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Short and long-term changes to bed mobility and bed composition under altered sediment regimes

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Abstract

Altered flow and sediment transport regimes from impoundment can result in significant channel bed composition changes that exacerbate the geomorphic and ecological effects of flow regulation. Using long-term discharge and cross-sectional data in combination with a two-fraction sediment transport model, we assess changes in the downstream bed of two flow-regulated rivers with equivalent dam-induced changes in flow but opposite changes in sediment flux. Supply limitation has led to incision and armoring in one case while supply excess has led to aggradation and embeddedness in the other. Under limited sediment supply, bed elevation variability decreases soon after impoundment, while excess sediment supply results in a decades-long gradual decrease in both bed elevation variability and depth of incision. Although the balance of sediment supply and transport differs between dam management styles, in both cases both the immediate and more gradual changes can be explained within the framework of a two-fraction sediment transport model. Our results demonstrate the importance of considering bed composition on sediment transport predictions and the development of management strategies for ecosystem maintenance.

Keywords: Flow-regulation; Channel morphology; Bed elevation; Sediment supply; Transport capacity

1. Introduction

Attempts to mitigate the ecological impacts of dams from large-scale changes in the hydrologic and sediment regime (Collier, 2002; Osmundson et al., 2002) have focused on releasing flushing flows capable of loosening the gravel bed and mobilizing fine sediment (Kondolf and Wilcock, 1996). Because of the high costs of flushing flows and the sensitivity of transport thresholds, accurately defining the duration, frequency, and magnitude of these flows is crucial (Topping et al., 2000a). Pre-dam hydrologic records can contextualize the frequency and magnitude of discharges required to maintain natural variability in channel bed morphology as they provide a normative index of pre-impact equilibrium between sediment supply and sediment transport. However, the strong coupling between sediment flux and fluvial characteristics means that post-dam geomorphic adjustments, particularly in overall bed composition, may alter the "natural" (i.e. pre-dam) relationship between discharge and channel maintenance (Dietrich et al., 1989; Lisle et al., 1993, 2000; Topping

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et al., 2000a). As a result, discharges common in the pre-impact dam period may have different geomorphic effects in the post-dam period. For example, changes to the bed sand fraction will affect entrainment thresholds and the availability of sediment, thus modifying both sand and gravel transport rates (Lisle et al., 2000; Wilcock, 2001; Wu and Chou, 2004).

While previous research has documented the hydrologic changes from impoundment (Poff et al., 1997; Magilligan et al., 2003) or characterized the relative changes in sediment inputs and flux following impoundment (Kondolf and Wilcock, 1996; Wu and Chou, 2003), few studies have fully addressed the coupling and timescales of interaction between changes in sediment transport capacity and stream competency resulting from hydrologic alterations and subsequent geomorphic adjustments due to impoundment (Topping et al., 2000a,b). In a conceptual model, Grant et al. (2003) argued that the specific geomorphic adjustments driven by impoundment depend on the relationship between the ratio of sediment supply upstream and downstream of the dam S^* and the change in sediment transporting flows T^*. Their plot of S^* vs. T^* depicts broad zones of geomorphic adjustments; when the difference in either discharge or sediment supply/transport is large, noticeable geomorphic effects (such as armoring or island formation) occur. However, their conceptual model does not consider the time dimension for these changes, and large areas of uncertainty occur in their plot surrounding the threshold relationship for specific geomorphic effects (Grant et al., 2003). This uncertainty reflects the complexity of the physical processes that link hydrologic and geomorphic processes (Topping et al., 2000a,b).

We seek to more precisely define the relationship between dam-induced changes in sediment supply (S^*) and hydrologic transport regime (T^*) and the attendant timescale for impact on channel properties, including channel bed storage of fine sediment (<2 mm), sediment entrainment thresholds, and bed load composition. We analyze two flow-regulated rivers with equivalent changes in flow but opposite changes in sediment supply downstream of the dam. In one case, trapping efficiency is high and the dam retains most of the upstream sediment supply. In the other case, storage of the sediment is seasonally dependent with sediment deposited in the reservoir during the winter and early spring later flushed downstream when the dam gates are opened and the reservoir drained in mid-spring. We use long-term records (~60 yr) of approximately bimonthly channel cross section measurements to assess the extent and timescale of bed elevation changes following impoundment and how these changes differ between rivers. These records show that in both cases bed elevations below the dam are less variable post-dam. We argue, however, that the increased stability in bed elevation is not simply due to burial as a result of increased sedimentation, but rather reflect dam-induced changes in bed composition and mobility. In order to elucidate the mechanisms by which differences in sediment supply and bed composition impact sediment transport, bed mobility, and channel morphology, we model the amount and the composition of sediment flux during pre-dam and post-dam periods on both rivers. We use measures of embeddedness – the degree to which fine particles surround coarse substrate – upstream and downstream of the dam to support our interpretation of the impact of the dam on downstream bed composition. We further relate these dam-induced changes in sediment mobility and embeddedness to previously observed changes in macroinvertebrate community structure (Salant, 2005).

As posited by Andrews (1986), our results show that flow regulation can have both short- and long-term effects on channel geomorphology. Immediately following dam construction, hydrologic changes dominate, resulting in nearly instantaneous changes in channel morphology. Unlike the more immediate hydrologic effects of dams, geomorphic changes that depend on the transport and deposition of sediment may occur gradually via the interaction of altered flow and sediment regimes (Topping et al., 2000a). Because he conducted his study less than two decades after dam construction, Andrews (1986) could only estimate the response time of long-term geomorphic change while acknowledging its ecological significance. The long-term, but high temporal resolution, records used in this study allow for a focus on both immediate and gradual changes of the stream bed following impoundment that incorporates the multifaceted, reciprocal relationship between flow, sediment supply, and bed composition. These long-term records provide a test of the applicability of sediment transport models and their ability to predict transport in regulated rivers with different management styles. We discuss our results in the context of dam management and river restoration, emphasizing the importance of controlling sediment supply (in addition to flow) on ecosystem maintenance.

2. Site descriptions

The Black and Ompompanoosuc Rivers are both flow-regulated, mixed gravel–sand tributaries of the

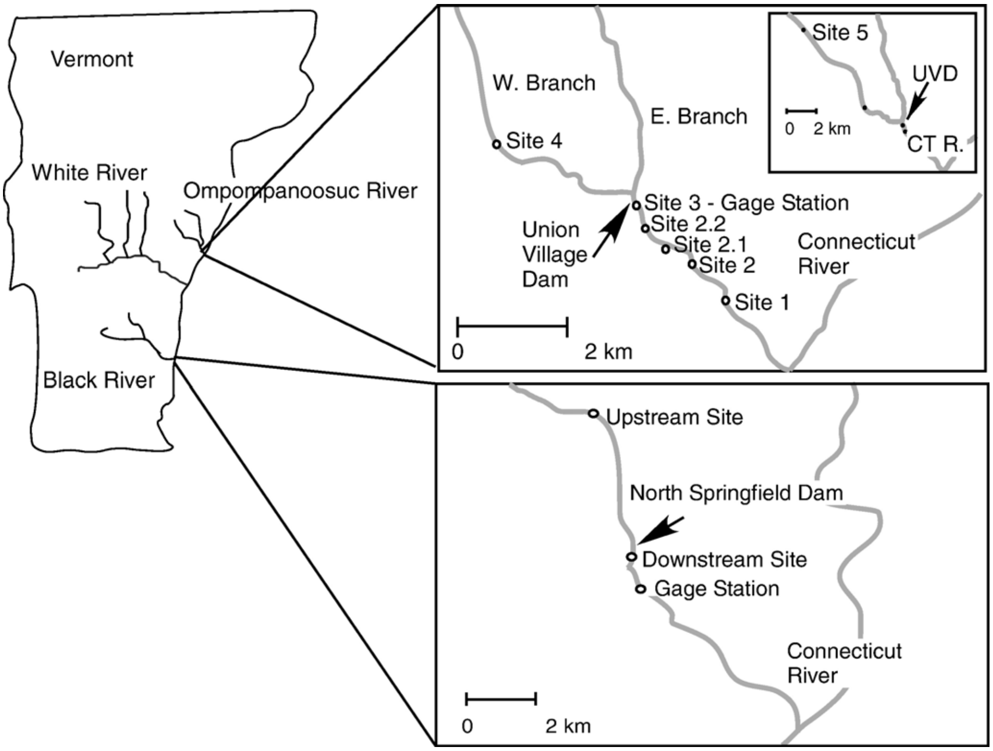

Fig. 1. Location of sampling sites, dams, and gage stations on the Ompompanoosuc and Black Rivers and location of the unregulated White River.

Connecticut River in eastern Vermont (Fig. 1). The Black River is regulated by the North Springfield dam, a flood-control/storage facility built in 1960. The Ompompanoosuc River is regulated by the Union Village dam, a flood-control/run-of-the-river facility built in 1950. See Table 1 for site characteristics directly below the North Springfield and Union Village dams. The U.S. Geological Survey (Black) and U.S. Corps of Engineers (Ompompanoosuc) maintain streamflow-gage stations immediately downstream of both dams. Long-term gage station records of channel morphology (width, area) and flow measurements (gage height, daily mean discharge, mean velocity) exist for both rivers spanning several decades both pre- and post-dam (more below).

Flow regulation has similarly reduced the magnitude and frequency of channel-maintaining flows on both rivers (Magilligan et al., submitted for publication). For both rivers, the post-dam 2-yr flood discharge at the gage stations just below the dams is about two-thirds of the pre-dam 2-yr flood discharge. In addition, discharges during the post-dam period have never exceeded the pre-dam 2-yr flood discharge on either river. Both dams were primarily designed for flood control, but dam operation differs considerably between the two. The dam on the Black River maintains a large storage reservoir throughout the year. Water discharge from the dam generally matches upstream flows, maintaining a relatively constant reservoir, except during large precipitation events and spring snowmelt. In the latter cases, storage behind the dam is temporarily increased to prevent downstream flooding. Because of the large reservoir size (0.4 km^2), the majority of sediment settles out in the upper end of the reservoir and little is drawn into the water release. Thus, the dam effectively eliminates the upstream sediment input. In contrast, the dam on the Ompompanoosuc River generally only maintains a storage reservoir during winter

Table 1
Site characteristics directly below the North Springfield dam on the Black River and the Union Village dam on the Ompompanoosuc River, Vermont

River	Drainage basin area (km^2)	Mean annual discharge (m^3/s)	Gradient (%)	Channel width (m)	Median particle size, D_{50s} (cm)
Black	409	~9	0.1	46	13
Ompompanoosuc	103	~6	0.1	25	10

and early spring. For the rest of the year, the dam gates are usually open, allowing the reservoir to drain during the mid-spring and allowing run-of-the-river discharges from late spring to early winter. Most of the sediment trapped in the reservoir during the winter and early spring is flushed downstream when the reservoir is drained (Salant, 2005). The differences in dam management are reflected in the differing impacts of the two dams on the downstream channel morphology: the bed of the Ompompanoosuc River has aggraded (Fig. 2A), while the Black River has incised (Fig. 2B) (Magilligan et al., submitted for publication).

3. Methods

3.1. Gage station cross sections

Since the construction of each gage station, the USGS has reported daily discharge data for each stream and conducted approximately bi-monthly direct measurements of channel cross-sectional area, channel width, mean water depth and discharge. For the Ompompanoosuc River, this data set includes 10 yr of pre-dam data and 40 yr of post-dam data. For the Black River, the data set includes 30 yr each of pre- and post-dam data. For the Ompompanoosuc River, we only consider data collected at the original stream gage location; the gage was moved farther upstream (~50 m) in 1995. These data were used to determine the mean bed elevation and mean water depth for each measurement date. For pre- and post-dam periods, mean water depth determined from the monthly cross section measurements was regressed against discharge and used to determine flow depth h from the record of daily discharge. Flow depth was then used to determine daily sediment discharge, as described below.

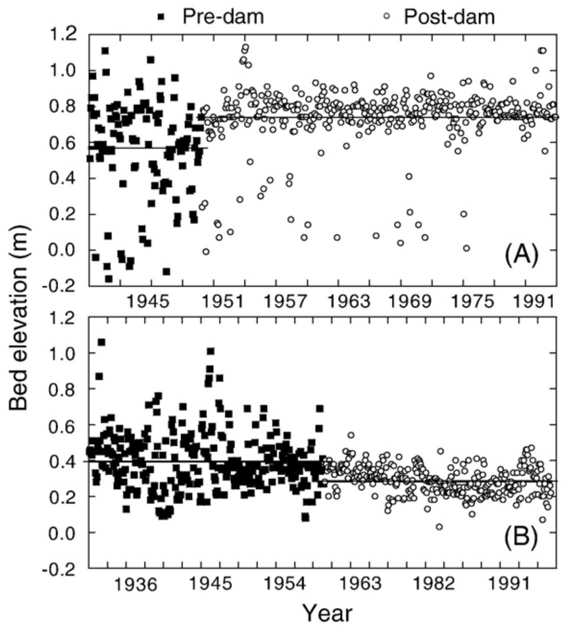

Fig. 2. Long-term changes in bed elevation for the (A) Ompompanoosuc and (B) Black Rivers, Vermont, for pre- and post-dam time periods on each river. Lines indicate average bed elevation for each time period.

3.2. Sediment transport model

Because direct measurements of sediment transport in the pre-dam period are not available for either river, we use a sediment transport model to estimate sediment flux in the pre- and post-dam periods. Previous studies have shown that models using only a one-fraction Shield's function to describe sediment transport (Meyer-Peter and Muller, 1948; Barry, 2004) inaccurately predict transport rates in mixed gravel–sand systems (e.g., Andrews, 2000; Salant, 2005). In contrast, Salant (2005) has shown that a calibrated two-fraction sediment transport model (Wilcock and Kenworthy, 2002) accurately predicts independently determined transport rates (Salant, 2005). According to this model, the unit bed load flux of sand or gravel per unit width is given as

$$q_{\mathrm{b}i} = \frac{W_i F_i g^{1/2} (hS)^{3/2}}{(R-1)} \tag{1}$$

where F_i is the fraction of sand or gravel on the bed, g is gravity, h is water depth, S is slope, R is ratio of sediment to water density, W_i is a dimensionless transport function, and the subscript i indicates either sand or gravel. Transport rates measured in the lab and the field can be fit to a transport function of the form

$$W_i = \begin{cases} 0.002\phi^{7.5} & \text{for} \phi < \phi' \\ A\left(1 - \frac{\chi}{\phi^{0.25}}\right)^{4.5} & \text{for} \phi \geq \phi' \end{cases} \tag{2}$$

where A, ϕ', and χ are empirical constants and $\phi = \tau / \tau_{\mathrm{r}i}$, where $\tau_{\mathrm{r}i}$ is a reference shear stress that scales with the shear stress required to entrain particles. The boundary shear stress is calculated as $\tau = \rho g h S$, where ρ is the density of water. The reference shear stress is a function of the grain sizes of the sand and gravels and of the critical shear stresses required to mobilize these limiting values. In dimensionless form, the reference shear stress is empirically defined as

$$\tau_{ri}^* = \left(\tau_{ri}^*\right)_1 + \left[\left(\tau_{ri}^*\right)_0 - \left(\tau_{ri}^*\right)_1\right] e^{-14F_s} \tag{3}$$

where the subscripts indicate the critical Shields number for entraining sand or gravel when F_s equals zero or one, respectively. Wilcock and Kenworthy (2002) find that their laboratory and field data are best fit by taking $(\tau^*_{rg})_0=0.035$, $(\tau^*_{rg})_1=0.011$, and $(\tau^*_{rs})_1=0.065$ and using the relation

$$\left(\tau^*_{rs}\right)_0 = \alpha\left(\tau^*_{rg}\right)_0\left(D_g/D_s\right) \tag{4}$$

where α is a constant of order one and D_i is grain size. For the characteristic sediment sizes, we set D_g equal to the D_{50} determined using a Wolman pebble count and set $D_s=1$ mm, based on the median grain size of the sieved samples of fine stream bed sediment (more below). See Table 2 for all model parameters.

We correct for the effect of changes in channel morphology on sediment transport by normalizing bed load flux (q_{bi}) by the measured pre- and post-dam channel widths and by accounting for the changes in slope that have occurred post-dam (Magilligan et al., submitted for publication). The changes in slope are estimated from changes in channel sinuosity, as determined from air photos both pre- and post dam.

For the pre- and post-dam time periods on each river, we created effective discharge plots as follows. Daily flow discharge data were binned into 5 m^3/s discharge classes. For each discharge class, the mean sediment flux was calculated by averaging the sediment discharge of every day that fell within that discharge class. Then, the number of days within each discharge class was multiplied by the mean sediment flux to determine the effective daily sediment flux for each class. The effective flux was divided by the total flux for the pre- or post-dam time period to determine percent sediment flux for each discharge class. Percent of total sediment flux was plotted against discharge class for pre- and post-dam time periods on both rivers. In addition, the maximum gravel size entrained by each discharge class was determined based on the transport thresholds for a given sand fraction according to the two-fraction model described above (Eq. (4)).

3.3. Grain size and embeddedness

Minimal knowledge exists about the historical downstream bed sediment composition, particularly prior to the emplacement of the dams. However, changes in bed composition between locations upstream and downstream of the dam suggest dam-induced variations in sediment supply and transport. To quantify these changes, surface and subsurface grain size distributions and embeddedness were measured at sites above and below the dam on both rivers, as well as on the unregulated, similarly sized White River, also a tributary of the Connecticut River. Surface grain size distributions were determined using Wolman pebble counts (Wolman, 1954). In addition, samples of bed sediment (<2 mm) were taken, dried, and sieved with a Sonic Sifter into representative sand size classes. Embeddedness was determined using the EPA EMAP technique (Lazorchak et al., 1998; Kauffman et al., 1999; Peck et al., 2000). In this method, embeddedness is measured as the average fraction of a gravel pebble's perimeter surrounded by sand or finer sediments. On the regulated rivers, average reach grain size distributions and embeddedness were measured upstream of the dam above the backwater of the storage reservoir and immediately downstream of the dam (Fig. 1). On the unregulated White River, measurements were taken at sites with drainage areas similar to sites on the regulated rivers. We used embeddedness to quantify bed composition because of its ubiquity in the literature and its ecological significance—numerous previous studies have correlated high embeddedness with degraded spawning habitat and a decline in macroinvertebrate diversity

Table 2

Model parameters used in a two-fraction transport model[a] to estimate sediment flux for pre- and post-dam periods on the Black and Ompompanoosuc (Omp.) Rivers, Vermont[b]

Dam time period	D_g (cm)	Gradient (%)	Channel width (m)	F_s (%)	Q_g/Q_t(%)	Gage station record
Omp. pre-dam	10	0.093	33	13	30	1940–1950
Omp. post-dam	10	0.100	25	15	2	1950–1995
Black pre-dam	13	0.104	50	10	7	1929–1960
Black post-dam	13	0.100	46	1	98	1960–1989

[a] Parameters used in two-fraction model: $A=115$, $\Phi'=1.27$, $\chi=0.923$, $D_s=0.001$ m, $(\tau^*_{rg})_0=0.035$, $(\tau^*_{rs})_1=0.065$, $(\tau^*_{rg})_1=0.011$, $\alpha=1$ (Wilcock and Kenworthy, 2002).

[b] D_g is average gravel size, F_s is bed sand fraction, Q_g/Q_t is the ratio of gravel flux to total sediment flux. See text for model details.

and abundance (Angradi, 1999; Lowe and Bolger, 2000; Collier, 2002).

4. Results

4.1. Channel morphology

Channel cross section measurements below the dam on the Black River (USGS, written communication, 2004) reveal an immediate stabilization of bed elevation following impoundment, indicated by a large decrease in bed elevation variance in the first decade after construction of the dam (Fig. 2B). Bed elevation variance then remains approximately constant throughout the following decades (Fig. 3). In contrast, channel cross section data for the Ompompanoosuc River indicate a gradual decrease in bed elevation variance over several decades. In addition to a decrease in the frequency of bed elevation changes, the bed of the Ompompanoosuc River also becomes increasingly more difficult to mobilize, ultimately requiring larger discharges for significant incision to occur. Fig. 4 shows channel incision (decrease in mean bed elevation between two consecutive measurements) versus the maximum daily discharge that occurred in the time period between the channel cross section measurements. Channel incisions of >30 centimeters occur 13 times prior to the construction of the dam and occur when the maximum discharge is as low as 5 m^3/s (Fig. 4A). Similarly large incision events become increasingly less frequent after construction of the dam and require ever greater discharges; in the 15-yr period after dam construction, the 13>30-cm incision events required discharges of at least 10 m^3/s (Fig. 4B). In the following 15-yr period, the six similarly large incision events required discharges of >20 m^3/s (Fig. 4C). During the last 15-yr period, only two >30-cm incision events occurred, and they required discharges >45 m^3/s (Fig. 4D). This indicates that while post-dam flows still reach discharges associated with significant incision prior to the construction of the dam, the bed has become increasingly more resistant to incision and, consequently, bed elevation has gradually stabilized over time.

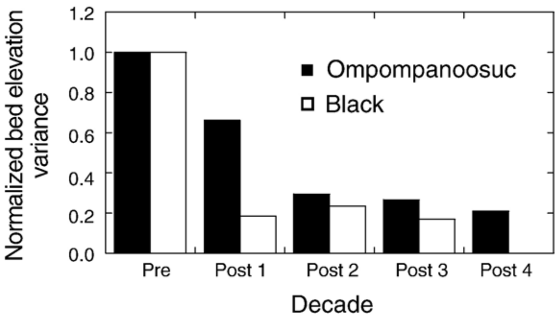

Fig. 3. Normalized variance in bed elevation for the Ompompanoosuc and Black Rivers, Vermont, for pre- and post-dam time periods on each river. “Pre” indicates all years of record for the pre-dam period (Ompompanoosuc 1940–1949; Black 1929–1959). Variances are normalized by pre-dam variance. Variance in the post-dam period was calculated for each decade following construction of the dam, where “Post 1” indicates the first decade after construction, “Post 2” indicates the second decade, etc. Records used for the post-dam period differ for each river (Ompompanoosuc 1950–1989; Black 1960–1989).

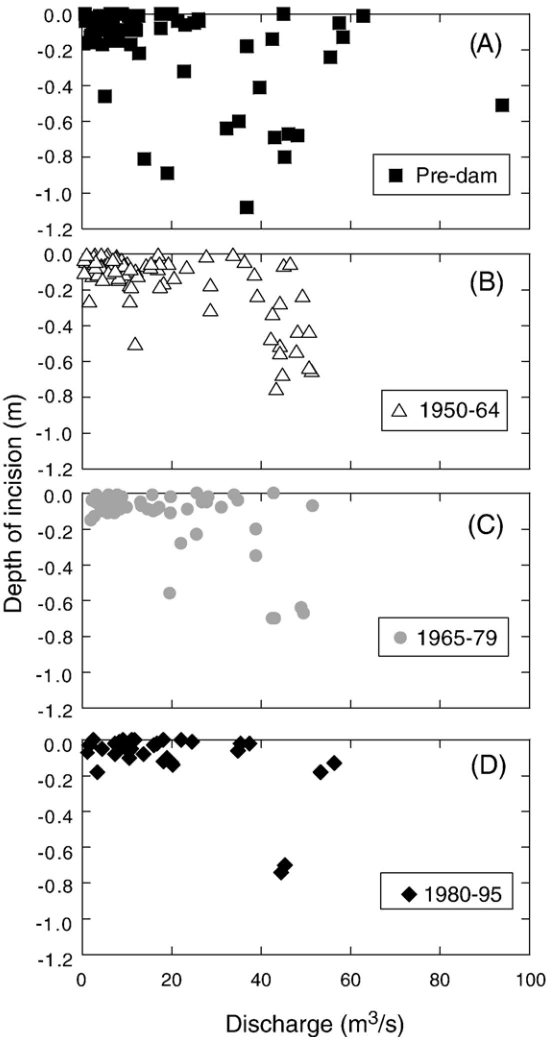

Fig. 4. Depth of incision versus maximum discharge for four time periods on the Ompompanoosuc River, Vermont: (A) pre-dam (1940–1949); (B) 1950–1964; (C) 1965–1979; and (D) 1980–1995. Incision is calculated as the decrease in mean bed elevation between two consecutive channel cross section measurements; maximum discharge is the highest daily discharge that occurred in the time period between channel cross section measurements.

4.2. Sediment transport

For the Ompompanoosuc and Black Rivers, the extent and frequency of bed elevation changes decrease after impoundment, but on different timescales. This temporal difference may be related to the strong interaction between bed mobility and bed composition. Without knowing pre-dam bed conditions, a two-fraction sediment transport model provides a method for estimating changes in bed composition and transport following impoundment. In this model, average bed sand fraction (F_s) is representative of bed compositional differences.

4.2.1. Ompompanoosuc River

A baseline average sand fraction of 15% was established for the post-dam period on the Ompompanoosuc River downstream of the dam (F_s; Table 2) from calibration of the two-fraction sediment transport model to measured sediment transport rates obtained using short-lived fallout radionuclides (Salant, 2005). Because the Union Village dam only traps sediment seasonally, we assume that the average annual sediment flux in the Ompompanoosuc River during the post-dam period approximately equals the pre-dam average annual sediment flux. This assumption implies that a decrease in flow after impoundment is compensated by an increase in bed sand fraction. Thus, a post-dam sand fraction of 15% reflects an increase from pre-dam conditions. By altering the sand fraction of the pre-dam period in the two-fraction transport model (Eq. (1); Table 2), we can adjust the pre-dam annual sediment flux to equal the known post-dam annual sediment flux. In doing so, we find that the bed sand fraction required during the pre-dam period to match the post-dam average annual sediment flux is 13% (Table 2), implying that the bed sand fraction may have increased by ~2% following impoundment. To determine the sensitivity of this result to the post-dam sand fraction, we performed the same analysis using a post-dam sand fraction of 10%. A similar ~2% increase in sand fraction between time periods is required under these conditions, indicating that the model is sensitive only to *relative* changes in sand fraction, not absolute values, at least within a likely range of sand fractions. A similar ~2% increase in sand fraction is obtained when only the sand flux is balanced between the two time periods. The small change in sand fraction (2%) between the two time periods reflects the high sensitivity of sediment flux predicted by the transport model to the sand fraction parameter and demonstrates how small changes in sand fraction can compensate for much larger changes in flow (e.g., a 30–40% reduction in the 2-yr flood).

Although average annual sediment flux on the Ompompanoosuc River is the same in both time periods, the particle sizes in the pre- and post-dam bed loads differ significantly. In the pre-dam period, more than 30% of the modeled total flux was gravel, compared to only 2% for the post-dam period (Q_g/Q_t; Table 2). This suggests that even while total transport capacity remains constant, stream competence decreases significantly; the post-dam bed load is composed of less gravel and more sand than the pre-dam bed load. Reduced mobilization of gravels is due to the post-dam decrease in the magnitude of high flows. Prior to construction of the dam, nearly 20% of the total sediment flux was transported by flows >55 m^3/s (Fig. 5A)—highly competent but relatively rare high discharge events. Dam management now eliminates these events, but the modeled increase in sand fraction increases the capacity of the more frequent moderate discharge events, resulting in the same overall average annual sediment flux. However, these more moderate discharge events are less competent and thus not able to mobilize the largest gravels. For example, reducing the peak discharge from 95 m^3/s during the pre-dam period to 55 m^3/s reduces the maximum entrained gravel size from 7.0 to 5.5 cm, an ~20% decrease (Fig. 5A).

4.2.2. Black River

Without a fully calibrated model available for the Black River, we consider a range of post-dam sand fractions between 5% and 15% so as to include values less than and equal to the sand fraction of the Ompompanoosuc River. Within this range, the average annual sediment flux is identical pre- and post-dam regardless of the assumed sand fraction. In contrast to the Ompompanoosuc River where the reduction in high flows resulted in a decrease in transport capacity and a compensating increase in sand fraction, reduced flows on the Black River have not significantly decreased transport capacity. Because the actual post-dam bed sand fraction selected for the model does not affect the analysis, we use a sand fraction of 10% for both time periods.

Although average annual sediment capacity is similar between the time periods, the style of transport differs: the proportion of total sediment formerly transported by rare high-flow events (>100 m^3/s occurring <0.1% of the time) is now transported by more frequent moderate flow events (Fig. 5B). In addition, sediment supply downstream of the dam on the Black River has changed. Most of the upstream sediment supply is trapped by the dam, thus the available transport capacity is now used to scour the bed below the dam, resulting in the observed channel degradation below the dam.

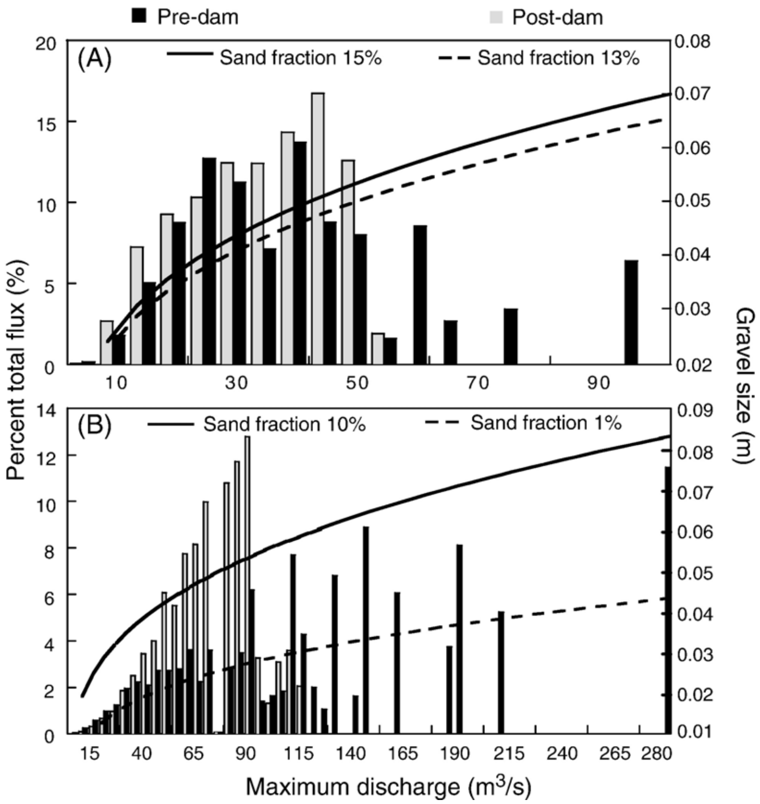

Fig. 5. Effective discharge plots for pre- and post-dam time periods on the (A) Ompompanoosuc and (B) Black Rivers, Vermont. The percent of total sediment flux (gray and black bars) for each discharge class was calculated based on daily discharge measurements and the predicted sediment flux from a two-fraction transport model (Wilcock and Kenworthy, 2002). The transport model was also used to calculate the maximum gravel size entrained for each discharge class (solid and dashed lines) for two different bed sand fractions. See text for calculation and model details.

However, not all bed sediment is equally mobile: at 10% sand fraction (our estimate for the initial post-dam conditions), more than 90% of the average annual flux is sand (Q_g/Q_t; Table 2). Thus, the sand will be preferentially removed, and the sand fraction of the bed will decrease.

4.3. Embeddedness

Changes in sand fraction predicted by the sediment transport model are consistent with changes in embeddedness upstream and downstream of the dam on both rivers. For both the Black and Ompompanoosuc Rivers, the mean annual reach embeddedness value for the sites upstream of the dam is ~20%. This is similar to the typical level of embeddedness found in the unregulated White River. Downstream of the North Springfield dam on the Black River the average embeddedness decreases to <1%, while downstream of the Union Village dam on the Ompompanoosuc River the embeddedness increases to >60%.

These changes in embeddedness are consistent with the modeled changes in sand fraction of the bed, although the change in embeddedness exceeds the change in sand fraction. As demonstrated in the transport model, changes in sand fraction (and correspondingly embeddedness) reflect the influence of impoundment on sediment supply and transport capacity. Below the dam, the Black River compensates for the reduction in sediment supply by decreasing the sand fraction on the bed and overall embeddedness. In the Ompompanoosuc River, the decrease in flow coupled with a nearly constant, albeit seasonal, sediment supply has resulted in deposition and an increase in sand fraction and overall embeddedness.

5. Discussion

5.1. Bed elevation stabilization

The results from this study demonstrate the complex nature of geomorphic adjustments from flow regulation.

Differences in sediment supply and bed sediment composition alter the timescale on which stabilization of the bed elevation occurs, where stabilization is indicated by a decrease in bed elevation variance. A reduction in bed elevation variability is not surprising because on both rivers flow regulation has significantly reduced the magnitude and frequency of the large discharge events necessary for the mobilization of large particles and subsequent incision. These hydrologically induced reductions in incision appear when the high flows are eliminated, i.e., soon after the dams are constructed (Fig. 2). Unexpectedly, however, additional stabilization occurring over a timescale of several decades occurs under excess sediment supply on the Ompompanoosuc River. This suggests that other factors, in addition to reduced discharges, are impacting bed elevation variability on the Ompompanoosuc River. The results from our transport modeling suggest that changes in bed composition may be among the most important of these additional factors.

On the Black River, sediment trapping by the dam abruptly reduces the upstream sediment supply, leading to a decrease in both embeddedness and percent bed sand fraction. In this case, the rapid stabilization of the bed elevation may be a consequence of a rapid flushing of fine sediment from the bed, as transport capacity significantly exceeds supply. Using the average sediment transport rate predicted by the model and a gravel and sand porosity of 35%, we estimate that immediately after construction of the dam sand could have been scoured from the bed of the Black River below the dam at a rate of ~6 cm/yr. Thus, any sand in the bed immediately below the dam was likely flushed further downstream soon after completion of the dam. Decreased bed sand fraction subsequently decreased transport competence, as predicted by the two-fraction model (Eq. (3)). This is illustrated in Fig. 5B where we plot the maximum gravel size entrained (as predicted using Eq. (3)) versus discharge class for two sand fractions. On the Black River at 10% sand fraction (our estimate of the pre-dam condition), decreasing the maximum flow from ~290 to ~115 m^3/s reduces the maximum entrained gravel size from 8.5 to 6.5 cm, an ~20% reduction. In contrast, at ~290 m^3/s, decreasing the sand fraction from 10% to 1% (our estimate for the change in sand fraction from impoundment) reduces the maximum entrained gravel size from 8.5 to 4.5 cm, an ~50% reduction (Fig. 5B). For the Black River, the change in sand fraction has a significant, and perhaps even dominant, effect on gravel mobility. The combined effect of reduced large discharges coupled with a reduction in sediment supply by the dam and the rapid flushing of sand from the bed results in an almost instantaneous decrease in bed mobility and bed elevation variability.

In contrast, stabilization of the bed elevation on the Ompompanoosuc River has occurred gradually under run-of-the-river dam management and is accompanied by an increase in embeddedness and bed sand fraction. As opposed to the Black River, where decreased high flows and decreased sand fraction abruptly reduced particle mobility, the increased sand fraction on the Ompompanoosuc River should, by itself, increase competence (Eq. (3)).

In some cases, increased sand fraction may actually reduce gravel mobility. For example, fine sediment deposition may gradually bury gravels and reduce their protrusion into the flow, thereby reducing their mobility (Kirchner et al., 1990). If the bed elevation of the Ompompanoosuc River is becoming stable because of gravel burial, this severely impacts the ability of the two-fraction model to accurately predict, for example, flushing flows; a decrease in gravel mobility as sand fraction increases runs counter to the predictions of the sediment transport model (Eq. (3)). However, field observations and ecological conditions lead us to question burial of the gravels as a primary explanation for the gradual stabilization of the bed elevation.

For instance, gradual burial of gravels is not consistent with the observed rate of aggradation of the bed on the Ompompanoosuc River. In contrast to the gradual decrease in bed elevation variance, bed aggradation is almost complete shortly after the construction of the dam (Fig. 2A), indicating that deposition occurred almost immediately. Additionally, if the gravels are buried by fine sediments, these sediments should be mobilized by the moderate discharge events that still occur after construction of the dam. However, Fig. 4 indicates that increasingly large flows are needed in the post-dam period to incise the bed.

Furthermore, ecological data from sites upstream and downstream of the dam suggest that flow regulation has reduced gravel mobility, but has not drastically increased the supply of fine sediments (Salant, 2005). Increased deposition of fines has been repeatedly shown to decrease invertebrate diversity and abundance (Richards and Bacon, 1994; Waters, 1995; Angradi, 1999; Weigelhofer and Waringer, 2003). In particular, clogging by fines may impair large-bodied filter feeding organisms. On the Ompompanoosuc River, the abundance of filter-feeding caddisflies (Hydropsychidae) is significantly greater below the dam relative to unregulated sites (Salant, 2005). These organisms are disturbance-vulnerable and require a clean and stable gravel substrate to proliferate. As filter-feeders, their dominance would be limited by excess fines. The abundance of this family of organisms provides further evidence that the dam has led to stabilization of the large clasts on the bed, but not an oversupply of fine sediments or the burial of gravels.

An alternative explanation for gradual stabilization of the bed elevation that is consistent with the sediment transport model involves both a gradual and slight increase in sand fraction and the preferential winnowing of small- and mid-sized gravels. The combined effect of sand deposition and preferential winnowing of small and mid-sized gravels will shift the particle size distribution to its end members, increasing the abundance of fines and large gravels without necessarily changing the mean particle size. As the easily mobilized smaller gravels are gradually removed, the remaining larger gravels become increasingly difficult to entrain with the available flows. Meanwhile, the upstream supply of these small- to mid-sized gravels is limited because of the presence of the dam during spring high flows and the lower sand fractions upstream of the dam. Lower bed sand fractions decrease the competence of upstream sites relative to downstream sites, such that these smaller gravels are only entrained during high flows when the dam gates are closed and block their passage downstream. When the gates are open, the upstream flows are too low to transport these gravels, and downstream replenishment of this size fraction does not occur. As a result, the average gravel size increases. A post-dam increase in gravel size should further increase the sand fraction required to balance total sediment flux between time periods, beyond that required to compensate for post-dam reductions in flow. Our field observations suggest that this modest increase in sand fraction is not sufficient to impact filter-feeding caddisflies. In fact, it appears that any negative impact of the increased sand fraction is offset by the benefit of a more stable gravel substrate from the reduction in flow.

6. Conclusion

Our findings demonstrate that the timescale and type of changes in bed mobility and bed sediment composition below a dam depend on dam type and operation. We find that for the Black River where sediment supply is reduced, bed mobility and bed elevation variability rapidly decrease. We attribute this to the rapid flushing of sand from the bed. In contrast, on the Ompompanoosuc River, the reduced transport capacity coupled with a constant sediment supply gradually reduced bed elevation variability, increased sand deposition, and (we believe) preferentially removed small and mid-sized gravels. However, for both the end-member cases considered here, the measured changes can be explained within the framework of a two-fraction sediment transport model. This provides support for the application of this type of model to predict sediment transport in mixed sand/gravel rivers, particularly for analyzing the potential impact of proposed flushing flows.

This study is limited to a relatively short length scale below the dam. Previous studies have considered the influence of downstream tributaries potentially mediating or exacerbating the effect of the dam (Wilcock et al., 1996; Collier, 2002) such that conditions farther downstream may be very different. However, one of the main objectives of this study was to evaluate the applicability of sediment transport models to explain how differences in dam management affect bed composition. For this purpose, excluding potentially confounding effects of sediment flux from tributaries is preferable, particularly as we are primarily concerned with dam-induced changes in sediment supply.

The results from this study suggest that simply managing flows may be not be the most efficient strategy for maintaining bed mobility and natural variability in bed elevation, at least in reaches directly below a dam. As revealed by the case of the Black River, small decreases in sand fraction dramatically increase the amount of flow required to mobilize the bed. In principle, reducing the flow required to mobilize the bed of the Black River is possible by releasing some of the fine sediment now permanently trapped by the dam. However, as demonstrated by the results from the Ompompanoosuc River, releasing too much sediment from the dam can result in the sand fraction and embeddedness increasing beyond their pre-dam values. An increase in embeddedness is ecologically harmful (Lowe and Bolger, 2000), while an increase in sand fraction will increase the duration of the flushing flow required to clean the bed. Furthermore, given the different timescales of response exhibited by these two rivers, management must consider how frequently a flushing flow is required to maintain bed mobility. Thus, to maintain natural conditions of embeddedness and optimize the minimum flow required for mobility, the reach just below the dam will optimally benefit from the release of enough sediment to balance supply and capacity. Although maintaining embeddedness does not ensure ecological integrity, it will minimize the magnitude, duration, and frequency of flows required to flush fine sediments from the bed.

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