15

The Geomorphic Response of Gravel-bed Rivers to Dams: Perspectives and Prospects

Gordon E. Grant

15.1 INTRODUCTION

Dams and reservoirs represent the single most profound human alteration of the fluvial system. In almost all cases, dams interrupt and modify the downstream flux of sediment through watersheds; they typically also affect the flow regime. Because they directly influence the two overarching controls of channel form – sediment and water – dams have the potential to alter the entire hierarchy of channel variables (*sensu* Schumm and Lichty, 1965).

The geomorphic literature is replete with case studies of river response to dam regulation, with review papers and monographs providing useful reference (e.g., Petts 1980, 1984; Williams and Wolman, 1984; Brandt, 2000; Grant *et al*., 2003; Petts and Gurnell, 2005; Schmidt and Wilcock, 2008.) Beyond case studies, however, there is a growing need to develop predictive tools and models that can be used to forecast likely channel response to dam construction and operation. Motivating the need for such tools is the recognition that dams and their flow regimes are likely to be a focal point for energy, ecology, and economy in the future. There is increasing interest in changing or modifying flow regimes at existing dams to meet various objectives (more natural or normative flow regimes, controlled floods, or ecological or geomorphic restoration) (e.g., Poff *et al*., 2007). Many rivers are likely to experience altered flow regimes due to climate changes, and modifying dam operations may be one approach to mitigate or accommodate such alterations (Payne *et al*., 2004). At the same time, hydropower is widely seen as a relatively clean and low-emission source of energy, although there is some debate on this point (Fearnside, 1997). Both economic development and environmental pressures are already resulting in major dam construction in the developing world, and these pressures are likely to grow in the future (Oud, 2002). These converging trends underscore the need for improved predictive capacity to help guide management decisions with respect to dam construction and operation around the world.

Developing such predictive models represents a significant challenge for fluvial geomorphology. Predicting the effects of dams on rivers can be viewed as an acid test for the discipline as a whole. A dam represents a discrete, geographically localized, and measurable perturbation of the fluvial system. The effect of a dam on the distribution and magnitude of flows is known or can be reasonably specified, and the trap efficiency of the reservoir, and hence magnitude of change to sediment flux, is equally predictable. The ability of geomorphologists to rigorously forecast changes to the downstream river's planform, hydraulic geometry, grain-size distribution, and slope from changes in the controlling variables of discharge and sediment supply represents a real-world application and test of the most fundamental principles of the science. Because the boundary conditions are generally known, predicting geomorphic response of rivers to dams is an ideal experiment and learning opportunity.

The questions posed by this paper are: Where do we stand with respect to this type of quantitative prediction? Is our ability to predict downstream response improved by focusing on the effects of dams on a specific type of channel, those with beds primarily composed of gravel? Motivating the second question is the observation that despite decades of geomorphic research demonstrating that rivers occupy distinct process domains as a function of where they sit in the landscape (e.g., Schumm, 1977; Montgomery, 1999), and a wide range of approaches to

Gravel-bed Rivers: Processes, Tools, Environments, First Edition. Edited by Michael Church, Pascale M. Biron and André G. Roy.

river classification (see Kondolf *et al.*, 2003 for review), there has been very little emphasis on looking at the effects of dams through the lens of specific river morphologies. One exception is the work of Gaeuman *et al.* (2005), who examined the difference between gravel-bed and sand-bed reaches along the same river to changes in flow (due in part to upstream regulation) and sediment supply. This approach has not been widely followed, however.

The object here is to consider whether there are distinctive aspects of gravel-bed rivers that might constrain the wider range of potential responses to impoundment and thus improve prediction. Beginning with some considerations about the number and location of dams on gravel-bed rivers, I follow with a brief discussion of the history of predicting geomorphic responses to dams on rivers in general. Both analytical approaches and field studies are then examined to determine whether there is a characteristic style of channel adjustment below dams on gravel-bed rivers. Finally, I consider future research directions and implications for management. The focus is specifically on dams that are large enough to have the capacity to measurably affect the flux of water, sediment, or both, thereby excluding the effects of weirs and small check dams. Diversion dams are included insofar as they affect water and sediment transport, but the specific effects of diversions are not considered, since the issue of de-watering and re-watering channels adds another dimension to the problem (see Ryan, 1997; Baker *et al.*, 2010 for recent reviews).

15.2 A GLOBAL PAUCITY OF DATA

No one knows how many dams are located on gravel-bed rivers, or any other type of river for that matter. Our inability to conduct a quantitative census points to data gaps that limit our understanding of the scale and dimension of dam issues globally. The problem is twofold: first, we don't know where all the gravel-bed rivers are, and second, virtually all local or national databases treat dams and their associated reservoirs as points in space; attributes that are associated with these points focus on the dimensions and characteristics of the dam (length, height, construction materials) or reservoir (volume, surface area), without any reference to the channel on which the dam is located. For example, the Dams, Lakes and Reservoirs Database for the World Water Development Report is a global databank of 633 large impoundments from a series of world dam registers published by the International Commission on Large Dams (ICOLD) and International Water Power and Dam Construction (IWPDC) (available at: http://wwdrii.sr.unh.edu) (Figure. 15.1). "Large" dams are defined as over 75 m in height or producing 1×10^6 m^3 of storage. Only latitude and longitude for each dam are given, and with 30-minute resolution for both, this would make it

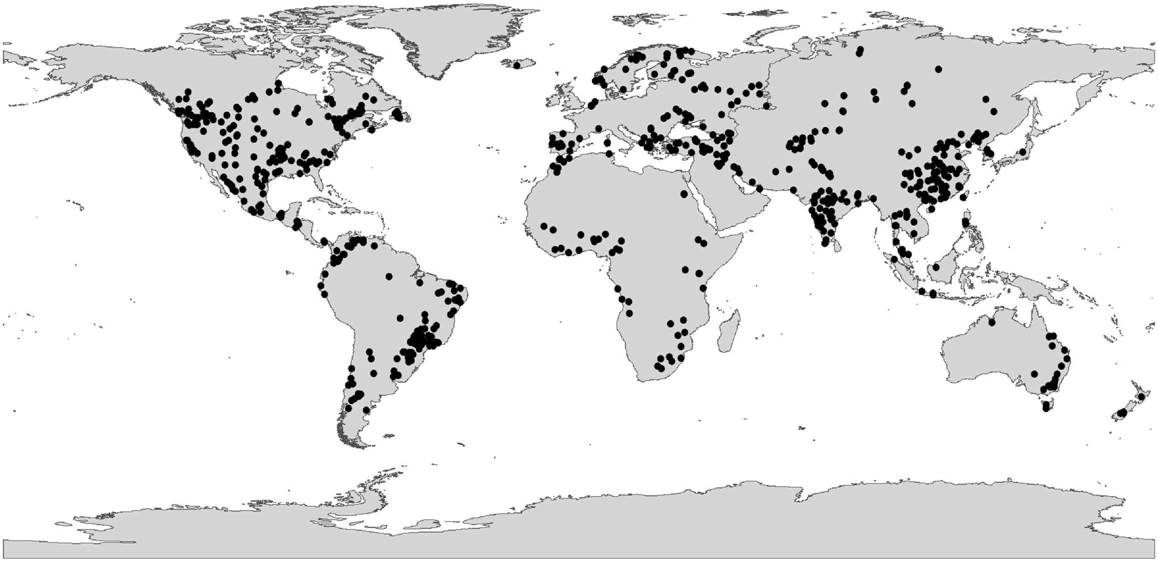

Figure 15.1 Location of large dams contained in the global databank of 668 large impoundments from a series of world dam registers published by ICOLD and IWPDC (ICOLD, 1984, 1984; IWPDC, 1989; 1994); data available at: wwdrii.sr.unh.edu.

impossible to map the dams onto an accurate channel network. The US Army Corps of Engineers maintains the United States National Inventory of Dams (NID; available at: https://nid.usace.army.mil). The database includes over 79 000 dams that equal or exceed 7.6 m in height and exceed $1.8 \times 10^4\,\mathrm{m}^3$ of storage, or that equal or exceed $6.2 \times 10^5\,\mathrm{m}^3$ storage and exceed 1.8 m in height, or that pose a significant or high risk to life or property if they were to fail. The dataset that accompanies these dams and reservoirs is more extensive than the ICOLD dataset, and includes drainage area of the dam as one of its attributes. There are no data on the channel itself, however. A potentially more useful, although spatially limited, data set is one maintained by local reservoir management agencies in Japan, termed here the Japanese Reservoir Database (JRD). Detailed information on channel characteristics associated with 131 dams, including stream gradient, along with annual surveys of sediment and woody debris has permitted spatial analysis of controls on woody debris export (Seo *et al.*, 2008; Fremier *et al.*, 2009; Seo and Nakamura, 2009).

The lack of grain-size data for channels where dams are located reflects a general paucity of such data for most rivers – even those where long-term USGS stream gauging sites are located. In the absence of such data, even a reach-averaged channel slope along with discharge could be used to predict grain size, following a recast Strickler equation (e.g., Henderson, 1966, pp. 453–454). But with the exception of the JRD, slope data are lacking for all major dam datasets. For the JRD, channel slopes range from 0.02–0.26, clearly placing most if not all channels within the domain of gravel-bed streams (Seo *et al.*, 2008). Drainage area alone provides a very indirect estimate of discharge (since runoff per unit area varies widely) or the character of the channel, but in conjunction with slope data permits the channel to be geomorphically classified, at least to a first approximation (Montgomery and Buffington, 1998). On-going (but *ad hoc*) efforts to digitize the location of dams and reservoirs using platforms such as Google Earth (see: http://www.kcl.ac.uk/schools/sspp/geography/research/emm/geodata/geowikis.html) could improve the georeferencing of dams in such a manner as to permit more detailed analyses in the future.

15.3 CHARACTERIZING THE GEOMORPHIC RESPONSE OF RIVERS TO IMPOUNDMENT

The chronology of scientific investigations on the geomorphic response of rivers to dams reflects a sometimes wandering trajectory from field studies of dams on individual rivers to comparative empirical analyses of dams on multiple rivers, through conceptual models of channel response, and, most recently, analytical and predictive models (Figure 15.2). The science of predicting geomorphic response to dams began over 50 years ago with field studies of the effects of dams on individual rivers, such as the Colorado (e.g., Borland and Miller, 1960) and Rio Grande, (e.g., Lawson, 1925), as well as efforts to understand the causes and rates of bed degradation below dams (Komura and Simons, 1967; Pemberton, 1976). Early papers on hydraulic geometry

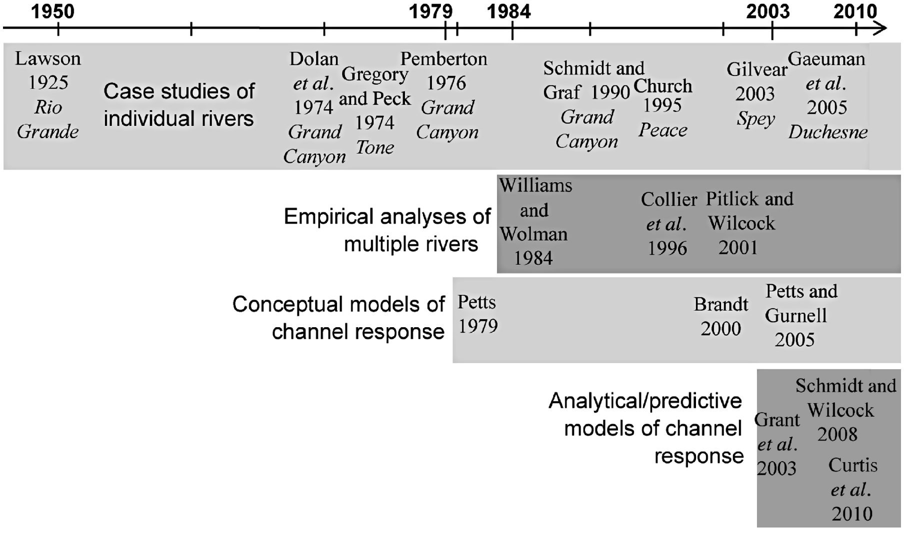

Figure 15.2 Chronology of primary approaches for examining geomorphic response of rivers to dam removal highlighting keystone or representative papers.

adjustments below dams expanded the range of potential impacts (Gregory and Park, 1974; Park, 1977). Petts (1979) offered one of the first examples of a conceptual model for depicting geomorphic response through space and time. (Figure 15.3). But it was not until the publication of the classic paper by Williams and Wolman (1984) that these studies were synthesized into a set of empirical relations. The conclusions of that paper were generalized trends supported by data, rather than analytical and predictive models (Figure 15.4). Wolman (pers. comm., 1982) commented about the difficulty of extracting general relations from the data, particularly with regard to predicting the depth and downstream extent of bed incision below dams.

In the 25 years since publication of Williams and Wolman's report, the scientific literature on understanding and predicting effects of dams on rivers has followed three distinct themes: (i) case studies of geomorphic effects of individual dams or dam complexes on specific rivers; (ii) conceptual models based on geomorphic first principles that broadly predict the direction and magnitude of channel changes; and most recently (iii) analytical models based on coupled flow and sediment transport relations that provide more rigorous predictions of potential channel changes (Table 15.1). Although not directly making this distinction, a recent review paper on the subject of geomorphic response to dams by Petts and Gurnell (2005) provides a useful summary of much of this work, emphasizing both the conceptual approaches and the importance of folding considerations of riparian vegetation dynamics into geomorphic response models. While some of the more recent analytical approaches are not included in their state-of-the science assessment, it serves as a good and reasonably comprehensive assessment of the field, and will not be duplicated here. Beginning with an early analytical approach (Figure 15.5), I emphasize progress in quantitative prediction that these new methods allow.

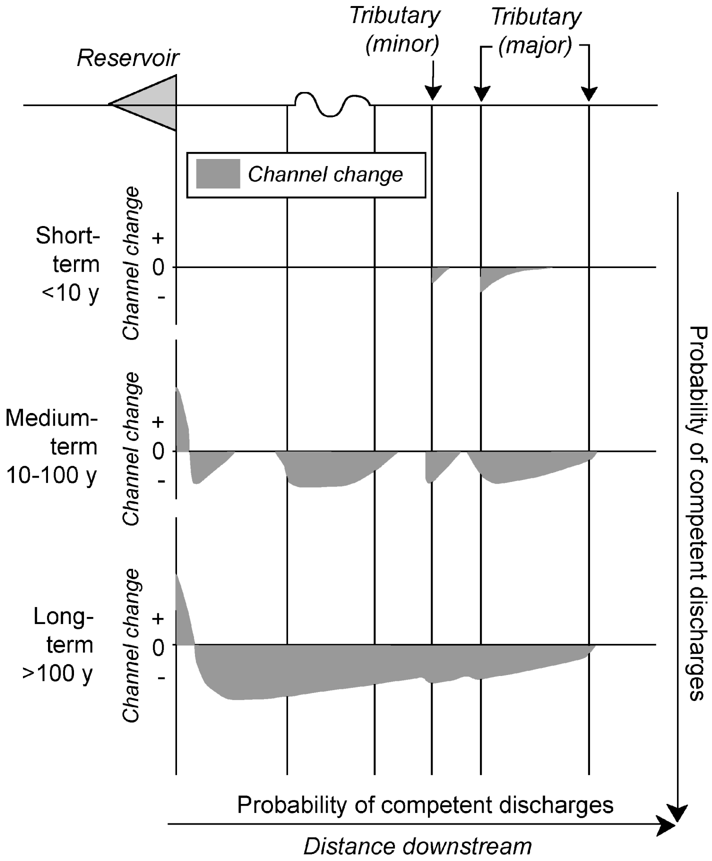

Figure 15.3 Conceptual model of longitudinal and temporal trends in channel width below a dam. Negative values correspond to channel narrowing while positive values correspond to channel widening. Reproduced, with permission, from Petts, G.E. 1979. Complex response of river channel morphology subsequent to reservoir construction. *Progress in Physical Geography*, **3**: 329–362.

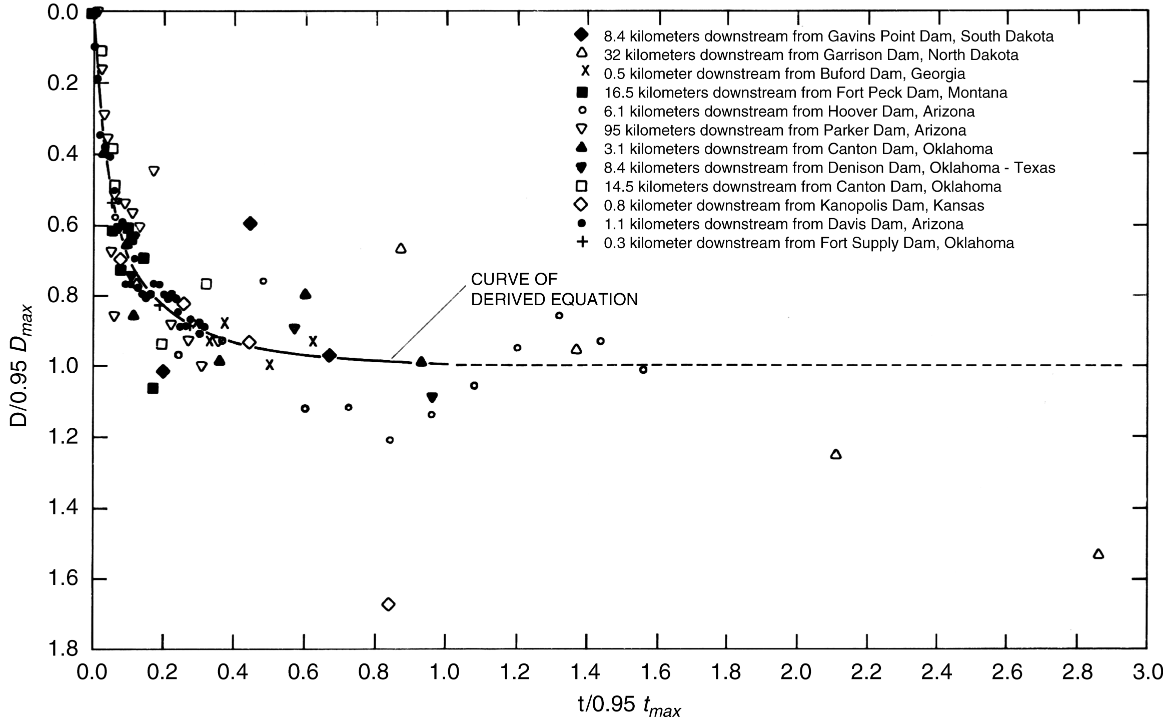

Figure 15.4 Normalized depth of degradation (*D*) as a function of normalized time (*t*) for 12 rivers after dam closure. Reproduced, with permission, from Williams, G.P. and Wolman, M.G. 1984. Downstream effects of dams on alluvial rivers. United States Geological Survey, Professional Paper 1286.

Emerging from this entire body of work to date is the wide range of downstream geomorphic responses that follow dam construction and river regulation. Petts (1984) provides a useful and simple framework for categorizing downstream response, distinguishing three broad styles of adjustment:

- *Passive response*, where flows are reduced below the river's competence threshold and channel dimensions are reduced accordingly but without significant change in bed elevations;
- *Degradation,* where bed elevations and lateral deposits are scoured as the channel moves toward a new equilibrium with the reduced sediment supply; and
- *Aggradation*, where reductions in discharges and competence due to dam operation are of sufficient magnitude to limit the channel's ability to entrain and transport sediment delivered by tributary or other inputs downstream of the dam, resulting in an increase in bed elevation.

Generally, both field studies and analytic models of river response focus on assigning one or more of these response styles to specific reaches and periods of time.

The complexity of predicting downstream response is due to several factors. While a dam represents a point perturbation to the fluvial system, a diverse suite of influences, inputs, and driving forces operating below the dam immediately come into play, making interpretation of the dam's effects more difficult. Downstream of the dam, water may be supplied from tributaries; sediment may be supplied from tributaries or available in the channel bed, banks, and floodplains; the channel boundaries may be constrained by bedrock or entirely alluvial and unconstrained. Typically, the flux of sediment from tributaries or channel storage is not well known. These extrinsic controls can also vary spatially. The response of the downstream channel can therefore be viewed as a trajectory of potential changes that are not entirely predictable from first principles (Grant *et al.*, 2003) – a classic example of deterministic uncertainty (*sensu* Phillips, 1994).

15.3.1 Recent Analytical Approaches

As previously indicated, a great deal of work has been done to describe both theoretical and documented examples of channel response to dams on rivers. Although

Table 15.1 Variables useful in prediction of morphological adjustment

Metric	Description	Application	Data required	Source
T^*	Ratio of pre- to post-dam frequency of sediment-transporting flows	Change in sediment transport capacity	Measured or modelled Critical threshold of flow required to transport sediment of particular grain size Pre- and post-dam flow regime	Grant *et al.*, 2003
$S_G{}^*$	Ratio of below to above-dam sediment supply	Change in sediment supply with distance downstream	Measured or modelled sediment supply for both main channel and tributaries	Grant *et al.*, 2003
$S_S{}^*$	Ratio of pre- to post-dam slope	Predicts sediment surplus of deficit	Measured or modelled sediment supply and sediment transport rate, for grain size of interest, pre- and post-dam flow regime and grain-size distribution	Schmidt and Wilcock, 2008
τ^*	Bed incision index based on Shield's number	Potential for bed incision based on competence of post-dam flows	Stage discharge relationship; pre-dam gradient; grain-size distribution	Schmidt and Wilcock, 2008
A_*	Proxy for degree of dam influence downstream of dam	Prediction of channel width for channels at or below tributary junctions	Drainage area at dam and points of interest downstream	Curtis *et al.*, 2010

much of the theoretical work prior to 2000 was fairly abstract, predicting general tendencies and trends as a function of the relation between the magnitude and direction of flow alteration and sediment supply, within the past 10 years a growing body of work has sought to develop a more rigorous predictive framework. Beginning with Brandt (2000), who used general formulations derived from Lane's (1955) balance between available stream power, sediment supply, and calibre, there have been several efforts to place predicting downstream effects of dams on a more solid technical foundation. Several of these recent approaches, developed to estimate trend or magnitude of probable response of rivers to impoundment, are considered here. These approaches introduce new predictive variables for evaluating predictive response and are summarized in Table 15.1. Following a brief description, each approach is examined from the standpoint of whether it provides evidence for a characteristic style of fluvial response of gravel-bed rivers to impoundment.

15.3.1.1 Semi-quantitative Estimation of Trend

Grant *et al.* (2003) developed a semi-analytical approach by proposing that geomorphic "response space" to dams could be defined in relation to two overarching controls: the change in the fraction of time that the river experiences flows capable of transporting sediment, and the upstream to downstream change in sediment supply. In a sense, these two axes capture the arms of Lane's balance. The first axis represents the change in the energy available for sediment transport due to the dam, and is defined by the fraction of time T that flow Q is greater than critical flow for sediment transport (Q_{cr}) downstream of the dam or:

$$T = \frac{\sum t_{(Q \geq Q_{cr})}}{\sum t_{(Q)}} \qquad (15.1)$$

where $t_{(Q)}$ refers to time at flow Q. The effect of the dam on the fractional time of sediment transport can be expressed as the dimensionless ratio T^* between the

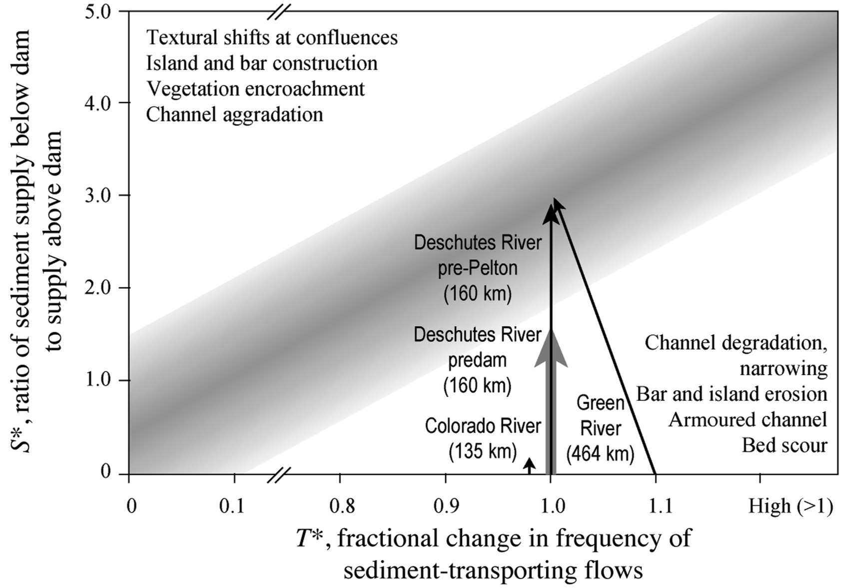

Figure 15.5 Predicted morphologic response to river impoundment as a function of two dimensionless variables, T^* and $S_G{}^*$, as defined in text. Shown are trajectories of change for rivers selected to show a diversity of responses. Reproduced, with permission, from Grant, G.E., Schmidt, J.C. and Lewis, S.L. 2003. A geological framework for interpreting downstream effects of dams on rivers. In O'Connor, J.E. and Grant, G.E., editors. *A Peculiar River. American Geophysical Union, Water Science and Applications* **7**: 203–219.

pre-dam (T_{pre}) and post-dam (T_{post}) frequency of sediment-transporting flows:

$$T^* = \frac{T_{post}}{T_{pre}} \qquad (15.2)$$

Grant *et al.* (2003) note that this definition of T and T^* is grain-size dependent, since the magnitude, and hence frequency, of competent flows varies by grain size. In practice, transport thresholds are usually indexed to a particular grain size, D_{50}. T^* may also vary over time in response to textural adjustments downstream. As the channel bed armours, T_{post} may actually decrease, even with no change in the dam-imposed flow regime. Here lies one key aspect of the response of gravel-bed rivers to dams: *the presence of a mixed grainsize, which is typical of gravel-bed streams, creates the opportunity for textural adjustments that would not be present if the grain-size distribution were more homogeneous, as in sand-bed channels.*

A related complication is that both T and T^* can change over time as channel geometry adjusts to the changed flow and sediment regimes due to the dam. As previously noted, this implies that downstream change is best viewed as a trajectory of response (in both space and time) rather than a singular and deterministic value.

The other axis represents the rate of sediment resupply below the dam (S_B) relative to the sediment flux above the dam (S_A); this is defined by another dimensionless ratio, $S_G{}^*$ as:

$$S_G{}^* = \frac{S_B}{S_A} \qquad (15.3)$$

The G in the subscript is used to distinguish this variable from the S^* defined by Schmidt and Wilcock (2008, below), which is denoted here as $S_S{}^*$. As Grant *et al.* (2003) note, large dams that capture virtually all bedload will have S_B, hence $S_G{}^* = 0$. Downstream of the dam, $S_G{}^*$ will increase as a function of input from hillslopes and tributaries, defining a longitudinal trajectory of change. Tributary flux is not typically known, but can be estimated from regional sediment yield relations or sediment transport models. Channel adjustment will also vary accordingly, as discussed below. Although $S_G{}^*$ is defined in terms of total mass flux above and below the dam, it is likely that the dam will impose changes in the type and calibre of sediment supply as well. Such changes are partially captured by the change in T^*, but a further (and unexplored) refinement may be to consider a size-dependent $S_G{}^*$ – to consider defining $S_G{}^*$ separately for the coarse and fine fractions.

Grant *et al.* (2003) propose that these two dimensionless variables, T^* and $S_G{}^*$ (Table 15.1), can be thought of as defining a morphologic response space (Figure 15.5); the corresponding plot has been used to broadly predict or explain morphologic response of rivers in different geographic settings (Wampler, 2004; Kummu and Varis, 2007; Ambers, 2007).

What does this approach tell us about the response of gravel-bed rivers to dams? From first principles, T (either pre- or post-dam) for gravel-bed rivers is likely to be relatively small; that is, the frequency of sediment-transporting flows tends to be much less for gravel- than for sand-bed rivers. Entrainment frequencies for gravel are typically given as slightly less than bankfull flow (Q_{bf}) (Andrews, 1984; Whiting *et al*., 1999; Torizzo and Pitlick, 2004), whereas sand transport on many rivers occurs at much more frequent flows. For example, detailed sediment sampling in the Grand Canyon reveals sand transport occurring from 40 to 97% of the time, depending on season (Topping, 2000a, 2000b). Wilcock (1998) and Wilcock and Kenworthy (2002) shows a three- to fourfold increase in critical dimensionless shear stress for gravel versus sand entrainment. Gravel-bed rivers are fundamentally more stable than sand-bed rivers, and the presence of a dam does not alter that fact. Therefore, T_{pre} (and T_{post}) in gravel-bed streams is usually small and, for dams that reduce peak flows (flood control dams), T^* will be less and sometimes much less than 1, depending on the degree to which peak flows are reduced. Trapping efficiency for coarse sediment in reservoirs is usually very high, approaching 100% (Brune, 1953). So the response of most gravel-bed rivers, at least immediately downstream of flood control dams, will generally lie in the lower right-hand quadrant of the plot, where channel degradation and bed armouring are the dominant adjustment mechanisms (Figure 15.5). Although plotted together, degradation and armouring are somewhat antagonistic processes, in the sense that armouring may limit degradation.

Sand-bed streams, on the other hand, are likely to have T^* much closer to 1, since reduction in peak flows is usually offset by an increase in base flows, and Q_{cr} is generally exceeded for virtually all flows. This brings up a second key difference between the response of gravel- versus sand-bed channels below dams: *gravel-bed streams are active a small fraction of the time, whereas bed material is in transport at some small rate at virtually all flows in sand-bed streams. Hence channel changes and adjustments in gravel-bed streams will inevitably be slower and take longer to be reflected in channel morphology.*

One situation where other responses are possible is where low-storage dams are operated to reduce peak flows, but are also periodically flushed of their accumulated sediments. In this case, bed aggradation can occur below the dam (upper left-hand quadrant), as described by Salant *et al*. (2006). The other, more common, case where bed aggradation can occur below dams in gravel-bed rivers is where sediment is introduced from tributaries or other sources. As discussed below, the nature of the channel response can vary depending on the grain size and amount of introduced sediment.

Although Figure 15.5 can be used to predict the general direction and magnitude of channel response, there are a number of limitations to this approach. First, it is only semi-quantitative in the sense that the axis values are poorly constrained, as is the general shape of the response surface. The central portion of the graph, which indicates how local factors, including bedrock geology and channel geometry, can control or override hydraulic and sedimentalogic factors, is similarly poorly constrained. Moreover, the data used to derive T^* and $S_G{}^*$ can be difficult to obtain, requiring measurements of sediment transport and estimates of sediment flux that are not readily available. Finally, as previously indicated, T^* is both grain-size dependent and can change over time in response to morphodynamic adjustments, such as armouring and changes in channel geometry, and $S_G{}^*$ changes over space in response to downstream inputs. As discussed by Grant *et al*. (2003), the response surface in Figure 15.5 is best viewed as a general trajectory of change rather than a rigorous prediction.

15.3.1.2 Quantitative Prediction of Trend and Magnitude

A more quantitative approach to predicting downstream effects of dams was developed by Schmidt and Wilcock (2008), who used three dimensionless metrics characterizing the sediment mass balance, bed incision potential, and magnitude of flood reduction to predict downstream response. This last metric, Q^*, had little explanatory power and is not considered here. In particular, they defined the sediment mass balance using a reformulation of Lane's (1955) balance, in terms of the ratio of pre-dam to post-dam slope needed to transport the rate and calibre of the sediment supply at the imposed discharge, which they defined as $S_S{}^*$ (again the subscript is introduced here to distinguish from S^* as previously defined by Grant *et al*. (2003)):

$$S_S^* = \frac{S_{post}}{S_{pre}} = \sqrt{\frac{qs_{post}}{qs_{pre}}}\left(\frac{q_{pre}}{q_{post}}\right)\left(\frac{D_{post}}{D_{pre}}\right)^{0.75} \tag{15.4}$$

where S is the slope necessary to transport the sediment supply of rate qs and calibre D at flow rate q; the subscripts refer to pre- and post-dam. $S_S{}^* > 1$ implies that for the change in flow produced by the dam, there must be an increase in post-dam slope in order to transport the post-dam sediment supply; this corresponds to a post-dam sediment surplus. Conversely, a post-dam sediment deficit exists when $S_S^* < 1$. Although such a sediment surplus or deficit could be interpreted as indicating whether the downstream bed will aggrade or incise, Schmidt and Wilcock (2008) argue that an additional criterion that must be met is that the post-dam flows are competent to transport sediment and actually incise the bed. They define a bed incision index in terms of a Shield's number τ^*:

$$\tau^* \propto \frac{h_{post} S_{pre}}{D_B} \tag{15.5}$$

where h_{post} is defined as the mean depth of post-dam floods, S_{pre} is the pre-dam gradient, and D_B is a characteristic grain size. The Shields number is the ratio of downstream shear stress to submerged particle weight or:

$$\tau^* = \frac{hS}{(G-1)D_B} \tag{15.6}$$

where G is the specific gravity of sediment particles. Empirical results from application of this and the previous metric suggest that bed incision will occur where $S_s^* > 1$ and $\tau^* > 0.1$. Similar to S_G^*, sediment mass balance as defined by S_s^* varies with distance downstream from the dam as sediment is re-supplied from tributaries, and may also vary with time.

The metrics (see Table 15.1) developed by Schmidt and Wilcock (2008) show real promise in terms of placing prediction of downstream response of rivers to dams on a more rigorous foundation. Despite the many assumptions that underlie this approach, they show that combining a metric for sediment mass balance (essentially sediment transport capacity) and flow competence is reasonably successful in identifying where channels have aggraded or incised. Moreover, the data suggest that there may be discernible thresholds in both S_s^* and τ^*. If so, this approach provides an *a priori* basis for predicting channel response.

This approach also provides insight into the adjustment of gravel-bed rivers below dams. Of the 14 river reaches used to test the metrics, only four (upper Colorado, Trinity, upper Snake, and Deschutes Rivers) were gravel-bed reaches. Of these, the upper Colorado and Snake were in sediment surplus (S_s^* ranging from 1.18 to 1.61), the Deschutes showed the greatest sediment deficit (S_s^* ranging from 0.08 immediately below the dam to 0.76 approximately 160 km downstream), and the Trinity had reaches showing both deficit ($S_s^* = 0.35$, immediately downstream from the dam) and surplus ($S_s^* = 1.40$ more than 13 km downstream). All gravel-bed streams had very low bed incision indices (ranging from 0.01–0.05), reflecting their greater stability. What is most significant is that despite the large range of sediment mass balance, the range of observed changes in channel bed elevation was very small, less than 0.5 m of either incision or aggradation, with most responses very close to zero (Figure 7a in Schmidt and Wilcock, 2008). Compare this with their reported range of bed elevation changes for rivers with finer (sand and fine gravel) beds, from 2.5 m of aggradation (Rio Grande below Elephant Butte) to 4 m of incision (Colorado River below Parker and Hoover Dams).

These data are broadly consistent with other published accounts of downstream response of rivers to dams. Williams and Wolman (1984) did not provide comprehensive grain-size data for the population of dams that they studied. Of the rivers for which they did report grain-size data from pebble counts, only two – the Smoky Hill River below Kanopolis Dam in Kansas, and the Red River below Denison Dam in Oklahoma – appear to be gravel-bed; measured grain size was approximately 20 mm on the Smoky Hill River below the dam, and 50–60 mm on the Red River. Incision rates are on order of 1 m for the Smoky Hill River and 2.5 m for the Red River immediately below the dam; both incision rates decrease with distance downstream (Figure 14 in Williams and Wolman, 1984). Grain sizes were measured 13 to 16 years after closure, however, so the pre-dam grain-size distribution is difficult to establish. Much less incision, approximately 0.2 m, is reported by Salant *et al.* (2006) for the Black River, a gravel-bed ($D_{50} = 130$ mm) stream in eastern Vermont. Wampler (2004) reported an average of 0.3 up to 1.0 m of incision below River Mill Dam on the Clackamas River in Oregon; D_{50} ranged from 5–10 cm. The Peace River, a classic gravel-bed channel in British Columbia, Canada, has degraded no more than 0.5 m below Bennett Dam (M. Church, pers. comm., 2010). Kellerhals (1982) similarly notes lack of degradation on at least three other gravel-bed Canadian rivers. Gaeuman *et al.* (2005) compare the complex response of gravel-bed to sand-bed reaches subject to the same flow and sediment alteration due to dams and flow diversions on the Duchesne River in Utah. The gravel-bed reaches narrowed, then aggraded and widened in response to varying flow regimes, while the sand-bed channels aggraded and avulsed, then incised.

15.3.1.3 Importance and Prediction of Armouring

The key conclusion to extract from this admittedly incomplete census of the literature is that the magnitude of bed elevation change due to dam closure alone in gravel-bed rivers is generally relatively small, on order of 1 m or less of degradation. A primary reason for this is the natural armouring process that results from the mixed grain size. Armouring limits the magnitude of degradation by increasing bed D_{50}, thereby requiring flows of increasing competence in order to entrain the bed. This armouring can result from both the decreased magnitude of peak flows and the decreased sediment supply from upstream. The conclusion that channel beds tend to armour below dams is hardly novel; dam construction engineers anticipated it in the design of Glen Canyon Dam (Pemberton, 1976), and Williams and Wolman (1984, p. 29) describe the process succinctly:

> Few if any natural channels are underlain by perfectly uniform sediments. Because magnitude and frequency of high flows are significantly decreased by dams, and because released flows may not be able to transport sizes previously moved by higher flows, successive flows can winnow finer materials from the bed. Progressive winnowing concentrates the coarser fraction. As degradation proceeds, the average particle size on the bed increases, possibly resulting in a surface or armor of coarse particles alone. This idealized theory has long been accepted in engineering planning.

Agreement on the mechanism of armouring remains more elusive than suggested in the paragraph above (see Wohl, 2000, pp. 95–97). But the key point here, and what has perhaps been underappreciated, is that because the range of grain sizes in gravel-bed rivers is fundamentally greater than finer bed rivers, gravel-bed rivers will tend to armour much more readily; as a consequence the downstream effects of dams on channel incision will be less pronounced.

Predicting the intensity, longitudinal extent, or time scales of armouring remains a challenge, though theoretically possible. Empirically, the coarsening of channel beds below dams occurs relatively rapidly, typically within the first 5 to 10 years following dam closure (see Williams and Wolman, 1984, Figure 13), while the downstream extent of coarsening appears to be on order of 10–20 km, diminishing downstream (see Williams and Wolman, 1984, Figure 14). Longer distances (up to 70 km) were noted for some rivers, such as the Colorado below Hoover Dam. Wampler (2004) noted surface coarsening on the Clackamas River on the order of two to three times D_{50} that extended 3 km downstream of the dam and resulted in skeletal boulder bars with little residual gravel (Figure 15.6).

In theory, we can predict intensity or time scale of armouring from first principles, but in practice there has been little work to rigorously develop and test predictions. Such predictions would be useful for constraining both the magnitude and time scales of bed degradation below dams. They would also be valuable for predicting depth of scour of fish redds in rivers (May *et al.*, 2009). Recent advances in remote monitoring of changes in the size distribution of bed material using digital photogrammetry (e.g., Graham *et al.*, 2005; Carbonneau *et al.*, 2004, 2005, 2006) may improve the situation here, but widespread application of these techniques is still a distance off (Marcus and Fonstad, 2008).

In general, we can better predict the degree of armouring than the time scale over which armour will develop. For example, Parker and Sutherland (1990) showed that the surface composition of both the static armour that

Figure 15.6 Coarse gravel bar devoid of fines, located approximately 1.5 km below River Mill Dam on the Clackamas River, OR, USA. Photo by Peter Wampler.

results from selective transport (as described by Williams and Wolman, above), and the mobile armour which forms during bedload transport of non-uniform sediment, could be numerically predicted from a known set of flow conditions and a bedload transport rate. Given that armour development below dams is most likely in response to clear water releases, a focus on static armour development seems warranted; the grain-size distributions of both the static and mobile armour were similar to each other in any case (Parker and Sutherland, 1990). As demonstrated by Parker (2004), and Parker *et al.* (2007), the armour layer that develops in response to time-varying hydrographs results in an equilibrium grain-size distribution that is somewhat independent of the immediate flow history.

Predicting the time scale over which armour develops, on the other hand, is more problematic. A critical issue is the time scale to reach equilibrium; this sets the adjustment time for the channel as a whole downstream of the dam and is a function of the thickness of the active layer, which exchanges with the surface layer under conditions of bedload transport. This thickness is not well constrained, however, but typically defined as some multiple of the maximum grain size, nD_{90}. For example, data from DeVries (2002) suggests 1.5 D_{90}, while Haschenberger and Church (1998) report a range from 0.4 to 2.0 D_{90}; the latter is close to the value proposed by Wilcock and McArdell (1997). The point is that the thicker the active layer, the more exchange and overturning occurs, hence longer time required to reach equilibrium (G. Parker, 2010, pers. comm.). Recent flume studies show that the active layer scales with both grain size and flow strength (Wong *et al.*, 2007). A simple one-layer model based on kinematic wave theory that assumes an active layer thickness equal to D_{100} has been proposed, but gives highly idealized results (Bettess and Frangipane, 2003).

In the absence of more analytical methods, perhaps the simplest approach to estimating time required to reach a bed pavement in equilibrium with the flows below a dam would be to calculate the size of sediment that is likely to be stable under the post-dam flow regime, and consider the fraction of the bed material that is finer than this grain size. Re-casting Equation (15.5) as:

$$D_B \propto \frac{h_{post} S_{post}}{\tau^*} \tag{15.7}$$

where S_{post} refers to the post-dam slope, one can solve for the grain size D_B that is likely to be stable for the predicted range of post-dam flows and depths. Assuming that grain size D_B represents the nth percentile of the surface grain-size distribution, then the time T_a for an equilibrium pavement may be estimated as the time required for flows to transport that volume of sediment made up of size fractions D_B, obtainable from the flow release schedule coupled to an appropriate sediment transport relation.

In sum, new analytical approaches advance our ability to predict downstream geomorphic response to dams as general trends in the direction and magnitude of adjustments. Textural coarsening of the surface layer and bed incision are the predominant responses, with the former limiting the latter to only a few metres or less; in some cases little or no incision occurs. Predicting the time scale over which armouring develops, the resulting grain size of the bed, and the longitudinal extent of armouring below the dam are less certain, although empirical evidence suggests that textural adjustments occur rapidly – within 5–10 years following dam closure.

Armouring is not the only mechanism limiting degradation below dams, however. Local controls, such as presence of bedrock in the channel can also limit incision, as in the case of Hoover Dam on the Colorado River (Williams and Wolman, 1984), the Glenbawn Dam in New South Wales, Australia (Erskine, 1985), and other rivers.

15.3.1.4 Longitudinal Trends and the Role of Tributaries

The focus thus far has been on evaluating where we stand with respect to predicting downstream effects of dams on gravel-bed rivers using basic principles of channel adjustments in response to changing sediment and flow regimes. As previously noted, however, such alluvial controls are not fixed, but change with distance downstream, primarily in response to inputs of water and sediment from tributaries. Until recently, there has been little effort to rigorously characterize how these tributary inputs change the style of adjustment. Such inputs can result in the nature of the response transforming from degradational to aggradational domains (Grant *et al.*, 2003), or from sediment deficit to sediment surplus (Schmidt and Wilcock, 2008). A key factor appears to be the grain size of the sediment contributed relative to the mainstem channel competency and capacity. Here I examine new approaches to evaluating the response of gravel-bed rivers to influx of both coarse (sediment whose calibre is equal or greater than the mainstem bed material) and fine (sediment whose caliber is less than the mainstem bed material) sediment into regulated reaches downstream of dams. Again, the intent is to explore where we stand with respect to making rigorous predictions of dam-related impacts.

Coarse Sediment Influx: There is abundant literature documenting how tributary input of coarse material can aggrade the channel bed below dams, resulting in coarse-grained deposits and rapids that form distinct slope breaks or steps in the longitudinal profile at tributary junctions (Graf, 1980; Kieffer, 1985; Petts and Thoms, 1987; Magirl *et al.*, 2005). This arises if dam operations reduce peak flows, and thereby flow competence and the channel's capacity to excavate material delivered down tributaries. Such a scenario resulted in a stepped longitudinal profile on the mainstem Peace River following river regulation (Church, 1995). An interesting ancillary effect of flow regulation on the Peace was that the tributaries tended to degrade near their confluences with the mainstem due to lower peak flows – hence flood stages – on the mainstem, and asynchrony in flood discharges between the tributaries and the mainstem (M. Church, pers. comm., 2010).

A detailed analysis of channel changes at tributary junctions below two dams in New England where peak flow has been reduced revealed both bar growth and bed coarsening at and downstream of tributary junctions with concomitant narrowing of channel width (Curtis *et al.*, 2010); they also note fining of the bed upstream of confluences. The mainstem channel bed immediately downstream of the confluence appears to reflect the grain size of the tributary more than the grain size of the upstream mainstem, as has been noted by others (Graf, 1980; Petts and Thoms, 1987). Following the general approach of Schmidt and Wilcock (2008), Curtis *et al.* (2010) have developed a quantitative analysis that generally predicts the magnitude of adjustment of both channel slope and width in response to the changed flow regime. This analysis rests on the assumption that the Shield's parameter of the formative flows (both pre- and post-dam) is near the critical value required for the mobilization of the average size sediment on the bed; that is $\tau^* \approx \tau^*_{cr}$. This assumption, in turn, is supported by the work of Dade and Friend (1998), along with hydraulic modelling. The concept is that under both the pre- and post-dam flow regime, the channel geometry, slope, and grain size adjust to maintain this near equality. From this, they show how the ratio of pre- to post-dam slope ($S*$) at tributary junctions varies as a function of $A*$ (Table 15.1), which they define as the drainage area A at some point below a dam (for example at a tributary junction) normalized by the drainage area at the dam, A_{dam}, or:

$$A* = \frac{A - A_{dam}}{A} \tag{15.8}$$

$A*$ therefore approaches 1 as drainage area increases below a dam and the proportion of dam-influenced drainage area diminishes. They also demonstrate that the same analysis can be used to predict channel width adjustment below dams, and argue that the time scale of adjustment for channel width might be on the order of a century or more for the channel geometry to reach equilibrium with the new flow regime. As with the work previously cited, these analyses provide a much firmer foundation for predicting dam effects that includes the role of downstream tributaries that deliver coarse sediment.

Fine Sediment Influx: A different situation applies where fine sediment is delivered from tributaries to the mainstem of a gravel-bed channel that has been regulated by a dam. Whereas the response of the channel to coarse bedload input is limited by the competence of the channel to transport the material, the response to fine-grained input is limited by the sediment transport capacity of the channel, since the available shear stress is almost always greater than that necessary to mobilize sediment (Dade and Friend, 1998). That is not to say that all fine sediment input to a gravel-bed river will necessarily be transported downstream, however. If post-dam flows, hence transport capacity, are sufficiently reduced, the effect will be aggradation of fine sediment at and downstream of tributary junctions, fining of the bed surface layer, and intrusion of fine sediment into interstices in the gravel. Classic examples of this include the Trinity River downstream of Lewiston Dam (Wilcock *et al.*, 1996a; Trush *et al.*, 2000), the Green River below Flaming Gorge Dam (Andrews, 1986; Allred and Schmidt, 1999), and the upper Colorado River (Van Steeter and Pitlick, 1998). Gaeuman *et al.* (2005) note that fine sediment from gully erosion entered but did not aggrade the Duchesne River following water diversions and reservoir construction, but aggradation did occur when coarser gravel with the same calibre as the bed material was eroded from bank deposits. Both the geomorphic and ecological consequences of these impacts may be severe, including loss of invertebrate or aquatic habitats, stabilization of bars by vegetation, and changes in the frequency of bedload transport (for review, see Pitlick and Wilcock, 2001).

The nature of this problem lends itself to the idea of flushing or sediment maintenance flows – deliberate releases of flows that are capable of entraining the fine material stored in the surface and subsurface of the bed. Identifying the flows required to flush fines from the bed without entraining the gravel layer, which is often limited below sediment trapping dams, and viewed as a resource, is a delicate problem, however, since some dilation of the bed is required in order to entrain fines stored in gravel interstices.

Recent progress in specifying such flows has been made by using rating curves for sand and gravel transport, together with estimates of the efficiency of pool sediment trapping and upward flux of sand from the subsurface of the bed, and coupling these with sand and gravel routing algorithms (Wilcock *et al.*, 1996b). These can provide useful estimates of the flow discharges needed, and also highlight the importance of pool dredging as an adjunct to flushing flows.

15.3.2 Width Adjustments and the Role of Vegetation

Although this paper has tended to emphasize vertical adjustments to the channel, changes in channel width are also important. Both channel narrowing and widening have been reported, although narrowing appears to be more common. Gaeuman *et al.* (2005) describe both processes for a regulated gravel-bed reach of the Duchesne River; they attribute narrowing to fine sediment accumulation along channel margins and backwaters, and widening to feedback between bed aggradation and infrequent transport events concentrating erosion along lateral channel margins, leading to introduction of more coarse sediment.

Vegetation plays a key role in mediating channel narrowing. As noted by Petts and Gurnell (2005), vegetation acts to stabilize bars and other channel surfaces that have either been formed or stranded by the dam-induced changes in flow regime. Typically this results in dramatic channel narrowing, as documented in the Trinity, Green, and Colorado River examples already cited. Gilvear (2003) documented channel narrowing accompanying vegetation encroachment along benches over a 60-year timeframe on the River Spey in Scotland. Rates of vegetation encroachment and channel narrowing on both the Duchesne and Spey are strongly influenced by the flow regime itself, particularly the presence or absence of large flows.

In all of these cases, the primary mechanism leading to narrowing was deposition of fine sediment (primarily sand) along channel margins that was subsequently colonized by vegetation, even though the channel beds were composed of gravel. An interesting though unanswered question is the relative importance of vegetation as a stabilizing influence in gravel- versus sand-bed channels. One is tempted to claim that vegetation exerts a greater role in sand-bed channels, since the cohesion afforded by its root systems would seem to impart stability to otherwise unstable substrates and surfaces. On the other hand though, if many gravel-bed rivers are poised close to the critical threshold for transport under formative flows, as suggested earlier, then the increased flow resistance coupled with root cohesion might easily tip the balance in favour of stability for vegetated bars. Recent efforts to physically model the role of vegetation in the laboratory in coarse-grained channels certainly suggest that vegetation plays a dominant role in influencing channel form and pattern (Gran and Paola, 2001; Tal and Paola, 2007; Braudrick *et al.*, 2009).

We are still some distance from being able to predict width adjustments below dams, however. In general, predicting width adjustments in channels in response to changing flow regime remains one of the more difficult challenges, since deterministic models of bank erosion and deposition are still rudimentary. Moreover, the importance of vegetation, both as a promoter of deposition and a component of hydraulic roughness introduces a suite of biological processes (colonization, propagation, reproduction, mortality) that do not lend themselves to process-based modelling, and may not be directly coupled to the flow regime. Empirical studies remain the best approach to constraining the magnitude and direction of planform changes.

15.4 SOME PERSPECTIVES AND CONCLUSIONS

The number of dams that regulate the flux of water and sediment on gravel-bed rivers worldwide is unknown. Perhaps as global databases coupled with remote sensing improve, a more coherent picture will emerge, not only of where dams sit, but of what types of rivers they affect. Building spatial databases that characterize the fundamental descriptors of river channels – slope, grain size, channel dimensions, and bed morphology – represents an ambitious, though tractable task that would dramatically improve our ability to predict geomorphic response of rivers, not just to impoundment, but to other anthropogenic and natural drivers of channel change.

Over 50 years of field observations from around the world reveal that the geomorphic response of rivers downstream of dams has to be viewed as a trajectory of potential changes that are not entirely predictable from first principles. The new analytical approaches and data presented here, however, suggest that knowing the grain size of the channel below a dam can provide, at least to a first approximation, much-needed information about the likely direction and magnitude of dam-induced changes to river geomorphology. This conclusion echoes the one put forth by Gaeuman *et al.* (2005; p.205): "…the uncertainty inherent in predicting the direction of channel adjustment could be reduced by distinguishing between gravel-bed and sand-bed channels and by considering the size of the imposed sediment load relative to the bed material size". The evidence indicates that bed incision on most gravel-bed rivers below dams is typically modest – on the order of a metre or two or less. The mixed grain-size ranging from sand to large gravel that is typical of many gravel-bed streams creates the opportunity, through selective entrainment, winnowing, and scour, for textural adjustments that would not be present if the grain-size distribution were more homogeneous, as

Table 15.2 Current level of confidence with respect to quantitative prediction of geomorphic response of rivers to dams: high (++), moderate (+) or low (?)

Response	Vertical Adjustments	Textural Adjustments	Lateral Adjustments (with tribs)	Lateral Adjustments (no tribs)
Direction	++	++	++	+
Magnitude	+	+	+	+
Timing	+	?	+	+
Longitudinal Extent	+	?	+	?
Persistence	?	?	?	?

in sand-bed channels. The ensuing bed coarsening and armouring limits bed incision to values much smaller than found in finer-grained channels.

New generations of analytical tools and metrics offer real prospects for predicting downstream changes due to impoundment (Table 15.1). We now have the capacity to generally predict the direction, magnitude, and timing of bed incision and armour development, as well as to anticipate the kinds of changes that are likely to occur at tributary junctions (Table 15.2). Less well developed are the tools to predict changes in channel width, the longitudinal extent of adjustments, or the persistence of dam-related impacts. These tools provide a strong foundation for moving forecasts of fluvial response out of the realm of simple conceptual approaches and towards more technically defensible predictive models.

What are some of the management implications of this trend? Will increased capacity for more rigorous predictions of the consequence of damming rivers result in improved management decisions? The jury is of course still out, but some observations may have bearing. First, more quantitative prediction is not likely to result in fundamental changes to management, in that the general direction of dam-induced changes in channel morphology has been known for decades. It is, however, likely to better constrain the magnitude and timing of response, and this may result in more efficient strategies for anticipating and mitigating change. For example, a more rigorous prediction of the extent and magnitude of incision below a dam may obviate the need for expensive countermeasures such as erosion control structures and check dams. Perhaps more importantly, the types of metrics presented here have utility for answering key questions that invariably come up when contemplating dam construction or re-licensing. For example, a critical question faced by dam managers is whether and how much gravel to introduce below a dam to offset the effects of sediment trapping on aquatic habitat and other river resources. A more quantitative prediction of channel scour and incision, and armour development can provide a first-order estimate of the volumes of gravel needed and some idea as to what grain sizes may be appropriate. Alternatively, current efforts to re-think operating schedules and flow regimes for existing dams, such as The Nature Conservancy's "Sustainable Rivers Project" (see: http://www.nature.org/initiatives/freshwater/partnership/) employ limited tools to evaluate the effects of proposed flow regimes on channel morphology; the approaches outlined here would expand that toolbox. Prediction of downstream effects becomes even more critical when rivers cross international boundaries, and upstream decisions with respect to dam construction and operation affect downstream river populations, managers, and ecosystems. The approaches described here can provide a common technical foundation for negotiation and mitigation (Kummu and Varis, 2007).

That being said, we should not consider the problem of predicting downstream adjustments to dams a closed problem. Significant challenges await, which will keep the next generations of geomorphologists and river managers happily occupied or frustrated, depending on your point of view. It is one thing to be able to speak to the likely effects of a particular dam and flow regime on a channel; it is quite another to design a flow regime to provide a range of physical and ecological benefits. Yet that is the challenge, as the operation and even existence of many dams is being re-considered in light of changing environmental and societal concerns. Optimizing a flow regime involves a very complex calculus that includes ecological, geomorphic, and economic considerations, and no one has designed a template for this type of analysis. The tools and approaches described here can help resolve predictions of physical changes to channels, but few tools exist to provide robust models of ecological responses.

Moreover, dams are not the only impact on rivers, and do not function alone in changing flow and sediment regimes. Characterizing geomorphic response to multiple drivers and stressors in a basin is a much more daunting challenge, because the responses are not unique or linear, and responses to multiple drivers can be synergistic or antagonistic. There have been relatively few studies that place dam impacts within a broader context of watershed changes, and those that do exist tend to rely more on historical analyses and measurements than analytical tools to weave a compelling narrative (e.g., Wallick *et al.*, 2008).

Taking the long view, then, interpreting the response of gravel-bed rivers to dams must be viewed within a broader framework that includes the full range of anthropogenic and natural drivers of system change: climatic variation, channelization, urbanization, and even efforts to restore rivers. All of these represent interventions in the fluvial system that must be accounted for if we are to understand how our rivers are changing. Analytical approaches will continue to provide useful foundations for this effort, but must be complemented by comprehensive case studies and histories drawing on diverse types of data. Every river is different, every dam is unique, and understanding the impact of the latter on the former will always have an element of art to complement the science.

15.5 ACKNOWLEDGEMENTS

The author would like to thank Mike Church, Gary Parker, Jack Schmidt, and Peter Wilcock for helpful discussions and data, and Sarah Lewis and Kathryn Ronnenberg for editorial and review suggestions. Reviews by David Gaeuman, David Gilvear, and Colin Rennie greatly improved the manuscript.

15.6 REFERENCES

Allred, T.M. and Schmidt, J.C. 1999. Narrowing by vertical accretion along the Green River near Green River, Utah. *Geological Society of America Bulletin* **111**: 1757–1772.

Ambers, R.K.R. 2007. Effects of a small, century-old dam on a second-order stream in the Virginia Piedmont. *Southeastern Geographer* **47**: 181–201.

Andrews, E.D. 1984. Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado. *Geological Society of America Bulletin* **95**: 371–378.

Andrews, E.D. 1986. Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah. *Geological Society of America Bulletin* **97**: 1012–1023.

Baker, D.W., Bledsoe, B.P., Albano, C.M., and Poff, N.L. 2010. Downstream effects of diversion dams on sediment and hydraulic conditions of Rocky Mountain streams. *River Research and Applications* doi: 10.1002/rra.1376.

Bettess, R. and Frangipane, A. 2003. A one-layer model to predict the time development of static armour. *Journal of Hydraulic Research* **41**: 179–194.

Borland, W.M. and Miller, C.R. 1960. Sediment problems of the lower Colorado River. American Society of Civil Engineers, *Journal of the Hydraulic Division* **86**: 61–87.

Brandt, S.A. 2000. Classification of geomorphological effects downstream of dams. *Catena* **40**: 375–401.

Braudrick, C.A., Dietrich, W. E, Leverich, G.T., and Sklar, L.S. 2009. Experimental evidence for the conditions necessary to sustain meandering in coarse-bedded rivers. *Proceedings of the National Academy of Sciences, USA* **106**: 16936–16941.

Brune, G. M. 1953. Trap efficiency of reservoirs. *Transactions of the American Geophysical Union* **34**: 407–418.

Carbonneau, P.E., Lane, S.N., and Bergeron, N.E. 2004. Catchment-scale mapping of surface grain size in gravel bed rivers using airborne digital imagery. *Water Resources Research* **40**: W07202. doi: 10.1029/2003WR002759.

Carbonneau, P.E., Bergeron, N.E., and Lane, S.N. (2005) Texture-based image segmentation applied to the quantification of superficial sand in salmonid river gravels. *Earth Surface Processes and Landforms*, **30**: 121–127.

Carbonneau, P.E., Lane, S.N., and Bergeron, N.E. 2006. Feature based image processing methods applied to bathymetric measurements from airborne remote sensing in fluvial environments. *Earth Surface Processes and Landforms* **31**: 1413–1423.

Church, M. 1995. Geomorphic response to river flow regulation: case studies and time-scales. *Regulated Rivers* **11**: 3–22.

Curtis, K.E., Renshaw, C.E., Magilligan, F.J., and Dade, W.B. 2010. Temporal and spatial scales of geomorphic adjustments to reduced competency following flow regulation in bedload-dominated systems. *Geomorphology* **118**: 105–117. doi: 10.1016/j.geomorph.2009.12.012.

Dade, W.B. and Friend, P.F. 1998. Grain-size, sediment-transport regime, and channel slope in alluvial rivers. *Journal of Geology* **106**: 661–675.

DeVries, P. 2002. Bedload layer thickness and disturbance depth in streams. *Journal of Hydraulic Engineering* **128**: 983–991.

Erskine, W.D. 1985. Downstream geomorphic impacts of large dams: The case of Glenbawn Dam, NSW. *Applied Geography* **5**: 195–210.

Fearnside, P. 1997. Greenhouse-gas emissions from Amazonian hydroelectric reservoirs: the example of Brazil's Tucuruí Dam as compared to fossil fuel alternatives. *Environmental Conservation* **24**: 64–75.

Fremier, A.K., Seo, J.I., and Nakamura, F. 2009. Watershed controls on the export of large wood from stream corridors. *Geomorphology* **117**: 33–43. doi: 10.1016/j.geomorph.2009.11.003.

Gaeuman, D., Schmidt, J.C., and Wilcock, P.R. 2005. Complex channel responses to changes in stream flow and sediment supply on the lower Duchesne River, Utah. *Geomorphology* **64**: 185–206.

Gilvear, D.J. 2003. Patterns of channel adjustment to impoundment of the upper River Spey, Scotland (1942–2000). *River Research and Applications* **19**: 1–15, doi: 10.1002/rra.741.

Graf, W. 1980. The effect of dam closure on downstream rapids. *Water Resources Research* **16**: 129–136. doi: 10.1029/WR016i001p00129.

Graham, D.J., Rice, S.P., and Reid, I. 2005. A transferable method for the automated grain sizing of river gravels. *Water Resources Research* **41**: W07020.

Gran, K. and Paola, C. 2001. Riparian Vegetation Controls on Braided Stream Dynamics. *Water Resources Research* **37**: 3275–3283. doi: 10.1029/2000WR000203.

Grant, G.E., Schmidt, J.C., and Lewis, S.L. 2003. A geological framework for interpreting downstream effects of dams on rivers. In O'Connor, J.E. and Grant, G.E., editors. *A Peculiar River*. American Geophysical Union, Water Science and Applications 7, pp. 203–219.

Gregory, K. and Park, C.C. 1974. Adjustment of river channel capacity downstream from a reservoir. *Water Resources Research* **10**: 870–873.

Haschenberger, J.K. and Church, M. 1998. Bed material transport estimated from the virtual velocity of sediment. *Earth Surface Processes and Landforms* **23**: 791–808.

Henderson, F.M. 1966. *Open Channel Flow*. New York, Macmillan.

ICOLD 1984 (1988). *World Register of Dams*. 1984 full edition (1988 update) Paris. International Commission on Large Dams.

IWPDC. International Water Power and Dam Construction. 1989. *The World's Major Dams and Hydro Plants*. Global map. Sutton, Surrey, UK, Reed Business Publishing.

IWPDC. 1994. *Handbook*. Sutton, Surrey, UK, Reed Business Publishing.

Kellerhals, R. 1982. Effect of river regulation on channel stability. In Hey, R.D., Bathurst, J.C., and Thorne, C.R., editors. *Gravel-Bed Rivers*. Chichester, John Wiley & Sons, Ltd, 685–705.

Kieffer, S.W. 1985. The 1983 hydraulic jump in Crystal Rapid: Implications for river-running and geomorphic evolution in the Grand Canyon. *Journal of Geology* **93**: 385–406.

Komura, S. and Simons, D.B. 1967. River bed degradation below dams. American Society of Civil Engineers, *Journal of the Hydraulics Division* **93**: 1–14.

Kondolf, G.M., Montgomery, D.R., Piegay, H., and Schmitt, L. 2003. Geomorphic classification of rivers and streams. In Kondolf, G.M. and Piegay, H., editors. *Tools in Fluvial Geomorphology*. Chichester, John Wiley & Sons, Ltd, pp. 171–204.

Kummu, M. and Varis, O. 2007. Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. *Geomorphology* **85**: 275–293.

Lane, E.W. 1955. The importance of fluvial morphology in hydraulic engineering. *Proceedings of the American Society of Civil Engineers* **81**: Paper 745, 1–17.

Lawson, J.M. 1925. Effect of Rio Grande storage on river erosion and deposition. *Engineering News Record* **95**: 327–334.

Magirl, C.S., Webb, R.H., and Griffiths, P.G. 2005. Changes in the water surface profile of the Colorado River in Grand Canyon, Arizona, between 1923 and 2000. *Water Resources Research* **41**: W050201. doi: 10.1029/2003WR002519.

Marcus, W.A. and Fonstad, M.A. 2008. Optical remote mapping of rivers at sub-meter resolutions and watershed extents. *Earth Surface Processes and Landforms* **33**: 4–24. doi: 10.1002/esp

May, C.L., Pryor, B., Lisle, T.E., and Lang, M. 2009. Coupling hydrodynamic modeling and empirical measures of bed mobility to predict the risk of scour and fill of salmon redds in a large regulated river. *Water Resources Research* **45**: W05402. doi: 10.1029/2007WR006498.

Montgomery, D.R. 1999. Process domains and the river continuum. *Journal of the American Water Resources Association* **35**: 397–410.

Montgomery, D.R. and Buffington, J.M. 1998. Channel process, classification and response. In Naiman, R. and Bilby, R., editors. *River Ecology and Management*. New York, Springer Verlag, pp. 13–24.

Oud, E. 2002. The evolving context for hydropower development. *Energy Policy* **30**: 1215–1223.

Park, C.C. 1977. Man-induced changes in stream channel capacity. In Gregory, K.J., editor. *River Channel Changes*. Chichester, John Wiley & Sons, Ltd, pp. 121–144.

Parker, G. 2004. Response of the gravel bed of a mountain river to a hydrograph. *Proceedings of the International Conference on Slopeland Disaster Mitigation, Taipei, Taiwan, 5–6 October* (available at http://vtchl.uiuc.edu/people/parkerg/_private/ConferenceProceedings/Taiwan04Parker.pdf)

Parker, G. and Sutherland, A.J. 1990. Fluvial armor. *Journal of Hydraulic Research* **28**: 529–544.

Parker, G., Hassan, M., and Wilcock, P. 2007. Adjustment of the bed surface size distribution of gravel-bed rivers in response to cycled hydrographs. In Habersack, H., Piegay, H. and., Rinaldi, M., editors. *Gravel-bed Rivers VI: From Process Understanding To River Restoration*. Amsterdam, Elsevier, Developments in Earth Surface Processes 11, pp. 241–289.

Payne, J.T., Wood, A.W., Hamlet, A.F., Palmer, R.N., and Lettenmaier, D.P. 2004. Mitigating the effects of climate change on the water resources of the Columbia River Basin. *Climatic Change* **62**: 233–256.

Pemberton, E.L. 1976. Channel changes in the Colorado River below Glen Canyon Dam. In *Proceedings of the Third Federal Inter-Agency Sedimentation Conference, Denver, CO*, pp. 5-61–5-73.

Petts, G.E. 1979. Complex response of river channel morphology subsequent to reservoir construction. *Progress in Physical Geography* **3**: 329–362.

Petts, G.E. 1980. Long-term consequences of upstream impoundment. *Environmental Conservation* **I7**: 325–332.

Petts, G.E. 1984. *Impounded Rivers*. Chichester, John Wiley & Sons, Ltd.

Petts, G.E. and Gurnell, A.M. 2005. Dams and geomorphology: research progress and future directions. *Geomorphology* **71**: 27–47.

Petts, G.E. and Thoms, M.C. 1987. Morphology and sedimentology of a tributary confluence bar in a regulated river – North Tyne, UK. *Earth Surface Processes and Landforms* **12**: 433–440.

Phillips, J.D. 1994. Deterministic uncertainty in landscapes. *Earth Surface Processes and Landforms* **19**: 389–401.

Pitlick, J. and Wilcock, P.R. 2001. Flow, sediment transport, and aquatic habitat in large rivers. In Dorava, J., Fitzpatrick, F., Montgomery, D., and Palcsak, B., editors. *Geomorphic Processes and Riverine Habitat*. American Geophysical Union, Water Science and Application 4, pp. 185–198.

Poff, N. L, Olden, J.D., Merritt, D.M., and Pepin, D.M. 2007. Homogenization of regional river dynamics by dams and global biodiversity implications. *Proceedings of the National Academy of Sciences, USA* **104**: 5732–5737.

Ryan, S. 1997. Morphologic response of subalpine streams to transbasin flow diversion. *Journal of the American Water Resources Association* **33**: 839–854.

Salant, N.L., Renshaw, C.E., and Magilligan, F.J. 2006. Short and long-term changes to bed mobility and bed composition under altered sediment regimes. *Geomorphology* **76**: 43–5. doi: 10.1016/j.geomorph.2005.09.003

Schmidt, J.C. and Wilcock P. R. 2008. Metrics for assessing the downstream impacts of dams. *Water Resources Research* **44**: W04404. doi: 10.1029/2006WR005092.

Schumm, S.A. 1977. *The Fluvial System*. New York, Wiley-Interscience.

Schumm, S.A. and Lichty, R.W. 1965. Time, space, and causality in geomorphology. *American Journal of Science* **263**: 110–119.

Seo, J.I. and Nakamura, F. 2009. Scale-dependent controls upon the fluvial export of large wood from river catchments. *Earth Surface Processes and Landforms* **34**: 786–800. doi: 10.1002/esp.1765.

Seo, J.I., Nakamura, F., Nakano, D., Ichiyanagi, H., and Chun, K.W. 2008. Factors controlling the fluvial export of large woody debris, and its contribution to organic carbon budgets at watershed scales. *Water Resources Research* **44**: W04428. doi: 10.1029/2007WR006453.

Tal, M. and Paola, C. 2007. Dynamic single-thread channels maintained by the interaction of flow and vegetation. *Geology* **35**: 347–350.

Topping, D.J., Rubin, D.M., and Vierra, L.E., Jr 2000a. Colorado River sediment transport. 1. Natural sediment supply limitation and the influence of Glen Canyon Dam. *Water Resources Research* **36**: 515–542.

Topping, D.J., Rubin, D.M., Nelson, J.M., Kinzel, P.J., III, and Corson, I.C. 2000b. Colorado River sediment transport. 2. Systematic bedelevation and grain-size effects of sand supply limitation. *Water Resources Research* **36**: 543–570.

Torizzo, M. and Pitlick, J. 2004. Magnitude-frequency of bed load transport in mountain streams in Colorado. *Journal of Hydrology* **290**: 137–151.

Trush, W.J., McBain, S.M., and Leopold, L.B. 2000. Attributes of an alluvial river and their relation to water policy and management. *Proceedings of the National Academy of Sciences, USA* **97**: 11858–11863.

Van Steeter, M.M. and Pitlick, J. 1998. Geomorphology and endangered fish habitats of the upper Colorado River 1. Historic changes in streamflow, sediment load and channel morphology. *Water Resources Research* **34**: 287–302.

Wallick, J.R., Grant, G.E, Lancaster, S.T., Bolte J.P., and Denlinger, R.P. 2008. Patterns and controls on historical channel change in the Willamette River, Oregon USA. In Gupta, A.V., editor. *Large Rivers: Geomorphology and Management*. Chichester, John Wiley & Sons, Ltd, pp. 491–516.

Wampler, P. 2004. *Contrasting geomorphic responses to climatic, anthropogenic, and fluvial change across modern to millennial time scales, Clackamas River, Oregon*. Ph.D. thesis, Department of Geosciences, Oregon State University.

Whiting, P.J., Stamm, J.F., Moog, D.B., and Orndorff, R.L. 1999. Sediment-transporting flows in headwater streams. *Geological Society of America Bulletin* **111**: 450–466.

Wilcock, P.R. 1998. Two-fraction model of initial sediment motion in gravel-bed rivers. *Science*, **280**: 410–412.

Wilcock, P.R. and Kenworthy, S.T. 2002. A two-fraction model for the transport of sand–gravel mixtures. *Water Resources Research* **38**: 1194. doi: 10.1029/2001WR000684.

Wilcock, P.R. and McArdell, B.W. 1997. Partial transport of a sand-gravel mixture. *Water Resources Research* **33**: 235–245.

Wilcock, P.R., Barta, A.F., Shea, C.C. *et al.* 1996a. Observations of flow and sediment entrainment on a large gravel-bed river. *Water Resources Research* **32**: 2897–2909.

Wilcock, P.R., Kondolf, G.M., Matthews, W.V.G., and Barta A.F. 1996b. Specification of sediment maintenance flows for a large gravel-bed river. *Water Resources Research* **32**: 2911–2921.

Williams, G.P. and Wolman, M.G. 1984. *Downstream Effects of Dams on Alluvial Rivers*. United States Geological Survey, Professional Paper 1286.

Wohl, E. 2000. *Mountain Rivers*. American Geophysical Union, Water Resources Monograph 14.

Wong, M., Parker, G., DeVries, P., Brown, T.M., and Burges, S.J. 2007. Experiments on dispersion of tracer stones under lower-regime plane-bed equilibrium bed load transport. *Water Resources Research* **43**: W03440. doi: 10.1029/2006WR005172

15.7 DISCUSSION

15.7.1 Discussion by Bruce MacVicar

One interesting point from the chapter was that new construction of large dams has shifted to the developing world, with large projects in sub-Saharan Africa, India, and China. It is worth noting that the developed world is also experiencing an explosion of new dam construction, with many thousands of mini-dams being constructed specifically for stormwater management. These dams collect water from what would have been small headwater swales and streams and then control outflow to address various goals, including water quality, quantity, and sediment criteria. They are interesting cases of dams because they have no power or irrigation utility. There is considerable debate as to how best to utilize these dams to mitigate problems such as urban river degradation. It may be useful to use the available research on stream response to dams as a means of improving the design of stormwater management facilities.

15.7.2 Reply by Gordon E. Grant

MacVicar makes an interesting point that the locus of dam construction in developed countries has shifted towards small ("mini") dams that are being built for various purposes, including in places not normally associated with dam construction (i.e., urban environments). Although not mentioned, another arena where dam construction may be increasing is for low head or micro-hydropower dams. In principle, the analytical approaches discussed here should help engineers and planners predict the downstream consequences of these new developments, and design dams accordingly. It is likely that the relatively small storage volumes associated with these low head projects will have only a modest effect on an individual basis. More significant channel changes could be anticipated if large numbers of these structures are built throughout a basin, in which case the cumulative effect could be more pronounced.