A Geological Framework for Interpreting Downstream Effects of Dams on Rivers

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Despite decades of research and abundant case studies on downstream effects of dams on rivers, we have few general models predicting how any particular river is likely to adjust following impoundment. Here we present a conceptual and analytical framework for predicting geomorphic response of rivers to dams, emphasizing the role of geologic setting and history as first-order controls on the trajectory of change. Basin geology influences watershed and channel processes through a hierarchical set of linkages, extending from the drainage basin to the valley and channel, which determine the sediment transport and discharge regimes. Geology also directly shapes the suite of hillslope processes, landforms, and geomorphic disturbances impinging on the channel and valley floor. These factors, in turn, affect the "lability" or capacity for adjustment of the downstream channel, determining the type, direction, and extent of channel adjustments that occur, including incision, widening, and textural changes. We develop an analytical framework based on two dimensionless variables that predicts geomorphic responses to dams depending on the ratio of sediment supply below to that above the dam ($S*$) and the fractional change in frequency of sediment-transporting flows ($T*$). Drawing on examples from the Green, Colorado, and Deschutes Rivers, we explore how trajectories of geomorphic change, as defined by these two variables, are influenced by the geological setting and history of the river. This approach holds promise for predicting the magnitude and trend of downstream response to other dammed rivers, and can identify river systems where geological controls are likely to dominate.

INTRODUCTION

Because dams influence the two primary factors—water and sediment—that determine the shape, size, and overall morphology of a river, they represent fundamental interventions in the fluvial system. Decades of research on effects of dams on rivers have yielded abundant case studies of down-

stream response to impoundment, but there are few general models that predict how any particular river is likely to respond once a dam is in place. Geomorphic theory and previous studies provide some basis for predicting general trends, but case studies are distinguished as much by variation as consistency in response [*Williams and Wolman*, 1984].

Dams alter two critical elements of the geomorphic system: the ability of the river to transport sediment and the amount of sediment available for transport. If the transport capacity exceeds the available supply, a sediment deficit exists and the channel can be expected to evacuate sediment from its bed and/or banks. If the transport capacity is less than the available sediment supply, then the channel can be expected to accumulate sediment. There are many adjustable attributes of a channel—its cross-section, bed material, planform, and gradient—and the response of a channel to sediment deficit or surplus varies. [*Petts*, 1980, 1982; *Willams and Wolman*, 1984; *Carling*, 1988; *Brandt*, 2000]. Typical downstream responses can include channel bed degradation or incision, textural changes such as coarsening or fining of surface grain-size distributions, and lateral adjustments, including both expansion and contraction of channel width.

Grams and Schmidt [2002] showed that the magnitude and style of adjustment varies with geomorphic organization of the fluvial system, even where the magnitude of the sediment budget does not change. Although planform or textural changes can occur, there are also instances where dams have little or no effect on channel morphology [*Williams and Wolman*, 1984; *Inbar*, 1990; *Fassnacht et al.*, this volume]. In such cases, it is often possible to identify *post facto* why the dam had little effect, such as little change in the frequency and magnitude of geomorphically effective flows, presence of bedrock or other resistant channel boundaries, or intrinsically low sediment transport rates.

But despite both theory and ample case studies, there are few means of predicting in advance of construction or investigation which dams will result in small versus large adjustments downstream. Such general predictive models or frameworks are essential as core components of environmental analyses accompanying either new dam construction or assessments of existing dams. The need for such predictions of dam effects is growing as new dams are constructed, particularly in developing countries. During the 1990s, an estimated $32-46 billion was spent annually on large dams, four-fifths of it in developing countries [*World Commission on Dams*, 2000]. In these locales, data and technical resources are limited, prompting the need for general assessment tools and methods. Although virtually no new dams are presently being constructed in the U.S., on-

going relicensing of non-Federal hydropower dams by the Federal Energy Regulatory Commission, reconsideration of operating strategies for Federal dams such as those on the Missouri River [*National Research Council*, 2002], and growing scientific and public interest in dam removal [*Heinz Center*, 2002] are all focusing attention on dams and their downstream effects.

Existing approaches for assessing impacts of dams have almost exclusively emphasized empirical relationships relating pre- to post-dam hydrology to predict response, which is usually defined in terms of some change in channel cross-sectional geometry, grain size, or sediment storage. In their classic paper, *Williams and Wolman* [1984] describe general empirical trends in timing and magnitude of downstream channel adjustments, particularly bed degradation and channel narrowing, following dam construction, but variability in downstream response is high, and the authors note many exogenous factors, such as vegetation or bedrock, that can affect these trends. *Brandt* [2000] proposed a classification scheme for distinguishing geomorphic effects downstream of dams based loosely on *Lane's* [1955] conceptualization of the balance between grain size, sediment load, discharge, and channel slope. Though rooted in established principles, this approach relies on determining sediment transport capacity and influx, quantities that may vary spatially in relation to tributary influences and external controls.

Lacking in these approaches, however, is almost any reference to the geological setting of dams and dam-affected reaches as a factor controlling channel response. Motivated by studies of dams in the Deschutes River basin in Oregon [*Fassnacht et al.*, this volume], in this paper we explore the relation between the downstream response of rivers to dams, the overall geologic setting of the watershed, and the specific locations of dams within that watershed. We begin with a framework for interpreting how geology affects both the hydrologic and sediment transport regimes of basins in ways that influence channel morphology downstream from dams, and present a simple model derived from this framework that may be useful for predicting specific directions and magnitudes of downstream effects. Finally, we illustrate these points, drawing on examples from several dammed western rivers, and consider how this framework can be used in a predictive capacity.

A GEOLOGIC FRAMEWORK FOR INTERPRETING GEOMORPHIC EFFECTS OF DAMS

As a means of exploring how geology affects channel response to dams, we begin by examining the role of geology in influencing channels at a range of scales, independent
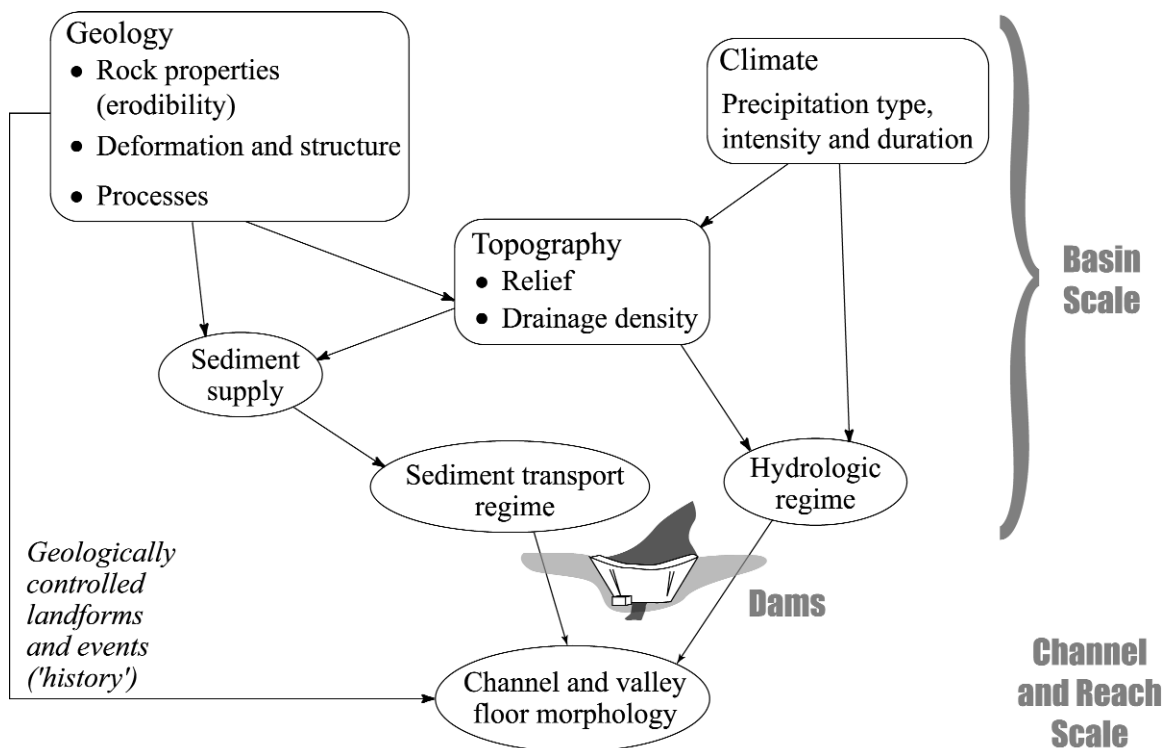
Figure 1. Conceptual model of hierarchical linkages influencing channel and valley floor morphology. Dams can direct-ly modify the hydrologic and sediment transport regimes.

of dams or other human impacts. The geology of a water-shed exerts first-order controls on watershed and channel processes through a hierarchical set of linkages (Figure 1). At the scale of the drainage basin, the geology, including both the physical properties of the underlying rocks and their structural features and tectonic deformation, interacts with climate to produce topography, including relief and the drainage network pattern. The hydrologic regime of a water-shed, defined as the frequency, magnitude, timing, duration, and variability of streamflows, results from the interplay between the topography and climate. Key factors control-ling the discharge regime are the volume and phase of water storage on the landscape, with lakes and groundwater as important storage reservoirs for liquid water, and glaciers, ice, and snowpacks as storage for solid water. Also at this largest scale, the geological properties of rocks, such as their composition, degree of weathering, and relative hardness interact with climate to determine both the grain size distri-bution and rate of supply of sediment to the stream system.

At basin and finer scales, the hydrology and sediment delivery processes interact to determine the sediment- trans-port regime, including the frequency, volume, timing, and grain-size distribution of sediment transport. Hydrology interacts with sediment transport and delivery at the scale of the valley floor to give rise to a suite of alluvial landforms, including terraces, floodplains, bars, and islands which, in turn, feedback on the in-channel hydraulics and transport regime. So in the broadest sense, the geology and climate are coupled through a hierarchical set of processes and land-forms to control the hydrologic and sediment-transport regimes within the channel.

Geology also exerts a first-order control on the valley floor and channel through two other related mechanisms. First, geology directly affects the suite of hillslope process-es and landforms that impinge on the channel and valley floor. Such processes can include large landslides and earth-flows that can move blocks or masses of material into the channel, or debris flows that rapidly bring coarse material down tributaries, resulting in constrictions, blockages, or natural dams [*Swanson et al.*, 1985; *Kieffer*, 1985; *Schmidt and Graf*, 1990; *Schmidt and Rubin*, 1995; *Grant and Swanson*, 1995]. Other landforms may include resistant bedrock outcrops, forming cliffs or canyons. Wide valleys form where the surrounding rock is soft and easily erodible.

All of these features result directly from geotechnical properties of the surrounding rock. In the case of large earth-flows, landslides, and debris flows such properties can include the proportion of clay, shear strength, and water-holding capacity and permeability of the regolith and weathered material. Crystalline, highly dense, or cemented rocks, on the other hand, give rise to resistant outcrops. The geotechnical properties of the rock can thus be directly related to the morphology and character of the river canyon [*O'Connor et al.*, this volume].

Geology also controls valley floor and channel features through a second, related mechanism: the specific history of geologically mediated disturbances to the river bottom. These can include mass movements and debris flows as above, but may also involve more exotic events such as volcanic lahars, lava flows, and glacial-outburst floods. Whether or not a particular river is subject to these events is defined primarily by its geographic setting in relation to volcanoes or glaciers where such events commonly initiate. The Deschutes River in central Oregon, for example, drains the eastern margin of an active volcanic arc located in a northern latitude temperate zone. Because of this, the river canyon has received floods from a wide variety of geological mechanisms, including lahars, glacial outbursts, and landslide dam outbreaks, as well as meteorologically driven events [*O'Connor et al.*, this volume]. These disturbances are, in turn, recorded in the stratigraphy and distribution of valley bottom features, including floodplains, terraces, flood bars, etc., that both define the current channel morphology and constrain the channel's lateral and vertical adjustments and movement [*Curran and O'Connor*, this volume].

By this view, geology is an underlying control on both the hydrologic and sediment-transport regimes of a channel as well as the form of the channel itself and, to some degree, the extent to which it can adjust its boundaries. How do dams figure into this framework? We propose that dams both modify the underlying geologically controlled transport regimes and introduce new processes into the channel system—in essence acting in the latter case as a type of geological disturbance. The consequence is that rivers downstream of dams are responding not only to the "native" discharge and sediment transport regimes but to those introduced by dams as well. A direct corollary of this is that downstream effects of dams on rivers can be scaled by the degree to which the dams change the pre-dam flow and transport regimes. This is not a new concept; most analyses of geomorphic effects of dams have recognized that the effect of any given dam is in some way related to the degree to which it alters the hydrograph and flux of sediment through the system [*Petts*, 1980, 1982; *Willams and*

Wolman, 1984; *Carling*, 1988; *Brandt*, 2000]. But we maintain that understanding the geomorphic effect of any given dam requires that the specific changes in hydrology and sediment flux caused by the dam be placed within a larger geological framework which includes broader-scale controls on the source and volume of water and sediment both upstream and downstream of a dam, and the geologically-mediated disturbance regime and history. In short, the downstream effects of a dam cannot be analyzed solely by looking at the dam effects independent of its broader geological setting (Figure 1).

Consider, for example, how the large-scale organization of watersheds and the distribution of runoff- and sediment-producing areas influence the effects of dams in the Colorado River and Rio Grande River basins. In these basins, streamflow arises in the Rocky Mountains at the exterior boundaries of the watershed and sediment is delivered to the mainstem by lower elevation tributaries that drain deserts [*Iorns et al.*, 1965; *Schmidt et al.*, in press]. Thus, streamflow does not significantly increase in the downstream direction despite a downstream increase in sediment delivery to the channel. Dams located in the headwaters of these watersheds control streamflow but not sediment delivery. Further downstream, dams such as Glen Canyon and Hoover Dams on the Colorado and Elephant Butte Dam on the Rio Grande control most of the sediment, as well as water flux. So dams in the headwaters can be expected to have a different range of impacts than those located further downstream, as illustrated below in the contrasting cases of Flaming Gorge and Glen Canyon Dams.

To expand on this, the geological framework greatly influences several key factors determining what we call the "lability" of the downstream channel—its capacity for adjustment. Specifically, the lability of the channel is a function of: 1) the transportability of the bed sediment, which is indexed by its grain size relative to the shear stresses exerted by the flow across the full spectrum of the discharge regime; 2) the erodibility of the bed and banks, as influenced by their cohesiveness and/or the prevalence of bedrock; and 3) the opportunity for lateral mobility, within the limits of the overall width and topography of the valley floor. Taken together, these factors determine where and to what extent channel adjustments below dams (such as incision, widening, and textural changes) can occur, and, as discussed above, all are at least partially under geological control. The grain-size distribution of sediment, for example, reflects both the balance of forces between the flow regime and the sediment supplied from upstream and locally, and the geologically mediated disturbance history. A history of large landslide dam collapse floods, as observed in rivers

such as the Deschutes [*O'Connor et al.*, this volume] or the Middle Fork Salmon [*Meyer and Leidecker*, 1999] can leave coarse bouldery lag deposits along and within the channel that are outside the range of competence of the modern discharge regime. These deposits effectively "freeze" the channel position by constraining both the lateral and vertical movement of the channel. Under these circumstances, dam-imposed changes on either the sediment flux or flow regime are likely to have only minor effects on channel position (although other types of effects are still possible).

Geology may also control sediment sources within a watershed that influence downstream channel changes. On the Trinity River in Northern California, influx of fine-grained sediments derived from a weathered granitic terrain just below the Lewiston Dam results in deposition of sand on the bed of the channel. Prior to reservoir regulation, this sand would have been transported rapidly downstream during high peak flows; post-regulation it is widely stored as patches and deposits within the gravel channel bed, where it affects sediment transport rates and aquatic habitat [*Pitlick and Wilcock*, 2001]. These downstream effects are influenced by, but cannot be uniquely attributed to, flow regime modification at the dam itself, and require a broader view of the dam's location relative to downstream versus upstream sediment sources.

To summarize, *hydrogeomorphic changes*—changes in discharge and sediment-transport regimes—induced by dams and their operation are only part of the equation for predicting downstream impacts. The geological setting of dams within the watershed also contributes, both in the sense that the geology strongly influences the distribution of water and sediment sources within the watershed, and because potential adjustments of the downstream channel are strongly influenced by the geologically mediated disturbance history (Figure 1).

COMBINING HYDROGEOMORPHIC AND GEOLOGIC CONTROLS TO PREDICT DOWNSTREAM IMPACTS OF DAMS

Given the complexities of factors contributing to channel adjustments downstream of dams, rigorous predictions of dam-related geomorphic impacts have proven difficult [*Brandt*, 2000]. Here we suggest a simple conceptual model of downstream channel changes due to dams in response to both hydrogeomorphic changes and geological controls. We begin by considering dam effects on flow and sediment supply alone. To interpret dam effects, each hydrogeomorphic variable must be scaled by how operation of a dam has influenced it. Although dams can affect the entire flow fre-

quency distribution, a downstream geomorphic response is most likely where the geomorphically effective flow regime [*sensu Costa and O'Connor*, 1995; *Andrews and Nankervis*, 1995] has been altered—that is, a change in the frequency and magnitude of flows that are capable of mobilizing and transporting sediment. Change in these flows can be usefully indexed as the fraction of time T that flows (Q) are greater than the critical flow (Q_{cr}) for sediment transport, expressed as:

$$T = \frac{\sum t_{(Q \geq Q_{cr})}}{\sum t_Q} \tag{1}$$

where t_Q refers to time at flow Q. Changes in the frequency of critical flows can then be compared as the dimensionless ratio (T^*) between the pre-dam (T_{pre}) and post-dam (T_{post}) frequency of sediment-transporting flows:

$$T^* = \frac{T_{post}}{T_{pre}} \tag{2}$$

In general $T^* \leq 1$, since $T_{pre} \geq T_{post}$, both because dams typically suppress peak flows and because coarsening and armoring of bed sediment below dams increases Q_{cr}. Dams that increase daily flows on rivers where sediment transport occurs frequently (as with sand or finer transport regimes) can have $T^* > 1$, as in the Green River example discussed below. Actual calculation of T^* can be difficult, since sediment moves over a range of discharges as a function of the grain-size distribution, and the grain size distribution below a dam may change with time in response to textural adjustments. Although partial sediment transport rates have been calculated for some rivers below dams [e.g., *Andrews*, 1986; *Wilcock et al.,* 1996], the usual practice is to index transport to a specific grain size (D_{50} or similar) and then calculate the frequency of transporting events based on empirical or theoretical sediment transport equations [e.g., *Fassnacht et al.*, this volume].

The question of which grain size T* should be indexed to relates directly to the specific resource issue under consideration, as discussed below. For example, this grain size will vary depending on whether a dam is being evaluated for its impacts on spawning gravels for fish as opposed to sand beaches for recreationists.

Turning to the effect of dams on sediment supply, most large dams trap virtually all of the sediment delivered from upstream into the reservoir, although trap efficiencies for smaller dams can range from 10-90% or higher [*Brune*,

1953; *Meade et al.*, 1990). In predicting downstream effects of moderate to large-sized dams, considered here as dams larger than approximately 10^7 m^3 of storage [*sensu Graf*, 1999], virtually all sediment is assumed to be trapped by the reservoir. In this case, downstream impacts due to truncated sediment supply from upstream are most directly influenced by the rate at which sediment is re-supplied to the channel from tributaries, hillslopes, and channel erosion. This relation can also be expressed as a dimensionless supply ratio (S*) of the below-dam sediment supply S_B to the above-dam sediment supply S_A, at a particular location below the dam:

$$S^* = \frac{S_B}{S_A} \qquad (3)$$

Where S_A is low—that is, where background sediment supply rates from the surrounding landscape are naturally low or sediment is intercepted by upstream reservoirs—then S* will primarily vary with S_A, which depends on the volume of sediment delivered to channels by downstream tributaries relative to what was coming down the river from upstream. Where S_A is large—that is, where dams are located in highly erosive terrain—S* will almost invariably be small, at least until downstream tributaries have contributed enough sediment so that S_B approaches S_A.
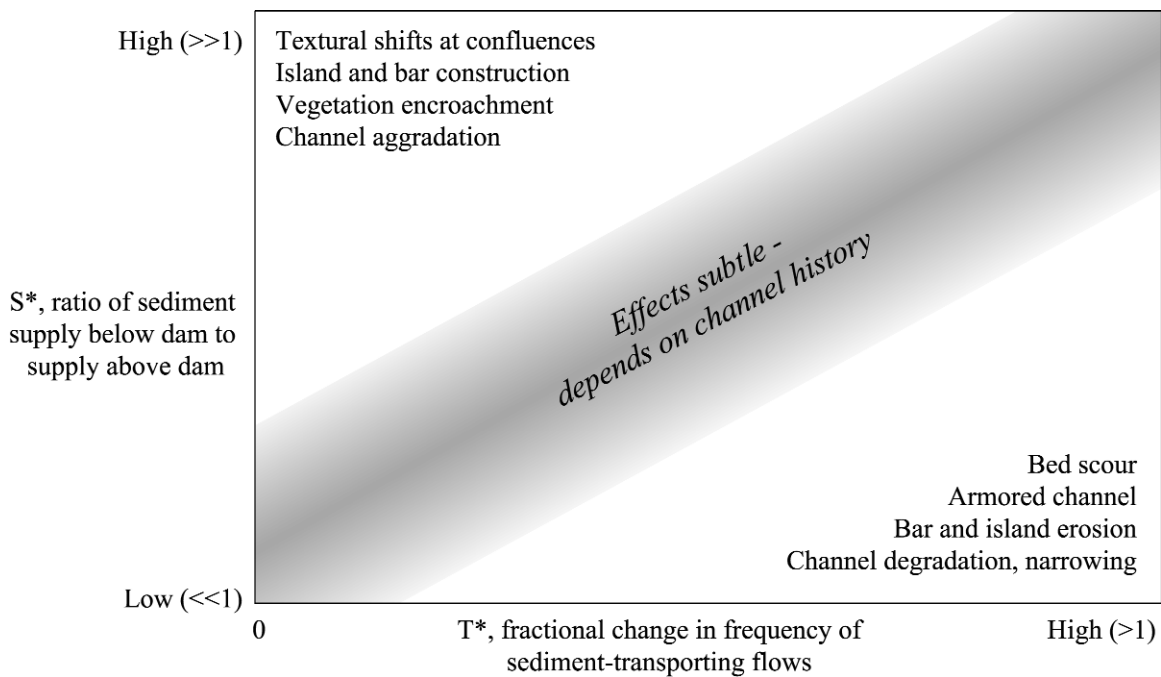
Geomorphic response to changing sediment supply alone can reflect a full spectrum of channel adjustments, from subtle textural shifts in the grain-size distribution on the bed (increased armoring or fining) to changes in within-channel storage of sediment, to changes in channel planform (widening or incision) to complete shifts in channel pattern (meandering to braided or vice versa). Although exact thresholds in sediment supply at which these transitions occur in the continuum of responses can be difficult to discern, overall trends and directions are well established (Figure 2).

Predicted downstream effects of dams in relation to these two variables—flow and sediment supply—can therefore be thought of in terms of a bivariate plot of T* and S*, with end-member cases identified in a continuum of possible responses (Figure 3). As discussed below, both T* and S* can change with distance downstream, but can be initially evaluated with respect to the first several kilometers below a dam. Where sediment transport events occur frequently under the altered flow regime, and downstream sediment supply is low relative to upstream supply (lower right-hand corner), increased coarsening/armoring of the bed and possibly erosion of channel bed, bar, and island deposits should occur [*Leopold et al.*, 1964; *Williams and Wolman*, 1984; *Galay et al.*, 1985]. Where sediment-transporting flows are infrequent and downstream sediment supply is high (upper left hand corner), predicted channel responses include channel aggradation, [*Church*, 1995; *Collier et al.*, 1996], widening [*Petts*, 1979, 1980; *Xu*, 1996], and/or abrupt shifts in the longitudinal pattern of surface bed material near sediment sources [*Church and Kellerhals*, 1978; *Petts*, 1984]. Bars
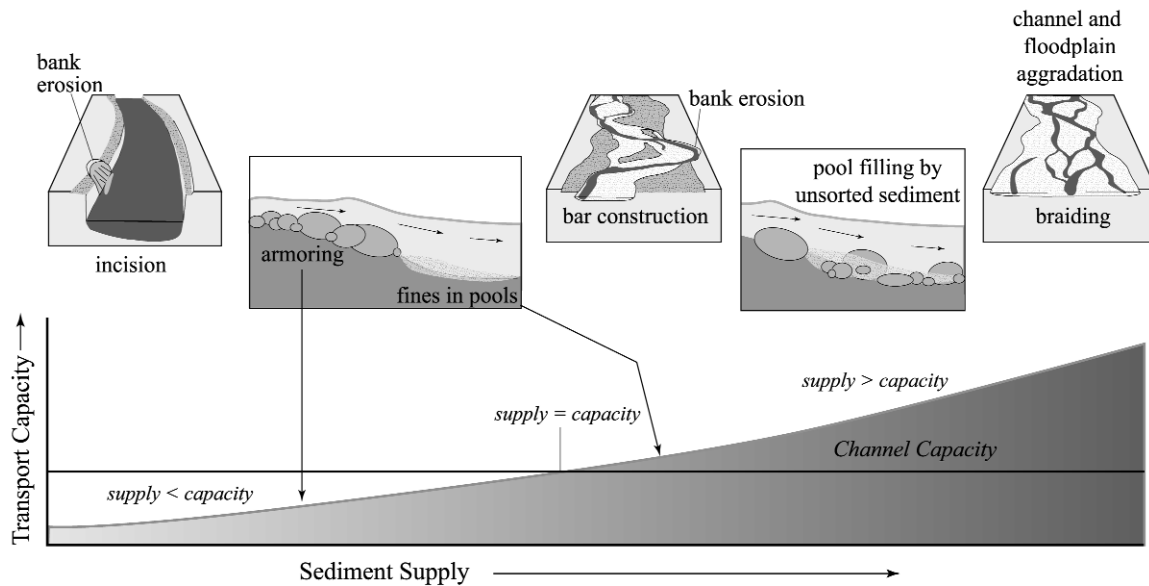
Figure 2. Expected textural, bedform, and planform adjustments of alluvial rivers in response to changing sediment supply in relation to transport capacity.

High (>>1)   Textural shifts at confluences
Island and bar construction
Vegetation encroachment
Channel aggradation

S*, ratio of sediment
supply below dam to
supply above dam

*Effects subtle –
depends on channel history*

Bed scour
Armored channel
Bar and island erosion
Channel degradation, narrowing

Low (<<1)

0   T*, fractional change in frequency of   High (>1)
sediment-transporting flows

Figure 3. Response domain for predicted channel adjustments in relation to the fractional change in frequency of sediment transporting flows (T^*) and the ratio of sediment supply below a dam to supply above the dam (S^*). End-member textural and morphologic adjustments are shown. Response of rivers plotting in the shaded diagonal region is likely to be strongly influenced by geological factors, including the history of floods and landslides leaving legacies of out-sized material and bedrock incision in the valley and channel bottom.

and islands may form near tributary confluences. Where both the frequency of sediment transport events and sediment supply are low, there may be little or no change to the downstream channel, other than subtle textural shifts in the grain size distribution. On the other hand, high introduced sediment loads and frequent transport events may give rise to poorly sorted or armored channels with abundant fines [*Dietrich et al.*, 1989].

But within the central domain of this plot, downstream adjustments will be unpredictable, since these will be strongly determined by the relationship between the sediment supply and flow competence and capacity, both of which are likely varying in time and space. In particular, changes due to dams may be offsetting, as where a reduction in flow peaks or volumes is coupled with a decrease in sediment supply. Under these circumstances, little geomorphic change may result. A further consideration is that sediment re-supplied to the channel may not be of the same grain-size distribution as that which the dam removes, as in the case of the Trinity River downstream of Lewiston Dam [*Pitlick and Wilcock*, 2001]. This has the effect of changing Q_{cr}, hence T^* as well as S^* for the downstream channel. Similarly, if

flow or sediment input regimes change markedly below a dam, as, for example, if the dam is located near the boundary between different hydrologic or geomorphic regions [*Riggs and Harvey*, 1990], both T^* and S^* can also change downstream. This suggests that plots of individual dams in T* and S* space might best be thought of as describing trajectories of change, as suggested by *Madej* [2001] and discussed below, rather than individual points (Figure 3).

We maintain that the large indeterminate region in the response field of T*-S* space is the main reason for the wide variance in downstream responses to dams. It is within this indeterminate domain that clear trends in downstream responses are most likely to be difficult to detect, and where the geologically mediated channel history is most likely to assert a controlling role. In particular, within this central region, past events, such as large floods, landslides, and bedrock incision, may result in anomalously resistant or erodible channel and valley materials that either restrict or augment channel adjustment to altered regimes. In the next section, we examine some examples of how the geologic setting affects the direction and magnitude of downstream response.

EXAMPLES OF DOWNSTREAM RESPONSE TO DAMS: THE ROLE OF GEOLOGY

For reasons discussed earlier, precise values of T* and S* can be difficult to obtain. It is possible, however, to use existing literature and inference to plot approximate trajectories of individual dams and rivers in T* and S* space. For example, critical discharges (Q_{cr}) for many gravel-bed channels are at or slightly less than bankfull stage, flows that typically occur several times each year [*Andrews*, 1980, 1983, 1984, 2000], while sand-bed rivers typically have critical discharges that occur much more frequently over the entire range of flows [*Bennett*, 1995]. Most sand- and gravel-bed rivers for which flow has been significantly regulated would therefore plot towards the right-hand side of Figure 3. Assuming that reservoir trap efficiencies are high, the plotting position on the y-axis will vary in relation to downstream sediment supply. As discussed above, sediment input can change with distance downstream as successive tributaries enter the channel, so that S* typically increases downstream.

By our analysis, interpreting the downstream effects of dams will strongly depend on the downstream trajectories of both T* and S*. In fact, we propose that the slope of the trajectory of change in T* and S* space constitutes a characteristic predictor of the downstream response. Here we focus on how T* and S* change longitudinally for three different rivers, and compare trajectories and downstream responses to dams for the Green, Colorado, and Deschutes Rivers. We consider how these trajectories and responses reflect the underlying geological settings of these three rivers. For comparison we consider both the absolute longitudinal distance (L) and dimensionless distance (L*), the latter scaled by a characteristic length which we take as the channel width (W_c), or $L* = L/W_c$.

Green River, Utah

Flaming Gorge Dam is located on the upper Green River and completely traps sediment delivered to the river from the mountains and deserts of western Wyoming and the north flank of the Uinta Mountains of Utah. *Andrews* [1986] calculated the change in sediment supply, effective discharge, and sediment transport for pre-dam and post-dam periods, and identified reaches of differing balance between sediment supply and sediment transport capacity. His analyses have been updated and the extent of associated channel changes examined in detail by *Lyons et al.* [1992], *Orchard and Schmidt* [1998], *Allred and Schmidt* [1999], and *Grams and Schmidt* [1999, 2002]. Although some of *Andrews'* [1986] sediment budget numbers have been revised by these

more recent studies, we use his 1986 data here because it encompasses the entire 464 km from Flaming Gorge to the Green River (UT) gage; use of this earlier data does not change the underlying story as revealed by later work.

Andrews [1986] defined three different downstream reaches, bounded by USGS gaging stations: Reach 1 from Flaming Gorge Dam to the Jensen gage (termed the Brown's Park reach in this study, with initial flow and sediment measured at the Greendale gage); Reach 2 from the Jensen to the Ouray gage; and Reach 3 from the Ouray to the Green River gage, a total distance of 464 km. *Andrews* [1986] notes that the supply of sediment and water in the basin is not uniform, with most of the water coming from headwater areas in the Wind River Range, while most of the sediment comes from lower tributaries draining the semi-arid Colorado Plateau. In particular, most of the water and sediment in Reach 1 are supplied by the Yampa River at 105 river kilometers below Flaming Gorge.

Although total sediment transport is calculated over the entire discharge range, T* is difficult to calculate directly from the published graphs. However, from visual fitting it appears that sediment transport of the sand fraction that makes up most of the sediment load begins at a discharge of approximately 14 m^3/s (500 ft^3/s) at the different gages [*Andrews*, 1986, Figures 3-4]. Flows of this magnitude were exceeded 90–99% of the time under pre-dam conditions and over 99% of the time under post-dam conditions (since dam operation increased daily low flows) so T* decreased from 1.1 near the dam to very close to 1.0 further downstream (Table 1).

Prior to the dam, sediment discharge past the Greendale gage was calculated as 3.6·10^6 t/yr [*Andrews*, 1986; Table 1]. Flows released from Flaming Gorge reservoir contain no sediment, but large tributaries contribute sediment downstream, so that S*, which we calculate in terms of the volume of sediment delivered to the channel in each reach, rather than the net of supply less transport, increases from 0 at the dam to 3.0 at 464 km downstream (Table 1)(Figure 4a). We use sediment input rather than net input less transport in these calculations since transport may itself be a function of supply [*Topping et al.*, 2000a], which would confound comparisons between rivers.

Andrews [1986] measured changes in channel morphology from aerial photos and cross-sections. If the downstream trajectories of S* and T* are replotted on Figure 5, their correspondence to changes in channel morphology can be evaluated. The lower portion of Reach 1 (Brown's Park) is described as narrowing by 13% and degrading approximately 0.7 m; the sediment budget shows a net depletion of sediment since dam construction. Later work by *Grams and*
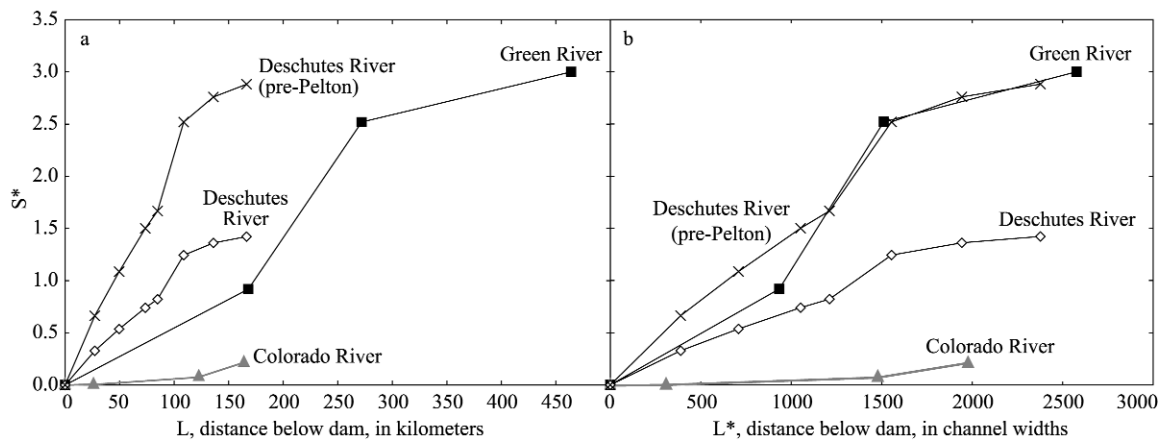
Figure 4. Longitudinal trajectories of change in S* for the Green, Colorado, and Deschutes Rivers below Flaming Gorge, Glen Canyon, and Pelton-Round Butte dams, respectively. Two trajectories are shown for the Deschutes, depending on whether the reference value for the above-dam sediment flux is calculated as pre- or post-upriver dam construction. (a) Absolute distance (L) in kilometers; (b) Non-dimensional distance (L*) equal to L/Wc where Wc is average channel width, and expressed in channel widths.

Schmidt [in press] could not distinguish between sediment deficit or balance in the segment of the Green River upstream from the Yampa and found no evidence that this reach had degraded during the post-dam period. Downstream from the Yampa River, *Andrews* [1986] and *Grams and Schmidt* [in press] both determined that sediment transport was less than sediment supply.

In Reach 2, both a degree of narrowing similar to upstream (13%) as well as vegetation encroachment and mid-channel bar construction were noted; the sediment budget for this reach indicates that there has been no net accumulation or depletion of sediment since dam construc-

tion. Reach 3 is aggrading where the supply of sediment from tributaries is exceeding transport, although the reaches are 10% narrower than prior to dam construction; apparently a new floodplain is being constructed at a reduced channel width.

Further work by *Grams and Schmidt* [2002, in press] showed that the Green River has narrowed throughout its length, both upstream and downstream from the Yampa River. Channel organization and bed material exert a large degree of control on the magnitude and style of channel adjustment, but the average magnitude of channel narrowing has been between 15 and 20% throughout.

Table 1. Calculation of T* and S* for the Green River below Flaming Gorge dam from data presented by *Andrews* [Figures 3-7, 1986]. Frequency of sediment transport calculated from sediment rating and flow duration curves, assuming $Q_{cr} = 14$ m³/s. S* is calculated using the pre-dam sediment supply rate at Greendale gage as the reference point. Average channel width is 180.00 m.

Reach	Distance below dam in km	Distance below dam in channel widths	% time flow above Q_{cr} Pre-dam	% time flow above Q_{cr} Post-dam	T*	Sediment supply to reach (tons·10⁶/yr) Pre-dam	Sediment supply to reach (tons·10⁶/yr) Post-dam	S* (pre)	S* (post)
Outflow from Flaming Gorge (measured at Greendale)	0	0	90.0	99.7	1.1	3.60	0.00	1.00	0.00
1—Greendale-Jensen	168	933.3	90.0	99.7	1.1	6.92	3.31	1.92	0.92
2—Jensen-Ouray	272	1511.1	99.5	99.9	1.0	12.80	9.06	3.56	2.52
3—Ouray-Green River	464	2577.8	99.5	99.9	1.0	17.00	10.80	4.72	3.00
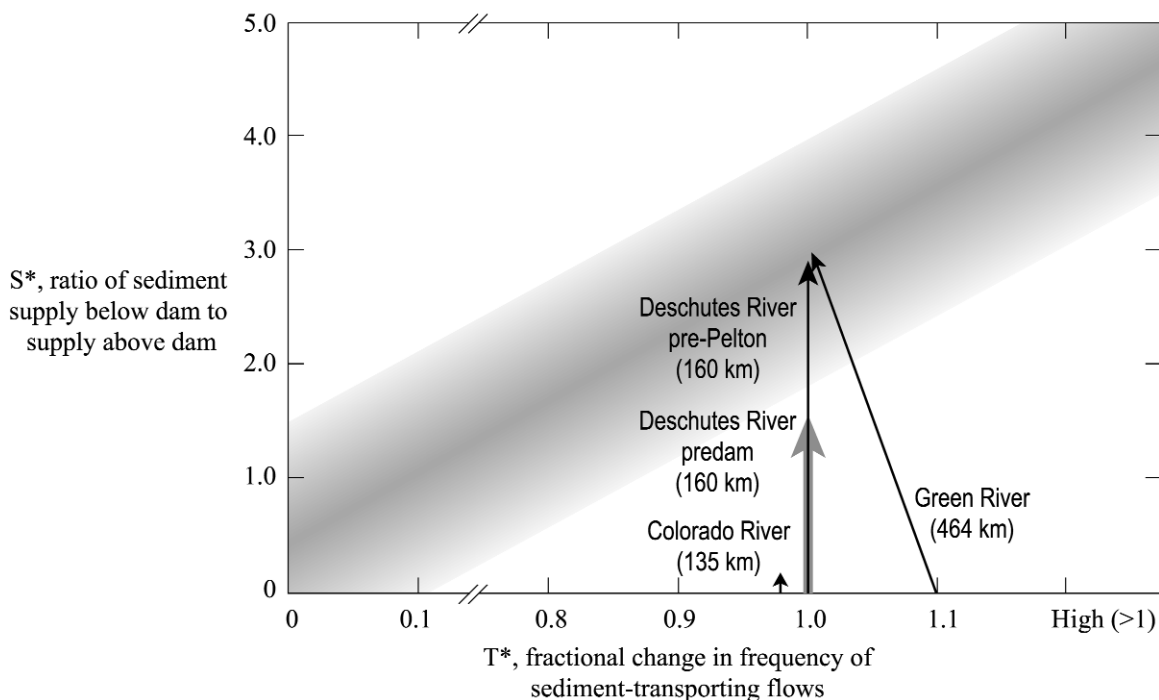
Figure 5. Endpoint trajectories of downstream change for the Green, Colorado, and Deschutes Rivers plotted on the response domain from Figure 3. See Figure 3 for expected morphological adjustments to the channel. As in Figure 4, two trajectories are shown for the Deschutes, depending on whether the reference value for the above-dam sediment flux is calculated as pre- or post-upriver dam construction. Longitudinal distances downstream of the dams are given.

These morphologic adjustments of moderate narrowing in all reaches but with near-equilibrium, and aggradation in the downstream reaches correspond well to those predicted by the trajectory plotted in S* and T* space (Figure 5). Moreover, the downstream increase in sediment supply with only a very minor change in frequency of sediment transport results in modest but measurable morphologic adjustments, with greater change in wide valley sections and almost no change in bedrock sections. These changes persist downstream where the more alluvial character of the river relative to upstream bedrock gorges allows them to be expressed. All of these responses reflect geological controls expressed over a range of scales.

Colorado River, Arizona

Topping et al. [2000a,b] constructed a detailed sediment budget for sand and finer material for the Colorado River in Marble Canyon and upper Grand Canyon, both prior to and following construction and closing of Glen Canyon Dam in 1963. Gages and suspended-sediment transport data used in constructing this budget were located at Lees Ferry and

Grand Canyon on the main Colorado, and on the Paria and Little Colorado Rivers, the two major tributaries in this section of the Colorado. On an annual basis the sediment budget characterizes the river as being approximately in equilibrium between supply and transport [*Topping et al.*, 2000a, Figure 9c]. More recent work using daily suspended sediment data indicates that the sediment budget is actually negative during moderate and high power plant releases (D. Topping, personal communication, 2003).

Based on pre-dam sediment rating curves, sand transport rates varied between the Lees Ferry and Grand Canyon sites. At Lees Ferry higher concentrations of sand moved at lower discharges relative to Grand Canyon, while at higher discharges, higher concentrations of sand moved at Grand Canyon [*Topping et al.*, 2000a; Figure 4]. Fitting these curves by eye, sand transport began at Grand Canyon at around 100 m³/s, although there was already substantial sand transport at Lees Ferry at this same flow. *Topping et al.* [2000a, Fig. 11] give the threshold between sand conveyance and accumulation as approximately 200-300 m³/s, with an estimated threshold at the mid-point of the range (250 m³/s). However, to maintain approximate consistency

with the Green and Deschutes River data, for which Q_{cr} is estimated on the basis of initial motion, we use the lower bound of the range (200 m³/s), which may still be too high for the Lees Ferry gage based on the sediment rating curve.

This discharge corresponds to a flow duration equaled or exceeded on average 97% of the time during the pre-dam snowmelt season (April-June), but only 40% of the time during the rest of the year; a composite flow duration curve for the entire year was not presented. Since we are interested in whether sand actually moved during the course of the year on an inter-annual basis, rather than the seasonal variation in sand transport that is the focus of the *Topping et al.* [2000a] study, we take the pre-dam value for T_{pre} as 97%, recognizing that a flow duration curve recalculated on an annual (as opposed to seasonal) basis would likely yield a slightly lower value. Using the same threshold of transport and flow duration data, T_{post} is calculated as 80% for the period 1966-98. This gives T* at Lees Ferry a value of 0.82; no data are presented for other gages. We take T* as constant over the entire section, although the authors suggest that it decreases very slightly downstream, since very little water is supplied by tributaries relative to the mainstem flow.

S* is calculated from the sediment budget presented by *Topping et al.* [2000a], showing inputs from the Paria and Little Colorado Rivers along with ungaged tributaries (Table 2). Because the spatial distribution of these tributaries is not shown, the 0.72·10⁶ t were apportioned on a distance-averaged basis over the 139 km to the Grand Canyon gage. Channel width was calculated as the average of values given by *Schmidt and Graf* [1990; Table 2] for the upper Grand Canyon.

Because so much of the sediment in the Colorado River prior to the dam was derived from upstream, the increase in S* with distance downstream is small (Figure 4a,b) (Table 2). From data presented in *Topping et al.* [2000a], only 21% of the pre-dam sediment volume at the Grand Canyon gage has been made up on an annual basis by tributary contributions. More recent data suggest that tributaries may make up only 10-15% of pre-dam sediment at this location (D. Topping, personal communication, 2003). Plotting this data in T* and S* space reveals that the upper Colorado River remains entirely within the degradational domain over its entire length, a finding consistent with the many studies that have documented overall erosion of the sand beaches in the upper Grand Canyon [*Schmidt and Graf*, 1990; *Topping et al.*, 2000a,b; *Rubin et al.*, 2002] (Figure 5). Erosion is not uniform along this section, however, and local geologic controls, including the morphology and orientation of debris fans from tributaries, play key roles in determining where erosion and deposition occur, either for beaches or the fans themselves [*Schmidt and Graf*, 1990*; Webb et al.*, 1999; *Pizzuto et al.*, 1999; *Andrews et al.*, 1999].

Deschutes River, Oregon

Data presented by *Fassnacht et al.* [this volume] and *O'Connor, Grant and Haluska* [this volume] permit calculation of S* but not T* for the Deschutes River below the Pelton-Round Butte dam complex, Oregon. There is no suspended-sediment data for this cobble-bedded river, so the analysis of sediment transport by *Fassnacht et al.* [this volume] focuses exclusively on transport of the coarse (gravel to cobble) material that comprises the channel bed. Although both Pelton and Round Butte dams are operated for hydroelectric peaking power production, the downstream re-regulation dam smoothes out discharge variations to the point that the complex has minimal effects on hydrology, with little change in Q_{peak} or Q_{mean}. Because the dam has imposed almost no change on the flow duration curves

Table 2. Calculation of S* for the Colorado River from data presented by Topping et al. [2000] using the pre-dam sediment supply rate at Lees Ferry gage as the reference point. Estimated contributions from ungaged tributaries (0.72·10⁶ tons) are apportioned on a distance-weighted basis between Lees Ferry and Grand Canyon. Average channel width is 83.00 m.

Reach	Distance below dam in km	in channel widths	Sediment supply to reach (tons·10⁶/yr) Pre-dam	Post-dam	S* (pre)	S* (post)
Outflow from Glen Canyon (measured at Lees Ferry)	24	289.1	57.00	0.24	1.00	0.00
1—Lees Ferry-Paria	25.4	306.0	57.01	0.26	1.00	0.00
2—Paria-Little Colorado	122.4	1474.7	60.50	3.74	1.06	0.07
3—Little Colorado-Grand Canyon	163.8	1973.5	68.81	12.01	1.21	0.21

we assume that T* is very close to 1.0 near the dam. The estimated frequency of sediment transport is quite low; depending on the assumptions used in the transport model, critical flows for sediment transport occur from 0.004 to 0.7% of the time over the entire period of record from 1924 – 1996 [*Fassnacht et al.*, this volume].

O'Connor, Grant and Haluska [this volume, Figure 15] show the effect of the Pelton-Round Butte dam complex on sediment supply to the lower Deschutes River in the context of other upstream dams that have diminished sediment supply. Here we consider how S* varies in relation to this history of dam construction on the Deschutes River (Table 3). The Pelton-Round Butte dam complex is both the youngest and downstream-most set of dams on the Deschutes. Construction of upstream dams over the past 80 years has therefore progressively reduced sediment supply to the river below Pelton-Round Butte even before its construction. This raises the question of what the "reference" value for S_A—the above-dam sediment flux—should be for calculating S*. Should it be the upstream sediment flux prior to all dams, or the flux with the other dams in place? It should be the latter if we are focused on the incremental effects of the Pelton-Round Butte dam complex on the river, and the former if we are interested in the overall effects of dams. We plot both trajectories for comparison (Figure 4).

These trajectories show that the rate of increase in S* with downstream distance is higher for the Deschutes River than either of the other two rivers, particularly when the below-dam input is compared with the influx calculated with the upriver dams in place. This rapid increase is due in large part to the geological setting of the Pelton-Round Butte dams. Due to geological factors, basin-wide sediment sup-

ply rates for the Deschutes are extremely low, with rates of 4.4-6.1 t/yr·km² calculated from reservoir filling rates among the lowest in the world [*O'Connor et al.*, this volume]. In addition, much of the water in the upstream reaches of the basin comes from a young (Pleistocene to Holocene) volcanic terrain with little weathering, a high degree of permeability, and a poorly developed drainage network [*Gannett et al.*, this volume]. With upstream dams intercepting much of the remaining sediment before it even reaches the Pelton-Round Butte dam complex, supply rates to the complex are intrinsically low. S* increases rapidly downstream due to both water and sediment influx from tributaries draining the higher and more erosive eastern ramparts of the Cascade Range [*O'Connor, Grant and Haluska*, this volume]. The location of the dam complex at the boundary between two geological terrains, and just downstream from a shift in hydrologic regime from a groundwater to a surface-water dominated system provides a setting where downstream supply of sediment quickly replenishes that intercepted by the dam. With the upriver dams in place, the volume of sediment intercepted by the Pelton-Round Butte dam complex is restored within 40 km (600 channel widths) downstream of the complex, where S* equals 1.0 (Figure 4a,b). For comparison, S* approaches 1.0 at 160 km (1000 channel widths) for the Green River, and from linear regression of the established trend, would require 700 km (8434 channel widths) for the Colorado.

The trajectory of the Deschutes River in T* and S* space is consistent with findings that the degree of geomorphic change in the reaches immediately downstream from the dam was minor. No significant morphologic or textural adjustments were observed in the 160 km downstream of the

Table 3. Calculation of S* for the Deschutes River below the Pelton-Round Butte hydroelectric project, from estimated sediment delivery data presented by *O'Connor, Grant and Haluska* [this volume, Figure 15]. The pre-Pelton reference value of S* is calculated using different values for the above-dam sediment supply (S_A): (1) before construction of any Deschutes dams; (2) following construction of all upstream dams. After closure of Pelton-Round Butte, S* is calculated using either the sediment delivered prior to any dams (3) and following upstream dam construction (4). Average channel width is 70 m.

Reach (in River Kilometers)	Distance below dam		Sediment supply to reach (tons·10⁶/yr)			S*1 before all dams	S*2 before Pelton Dam	S* after Pelton Dam	
	in km	in channel widths	Pre-dam	Pre-Pelton	Post-dam			S*3, using pre-dam flux	S* 4, using pre-Pelton flux
166.4 (at Pelton Dam)	0	0	0.50	0.25	0.00	1.0	1.0	0.0	0.0
139.2	27.2	389	0.66	0.41	0.16	1.3	1.7	0.3	0.7
116.8	49.6	709	0.77	0.52	0.27	1.5	2.1	0.5	1.1
92.8	73.6	1051	0.87	0.62	0.37	1.7	2.5	0.7	1.5
81.6	84.8	1211	0.91	0.66	0.41	1.8	2.7	0.8	1.7
57.6	108.8	1554	1.12	0.87	0.62	2.2	3.5	1.2	2.5
30.4	136	1943	1.18	0.93	0.68	2.4	3.8	1.4	2.8
0 (at Columbia R. confluence)	166.4	2377	1.21	0.96	0.71	2.4	3.9	1.4	2.9

dam [*Fassnacht et al.*, this volume; *Curran and O'Connor*, this volume]. Further inhibiting morphologic adjustments are the coarse bars and terraces that are remnant features of older paleofloods in the canyon due to landslide dam collapses and other flood events; the large cobbles and boulders that make up these deposits resist transport under all but the most exceptional floods [*O'Connor, Grant and Haluska*, this volume; *Beebee and O'Connor*, this volume]. As shown within the central region of Figure 5, the history of geological disturbances to the river and valley may dictate the nature of channel adjustments. This history may explain the difference in response between the Deschutes River and the Green River, which displays a similar trend of S^* with non-dimensionalized distance downstream (Figure 4b), but which exhibited a more demonstrable, though still modest response. The Green River, having no known history of paleofloods and landslide dam floods, lacks the coarse deposits that would limit channel adjustment; the finer and more easily transported sand-sized sediment in the Green River may be another factor in determining the channel's greater lability than the Deschutes.

IMPLICATIONS FOR INTERPRETING DOWN-STREAM RESPONSES TO DAMS: AN EXAMPLE FROM THE OREGON CASCADES

Along with its heuristic value, the geological framework proposed here provides first-order predictions on likely trajectories of response to dams based on geological setting. As an example, consider the major hydroelectric and flood control dams located in the Willamette River basin, Oregon, the basin adjacent to the Deschutes on the western side of the Cascade Range (Figure 6). While the downstream effects of several of these dams, notably those on the Clackamas River, are being studied as part of the FERC relicensing process, none of them have yet received the extensive geomorphic analysis that has occurred on the Deschutes River. Despite this paucity of data, however, an understanding of the geological setting of these dams provides the basis for interpreting likely directions and magnitudes of downstream response.

The geology of the western side of the Cascade Range can be broadly classified into two regions: the High and Western Cascades [*Ingebritsen et. al.,* 1991; *Grant,* 1997](Figure 6). The Western Cascades are dominated by well-weathered, overlapping, basaltic and andesite lava flows from periodic volcanic episodes during the Miocene Era. The steep, highly dissected landscape of the Western Cascades reflects the significant erosion that has occurred in this landscape. Drainage densities are high, averaging 3-4 km/km^2, reflecting an efficient well-organized drainage system [*Wemple et.*

al., 1996]. Streamflows are highly variable, with winter peaks several orders of magnitude larger than low summer base flows. Background sediment yields are on the order of 25 to 50 t/km^2·yr and may increase by as much as an order of magnitude following timber harvest, which is the dominant land use activity [*Grant and Wolfe,* 1991].

In contrast, the High Cascades are much younger geologically and reflect recent volcanic activity rather than erosional forms. Rock is dominated by basalt and andesite, mostly from shield volcanic lava flows. In areas of the High Cascades with the most recent volcanic activity, blocky basalt flows are often still visible at the surface. Surface hydraulic conductivities in these areas are exceptionally high and often remain high throughout deep permeable volcanic layers. Drainage density in the High Cascades province is significantly lower than in the Western Cascade Province, averaging 1-2 km/km^2. Streamflows are quite uniform throughout the year, with muted winter peaks and high summer base flows. Sediment yields from the western slopes of the High Cascades have not been measured directly, but are likely on the order of $10 - 20$ t/km^2·yr, based on eastside reservoir sedimentation rates [*O'Connor, Grant and Haluska,* this volume].

With this broad-scale understanding of the geological setting, we would predict that dams and reservoirs located within or at the western margins of the High Cascade province will trap little sediment, since little is produced by their upstream source areas. Most of the hydroelectric projects are operated as run-of-river, with little storage and flow variation imposed, so the dams impose only minor changes on hydrologic regime. Uniform streamflows and muted peak flows result in low frequency of transport, with or without dams. Therefore, we would predict that T^* will be close to 1.0 and that S^* will rapidly recover to 1.0 downstream of the dams, particularly where dams are located at the boundary with the more erosive terrain of the Western Cascades. Using these simple assumptions and the geologic framework of Figure 3, we would predict only subtle and modest channel changes downstream of dams located within the High Cascades province. In effect, these streams will act similarly to the Deschutes River. Watershed analyses conducted on other dams located at the High/Western Cascades boundary have borne this out [*Stillwater Sciences*, 1998].

The larger flood control dams located on streams whose drainage areas fall mostly or entirely within the Western Cascades may impose a different set of downstream changes than High Cascade dams. Dams located in this region will capture the larger quantities of sediment produced in the Western Cascades, although much of this sediment is silt and clay and thus not likely to substantially affect channel
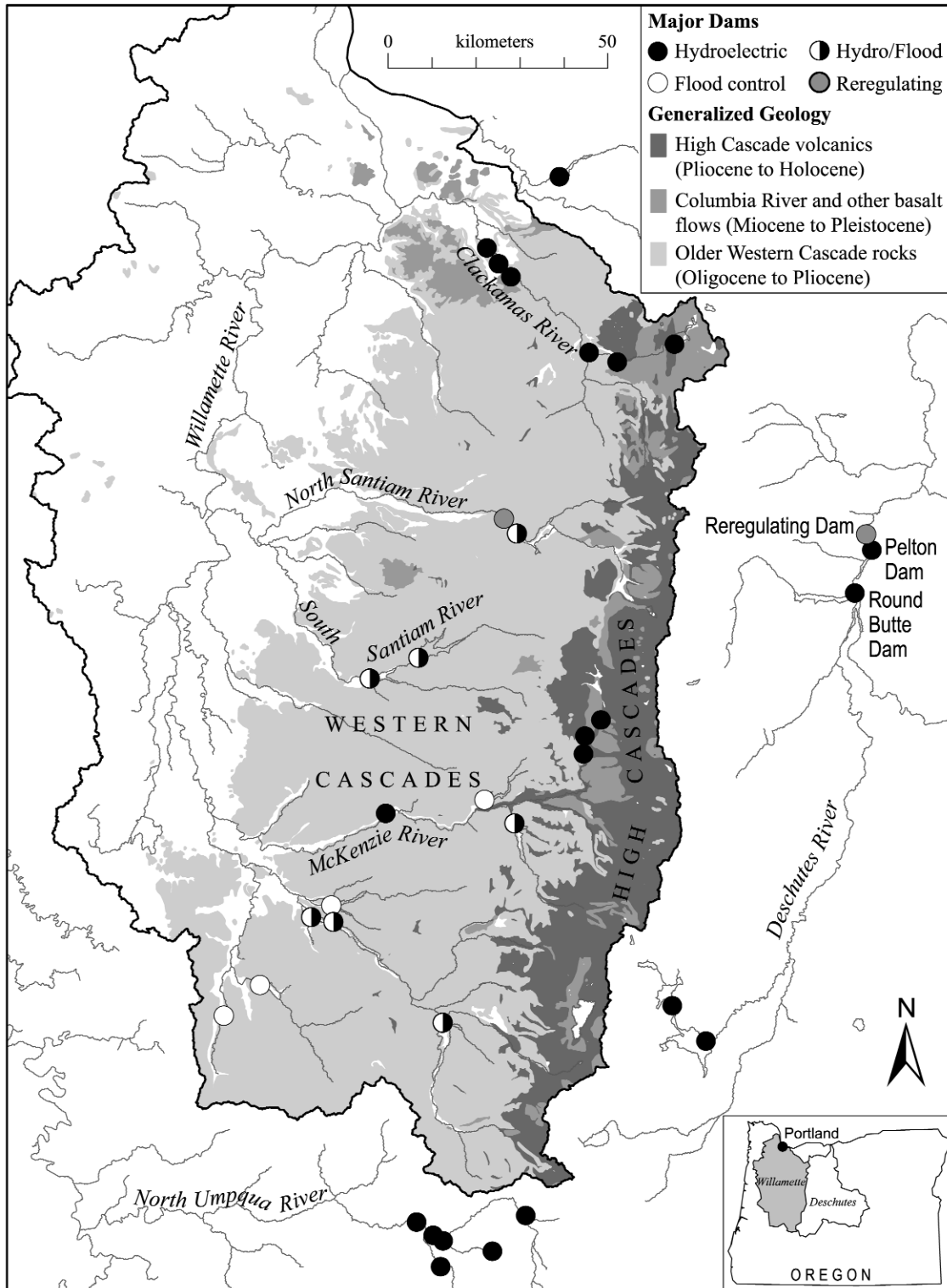
Figure 6. Distribution of large hydroelectric, flood control, and hydro/flood dams in the Willamette River basin of western Oregon in relation to geology. Also shown are large dams on the Deschutes and North Umpqua Rivers. Geological classification modified from Grant [1997].

morphology [*Ambers*, 2001a,b]. Moreover, these flood control dams are operated to suppress winter peaks, so frequency of sediment transport for the coarse fractions (but not necessarily the finer fractions) is likely reduced as well. We would therefore predict that T^* will be less than 1.0, while S^* will recover more slowly than for High Cascade dams. Consequently, we would expect to see downstream reaches below Western Cascade dams plotting in the lower left-hand corner of Figure 3. Since both sediment supply and frequency of transport have been reduced, it is possible that geomorphic response of these streams will also be subtle, but some degree of channel incision or coarsening might be expected. Although a detailed analysis of these streams has not been done, initial analyses are consistent with this interpretation [*Ligon et. al.,* 1995].

CONCLUSIONS

We have only begun to look at the downstream responses of rivers to dams through the lens of the river's geologic setting and history as well as the degree of hydrogeomorphic change imposed by the dams themselves. The examples considered here have only included dams with relatively modest alterations to the hydrology; we need a more exhaustive analysis of the existing case studies that includes dams showing the full range of hydrologic and geomorphic effects. Although our results are preliminary and qualitative, they suggest that our approach may have potential to help predict geomorphic responses to dams, at least in general terms, and to frame further studies and hypotheses.

A key strength of the analytical framework presented here is that it can be flexibly used to meet different management objectives by varying the grain size used in determining T^* and S^*. For example, if erosion of sand beaches used as campsites by river runners were the key issue, such as on the Colorado or Snake Rivers, then both variables should be calculated using the critical threshold for sand transport and the rate of sand resupplied from tributaries as the basis for the analysis. If, on the other hand, loss of spawning gravel below dams were the driving concern, then both variables would be calculated using the threshold and resupply rate for gravel. This ability to variously depict the downstream trajectory of rivers in response to loss of specific grain-size fractions and flow alterations offers river managers a more comprehensive way of evaluating tradeoffs between sometimes-competing management goals.

Detailed geomorphic studies of rivers, such as the Deschutes and the Colorado, are expensive and time-consuming undertakings. With the prospect of new dam construction in developing countries as well as dam removal for those countries with an aging dam infrastructure, these types of studies will continue. Conceptual and analytical frameworks, such as the one presented here, are needed so that these studies can be efficiently and effectively targeted towards the most likely fluvial responses. The testing and refinement of these frameworks then becomes a means of capturing the accumulated knowledge from individual projects and cases. This progression from site-specific studies to conceptual models to hypothesis testing to theory promises to advance not only our understanding of how dams affect rivers, but how rivers themselves evolve and behave.

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