Geomorphically Effective Flow Regimes in Gravel-bed Rivers

Thesis Proposal for the degree of Doctor of Philosophy in Geology

By

Laura A. Hempel

Gordon E. Grant (Advisor)

OREGON STATE UNIVERSITY

College of Earth, Ocean, and Atmospheric Sciences

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Gordon E. Grant, Research Hydrologist, USDA Forest Service, Courtesy Faculty in CEOAS, OSU

Catalina Segura, Assistant Professor, College of Forestry, OSU

Roy Haggerty, Professor, College of Earth, Ocean, and Atmospheric Sciences, OSU

John M. Buffington, Research Geomorphologist, USDA Forest Service
1. Introduction and Motivation

Stream channel form is a reflection of interactions among water, sediment, and conditions imposed by resistant boundaries such as bedrock. Consequently, numerous studies have focused on individual flows or the caliber and quantity of sediment supply in an effort to identify and quantify the physical processes that shape a stream channel. Missing from these analyses, however, is a clear understanding of how the entire flow regime, not just a single flow or event, structures a stream channel. The purpose of the proposed research is to comprehensively define the geomorphically effective flow regime, or the set of channel-organizing flow conditions that uniquely describe a channel.

1.1 Definitions

Here, flow regime refers to the pattern of temporal variation in streamflow, including range, duration, magnitude, timing, and sequencing of sediment-mobilizing flow. Our definition of channel organization is two-tiered. Organization, at the simplest level, refers to the presence of self-formed channel structures at varying spatial scales, including particle sorting (i.e., imbrication, armoring, distinct textural patches, fining upward sequence), bed forms (i.e., pool, riffle, step, rapid, cascade), and in-channel wood (i.e., log jams or piles sorted and/or organized by flowing water). At a higher order, organization refers to regularity in the spacing, frequency, and sequencing of channel structures. For example, a well-organized channel would be one with a well-sorted bed and clearly-defined, regularly spaced bed forms that occur in repetitive sequence. Conversely, a poorly organized channel would lack particle sorting, discernable bed forms, and/or features shaped by flowing water.

2. Objectives and Hypotheses

The purpose of the proposed research is to investigate the degree to which channel form and organization reflect the full hydrologic regime in gravel-bed channels through a coordinated set of field measurements, flume experiments, and numerical modeling. The proposed framework would be invaluable to stream ecologists and water managers for predicting channel response to changing flow regimes caused by dams, land management, and climate.

2.1 Identify organizational channel features

Objective 2.1: Rigorously define organization using operational definitions and quantitative descriptions; measure organizational metrics in field settings

Identify organizational metrics and measure them in flume experiment and field study, and examine changes to channel organization under different boundary conditions in the numerical model.

We define organization as regularity in the arrangement and orientation of self-organized channel features. Organization is present in river channel at multiple scales, which is why we will use both flume studies and field studies to study channel response at both small (e.g., grain, patch, and channel unit scale) and large scales (e.g., patch, channel unit, reach) respectively.
Lastly, we will use numerical modeling to examine the degree to which organizational features change under different boundary conditions, including changes in the supply and caliber of sediment delivered to the channel.

To rigorously define the degree of organization in a channel, we will first develop definitions of fluvially organized channel structures using physical and hydraulic descriptions. For example, at the channel unit scale, pools could be defined as areas of tranquil, subcritical flow that lack free-surface instabilities, and are typically deepest immediately downstream of the head and slope more gently toward the head, following Grant et al. (1990).

Next, we will evaluate the regularity in the size and spatial arrangement of channel features using statistical techniques. For example, we might use autocorrelation analysis to evaluate the patterning of channel units within a reach. A list of relevant, measurable channel properties is found in table 1.

**Table 1.** List of channel features to be measured, possible organizational variable to be calculated from measurements, and additional field observations to characterize degree of organization.

<table>
<thead>
<tr>
<th>Scale (channel widths)</th>
<th>Method for Study</th>
<th>Feature/Property</th>
<th>Metric/Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain ((10^{-2} - 10^{0}))</td>
<td>Flume</td>
<td>grain orientation</td>
<td>friction angle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>hiding</td>
<td>hiding ratio</td>
</tr>
<tr>
<td></td>
<td></td>
<td>protrusion</td>
<td>submergence ratio, projection, exposure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>packing</td>
<td>imbricated, interlocked, ‘open’</td>
</tr>
<tr>
<td>Patch ((10^{-1} - 10^{0}))</td>
<td>Flume, Field</td>
<td>armoring</td>
<td>armor ratio</td>
</tr>
<tr>
<td></td>
<td></td>
<td>textural patch</td>
<td>patch area, grain size distribution, physical description (e.g., degree of sorting, presence of boulder clusters or transverse ribs)</td>
</tr>
<tr>
<td>Channel Unit ((10^{0} - 10^{1}))</td>
<td>Field, Modeling</td>
<td>pool, riffle, cascade, rapid, step, gravel bar, etc.</td>
<td>length, slope, depth, width, area, characteristic grain size</td>
</tr>
<tr>
<td></td>
<td></td>
<td>wood</td>
<td>length, height above bed, diameter, orientation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cross-sectional geometries</td>
<td>w/d ratio, curvature, bank slope</td>
</tr>
<tr>
<td>Reach ((10^{2} - 10^{3}))</td>
<td>Field, Modeling</td>
<td>sources of roughness</td>
<td>fractional form drag, stress partitioning</td>
</tr>
<tr>
<td></td>
<td></td>
<td>patchiness</td>
<td># patches per reach, percentage of bed covered by a patch, average patch area</td>
</tr>
<tr>
<td></td>
<td></td>
<td>channel type</td>
<td>identification from channel units present</td>
</tr>
<tr>
<td></td>
<td></td>
<td>longitudinal bed topography</td>
<td>slope, relief, bed elevation variability</td>
</tr>
</tbody>
</table>
2.2 Use the hydrograph to describe conditions under which organization occurs

Objective 2.2: Quantify when the bed is active, and therefore when organization can occur in order to extract geomorphically relevant flow variables

Develop flow metrics that uniquely describe a hydrograph and that describe when sediment is moving, and thus when organization can occur. We will fine tune those metrics through field and flume studies and relate them directly to fluvially organized features.

Flow variables will be related to channel-shaping processes based on the magnitude of shear stresses acting on the bed at different flows. For example, I will identify flow thresholds by computing the range of discharges at which a certain channel features are likely to be mobile and subject to alteration, as shown in figure 2. Those thresholds will relate to channel features at multiple scales and will be unique to each channel based on the geometry, sediment size, lithology, and degree/source of roughness.

For example, a very high threshold (threshold 2 in figure 2) might correspond to high magnitude events during which the largest clasts (>D₈₄) that compose steps or cascade units are mobile in high gradient snowmelt runoff channels (Whittaker, 1987; Grant et al., 1990; Kondolf et al., 1991). Geomorphically, this high threshold might represent whole-scale reorganization of the bed. By comparison, a lower threshold (threshold 1 in figure 2) might represent moderate flows during which sands and gravels stored in low shear zones are mobilized (Griffiths, 1980; Ashida et al., 1981; Kondolf et al., 1991; Schmidt and Ergenzinger, 1992). This lower threshold might represent the flows at which channel units, like gravel bars, are maintained. Each flow variable will therefore represent a certain process operating at a certain scale.

Figure 2. Conceptual diagram of threshold approach to defining channel-organizing flow metrics. Threshold 1 would correspond to the flow that mobilizes a certain channel feature, while threshold 2 would relate to a different channel feature. Some regimes may not exceed a threshold, in which case the corresponding channel feature would not be present.
The first step to determining when organization occurs is therefore to compute flow thresholds for individual channel features. For example, to represent thresholds that describe features at the channel unit scale, I will compute $Q_{\text{pool}}$, $Q_{\text{step}}$, and $Q_{\text{bar}}$, which are the thresholds at which pools, steps, or gravel bars respectively, are mobile. Figure 3 illustrates the idea of flow thresholds for different generalized channel units superimposed on a hydrograph, along with potential flow variables.

![Threshold Variables](image)

Figure 3. Example hydrograph (solid black line) with flow thresholds (dashed lines) for incipient motion and the flow above which particles in generalized channel units 1 and 2 are mobile (these units could represent pools and steps, for example) along with flow variables that would be extracted from the flow thresholds.

**Hypothesis 1: Highly organized systems are created and reinforced by flows that exert a variety of applied stresses on the bed but only infrequently mobilize the entire bed or exceed the threshold of transport for key, framework-sized grains (i.e., $D_{84}$ size fraction or larger)**

Different channel-forming processes operate over a variety of flows and at a variety of scales. For example, frequent low flows flush fines and winnow the bed, less frequent moderate flows mobilize gravels and promote grain stabilization, and rare large events mobilize and re-organize the entire bed, which includes the largest grains (Dietrich et al., 1989; Montgomery and Buffington, 1999; Monteith and Pender, 2005; Hassan et al., 2006). In fact, one characteristic of organized channels may be a diverse flow regime. One study found that under a constant discharge, the planform pattern recreated by a numerical simulation of river meandering deviated from that observed in natural channels (Asahi et al., 2013). However, simulations that included discharge variation, or the combination of high flows that eroded the outer bank and low flows that accreted material along the inner bank, did produce a meandering planform pattern analogous to natural systems (Asahi et al., 2013). I therefore intend to develop a portfolio of flow variables that capture the range of fluvial processes operating within the channel.

Next, I will use time duration ratios to quantify the proportion of organizing flow over an event. Flow duration above the critical transport threshold is an important criterion for geomorphic change and development (Costa and O’Connor, 1995; Magilligan et al., 2014). I will therefore explore metrics that relate the duration of flow above critical organizing thresholds to the entire duration of an event as illustrated in figure 4. These might include, for example, the ratio of $T_{\text{pool}}$, $T_{\text{step}}$, and $T_{\text{bar}}$.  

<table>
<thead>
<tr>
<th>Variable</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{\text{peak}}/Q_{\text{crit}}$</td>
<td>Peak discharge ($Q_{\text{peak}}$) normalized by the discharge corresponding to the threshold for incipient motion ($Q_{\text{crit}}$)</td>
</tr>
<tr>
<td>$Q_{\text{unit1}}/Q_{\text{crit}}$</td>
<td>The discharge at which all grain sizes within channel unit 1 are mobile ($Q_{\text{unit1}}$) normalized by the discharge corresponding to the threshold for incipient motion</td>
</tr>
<tr>
<td>$Q_{\text{unit2}}/Q_{\text{crit}}$</td>
<td>The discharge at which all grain sizes within channel unit 2 are mobile ($Q_{\text{unit2}}$) normalized by the discharge corresponding to the threshold for incipient motion</td>
</tr>
</tbody>
</table>
T_{\text{step}}$, or $T_{\text{bars}}$, which are the durations of flow above the thresholds for pool, step, or gravel bar mobilization respectively to the duration of a storm event. In other words, I will calculate the percentage of time spent under ‘unit-mobilizing’ flow.

**Hypothesis 2: Opportunity for organization occurs during the recession limb, therefore regimes characterized by long-duration falling limbs correspond to highly organized channels**

Another set of variables will describe the shape of the hydrograph. I will use time duration ratios again, but in this case to capture the distribution of organizing flow. Several variables will be used to quantify the length of the falling limb, which is an indication of organizational opportunity and has been shown to control degree of armoring (Hassan et al., 2006), grain sorting and imbrication (Magilligan et al., 2014), and establishment of channel unit structure (Sawada et al., 1983; Whittaker, 1987b; Magilligan et al., 2014). For example, a previous study found that in a flume experiment, a long duration falling limb corresponded to a well-armored bed (Hassan et al., 2006). This research will build on previous studies and address questions such as: How does is the armor layer affected by a sequence of different flows? To what degree does the duration of the falling limb control organization at larger scales? For example, does the falling limb relate to regularity in the size and spacing of gravel bars? We will explore parameters to answer these questions that include $T_{\text{rise}}$ and $T_{\text{fall}}$ (the duration of the rising and falling limbs respectively) normalized by the duration of the flow event, depicted in figure 5. I will also use flow ratios to capture peakedness; for example, $Q_{\text{peak}}/Q_{\text{critical}}$ (the ratio of peak discharge to the discharge corresponding to the critical threshold for incipient motion), also illustrated in figure 5.

**Hypothesis 3: Sufficient intervening low flow promotes grain settling and stability and is therefore a trait of organized systems**

Lastly, I aim to capture the distribution and sequencing of organizing flow over multiple hydrographs. For example, instead of calculating the proportion of unit-mobilizing flow in a single event (figure 4), I will calculate the proportion of unit-mobilizing flow over a series of events, illustrated in figure 6. From this analysis, I will also calculate the frequency of unit-mobilizing flow over multiple events, also in figure 6. I also plan to quantify one measure of shear stress history, the intervening time between bed mobilizing flows, which has been shown to affect bed stability and thus opportunity for organization (Reid and Frostick, 1984; Reid et al., 1985; Klingeman and Emmitt, 1982; Monteith and Pender, 2005). For example, a measure of antecedent flow might include $T_{\text{unit1}}/T_{\text{event+antecedent}}$, or the duration of unit 1 mobilizing flow to the duration of the entire event plus antecedent subcritical flow, depicted in figure 7. Quantifying the distribution and sequencing will allow me to address questions such as: how often are pool-forming grains mobilized in a season? What is the proportion of pool mobilizing flow compared to step mobilizing flow?

The list of variables mentioned above and illustrated in figures 4, 5, 6, and 7 is meant to illustrate the types of variables I will use to quantify the geomorphically effective flow regime, but is not exhaustive. We will also explore previously identified flow metrics that describe the hydrograph, such as skew and kurtosis, which are used to describe hydrograph shape. I present several time duration ratios for illustration and simplicity, but I will also calculate flow volumes, which represents the total energy available for channel modification. To use the first listed variable
below as an example \(\frac{T_{\text{unit1}}}{T_{\text{event}}}\), in addition to calculating the fraction of time spent above \(Q_{\text{unit1}}\) as illustrated, I will also calculate the fraction of total flow volume above \(Q_{\text{unit1}}\):

\[
\int_{t_1}^{t_2} (Q > Q_{\text{unit1}}) \, dt
\]

**Figure 4.** Example hydrograph and description of flow variables that relate flow thresholds to the duration of organizing flow
### Figure 5
Example hydrographs and description of flow variables that describe peakedness (graph A) and hydrograph shape (graph B)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{\text{peak}}/Q_{\text{start}}$</td>
<td>Peak discharge divided by initial discharge</td>
</tr>
<tr>
<td>$Q_{\text{peak}}/Q_{\text{end}}$</td>
<td>Peak discharge divided by initial discharge</td>
</tr>
<tr>
<td>$T_{\text{unit1 rise}}/T_{\text{crit rise}}$</td>
<td>Duration of flow above $Q_{\text{unit1}}$ on the rising limb ($T_{\text{unit1 rise}}$) divided by the duration of $Q_{\text{crit}}$ on the rising limb ($T_{\text{crit rise}}$)</td>
</tr>
<tr>
<td>$T_{\text{unit1 rise}}/T_{\text{event}}$</td>
<td>Duration of flow above $Q_{\text{unit1}}$ on the rising limb ($T_{\text{unit1 rise}}$) divided by $T_{\text{event}}$</td>
</tr>
<tr>
<td>$T_{\text{unit2 rise}}/T_{\text{crit rise}}$</td>
<td>Duration of flow above $Q_{\text{unit2}}$ on the rising limb ($T_{\text{unit2 rise}}$) divided by the duration of $Q_{\text{crit}}$ on the rising limb ($T_{\text{crit rise}}$)</td>
</tr>
<tr>
<td>$T_{\text{unit2 rise}}/T_{\text{event}}$</td>
<td>Duration of flow above $Q_{\text{unit2}}$ on the rising limb ($T_{\text{unit2 rise}}$) divided by $T_{\text{event}}$</td>
</tr>
<tr>
<td>$T_{\text{unit1 fall}}/T_{\text{crit fall}}$</td>
<td>Duration of flow above $Q_{\text{unit1}}$ on the falling limb ($T_{\text{unit1 fall}}$) divided by the duration of $Q_{\text{crit}}$ on the falling limb ($T_{\text{crit fall}}$)</td>
</tr>
<tr>
<td>$T_{\text{unit1 fall}}/T_{\text{event}}$</td>
<td>Duration of flow above $Q_{\text{unit1}}$ on the falling limb ($T_{\text{unit1 fall}}$) divided by $T_{\text{event}}$</td>
</tr>
<tr>
<td>$T_{\text{unit2 fall}}/T_{\text{crit fall}}$</td>
<td>Duration of flow above $Q_{\text{unit2}}$ on the falling limb ($T_{\text{unit2 fall}}$) divided by the duration of $Q_{\text{crit}}$ on the falling limb ($T_{\text{crit fall}}$)</td>
</tr>
<tr>
<td>$T_{\text{unit2 fall}}/T_{\text{event}}$</td>
<td>Duration of flow above $Q_{\text{unit2}}$ on the falling limb ($T_{\text{unit2 fall}}$) divided by $T_{\text{event}}$</td>
</tr>
</tbody>
</table>

### Figure 6
Example hydrograph and description of flow variables that relate flow thresholds to the duration and frequency of organizing flow over multiple hydrographs

<table>
<thead>
<tr>
<th>Variable</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{unit1, total}}/T_{\text{total}}$</td>
<td>Combined duration of flow above $Q_{\text{unit}}$ divided by total time ($T_{\text{total}}$)</td>
</tr>
<tr>
<td>$T_{\text{unit2, total}}/T_{\text{total}}$</td>
<td>Combined duration of flow above $Q_{\text{unit}}$ divided by total time ($T_{\text{total}}$)</td>
</tr>
<tr>
<td>$T_{\text{crit, total}}/T_{\text{total}}$</td>
<td>Combined duration of flow above $Q_{\text{crit}}$ divided by total time ($T_{\text{total}}$)</td>
</tr>
<tr>
<td>$(#&gt;Q_{\text{unit2}})/(#Q_{\text{total}})$</td>
<td>Number of events that exceed $Q_{\text{unit2}}$ divided by the total number of events</td>
</tr>
<tr>
<td>$(#&gt;Q_{\text{unit1}}&lt;Q_{\text{unit2}})/(#Q_{\text{total}})$</td>
<td>Number of events between $Q_{\text{unit1}}$ and $Q_{\text{unit2}}$ divided by the total number of events</td>
</tr>
</tbody>
</table>
A threshold-based approach will quantitatively relate the hydrograph to channel-forming processes. Organization is a time dependent process that depends on multiple ‘organizational’ thresholds. I therefore plan to explore ways to capture the geomorphically effective flow regime using a set of variables that describe flow thresholds, flow magnitude, hydrograph shape, and flow duration.

### 2.3 Relate geomorphically relevant flow parameters to channel organization

**Objective 2.3:** Develop a set of relationships that resolve different degrees of organization using metrics derived from the flow regime

I will develop a series of relationships between flow metrics (objective 2.2) and measures of organization (objective 2.3) that describe individual channel units in addition to reach-scale organization. For example, a diagram of channel unit regularity vs percentage of time spent above the unit-mobilizing discharge might be one way to resolve scatter among systems with different flow regimes and boundary conditions, but similar channel units (fig 8a). Multiple channel types could then be evaluated at the reach-scale by comparing organization (e.g., the regularity or sequencing of channel units) with an organizational flow metric (e.g., hydrograph shape, distribution of organizing flow over time) (fig. 8b). Channel type might be separated by boundary conditions such as slope or sediment supply in the latter diagram, which could be useful for predicting the direction and magnitude of channel response to shifts in the flow regime, similar to a state diagram or regime diagram.
Figure 8. Examples of organization vs flow metric diagrams. A) example of channel unit regularity vs the percentage of time spent above the threshold for mobilization of that unit and B) a regime-type diagram with a measure of reach-scale organization on the x-axis (e.g., the regularity of a channel unit) vs an organizational flow metric (e.g., the shape of the hydrograph) with different channel types expressed in different colored X’s and divided by the governing boundary condition, S, which could refer to a measure of slope or sediment supply.

2.4 Sensitivity to changes in the flow regime

Objective 2.4: Identify geomorphic ‘tipping points’ in the flow regime, beyond which the channel might re-organize or ‘un’-organize.

Hypothesis 4: The greatest organizational changes will occur where the hydrograph shifts to flashier, short duration events; whereas regimes that experience a change in the magnitude or frequency of high flows but still maintain a characteristic hydrograph shape will be more stable.

Hypothesis 5: Shifts in the flow regime due to climate change, namely larger and more frequent high flows, may mean that the flow regime will play a larger role in structuring the channel, but not necessarily that the channel will become more organized.

Diagrams described in the previous section can be used to determine how channels will respond to a specific change in the flow regime and will address questions including: Which aspects of the flow regime are most important for maintaining certain channel features? In a planned dam release, what type of flow would preserve or maintain downstream channel features while conserving costs? How much would flow conditions have to change before the channel is pushed towards a new organizational style?

3 Background: Historical Approach to the Flow Regime

“Functional relationships between processes associated with variable channel-flow and resultant channel-form are exceedingly complex...so that sophisticated models, although intellectually satisfying, are often difficult to apply to natural rivers” Carling (1988)

The question “how does the flow regime shape a channel?” has been the subject of a longstanding debate in fluvial geomorphology and river engineering. The complexity to which Carling (1988) refers is the reason this discussion has endured and why the answer to the
question remains somewhat elusive. The idea that equilibrium channels are adjusted to accommodate a single flow, or ‘channel forming discharge’, has persisted since it was introduced by Wolman and Miller (1960) despite considerable debate surrounding both the concept and appropriate measures of the channel forming discharge.

Wolman and Miller (1960) interpreted geomorphic effectiveness to be a measure of the magnitude of sediment transported and degree of surface modification. They defined the ‘effective discharge,’ Q_{eff}, for alluvial streams as the single discharge that transports the most sediment compared to any other discharge for its given frequency of occurrence; although others have offered alternative definitions (e.g., Thornbury, 1954; Dury et al., 1963; Benson and Thomas, 1966; Marlette and Walker, 1968; Ackers and Charlton, 1970a). The Q_{eff} is therefore the maximum of the curve found by multiplying the flow frequency curve by the sediment discharge rating curve (fig. 9).

Since Q_{eff} is difficult to calculate directly because sediment rating curves are costly to collect and analyze, it has been approximated with other measures including the bankfull discharge, Q_{bf}, which is the flow that just fills the channel before spilling onto the floodplain (Williams, 1978), and the discharge of a certain recurrence interval, Q_r. In temperate alluvial streams, the bankfull discharge roughly corresponds to the flow that occurs every 1-2 years on average (Leopold and Wolman, 1957; Wolman and Brush, 1961; Dury 1961; Dury et al., 1963; Woodyer, 1968; Hey, 1975; Andrews, 1980; Leopold, 1994; Castro and Jackson, 2001). Andrews and Nankervis (1995) also found that the effective discharge could be estimated from the bankfull channel and was the flow that mobilized the D_{50} sediment size fraction. Bankfull discharge has therefore been used by geomorphologists, engineers, and managers as a simple way to identify the formative discharge (Leopold and Maddock, 1953; Leopold and Wolman, 1957; Doyle et al., 2007).

Upon further examination, however, the frequency of Q_{bf} varies among streams and along a channel (Harvey, 1969; Williams, 1978; Carling, 1988; Nash, 1994; Petit and Pauquet, 1997; Castro and Jackson, 2001), leading to erroneous estimates of Q_{eff}. The degree to which Q_{eff}, Q_{bf}, and Q_r agree depends on flow variability and channel form. The effective discharge is typically more frequent (<1 year recurrence interval) in flashy systems of the arid southwest (Carlston, 1965; Richards, 1982), whereas less frequent events (2-7 year recurrence interval) are related to channel capacity in spring-fed channels (Harvey, 1969; Petit and Pauquet, 1997). Flashy streams, that have frequent but short duration Q_{eff} events, tend to have smaller Q_{bf}/Q_{eff} ratios and high spread, which refers to the difference between 75% and 25% of total effective discharge (fig 9a) (Doyle et al., 2007). Conversely, snowmelt systems with infrequent long duration Q_{eff} events tend to have high Q_{bf}/Q_{eff} ratios and sharply defined unimodal effective discharge curves (fig 9c) (Doyle et al., 2007). Incised channels tend to be over-sized, therefore Q_{bf} tends to be much higher relative to Q_{eff} in incised channels (fig 9). Since Q_{bf}>>Q_{eff} in incised channels, a wider range of discharges are contained within the channel before spilling onto the floodplain, leading to larger spread in the effective discharge curve (fig 9). While Q_{eff}, Q_{bf}, and Q_r are convenient measures in certain systems, further studies have shown we these metrics don’t sufficiently describe all flow regimes and channel types.
Figure 9. Effective discharge curves for a) upper Lincoln Creek, WI, a flashy, non-incised stream; b) lower Lincoln Creek, WI, a flashy, incised stream; c) Teton River, MT, a non-incised snowmelt stream; d) Carson River, NV, an incised snowmelt river. Legends refer to different sediment transport relations used in the calculation. Dashed lines represent effective, bankfull, and 2-year flows, which are independent of the transport relation used since each effective discharge curve is unimodal and a function of discharge (modified from Doyle et al., 2007).

As an alternative explanation, some have argued that infrequent, high-magnitude events are more geomorphically effective compared to the less frequent, low-magnitude discharges (Baker, 1977). While several studies have observed dramatic and prolonged geomorphic responses to large-magnitude events (Schumm and Lichty, 1963; Stevens et al., 1975; Carling, 1986; Miller, 1990), other work shows that statistically large, rare events may have little to no lasting effects (Costa, 1974; Huckleberry, 1994; Magilligan et al., 1998). The importance of floods to overall effectiveness, therefore, remains uncertain.

Further complicating the debate, some have refuted the definition of effectiveness given by Wolman and Miller (1960), arguing that magnitude-frequency relations ignore landscape modification, which is an important component of effectiveness. An alternative definition of effectiveness is the ability of an event to affect the shape of the landscape and to persist despite restorative forces (Wolman and Gerson, 1978). But because landscapes reflect such a wide range of boundary conditions, there remains no universal measure of effectiveness nor a quantitative framework that describes effectiveness in all systems.

Perhaps rather than identify a single flow that describes the channel, the entire flow regime and associated channel-forming processes should be considered. As Pickup and Rieger (1979) point out, channel form reflects a range of hydrologic processes that operate over multiple flows, rather than a single flow. Yet, besides the conceptual model provided by Pickup and Rieger (1979), the degree to which the full flow regime systematically shapes a channel has not received rigorous quantitative treatment. If the flow that transports the most sediment is not always the
flow that fills the capacity of the channel and if in fact those measures are oversimplifications themselves, our question becomes: what combination of channel-organizing flow conditions might better describe the hydrologic processes that shape a channel?

4 Methods

A coordinated set of field measurements and flume experiments will provide the foundation for the analysis and will precede the numerical modeling component, which will be used to validate findings and examine the relative importance of sediment discharge in structuring a channel.

4.1 Field Study: Quantifying organizing flow conditions in mountain headwater streams

The purpose of the initial field study is to relate flow metrics to fluvially organized features in gravel-bed streams with distinctive flow regimes. I plan to make detailed geomorphic surveys to characterize the type of channel features present and their regularity. From the hydrograph and geomorphic measurements, I will extract flow metrics and thresholds. Together, hydrologic and geomorphic channel characterization will provide convergent lines of evidence towards defining the geomorphically effective flow regime.

The motivating questions behind the field component of the dissertation include:

• How do transport dynamics and thresholds differ between spring-fed and surface-runoff systems? (e.g., When does material move? How often is sediment mobile? How much is mobilized by different flows?)

• Which system is most sensitive to changes in the flow regime? (e.g., Where might I expect more frequent bed disturbance or significant re-structuring under modeled flow scenarios?)

• How does channel form differ between the two systems at the reach-scale? (i.e., How do cross-sectional geometries, bed textures, sources of roughness, and channel unit type/spacing differ among the systems?)

Initial field sites will be located in the Oregon Cascades, an ideal natural laboratory to study how differences in the flow regime translate to differences in stream channel morphology because spring-fed systems with stable discharge regimes can be found within the same landscape as surface-runoff systems with more variable discharges (fig. 10) (Manga, 1996; Tague and Grant, 2004; Jefferson et al., 2006).
The unique hydrogeology of the region reflects the underlying geology composed of two distinct provinces: the highly permeable, low relief high Cascades and the resistant, deeply dissected Western Cascades (Harr, 1977; Priest et al., 1983; Jefferson et al., 2006) (fig. 11).

Figure 10. Daily streamflow hydrographs, normalized by drainage area for predominantly High Cascades (McKenzie River) and Western Cascades (Little North Santiam) rivers. Modified from Tague and Grant (2004).

Figure 11. Map of study watersheds. Surface-runoff watersheds outlined in orange and spring-fed watersheds outlined in purple.
Besides observed hydrogeologic differences, spring-fed and surface-runoff streams in the Cascades have distinctly different channel structures (fig. 12). Based on field observations and limited published data (Whiting and Stamm, 1995; Manga and Kirchner, 2000; Whiting and Moog, 2001), spring-fed streams tend to have rectangular cross-sections, a multi-threaded thalweg, frequent in-channel wood with no indication of fluvial re-working (i.e., no jams, not oriented with the flow), frequent submerged or embedded wood, a narrow grain size range, absence of cobble-sized clasts or larger (>256mm), deeply undercut banks, and lack of discernable bedforms. In contrast, surface-runoff channels tend to have V-shaped cross sections, a well-developed single-thread thalweg, fluvially re-worked wood jams, very little submerged wood and no embedded wood, a wide grain size distribution, very little bank undercutting, and the presence of bedforms that include steps, pools, rapids, and cascades. The goal of the field study with be to rigorously quantify differences in the types of channel features present and their regularity along each channel. Channel differences also extend to aquatic organisms; spring-fed channels have measurably different taxonomic compositions of aquatic insects compared with surface-runoff channels and flow regime type is also associated with life-history differences (Yamamuro, 2009).

**Figure 12.** Photos of surface-runoff (Boulder Creek, West side) and spring-fed streams (Jack Creek, East Side). Photos by Laura Hempel

### 4.2 Flume Experiments

Flume experiments will complement field studies and will be used to identify hydrologic controls on channel form development. I will conduct a series of flume experiments with mobile coarse-bed channels to explore how a series of different shaped hydrographs (i.e. sharp peak, sustained peak, or flat) result in different channel forms and textural adjustments to the bed. My approach will be similar to Hassan et al. (2006), however I will examine the added dimension of flow sequencing, not just adjustment over a single hydrograph. Gravel will be well-sorted and re-circulated to reflect sediment conditions in natural streams. Results from flume experiments will allow me to develop quantitative relationships between key hydrologic parameters developed during field measurements, and thresholds that constrain bed form evolution over a series of hydrographs.
4.3 Numerical Modeling

Finally, I will use a 2D numerical model of sediment transport and channel stability (MD_SWMS) to explore channel organization, morphology, and stream habitat response to varied flow regime (McDonald et al., 2005). Simulations will allow me to track the development, maintenance, and destruction of specific channel features over multiple hydrographs and under a changing flow regime scenario. I will also examine channel response to changes in the supply and caliber of sediment supplied to the channel, which is difficult to achieve in natural channels under close observation. Results from the MD_SWMS model will validate conclusions from field and flume observations and will allow me to compare the relative importance of sediment supply to flow regime in predicting channel form over extended timescales.

5 Project Timetable

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6. Broader Impacts and Anticipated Products

6.1 Broader Impacts

The degree to which the natural flow regime controls stream channel morphology is an important issue given the pace and scale of flow alteration in recent decades. In the United States, for example, less than 2% of rivers remain un-modified (Graff, 1993). The effects of flow alteration on channel morphology, largely caused by the >2.5 million water-control structures in the US, have been pronounced and are well documented in the literature (Brandt, 2000; Pizzuto, 2002; Doyle et al., 2003; Grant et al., 2003; Petts and Gurnell, 2005). Pervasive and costly changes to the flow regime from dam operations, land-use change, and climate change underscore the need for further study.

Some of the most pronounced effects of altered flow regimes can be found downstream of dams, which increase base-flows and smooth flood peaks (Magilligan and Nislow, 2005). For example, nearly all sandbars along the Colorado River were eroded following construction of the Glen Canyon Dam, resulting in a 44% loss of campsite capacity (Kearsley et al., 1994). The sandbars have since been rebuilt during high-flow releases, although intervening elevated base-flow periods undermine sandbar enrichment (Hazel et al., 2010).

Channel response to urbanization is another example of how shifts in the flow regime lead to channel change. Urbanization typically leads to increases in the peak and duration of high flows and has been linked to channel widening, incision, and planform shift from single-thread to braided (Hammer, 1972; Booth, 1990; Hawley, 2009). Of course, intertwined with changes in the flow regime are changes in sediment supply, which has been shown to influence important elements of channel organization including channel stability, slope, and bed texture (e.g., Parker and Klingeman, 1982; Dietrich et al., 1989; Church et al., 1998; Buffington and Montgomery, 1999; Madej, 2001; Lisle et al., 2000; Church, 2006). For example, the trapping efficiency of dams can range from 33% to 99% for individual storms (Raush and Hainemann, 1975), which reduces supply downstream. I plan to address the relative importance of sediment supply to channel organization using numerical modeling (section 4), although the focus of this study remains on how streamflow influences channel form.

Climate change is another global driver of streamflow change with yet unrealized consequences to channel morphology. In North America, for example, an ensemble of 12 GCM’s projects a 10-40% increase in runoff in northern North America and a 10-30% decrease in western north America by 2050 (Milly et al., 2005). The way these changes will be manifest over the annual hydrograph depend on local factors such as geology, topography, ecology, and drainage network type, although the largest changes are generally predicted for snow-dominated basins where quickly melting snow will cause earlier and larger spring floods (Nijssen et al., 2001; Stewart et al., 2005; Hamlet and Lettenmaier, 2007). In the Pacific Northwest, for example, winters are projected to become wetter, the spring snowmelt peak flow will occur 1-4 weeks earlier in the season, and summer drought will become more severe and occur earlier in the season (fig. 1) (Stewart et al., 2005; Tague and Grant, 2009). Climate change will therefore lead to potentially major but poorly understood changes to flow regimes, even less understood are the impacts to channel morphology. The products of this research will not only be useful for predicting how
channels might change with respect to modeled changes in flow, but also for identifying potential geomorphic tipping points.

As a consequence of changes in the flow regime, physical habitat created and maintained under the natural flow regime has been degraded, which has led to a decline in the ecological integrity and biodiversity of streams (Poff et al., 1997; Bunn and Arthington 2002; Lytle and Poff, 2004; Bragg et al., 2005; Poff and Zimmerman, 2010). To use the Pacific Northwest as an example, a recent review of climate change found clear impacts on salmon and trout populations attributed to increasing peaks flows (ISAB, 2007). As a result of increased winter flows, the magnitude and frequency of streambed scour depth are predicted to increase in mountain streams (Tonina et al., 2008; Goode et al., 2013), which may disproportionately impact egg survival to emergence in fall spawners (e.g., coho and Chinook) and smaller bodied species with shallow egg burial depths, such as bull trout (Holtby and Healey, 1986; Montgomery et al., 1999; Tonina et al., 2008). Furthermore, shifts in the flow regime that lead to changes in reach-scale properties including bed texture, bed stability, and channel type can impact both habitat availability and egg survival (Montgomery, 1999; Curry and MacNeill, 2004; Buffington et al., 2004).

The impacts of climate change and shifts in the flow regime on stream channels are not well understood. Perhaps most concerning are projections that changes in river discharge, due to climate and increased water demands, will impact every populated basin in the world, and the most severely impacted basins will require proactive management to minimize risks to the nearly one billion people who live in vulnerable regions and to river ecosystems (Palmer et al., 2008). In light of pervasive and predicted changes to the natural flow regime, a richer and more complete understanding of the hydrologic processes that shape a channel is needed to improve river conservation and management practices. By studying how stream channels integrate a variety of flows, our research will determine where and how channels are expected to change.

### 6.2 Anticipated Products

The end product of this research will be an accessible, comprehensive, quantitative framework that describes channel form as a function of hydrologic regime. A comprehensive framework that describes channel organization as a function of the full complement of flows would be invaluable for predicting channel response to changing flow regimes caused by dams, land management, and climate.
My strategy to maximize the impact of my findings, which will predict channel form response to changes in flow regime, will be a two-fold focused effort:

1) **Seek out scientists and agencies who would benefit the most from an executable plan for preserving or restoring key channel structures.** In the near-term, I will promote my findings where there is an immediate need for stream conservation or restoration. For example, a predictive model would be indispensable to stream ecologists or dam removal agencies searching for the most effective solution to restore stream habitat for declining fish or benthic invertebrate populations. Once my model gains traction on a small-scale, I will explore longer-term applications in, for example, dam management schemes or climate change projections.

2) **Educate elementary-aged students on the importance of rivers and different discharges through guided nature hikes and hands-on flume activities.** I will draw from my research experience to engage future leaders through a graduate service-learning program, of which I am currently a member.
7. References


