than in forced pool-riffles with higher slopes between 0.010 and 0.015.

The combined effect of grain size and slope controls the hydrogeomoprhic response to bed occupation and bed preparation. The summation of functional ranges of Q* for each combination of S and D_{50} indicate that a habitat unit with low slope and fine grain size (S=0.001/

D_{50}=0.02) has the largest functional range of Q* for bed occupation and bed preparation, followed by low slope and intermediate grain size (S=0.001/ D_{50}=0.05), and then followed by low slope and coarse grain size (S=0.001/ D_{50}=0.1) (Fig. 10). Only these scenarios, plus the moderate slope and coarse grain size (S=0.05/ D_{50}=0.1) have both functional bed occupation and bed preparation flows. In general, scenarios appropriate for bed occupation are always suitable for bed preparation at higher flows, but the opposite is not always true. This can be explained by the fact that scenarios that are only functional for bed preparation in interstitial fines mobility and full mobility correspond to curves that begin at the interstitial fines mobility domain, and never cross superficial fines mobility domain which is the sediment transport stage functional for bed occupation.

Other model controls resulted in non-functional scenarios. The upper limit of Q* cut the f-curves before they reached the superficial fines mobility transport stage (Fig. 7B and 7C). In addition, the lower limit of Q* controlled the initiation of the f-curves either at superficial fines mobility or at interstitial fines mobility. This occurred in scenarios with fine gravel and steep slopes indicating that they reached higher mobility stages at very low discharge values losing their hydrogeomorphic functionality for spawning habitat (i.e. Fig. 7G, scenarios reached full mobility at discharges even lower than the lowest threshold of Q*) (Kondolf and Wolman, 1993).

5.2 FFM Uncertainties

The uncertainties in the FFM are analyzed from the perspectives of model completeness, parameters, inputs, and structure using the integrated assessment framework proposed by van Asselt and Rotmans (2002). Uncertainties from model completeness refer to whether the model includes all the relevant processes. Uncertainties from model parameters refer to the selection of parameters that represent relevant processes and the choice of equations to calculate them. Uncertainties from model structure refer to the organization of the algorithms to obtain results.

This study proposes the FFM to incorporate metrics from all hydrologic and geomorphic processes controlling ecological functions of the habitat. From this perspective, the FFM aims for more completeness than other approaches that focus on a lesser number of variables. Yet, other sources of uncertainties are present in the model development and are analyzed in the next five subsections.

5.2.1 Hydrologic Inputs

Time series of streamflow data, whenever available, is the key hydrologic input to the habitat unit that summarizes processes occurring at the watershed and larger scales (Poff *et al.*, 1997). Uncertainties of this input depend on the datasets used; however discharge time series are often the most available hydrologic input (Booker and Acreman, 2007). Streamflow data for functional flows can be used for analysis at different spatial scales of a) concrete applications of past and present status of ecological functions, or b) theoretical applications of future ecological response to supposed or modeled streamflow values (Fig. 11). For the former, hydraulic (i.e. slope) and geomorphic (i.e. cross section geometry, and grain size distribution) parameters need to concur with the selected streamflow period. For the latter, any values of hydraulic and geomorphic parameters that correspond to streamflow values can be considered because the outcome of the analysis would be a study of the theoretical ecological functionality to hypothetical discharge values (i.e. climate change scenarios).

5.2.2 Hydraulic Parameters

Estimating depth as a function of discharge from hydraulic geometry relations ($h=cQ^f$) assumes the existence of a stage-discharge power relation (Leopold and Maddock, 1953). Parameters c and f can be calculated for current conditions, or can be hypothesized for theoretical analysis at various spatial scales (Fig. 11). Applications of the model require calculations of f and c from stage-discharge time series which may or may not be available for the site where the analysis is to be performed. Also, for cross section geometries presenting terraces there will be a break in slope of the stage discharge relationship producing variable c and f values that need to be taken into account. When c and f are not available from field measures, an alternative is to use a numerical method to calculate discharge at different stages based on the geometry of the cross section. Several methods available present disadvantages and advantages (Hardy *et al.*, 2005). For instance, the widely used Manning's equation requires the use of a roughness coefficient, n, which can be quickly obtained by comparison with tables or photographs of natural channels (Hardy *et al.*, 2005).

5.2.3 Geomorphic Parameters

Uncertainties in the calculation of shear stress will come from the approach selected. The depth slope product used here includes the assumptions of steady uniform flow, of a wide channel, of no form drag. The assumption of uniform flow is appropriate for a channel that does not change cross section geometry in the downstream direction but may need to be checked depending on the conditions of a site (Brown and Pasternack, 2008a; Pasternack *et al.*, 2008). For instance, pool-riffle morphologies experience flow convergence, thus requiring the assessment of the relative importance of non-uniform terms to decide if they need to be included in the calculation of shear stress. One way of checking would be to compare the results of steady hydraulic calculations made with a cross-section analyzer against those made with a 1D hydraulic flow model that accounts for backwater conditions (Brown and Pasternack, 2008a). The steady flow assumption needs to be checked in cases when abrupt changes in discharge magnitude occur such as during floods. Steady flow also implies the assumption of a unique value of water surface slope as a hydraulic parameter. This assumption is convenient for data collection purposes, but accuracy in the calculation can be improved by either collecting additional field data to calculate slope at different flows, or by searching for existing upstream and downstream gauging sites with stage-discharge data series to calculate variable values of slope. In general, the conditions under which flow non-uniformity would require a 2D hydrodynamic representation to estimate shear stress are given as bed channel configuration elements such as larger grains in the substrate force streamlines to clump and expand irregularly. Similarly, the conditions under which depth and velocity differentials are created by ramping flow up or down very quickly would require an estimation of unsteady components of shear stress (Escobar-Arias, 2008).

The assumption of a wide channel implies that the hydraulic radius (R) approaches the value of average depth. When this assumption does not hold, hydraulic radius (R) needs to be calculated to obtain shear stress values (i.e. use Eq. 2 as opposed to Eq. 3).

The assumption of no form drag is an appropriate assumption in gravel bed rivers (Konrad *et al.*, 2002). When form roughness elements such as bar and wood are present, it may be necessary to incorporate form drag into the model. The consequent lower skin friction available for sediment transport (Knighton, 1998) will generate the occurrence of smaller median grain sizes (Buffington *et al.*, 2004). This change will have an effect in the model since curves of

τ_o* vs. Q* would initiate at lower values of τ_o*. Therefore scenarios with fine, but suitable median grain size, would shift from non-functional (i.e. fully mobile at low discharges such as in Fig.7G), to functional (i.e. not entrained at larger ranges of flow causing the occurrence of beneficial sediment transport stages such as superficial fines mobility for bed occupation and interstitial fines mobility for bed preparation).

Alternative equations to calculate shear stress such as those reported in Table 1 of Dietrich and Whiting (1989) and summarized in section 3.1 of this manuscript may be used to estimate shear stress. The selection of the method to estimate shear stress will depend on the criteria of the researcher to assess the resources available in relation to the objective of the study. For instance, ample available resources may allow for detailed topography survey and 2D hydraulic modeling to estimate shear stress. On the other hand, assessments at the watershed scale may require rapid cross sectional surveys at several sites to obtain a spatially distributed sample and the use of a simplified 1D model for shear stress calculations.

5.2.4 Data Uncertainties

Uncertainty also comes from field data collection of cross section geometry, water surface slope, and grain size distribution. The outcome of the model will rely on a conscientious collection of these three pieces of information. Cross section geometry is a measure that adequately characterizes morphology perpendicular to the downstream direction, but oversimplifies downstream geomorphic complexity. In addition, site selection will play a role in the outcome of the analysis. Yet, cross sectional data requires low cost equipment (i.e. rod, level, tape measure) making field data collection accessible. The calculation of slope from field data requires the same equipment as the cross section geometry survey.

Grain size distribution is a widely used method to characterize substrate and non-dimensionalize fluvial variables. The data can be collected by sieving or by the Wolman method and the calculation of is a straightforward normal distribution (Wolman, 1954). The use of the median grain size, D_{50}, is an appropriate simple representation of the whole distribution that is commonly used in sediment transport studies and in physical habitat characterization methods (Rosgen, 1994; Buffington and Montgomery, 1997). However, if a stream has a bimodal coarse sediment size distribution or a very wide distribution of coarse sediment sizes, then it might be more suitable to choose a larger size as representative of bed mobility, such as D_{90} (Thompson and Campbell, 1979).

5.2.5 Model Structure

The use of non-dimensional parameters, ecological functions, sediment transport stages and tables of functionality constitute characteristics of model structure that form the algorithm for the analysis. Each of these structure elements presents uncertainties.

The use of non-dimensional quantities, τ_o* vs. Q*, to incorporate the capability of sites comparison (Parker *et al.*, 2003) constitutes an uncertainty related to the model form. The comparability of sites may be restricted to the class size of the median grain. For instance, grain sizes in the range of gravel and cobble (2-64 mm and 64-256 mm respectively) reach suspension at shear stresses larger than two orders of magnitude from the initial motion threshold while grain sizes smaller than sand (<2mm) reach suspension at shear stresses within two orders of magnitude of the initial motion threshold (Knighton, 1998). Consequently, the sediment transport stages, stable bed, superficial fines mobility, interstitial fines mobility, and full mobility, measured from non-dimensional shear stress vary for different sediment size classes.

In the functional flows model, the use of ecological functions, namely bed preparation and bed occupation, represent a rough characterization of biological variables that add uncertainty to the approach. The definition of ecological functions requires well informed decisions about the nature of the interaction of the organisms with the river bed, and the timing at which those functions occur.

The Shields parameter values selected to delimit sediment transport stages constitutes an uncertainty that required specific assumptions. The threshold for stable bed assumes that no sediment transport occurs. The threshold for intermittent transport assumes that the median grain size is not mobile, but that finer grains can be entrained from the river bed. The threshold for partial transport assumes that the median grain size is mobile, and consequently, fines in the interstices can be entrained. The threshold for full mobility assumes that all the grains are mobile, hence there is reworking of the river bed. The upper threshold assumes that ecological functionality is lost due to destruction of the habitat unit. Despite the assumptions necessary to define thresholds, values of Shields parameters to delimit sediment transport stages provided simple thresholds to explore the relationship between hydrogeomorphic processes and ecological functionality. The thresholds for initial motion and full mobility of gravel were selected from values found in the literature but there is uncertainty associated with the variability of these thresholds. For example, extremely loose gravel beds could have their thresholds shifted much lower, while highly compacted beds could have them shifted higher (Wydzga *et al.*, 2005). Other thresholds could be selected depending on the application of the model. For instance, to examine habitat for invertebrates, lower Shields thresholds may be necessary to assess the effect of shear stress that trigger drift of organisms (Gibbins *et al.*, 2007).

The framework proposed in tables of functionality puts together uncertainties about ecological functions thresholds, sediment transport stages thresholds, and functionality decisions (Table 2). The work of defining whether a combination of ecological function and sediment transport stage is functional or non-functional consists of a rational interpretation of how river bed mobility will favor or deter the interaction of the organisms with the river bed. Tables of functionality also involve assumptions of sediment inputs and non-hyporheic flow. Still, tables of ecological functionality provide an opportunity to incorporate all the elements of the flow regime which are not included in methods that are not based on discharge time series. For instance, in Table 2, flow magnitude is considered in column 1; flow timing, duration, and frequency are implicitly considered because the assignment of functionality corresponds to specific periods of bed occupation and bed preparation; and flow rate of change can be incorporated into the analysis if the non-steady component of shear stress is used to calculate non-dimensional shear stress.

Despite the conjugation of uncertainties and assumptions, the development of the analytical framework is a required step in order to structure the model. The degree of uncertainty can be decreased by judiciously defining thresholds and functionality based on expert judgment. An advantage is that the information to develop the analytical framework can be obtained from literature review, without the need of a field campaign. Resources for field work can then be spent collecting data of the habitat units that will be analyzed.

5.3 Implications for Spawning Habitat Management

The analysis of several scenarios provides a context to observe the direction in which conditions can be improved by modifying parameters of the habitat unit. The results in Table 3 show potential alternatives. For instance, least functional scenarios would not be improved by a lower grain size because the river bed would become too mobile, then, functionality could be enhanced with a geometry with low f with the same S and D_{50} values, or by decreasing the slope.

In highly regulated rivers water is stored in reservoirs for multiple uses; consequently high flows that cause reworking of the river bed (i.e. FM, IFM) for bed preparation may not be available (Wheaton *et al.*, 2004). Still, base flows may provide some functions (i.e. SFM) necessary during bed occupation. In these cases, in-stream habitat rehabilitation practices such as gravel augmentation, which consists of adding washed gravel and cobble to a stream, is an alternative to improve the capacity of base flows to provide the required habitat conditions (Pasternack *et al.*, 2004). The effect of gravel augmentation on reducing depth response to discharge increments is shown by the functional flows analysis (Fig. 6). For example, a deep reach with f=0.5, a moderate slope S=0.005, and coarse grain size D_{50}=0.1 within the superficial fines mobility stage has a lower functionality than reaches with f=0.4, 0.3, and 0.2 and with the same S and D_{50} (i.e. range of $Q^*=2.7\times10^2$ < range of $Q^*=4.3\times10^2$, 7.9×10^2, 2.5×10^3 respectively). This particular result indicates that in scenarios of highly regulated rivers, with base flows most of the year, geometries with low f may provide more functionality during bed occupation in superficial fines mobility than geometries with high f (Elkins *et al.*, 2007).

The effect of slope on functionality of pool-riffles may act simultaneously with the effect of depth-response to discharge increments. In the context of in-stream habitat rehabilitation, the concept of slope creation proposes that gravel added at the base of a dam increases the local bed elevation allowing for a steeper slope that can be propagated down the reach. In a case study reported in Elkins (2007), an initial in-stream rehabilitation project changed mean bed elevation from 0.76±0.45 m to 0.68±0.51 m, increasing the riffle-to-riffle slopes from 0.0022 to 0.0084, and improving percentage of area of high habitat quality from 8% to 12%. A subsequent adjustment of the longitudinal profile did not change mean elevation, but reduced the slope to 0.0039 improving percentage of area of high habitat quality from 12% to 33%. Using functional flows analysis to understand the evolution of this particular case study shows that a reducing water depth created an initial positive effect on habitat quality, despite the negative effect that the high slope created, and the subsequent decrease in slope created an overall greater positive effect on habitat quality.

Grain size can also be modified to improve functionality, but according to the results, the optimal median grain size depends on the value of f. In order to observe the direction in which conditions would improve, the functional flows model can be used for actual conditions and supposed scenarios. A scenario producing the greater number of days with functional flows for a given hydrograph will provide insight into the necessary alterations to improve current conditions.

The use of the model for other species requires the adjustment of the conceptual framework. This can be easily done by defining relevant ecological functions and their timing as well as their dependence on sediment transport stages and incorporating this information on tables of functionality. The subsequent calculations can be performed as presented in previous sections to obtain functional flows analysis for the target species.

The comparability of scenarios provides a framework that can be used for comparison of concrete and theoretical applications. Also, even though this study does not present new data to corroborate actual functionality for bed occupation or bed preparation, it provides a framework for future field experiments to prove ecological response to specific combinations of variables.

6 Conclusions

The functional flows model presented in this paper integrates measures of discharge, depth, and shear stress time series, and links them to definitions of ecological functionality to assess physical habitat status. Using the salmon ecological functions of bed occupation (i.e. spawning, incubation, and emergence), and bed preparation, this study presents an analytical framework to assess habitat functionality based on the dependence of ecological functions on flow processes delimited by sediment transport thresholds. Applying the model to typical settings where the ecological functions occur, it was possible to perform a numerical experiment to identify the effect of controlling variables on functional flows. The results obtained may be interpreted from the perspective of management implications. A general trend indicates that functionality is greater for sites with lower slopes and for low-f cross sections representing channels that respond with short depth increments to flow increases. The functionality of deeper channels is greater with finer sediment and functionality of intermediate shallow channels is greater with coarser sediment.

By incorporating all habitat functions, the functional flows model concentrates on the emerging interactions. The analysis of uncertainties suggests future work to further refine the method by improving algorithms to calculate shear stress and by comparing model outputs to actual utilization and occurrence of the ecological functions. The functional flows model is a novel approach to characterize in-stream habitats and presents potential for use in scientific as well as in management applications.

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Approach	Process Considered			Spatial scale			Examples	Main characteristic
	Hydro	Geo	Eco	Habitat unit	Reach	Basin		
Biotic Integrity Indices	NO	NO	YES	X	XX	XX	Regional biotic integrity (Miller et al. 1988) Biotic integrity evaluation (Moyle and Randall, 1998)	Measures of species structure and function to monitor environmental changes
Geomorphic Classification Systems	NO	YES	NO	X	XX	XX	Rosgen classification (Rosgen, 1994) Channel morphology (Montgomery and Buffington, 1997) River Styles (Brierley and Fryirs, 2000)	Categorization framework to group morphological features
Indices of Hydrologic Alteration	YES	NO	NO			X	The Natural Flow Regime (Poff et al. 1997) IHA (Richter et al. 1996)	Statistical parameters of discharge to assess changes over time
Habitat Delineation	YES	YES	NO	X	XX		Reconnaissance survey (Thorne, 1998) Habitat mapping (Maddock, 1999)	Standard procedures to record geomorphic characteristics
Physical Habitat and Species Relations	YES	NO	YES	X	XX		Egg-to-smolt survival rates (McHugh et al. 2003) Fish guilds and hydraulics relations (Lamoroux and Cattaneo, 2006) Fish distribution from stream variables (Mugodo et al. 2006)	Statistical correlations of physical habitat parameters and biological measurements
Cross-sectional Habitat Modeling	YES	NO	YES	X	XX		PHABSIM (Bovee et al. 1998)	Analytical or 1D hydraulic modeling, cross sectional data, and habitat suitability curves to predict habitat availability
2D Habitat Modeling	YES	NO	YES	X			Numerical Habitat Model - NHM (Guay et al. 2000) FEWMS and GHSI (Pasternack et al. 2004) SHIRA (Weaton et al. 2004)	2D hydraulic modeling and topographic survey coupled to habitat suitability curves to predict habitat quality

1	2A	2B	3	4	5	6
Flow Magnitude/ Bed Mobility Stage	**Functional Flows Delimiters**		**Bed Occupation**			**Bed Preparation**
	In terms of t_o vs t_{c500}	**In terms of t_o* vs Shields #**	**Spawning**	**Embryo Incubation**	**Emergence**	
High/ Full mobility (FM)	$t_o > t_{c50}$	$0.06 < t_o^* < 0.1$	Non-functional	Non-functional	Non-functional	Functional
Intermediate High/ Interstitial fines mobility (IFM)	$t_o = t_{c50}$	$0.03 < t_o^* < 0.06$	Non-functional	Non-functional	Non-functional	Functional
Intermediate Low/ Superficial fines mobility (SFM)	$t_o < t_{c50}$	$0.01 < t_o^* < 0.03$	Functional	Functional	Functional	Non-functional
Low/ Stable bed (SB)	$t_o << t_{c50}$	$t_o^* < 0.01$	Functional	Non-functional	Functional	Non-functional

Bed Mobility Stage	Depth Geometry Exponent	A	B	C	D	E	F	G	H	I
		S=0.001			S=0.005			S=0.01		
		D_{50}=0.02	D_{50}=0.05	D_{50}=0.1	D_{50}=0.02	D_{50}=0.05	D_{50}=0.1	D_{50}=0.02	D_{50}=0.05	D_{50}=0.1
FM	f=0.2	5.6E+07 (1)	Truncated by upper limit Q*	Truncated by upper	1.4E+04	1.9E+05	1.0E+06	Full Mobility Off-Scale	5.4E+03	3.1E+04
	f=0.3	2.2E+06	4.8E+06	Truncated by upper	7.4E+03	2.5E+04	4.0E+04		2.2E+03	4.0E+03
	f=0.4	4.2E+05	4.3E+05	4.2E+05	5.1E+03	7.5E+03	7.6E+03		1.3E+03	1.3E+03
	f=0.5	1.5E+05	9.4E+04	6.7E+04	4.0E+03	3.8E+03	2.8E+03		9.2E+02	6.7E+02
IFM	f=0.2	4.6E+06	4.2E+06	Truncated by upper	Curves begin in FM	4.5E+03	8.2E+04	Full Mobility Off-Scale	Curves begin in FM	2.5E+03
	f=0.3	4.5E+05	9.7E+05	1.7E+06		2.4E+03	8.1E+03			7.9E+02
	f=0.4	1.3E+05	1.3E+05	1.3E+05		2.4E+03	8.4E+03			4.3E+02
	f=0.5	6.3E+04	3.9E+04	2.8E+04		1.5E+03	1.1E+03			2.7E+02 (2)
SFM	f=0.2	1.4E+05	1.5E+06 (3)	9.7E+05	Curves begin in FM	Curves begin in IFM	2.5E+03	Full Mobility Off-Scale	Curves begin in FM	Curves begin in IFM
	f=0.3	4.4E+04	1.0E+05	1.9E+05			7.9E+02			
	f=0.4	2.4E+04	2.7E+04	2.7E+04			4.3E+02			
	f=0.5	1.5E+04	1.2E+04	8.3E+03			2.7E+02 (4)			
SB	f=0.2	Curves begin in SFM	5.4E+03	3.4E+04	Curves begin in FM	Curves begin in IFM	Curves begin in SFM	Full Mobility Off-Scale	Curves begin in FM	Curves begin in IFM
	f=0.3		2.2E+03	4.8E+03						
	f=0.4		1.3E+03	1.8E+03						
	f=0.5		9.2E+02	9.4E+02						

Figures Captions

Figure 1. Different methods for evaluation the functions of physical habitat.

Methods (grey boxes) use different ways to measure variables, or metrics, (grey circles) from a subset of hydrological, hydraulic, geomorphic, and ecologic functions at the reach or habitat-unit scale. Other methods evaluating hydrologic or geomorphic functions (white boxes) may help infer ecological functions without addressing them explicitly. The proposed new model based on "functional flows" (grew box with dashed border) incorporates metrics from all functions. List of metrics: 1. Discharge, 2. Qualitative/quantitative hydraulics, 3. Qualitative/quantitative morphology, 4. Hydraulics measures (i.e. depth, velocity, grain size distribution), 5. Species response, 6. 1D/2D Hydraulic modeling, 7. Depth and slope time series, 8. Shear stress time series, 9. Ecological functions and their timing.

Figure 2. Interaction of hydrogeomorphic processes during salmon spawning (Wheaton, 2003).

Functional flows determine favorable conditions for spawning, incubation, and emergence.

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

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

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

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

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

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

Figure 6. Flowchart for evaluation of functional flows

Figure 7. Charts of non-dimensional shear stress vs. non-dimensional discharge for evaluation of functional flows for spawning habitat scenarios.

Figure 8. Comparison of ranges of Q* yielding flow functionality for three sediment transport stages as a function of grain size (scenarios A, B, C of Fig. 7)

Figure 9. Comparison of ranges of Q* yielding flow functionality for three sediment transport stages as a function of slope (scenarios C, F, I of Fig. 7)

Figure 100. Summary of ranges of Q* for combinations of slope and grain size

Figure 11. Possible uses of the functional flows model at different temporal and spatial scales.

Tables Captions

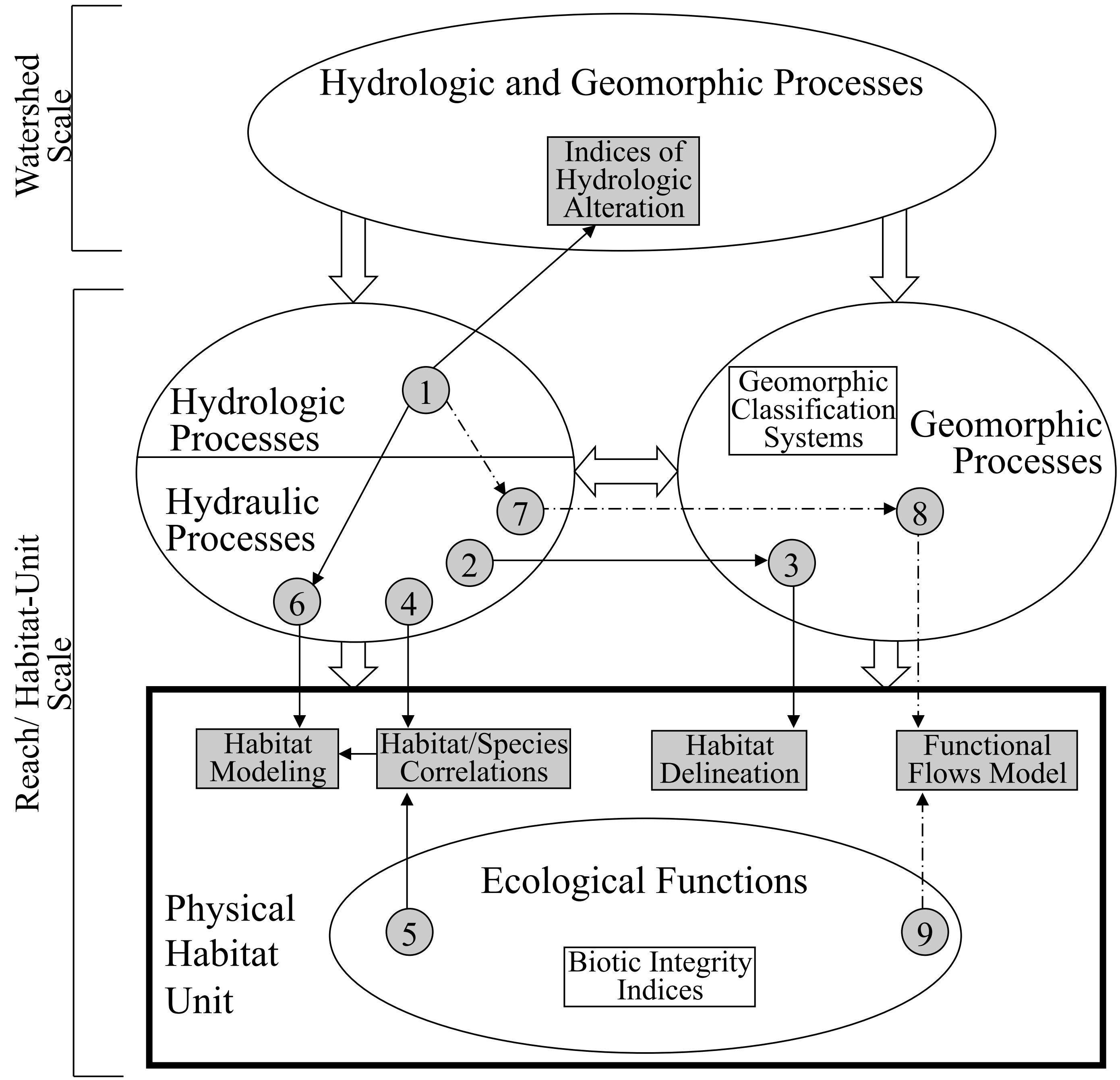
Table 1. Examples of approaches available for characterizing stream habitat. Approaches are grouped based on habitat processes and spatial scales considered. X indicates the scale at which it was developed, XX indicates other scales at which it has been applied.

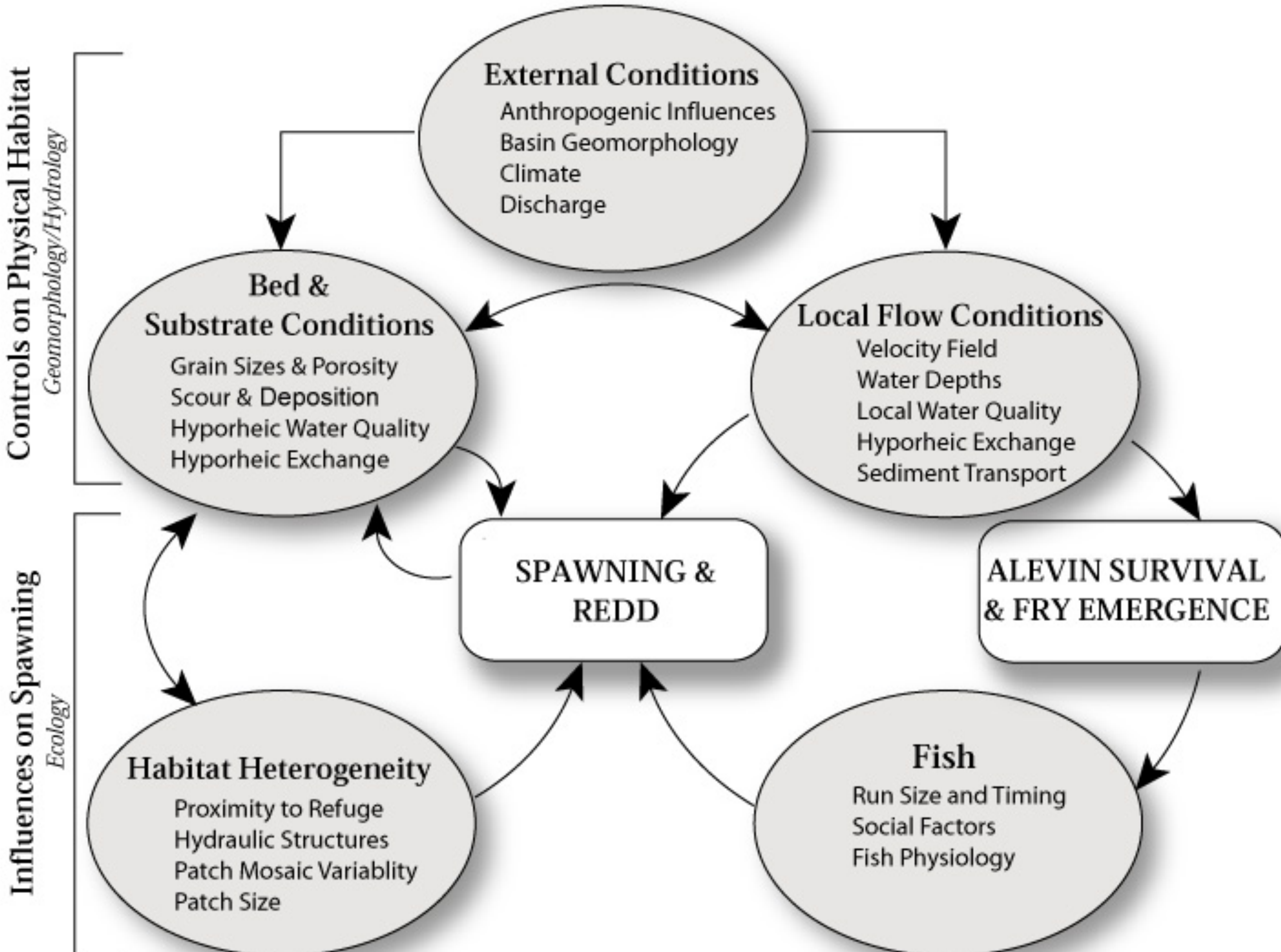
Table 2. Table of functionality.

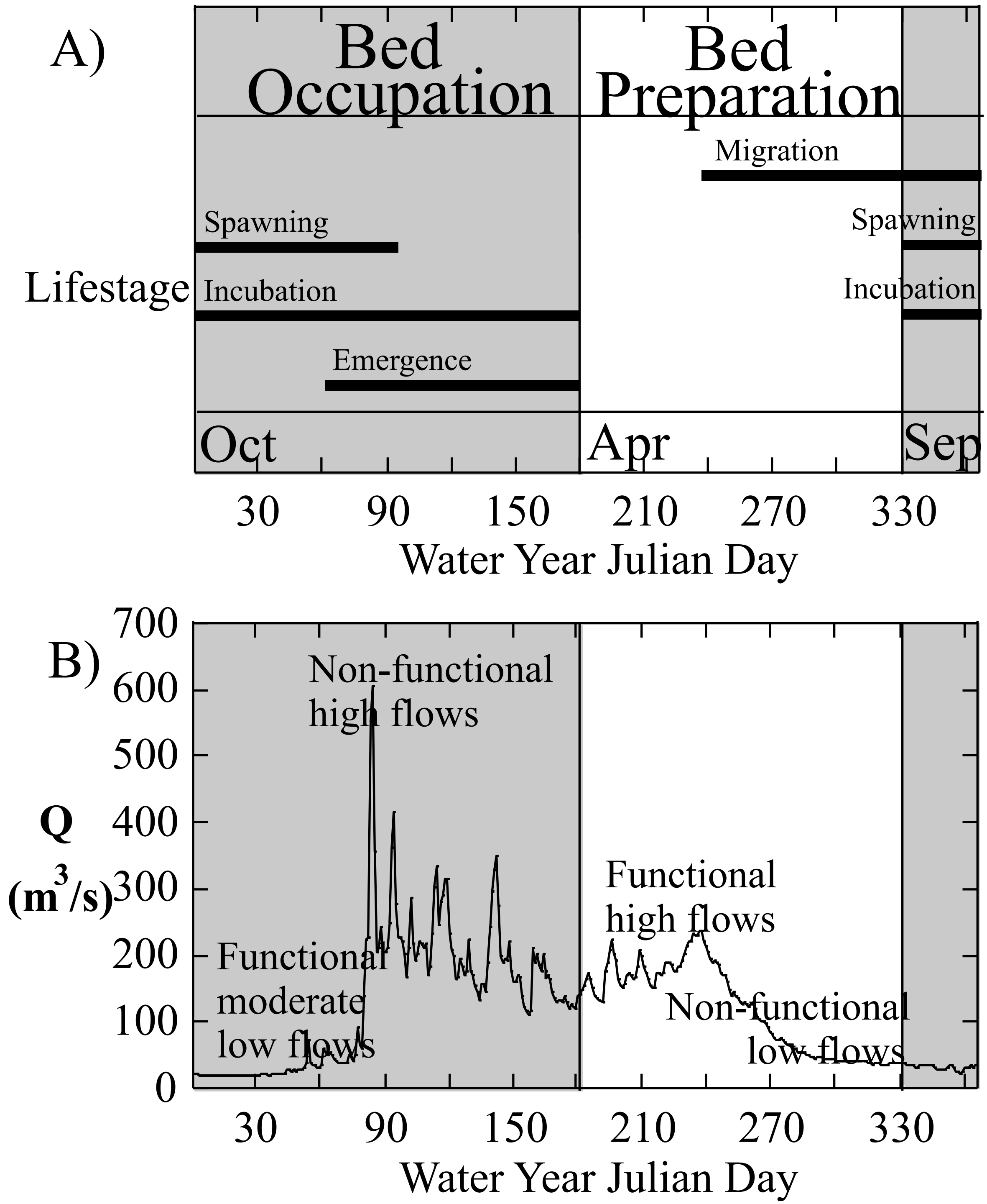
Flow magnitude and bed mobility stages delimited by Shields stress are used to determine functionality for bed occupation and bed preparation ecological functions during the spawning life stage. “Functional” refers to flow magnitudes associated with bed mobility stages that favor the life stage. “Non-functional”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

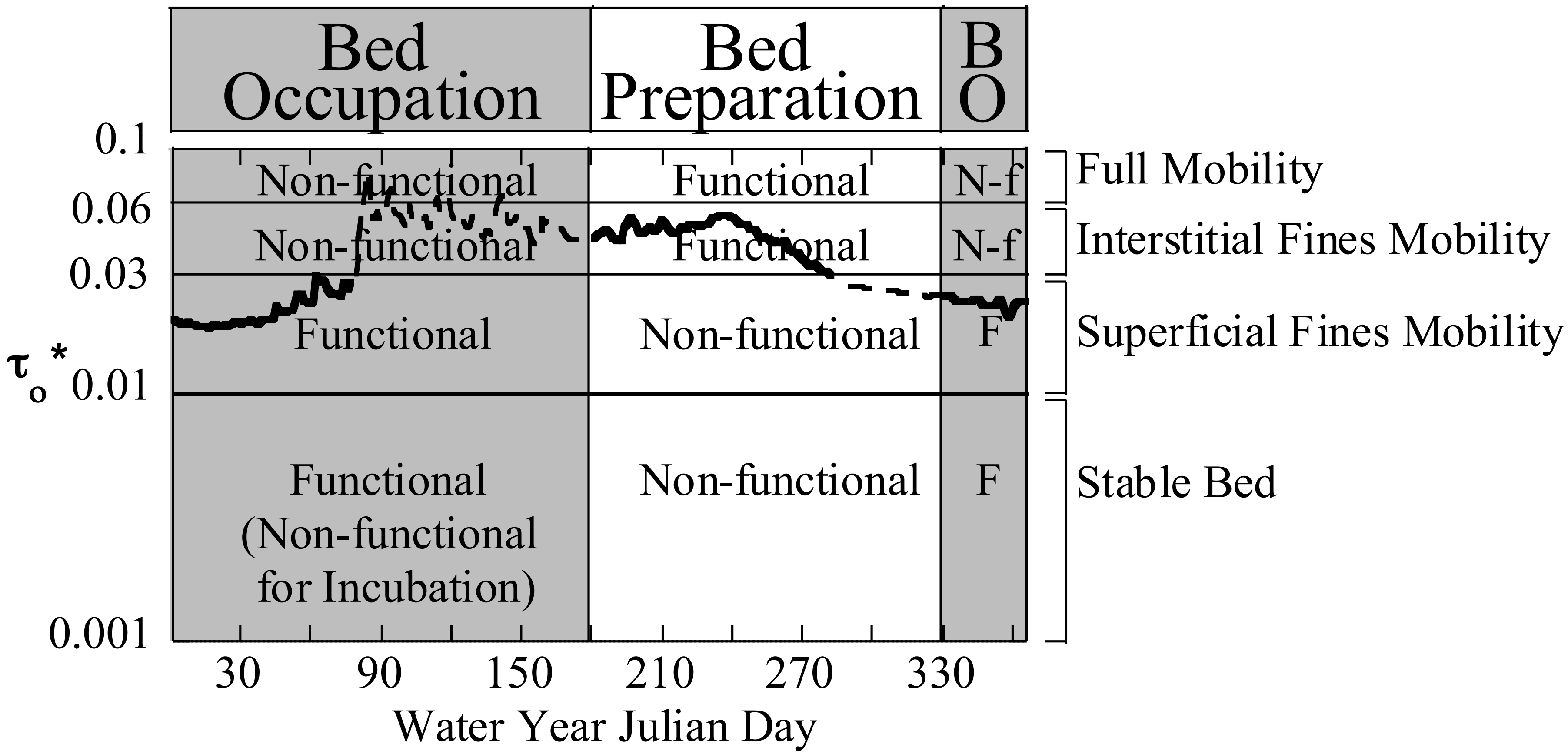
Table 3. Functional flows (ranges of Q*) for spawning habitat scenarios.

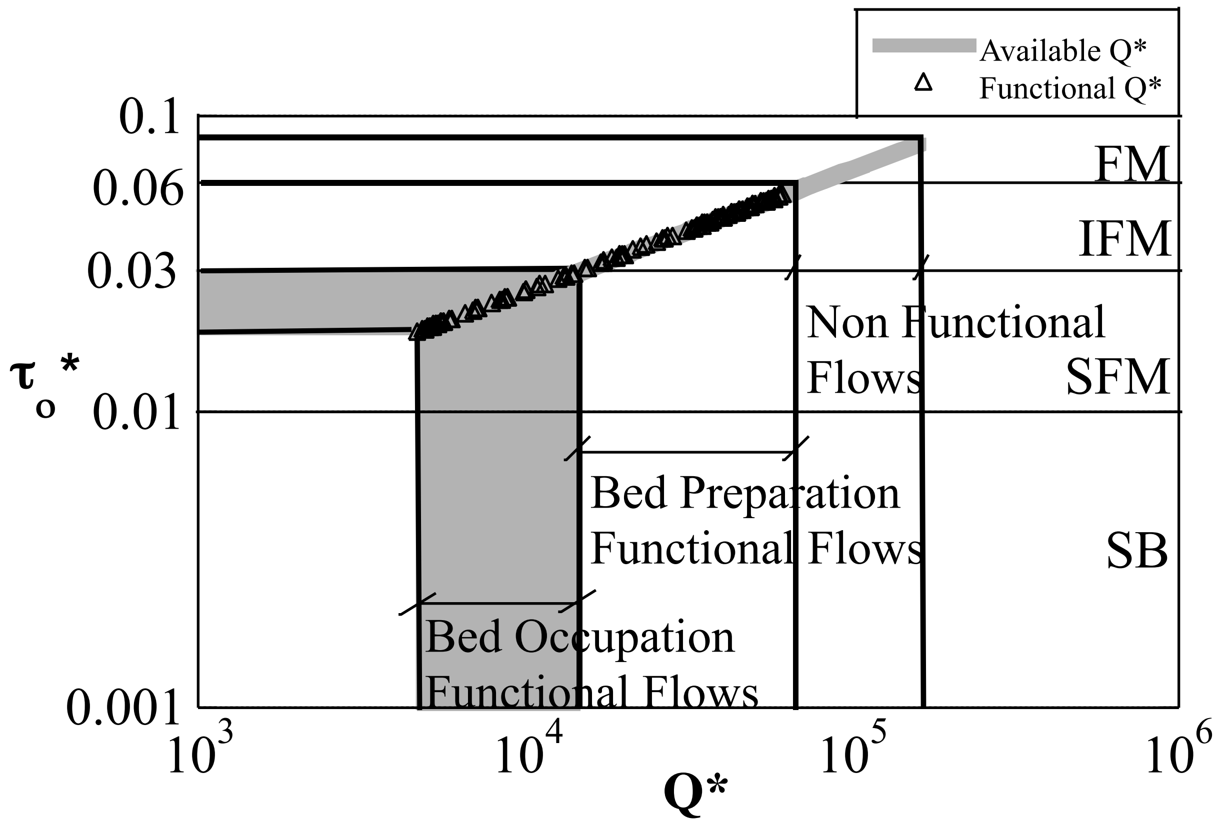
Note: (1) Most functional scenario for bed preparation, (2) Most functional scenario for bed occupation, (3) Least functional scenario for bed preparation, (4) Least functional scenario for bed occupation

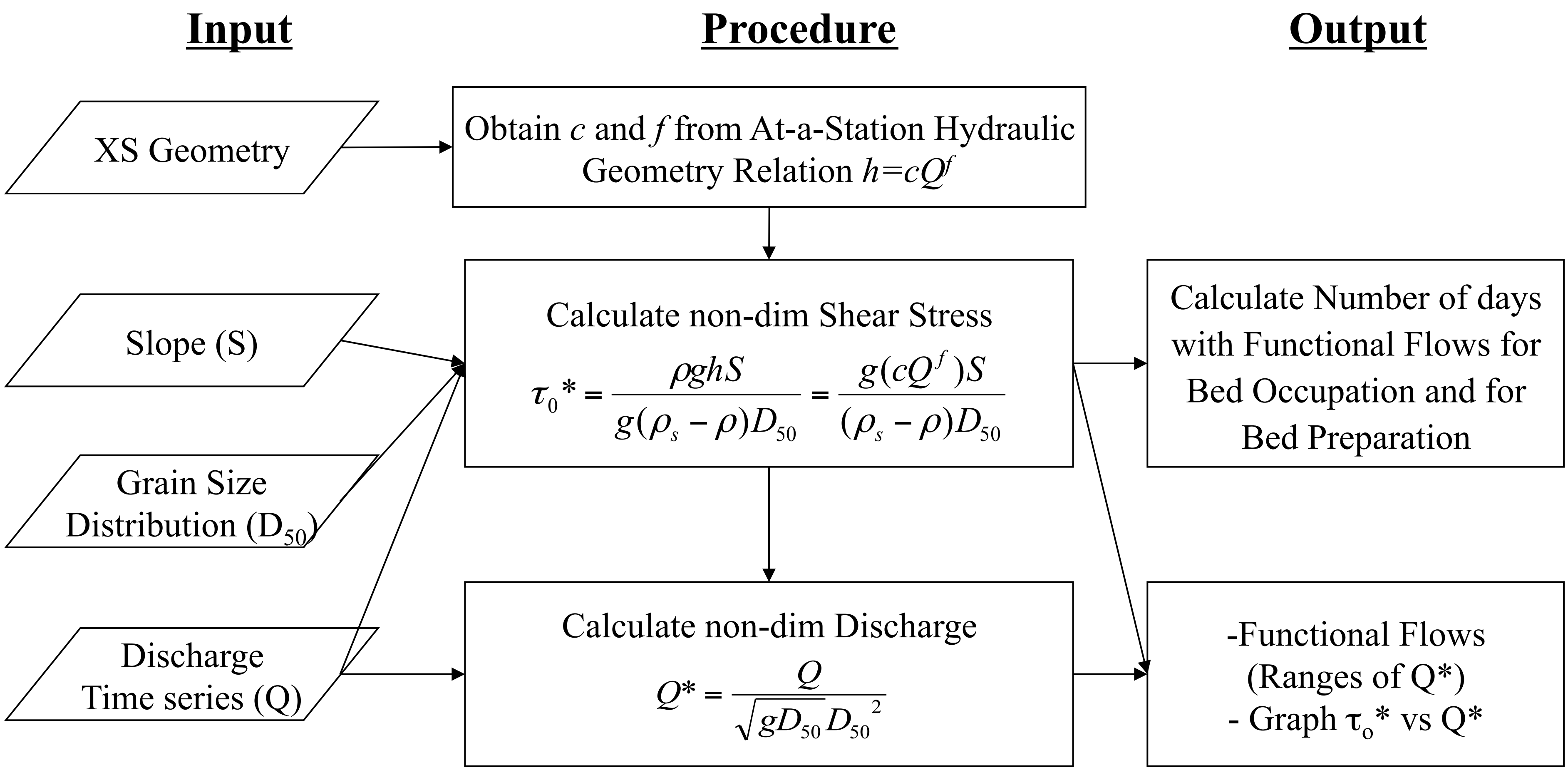

Watershed Scale
Reach/ Habitat-Unit Scale
Hydrologic and Geomorphic Processes
Indices of Hydrologic Alteration
Hydrologic Processes
Hydraulic Processes
Geomorphic Classification Systems
Geomorphic Processes
1
2
3
4
5
6
7
8
9
Habitat Modeling
Habitat/Species Correlations
Habitat Delineation
Functional Flows Model
Ecological Functions
Biotic Integrity Indices
Physical Habitat Unit

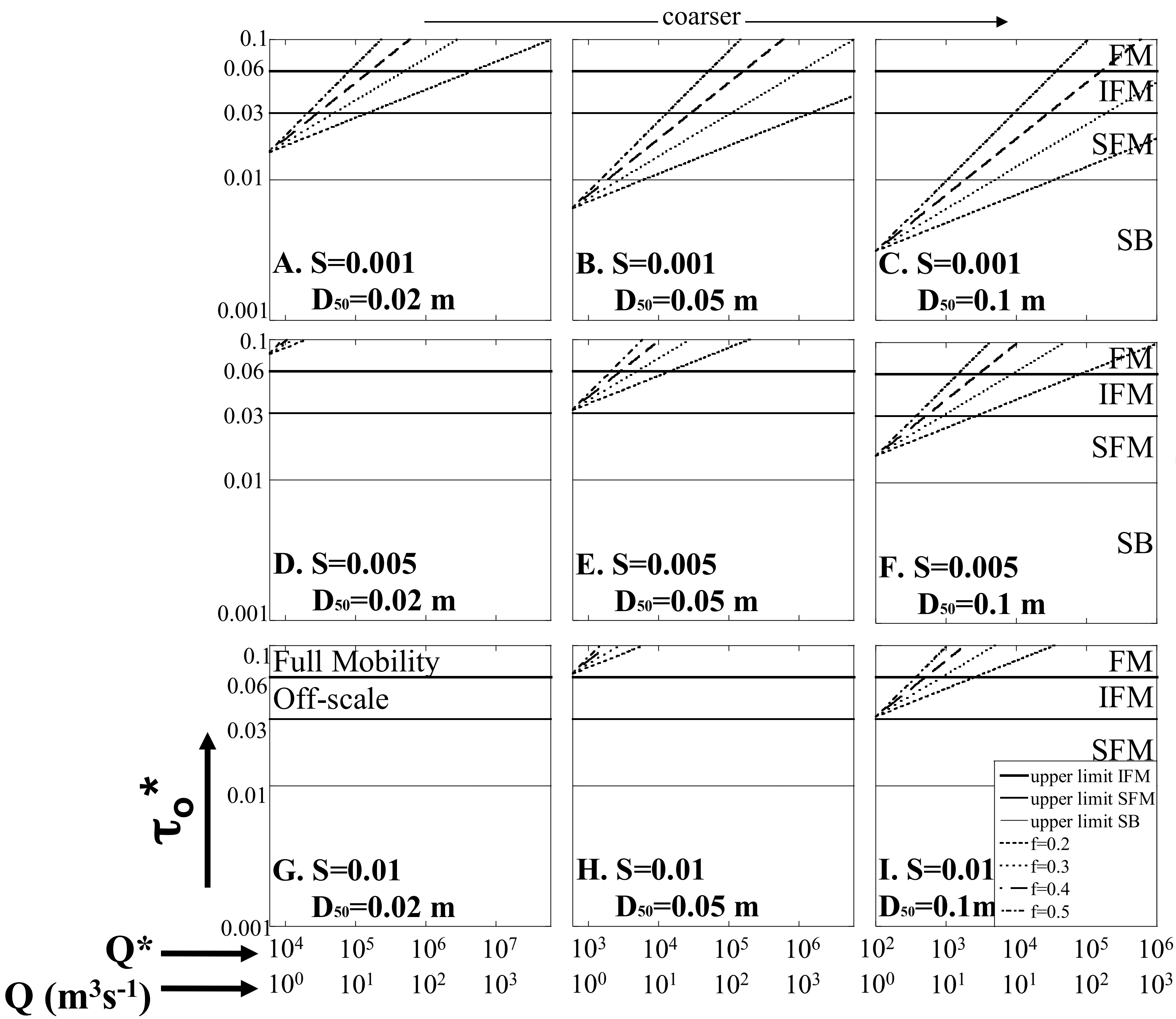

Controls on Physical Habitat
Geomorphology/Hydrology
Influences on Spawning
Ecology
External Conditions
Anthropogenic Influences
Basin Geomorphology
Climate
Discharge
Bed &
Substrate Conditions
Grain Sizes & Porosity
Scour & Deposition
Hyporheic Water Quality
Hyporheic Exchange
Local Flow Conditions
Velocity Field
Water Depths
Local Water Quality
Hyporheic Exchange
Sediment Transport
SPAWNING &
REDD
ALEVIN SURVIVAL
& FRY EMERGENCE
Habitat Heterogeneity
Proximity to Refuge
Hydraulic Structures
Patch Mosaic Variablity
Patch Size
Fish
Run Size and Timing
Social Factors
Fish Physiology


A)
Bed
Occupation
Bed
Preparation
Migration
Spawning
Spawning
Lifestage
Incubation
Incubation
Emergence
Oct
Apr
Sep
30
90
150
210
270
330
Water Year Julian Day
B)
700
600
500
400
300
200
100
0
Q
(m3/s)
Non-functional
high flows
Functional
high flows
Functional
moderate
low flows
Non-functional
low flows
30
90
150
210
270
330
Water Year Julian Day

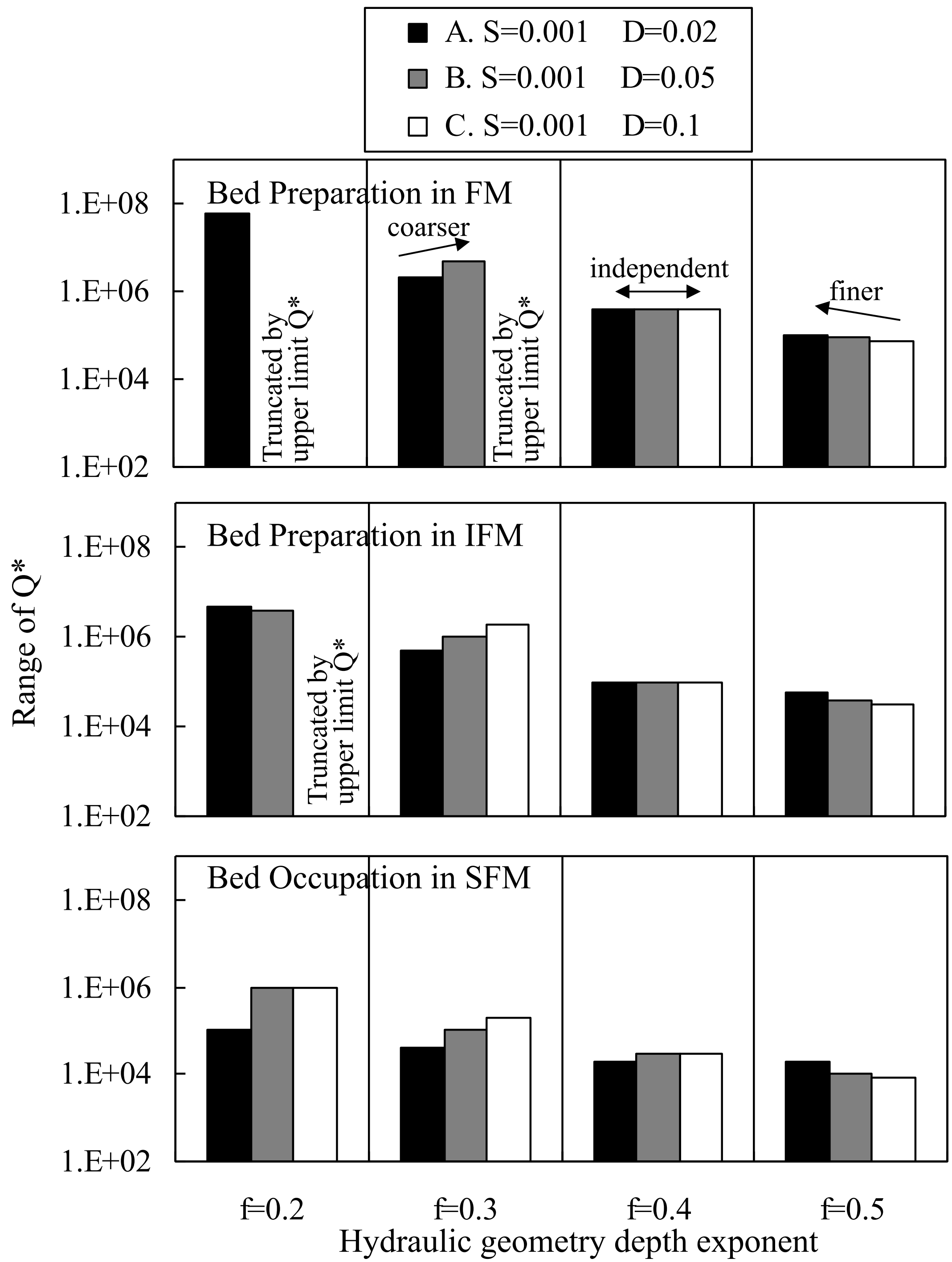

Bed Occupation
Bed Preparation
B O
0.1
0.06
0.03
0.01
0.001
τo*
Non-functional
Non-functional
Functional
Functional (Non-functional for Incubation)
Functional
Functional
Non-functional
Non-functional
N-f
N-f
F
F
Full Mobility
Interstitial Fines Mobility
Superficial Fines Mobility
Stable Bed
30
90
150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

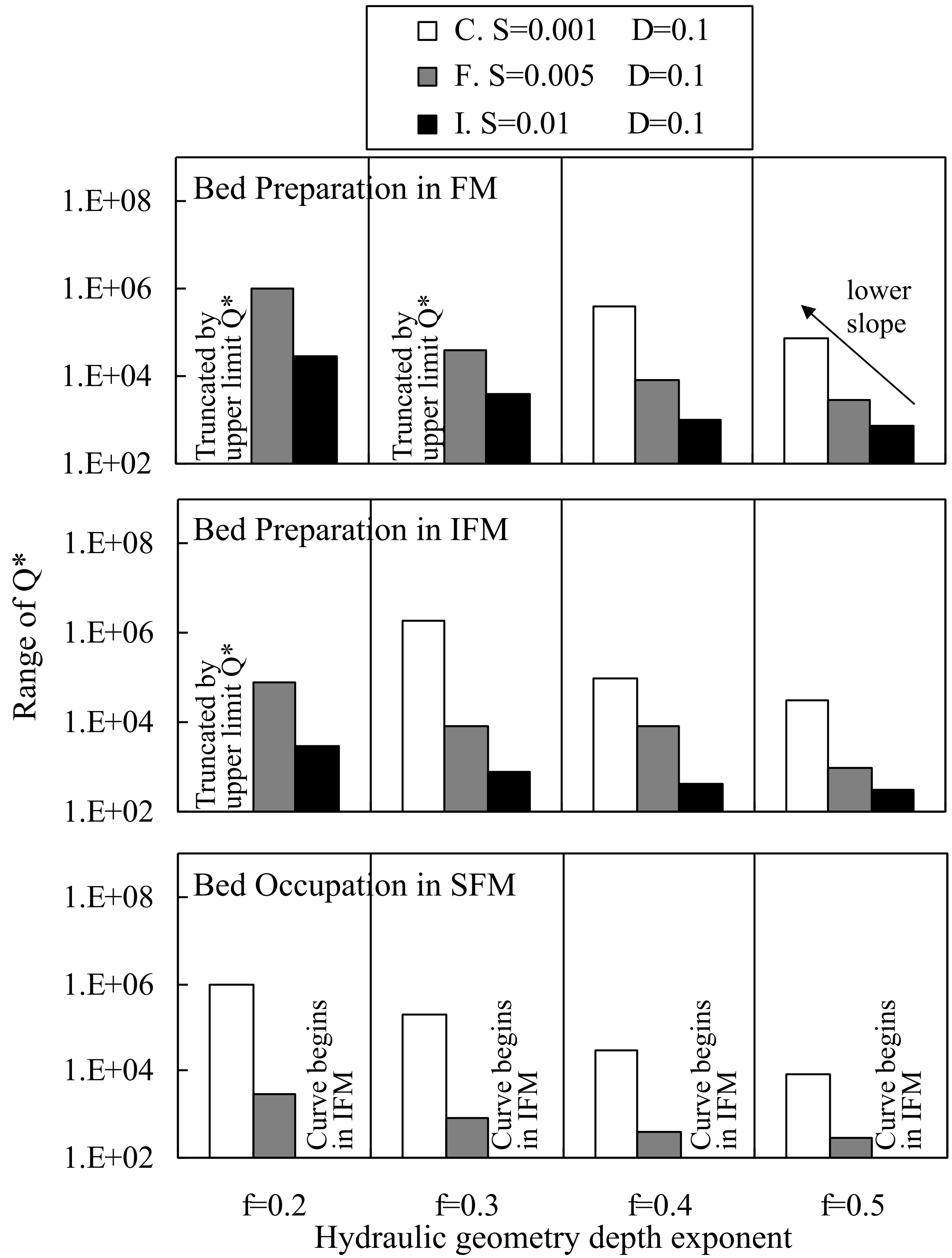

Available Q*
Functional Q*
0.1
0.06
0.03
0.01
0.001
τo*
FM
IFM
SFM
SB
Non Functional Flows
Bed Preparation Functional Flows
Bed Occupation Functional Flows
10^3
10^4
10^5
10^6
Q*


Input
Procedure
Output
XS Geometry
Slope (S)
Grain Size Distribution (D_{50})
Discharge Time series (Q)
Obtain c and f from At-a-Station Hydraulic Geometry Relation $h=cQ^f$
Calculate non-dim Shear Stress
$\tau_0* = \frac{\rho g h S}{g(\rho_s - \rho) D_{50}} = \frac{g(cQ^f)S}{(\rho_s - \rho) D_{50}}$
Calculate non-dim Discharge
$Q* = \frac{Q}{\sqrt{g D_{50}} D_{50}^2}$
Calculate Number of days with Functional Flows for Bed Occupation and for Bed Preparation
-Functional Flows (Ranges of Q*)
- Graph τ_o* vs Q*

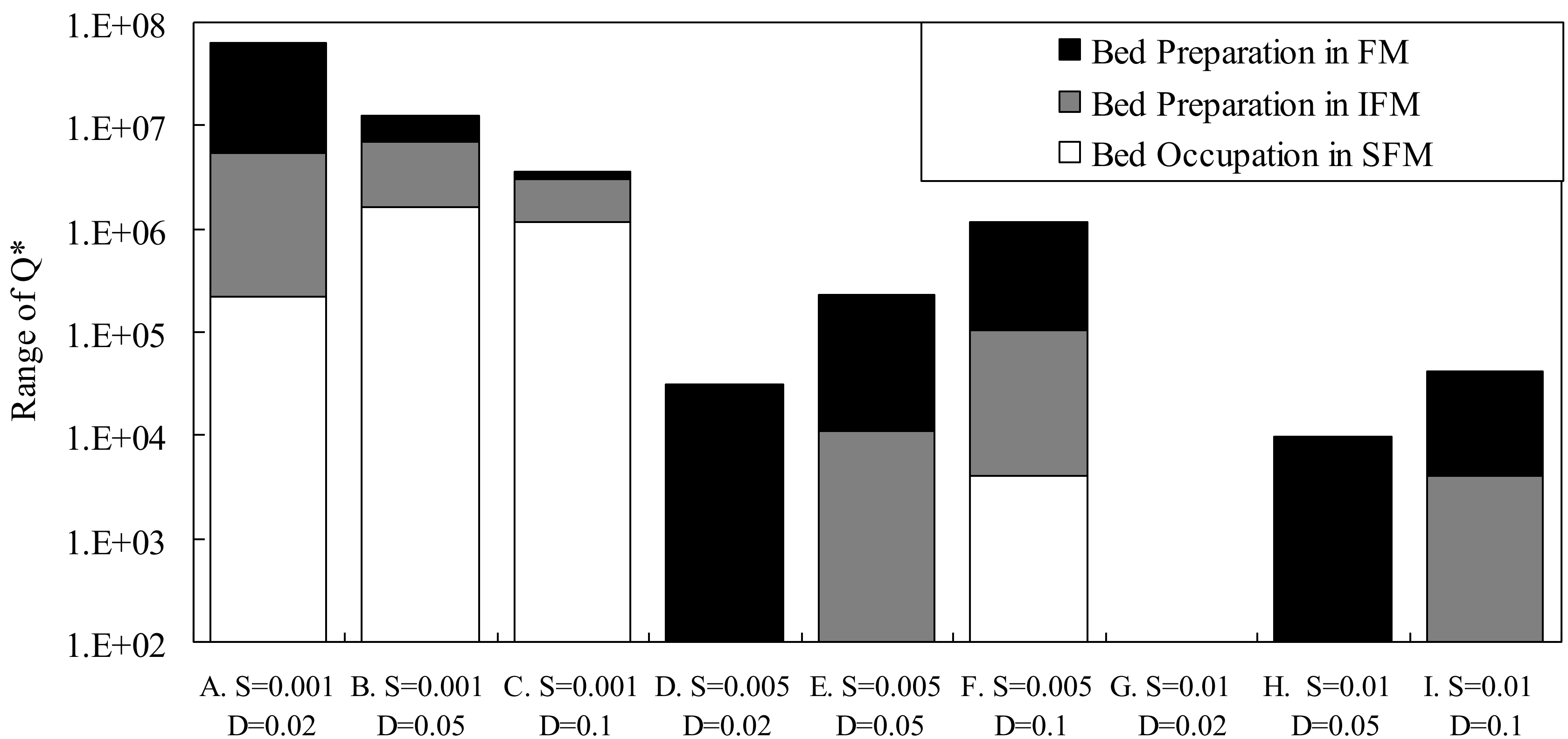


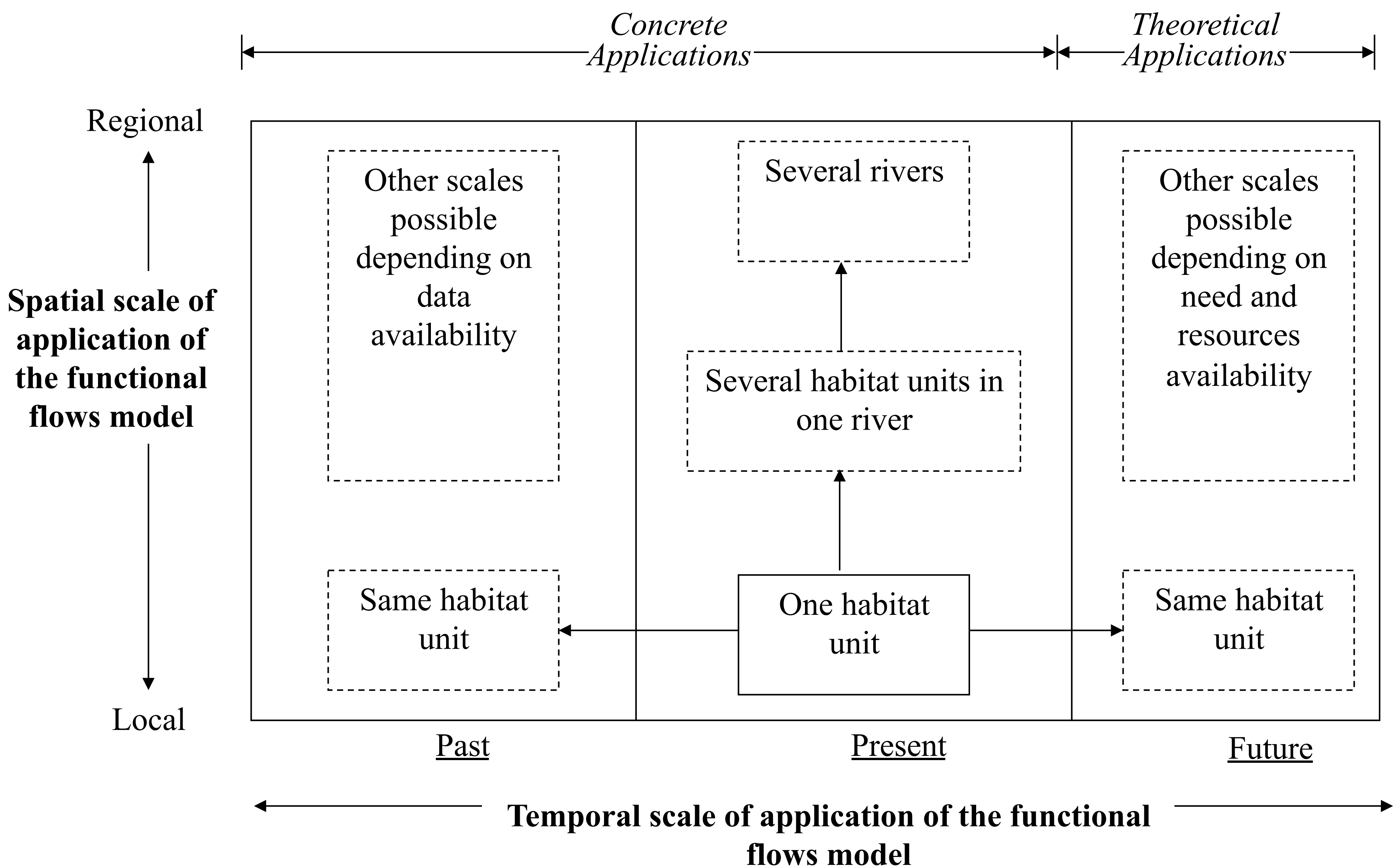
coarser
steeper
A. S=0.001 D50=0.02 m
B. S=0.001 D50=0.05 m
C. S=0.001 D50=0.1 m
D. S=0.005 D50=0.02 m
E. S=0.005 D50=0.05 m
F. S=0.005 D50=0.1 m
G. S=0.01 D50=0.02 m
H. S=0.01 D50=0.05 m
I. S=0.01 D50=0.1m
FM
IFM
SFM
SB
Full Mobility
Off-scale
upper limit IFM
upper limit SFM
upper limit SB
f=0.2
f=0.3
f=0.4
f=0.5
τo*
Q*
Q (m3s-1)
0.1
0.06
0.03
0.01
0.001


A. S=0.001 D=0.02
B. S=0.001 D=0.05
C. S=0.001 D=0.1
Bed Preparation in FM
coarser
independent
finer
Truncated by upper limit Q*
Bed Preparation in IFM
Bed Occupation in SFM
1.E+08
1.E+06
1.E+04
1.E+02
Range of Q*
f=0.2
f=0.3
f=0.4
f=0.5
Hydraulic geometry depth exponent



C. S=0.001 D=0.1
F. S=0.005 D=0.1
I. S=0.01 D=0.1
Bed Preparation in FM
Bed Preparation in IFM
Bed Occupation in SFM
Truncated by upper limit Q*
Curve begins in IFM
lower slope
Range of Q*
1.E+02
1.E+04
1.E+06
1.E+08
f=0.2
f=0.3
f=0.4
f=0.5
Hydraulic geometry depth exponent


Bed Preparation in FM
Bed Preparation in IFM
Bed Occupation in SFM
Range of Q*
1.E+08
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
A. S=0.001 D=0.02
B. S=0.001 D=0.05
C. S=0.001 D=0.1
D. S=0.005 D=0.02
E. S=0.005 D=0.05
F. S=0.005 D=0.1
G. S=0.01 D=0.02
H. S=0.01 D=0.05
I. S=0.01 D=0.1


Concrete Applications
Theoretical Applications
Regional
Spatial scale of application of the functional flows model
Local
Other scales possible depending on data availability
Same habitat unit
Several rivers
Several habitat units in one river
One habitat unit
Other scales possible depending on need and resources availability
Same habitat unit
Past
Present
Future
Temporal scale of application of the functional flows model