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Temporal and spatial scales of geomorphic adjustments to reduced competency following flow regulation in bedload-dominated systems

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ABSTRACT

Because of the combined effects of reduced sediment transport capacity and competency following flow regulation, morphological changes are expected to occur in channels downstream from dams and, specifically, at tributary junctions where local inputs of water and sediment occur. Using a combination of historical aerial photographs, mainstem- and tributary-channel pebble counts, and HEC-RAS flow modeling for two watersheds in south-central VT, one unregulated and the other regulated since 1961, we document the time series of post-regulation channel narrowing and associated bar growth due to the influx of tributary sediment. Channel adjustments at regulated tributary junctions have been significant in ca. 50 years following impoundment, with channels downstream of the confluences narrowing over 15% after an initial ca. 20-year lag before the onset of accelerated narrowing. Moreover, flow modeling suggests that downstream of regulated confluences, the modern median grain size (d_{50}) along the channel bed is immobile. No significant channel narrowing has occurred either above or below unregulated tributary junctions or on the mainstem upstream of regulated confluences. However, greater channel sediment fining is observed upstream of regulated confluences than above unregulated confluences. Thus, the primary mode of mainstem channel adjustment differs up- and downstream of regulated tributaries. These confluence effects have occurred where the tributary drainage area is only 0.2 times that of the mainstem, well below the threshold ratio of 0.6 required for significant geomorphic effects at unregulated confluences, highlighting the geomorphic scale shift of dams. Lastly, we evaluate the downstream length required for a river to recover from the impacts of impoundment and demonstrate that even distal locations are impacted by flow regulation. Unlike the impacts of flow regulation in the western US where channel incision and bar erosion predominate following impoundment, we find that in situations where bed incision is minimal and where sediment loads are low but bed caliber high, bar growth and channel narrowing are significant adjustments at tributary junctions following impoundment. Therefore, at our sites the effects of dams on reduced competency may be more profound than on reduced sediment transport capacity, highlighting the importance of geologic and geomorphic settings in understanding fluvial responses to impoundment.

1. Introduction

Results from studies of large dams, particularly those in the Colorado River basin of the western U.S. (Andrews, 1990; Schmidt et al., 1995; Pitlick and Van Steeter, 1998; Allred and Schmidt, 1999; Topping et al., 2000a,b, 2007; Grams et al., 2007) demonstrate that the geomorphic impacts of flow regulation are often strongly controlled by the balance between sediment supply and the sediment transport capacity of the river. Sediment trapping by a dam, for example, results in greater sediment transport capacity than supply immediately downstream of the dam; this imbalance, in turn, leads to channel incision (Williams and Wolman, 1984) and a narrowing of the bankfull channel width (Andrews, 1986). The abandonment of pre-dam floodplains results in their subsequent re-vegetation and the development of new, lower terraces that further reduce the channel width (Petts, 1984; Grams and Schmidt, 2002; Magilligan and Nislow, 2005). Evacuation of fine sediment associated with incision may also lead to sandbar erosion (Grams et al., 2007; Wright et al., 2008), decreased embeddedness (Salant et al., 2006), and decreased ecological diversity and health of native benthic species (Svendsen et al., 2009). Farther downstream, the impact of the dam is modified as the supply of newly derived sediment from downstream tributaries, in addition to sediment removed via evacuation upstream, ultimately exceeds the reduced sediment transport capacity of the regulated mainstem, leading to channel aggradation (Graf, 1980; Andrews, 1986; Everitt, 1993; Grant et al., 2003; Salant et al., 2006; Svendsen et al., 2009).

Because of the granitic terrain of New England, fines (silts and clays) are lacking in this region due to the abundant sand- and gravel-rich glacial till, and the lack of loess. Consequently, New England rivers are characterized by suspended-sediment concentrations that

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are among the lowest in the U.S.: New England values of generally <200 mg l^{-1} are at least an order of magnitude less than the ca. 5000 mg l^{-1} average annual sediment load in the lower Colorado River (Rainwater, 1962; Andrews, 1990). As a result, sediment flux in gravel-bedded rivers of New England, even if unregulated, rarely approaches sediment transport capacity. We propose that, under such conditions of limited fines supply, the impact of flow regulation on stream sediment transport competence is more significant than impacts on sediment transport capacity.

The effects of flow regulation on channel dynamics, particularly sediment transport competence and capacity, may be particularly pronounced at tributary junctions (Andrews, 1986; Petts and Thoms, 1987; Germanoski and Ritter, 1988). Tributary junctions represent critical locations where the addition of water and sediment into the main channel results in significant changes to channel morphology (Best, 1988; Benda et al., 2004a,b) and creates fundamentally important ecological hotspots (Rice et al., 2006; Svendsen et al., 2009). While previous research has determined the general evolution of a main channel's response to regulation (Everitt, 1993), there is limited knowledge specifically about the temporal period of readjustment at tributary junctions and how these effects may differ where sediment transport competency effects exceed sediment transport capacity effects.

Benda et al. (2004a) have shown that as the ratio of tributary (A_t) to mainstem (A_m) drainage area increases the likelihood of a tributary having a "geomorphically significant" effect increases above a critical minimum threshold value of ca. 0.6. Because regulation effectively increases the tributary to mainstem drainage area ratio by making the mainstem behave like a smaller basin from reduced flows and sediment loads, we expect that the impacts of a tributary will be exacerbated by flow regulation and that the critical minimum threshold for impact may be reduced.

To better understand the impact of regulation on a river with typically low suspended-sediment loads typical of New England, we use historical aerial photographs, channel pebble counts, and flow modeling to document and compare temporal changes between regulated and unregulated tributary junction morphology and sediment transport dynamics in two southern Vermont rivers. We find that, unlike many western U.S. rivers where downstream impacts of dams can be understood in terms of the balance between sediment transport capacity and supply, the impacts we observe are primarily controlled by the balance between reduced sediment transport competence and sediment grain size. We generalize our results with the introduction of metrics for the geomorphic impacts of changes in water and sediment flux resulting from flow regulation. Our analysis can provide insight into possible options for mitigating the impacts of dams as well as identifying the distal attenuation of a dam's geomorphic impact.

2. Site descriptions

The West and White Rivers are mixed bedrock-alluvium tributaries of the Connecticut River in southern Vermont (Fig. 1); the alluvium in both cases is comprised of gravel and sand. The two watersheds have similar drainage areas and are located within 50 km of each other, so each has similar underlying geology and hydroclimatology (Doll, 1970). Both watersheds receive ca. 115 cm of precipitation more or less uniformly distributed throughout the year, with about one-quarter of this falling as snow. The average annual temperature is 6.7 °C with large seasonal fluctuations (NOAA, 2009).

This study focuses on three tributary junctions in the regulated West River (Fig. 1, Table 1); one located above and two below the Ball Mountain dam. As a point of controlled comparison, we also consider a fourth tributary junction on the unregulated White River. The tributary on the unregulated White River is similar in drainage area to the unregulated Winhall tributary on the West River. As a second point of comparison, we also explore temporal changes in average channel characteristics at the Rock River tributary junction located 18 km below a second flood control structure on the West River, the Townshend dam, located downstream of the Ball Mountain dam. More detailed descriptions of each river and their tributaries follow below.

2.1. West River

The West River has an overall watershed area of 1091 km^2 and a mean annual discharge of 10.9 m^3/s at the United States Geological Survey (USGS) gage station in Jamaica, VT (drainage area = 464 km^2) just below Ball Mountain dam. The five primary tributaries on the West River range in drainage area from 72 km^2 to 154 km^2 (Fig. 1). The change in mean channel width at tributary junctions after the construction of the Ball Mountain and Townshend dams was determined for all five sites using historical aerial photographs, but only three of these sites were studied in detail with extensive field measurements (Fig. 1, Table 1); the unregulated Winhall River tributary junction above Ball Mountain dam and the two tributary junctions immediately below Ball Mountain dam (Ball Mountain Brook and Wardsboro Brook).

The U.S. Army Corps of Engineers completed the construction of both the Ball Mountain and Townshend dams on the West River as flood control structures in 1961. Townshend dam is located 16 km downstream from the Ball Mountain dam, well below both the Ball Mountain and Wardsboro tributaries and thus imposing no backwater effects on the main channel confluences of these tributaries. The reservoir behind Townshend dam is the smaller of the two (0.04 km^3) and maintained at a more or less constant year-round reservoir stage. The larger reservoir behind Ball Mountain dam (0.104 km^3) extends 7 km above the dam to just below the Winhall tributary junction. The reservoir water depth varies seasonally from 20 m in the spring to 8 m in the summer. The operation of both dams is coordinated primarily for flood control with two weekends of controlled releases from Ball Mountain dam each year for recreation. Regulation has significantly reduced peak flows on the West River below both dams. Although the average daily flows have been larger during the post-regulation era than before dam construction, the magnitude of the 50-year floods just below the Ball Mountain dam has been reduced by an order of magnitude from 1035 m^3/s to 167 m^3/s (Table 2). As a result, the contemporary 50-year flood is similar to the pre-dam 2-year flood and during the post-regulation interval, the pre-dam 2-year flood has not occurred on the West River below the dams (Svendsen et al., 2009). The sediment trapping efficiencies of the dams are unknown, but likely high given their persistent reservoirs and limited releases. Preliminary results from recent estimates of the volume of sediment stored behind Ball Mountain dam based on ground penetrating radar transects indicate that sediment is being stored behind the dam at a rate that is similar to the average erosion rate for northern New England (Kasprak et al., 2008), consistent with the purportedly high sediment trapping efficiency of the dam.

2.2. White River

The White River drains into the Connecticut River about 50 km above the West River and has a watershed area of 1843 km^2. The mean annual discharge is 34.1 m^3/s at the USGS gage station in West Hartford, VT (drainage area = 1787 km^2). There are five primary tributaries on the White River, ranging in drainage area from 112 km^2 to 355 km^2 (Fig. 1). Historical photographs of all five tributary junctions were analyzed to determine historical changes in mean channel width, but only one tributary junction, the West Branch, was selected for more detailed study. The West Branch of the White River will be referred to as WB-White to prevent confusion with the West

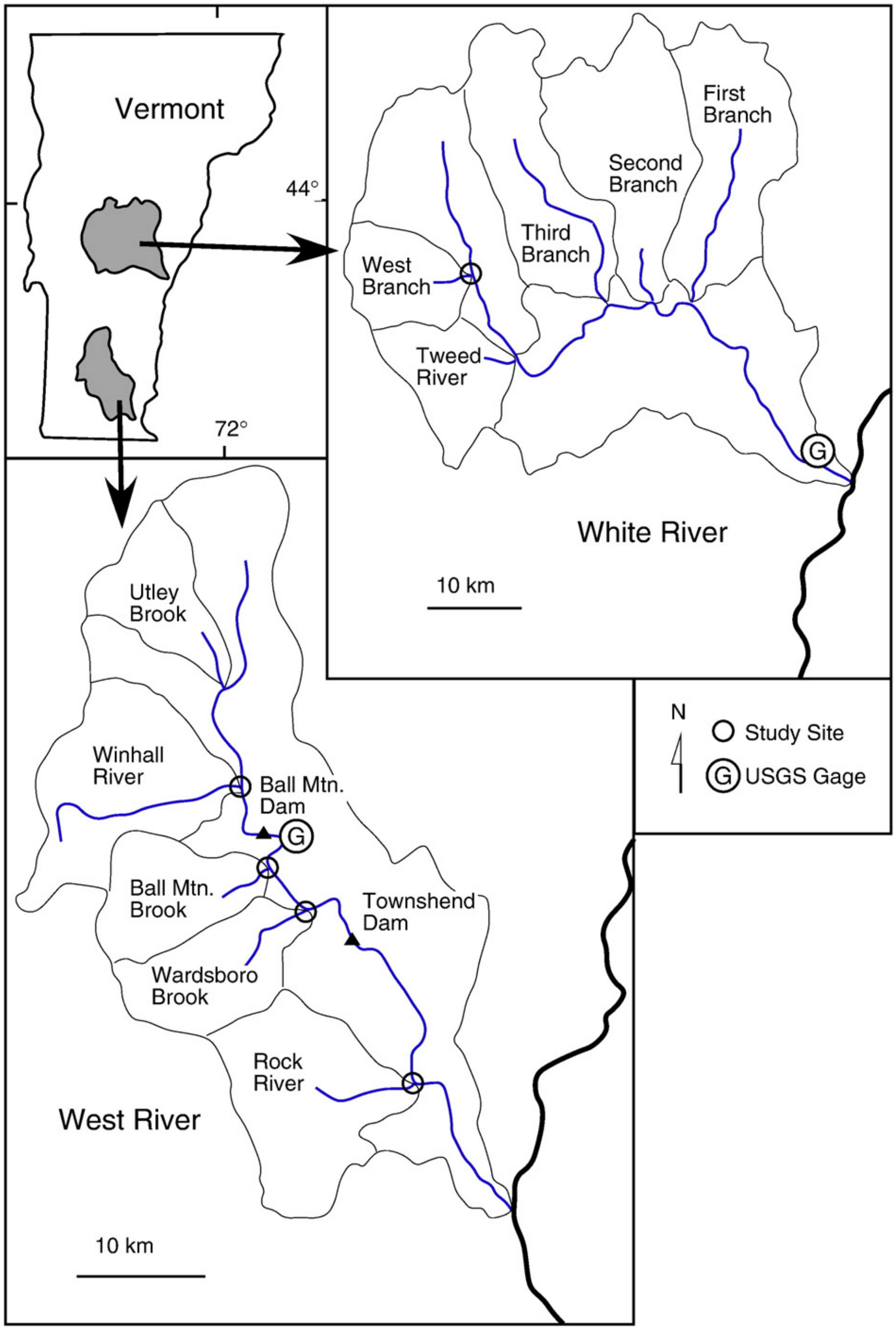

Fig. 1. Map of the White and West Rivers with the tributary watershed areas delineated.

Table 1
Site characteristics at the tributary junctions on the White and West Rivers.

Tributaries	Tributary drainage area (km^2)	Tributary/mainstem drainage area	Distance from CT River (m)	Distance from Ball Mountain/Townshend dam (km)	Mainstem mean bankfull width (m)
West River					
Winhall River	154.3	0.59	54.5	Unregulated	55
Ball Mountain Brook	87.3	0.19	43	3.9	40
Wardsboro Brook	91.1	0.15	38.1	8.9	50
Rock River	149.2	0.17	14.2	32.7/17.6	75
White River tributary					
West Branch	112.1	0.55	71.7	Unregulated	30

River. The WB-White has a similar tributary to main channel drainage area ratio (ca. 1:2) to that of the unregulated Winhall tributary on the West River.

Table 2
Peak 2-year (Q2) and 50-year (Q50) discharges (m^3/s) at USGS gages.

USGS gage	Gage number	Period of record	Pre-regulation		Post-regulation	
			Q2	Q50	Q2	Q50
West River at Jamaica, VT	01155500	1946–2009	228	1035	118	167
White River at West Hartford, VT	01144000	1915–2009	501	1470	N/A	N/A

3. Methods

3.1. Historical record

Historical aerial photographs were used to measure changes in channel width and bar area around tributary junctions over the past 50 years. U.S. Geological Survey and National Agriculture Imagery Program historical aerial photographs of the sites were taken approximately every 20 years since the 1950s. The resolution of all images is slightly better than 1 m^2/pixel, or about 2% of the typical channel width and 0.02% of the typical bar area. As in previous studies (Juracek, 2000; Winterbottom, 2000), to eliminate inconsistencies across photographs at different dates with different water levels, the bankfull channel width was defined as the region that encompasses the combination of the inundated area and the unvegetated or partially vegetated gravel bars. Where the bankfull channel was not clear from shadows or tree cover, the channel boundary was interpolated by assuming the trees closest to the channel edge mark the boundary (Juracek, 2000). Channel width was calculated every meter for 1 km above and 1.5 km below the junction for all major tributaries on the West and White Rivers.

The tributary bar area is defined as the exposed or sparsely vegetated sediment around the junction immediately downstream and connected to the tributary junction bar or in the mouth of the tributary. Any bars located upstream of the junction or on the opposite mainstem bank are not included. The bar area encompasses the bankfull width to the water's edge. Areas of post-regulation new vegetation on the original bars are included in the bar area.

As the exposed bar area is a function of the discharge at the time the aerial photograph was collected, the mean daily discharge on that day was estimated from USGS gage data. Vermont regional discharge curves (Jaquith and Kline, 2001) were used to extrapolate daily discharge from the gage to each of the tributaries. The West Hartford, VT, gage on the unregulated White River was used for all tributaries and the unregulated mainstem channels. The gage station below the Ball Mountain dam at Jamaica, VT, on the West River was used to extrapolate flows for the regulated mainstem. Because the historical channel topography is not known, no attempt was made to correct bar area for discharge. Further, because bar boundaries are somewhat subjective, all estimates of bar area should be taken only as useful approximations.

3.2. Modern channel morphology

Channel topographic surveys were conducted with a real-time differential GPS survey by taking cross section transects along the

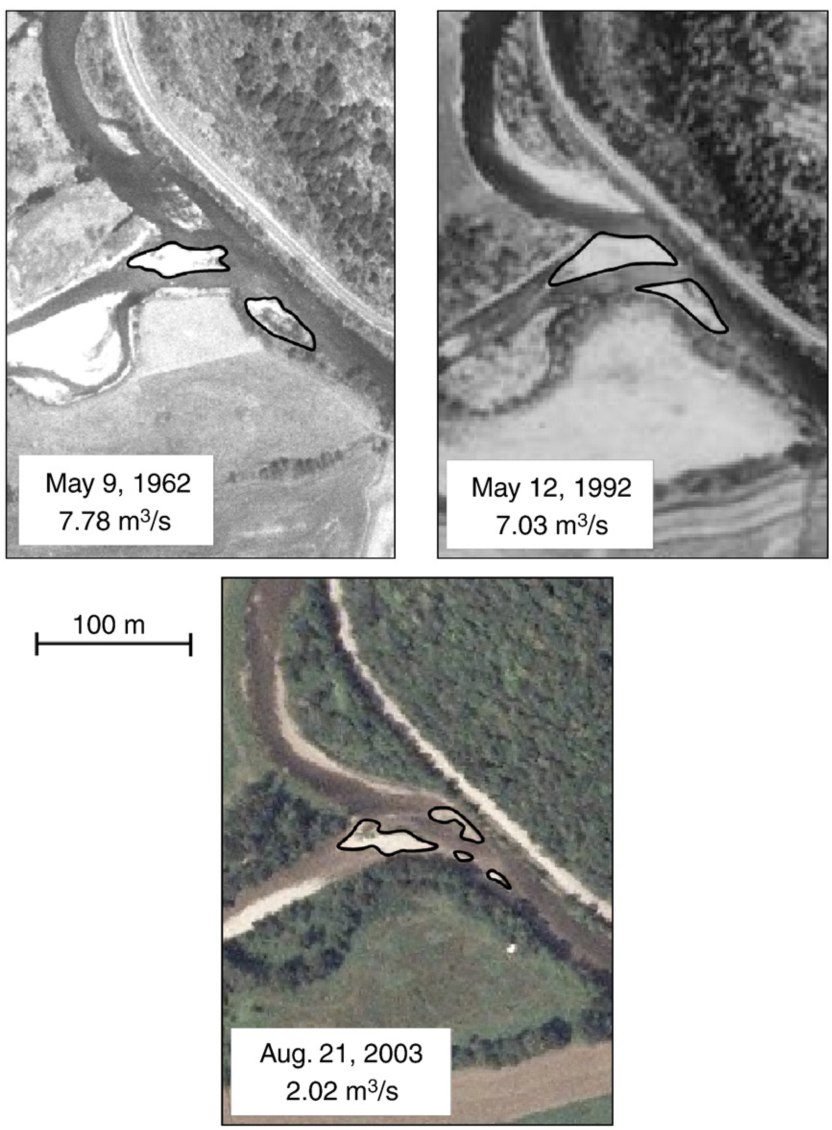

Fig. 2. Historical aerial photographs of the WB-White tributary junction with the date and discharge of the White River immediately above the tributary junction indicated. Tributary bar extent is highlighted. Flow direction is left to right.

channel. The accuracy of the GPS system was generally better than ca. 2 cm, except along the channel banks where trees interfered with satellite communication. A rotating leveling laser was used to determine bank elevation in areas with poor satellite reception. The topographic transects were used to construct a three-dimensional topographic map of each tributary junction.

Median grain size within the active channel was determined following the method of Wolman (1954). For each location, the median grain diameter (d_{50}) and 25% and 75% quartiles (d_{25} and d_{75}) were determined.

3.3. Flow modeling

The Army Corps of Engineers flow modeling program HEC-RAS was used to model the post-regulation 2- and 50-year floods at each tributary junction. Flood discharges along the regulated upstream mainstem reaches were extrapolated from the post-dam annual peak discharges observed at the USGS gage station below Ball Mountain dam using the Vermont regional discharge curve (Jaquith and Kline, 2001). Discharges for the tributary and unregulated mainstems were estimated using the pre-dam discharges. Flood magnitudes were estimated assuming a Log Pearson type III distribution.

Topographic cross-sections perpendicular to flow required for the flow modeling were extracted from the three-dimensional topographic map constructed from the topographic survey. Cross-sections were spaced approximately every 20 m. Flow was modeled along reaches extending 200 m upstream of the junction along both the mainstem and the tributary and 200 m downstream along the mainstem. Tributary confluences were modeled using HEC-RAS as stream junctions with the energy equation option. A normal depth boundary condition was used along the furthest downstream boundary by approximating the energy grade slope as equal to the downstream bed topographic gradient at that location. Typical values of Manning's n of 0.04 for the channel and 0.08 for the channel banks were assumed. Increasing Manning's n values by 50% for the 2-year floods had no significant impact on model results.

4. Results

4.1. Historical record

Aerial photographs of a representative unregulated (WB-White, Fig. 2) and regulated (Ball Mountain, Fig. 3) tributary junctions from 1962 to 2003 are shown with the bar areas highlighted. Significant upstream channel migration is apparent at the unregulated WB-White tributary junction, with the possible subsequent transport of large volumes of sediment from the newly eroded bank enlarging the bar just downstream of the junction. After the upstream channel stopped migrating sometime between 1992 and 2003, the bar downstream of the junction returned to within 10% of its 1962 size (Fig. 4). For the unregulated site not shown over the course of 60 years, the bar decreased in size by ca. 10% (Fig. 4). Thus at both unregulated tributary junctions, the modern bar area is within ±10% of what it was prior to the construction of the Ball Mountain and Townshend dams.

In contrast, bars on the regulated river have increased in size more or less linearly in time during the post-regulation era (Fig. 4), with significant extension of the tributary sediment into the main channel from the pre-dam to the 2003 photographs (Fig. 3). The discharge in the 2003 photographs for all junctions is less than the original photograph, so a portion of the apparent bar size increase may be partially from the decreased discharge. However, bar size is larger than in the original photograph in 1981 when the discharge was nearly double what it was in the 1962 image (Fig. 3). At all of the regulated sites the original exposed bar area has been at least partially revegetated during the dam-regulation epoch.

An analysis of variance (ANOVA) for the change in mean channel width determined from the historical photographs showed no statistically significant changes in mean channel width of the mainstem over the past 50 years either *above or below* unregulated tributary junctions or *above* regulated junctions. Over the same time period, mainstem mean channel widths *below* regulated tributary junctions have narrowed significantly by over 15% (p-value = 0.0052) within 1.5 km of the confluence (Fig. 5). A lag in the narrowing of ca. 20 years is apparent in the time series of width at all the regulated junctions; little narrowing is apparent during the first two decades post-regulation. However, since about 1980 there has been significant narrowing of all channels downstream of regulated tributaries and this appears to be continuing well into the fifth decade post-regulation, although at a somewhat slower rate.

4.2. Channel grain size

The pebble count data show coarsening along the main channel downstream of regulated tributary junctions (Fig. 6). For example, at Ball Mountain Brook (Fig. 6A), t-tests reveal that the spatially-averaged value of median grain size upstream of the junction (4 cm) is significantly different from that downstream of the junction (14 cm, $p < 0.001$). However, no significant difference exists between the spatially-averaged value of median grain size on the tributary (13 cm) and that downstream of the junction ($p = 0.36$). At Wardsboro Brook (Fig. 6B), the spatially-averaged value of median grain size downstream of the junction (13 cm) is significantly greater than that of the tributary (9 cm, $p < 0.001$) and of the upstream main channel (7 cm, $p < 0.001$). The source of these larger pebbles at Wardsboro may be tributary derived as the 75% quartile on the tributary approaches 20 cm versus only 13 cm on the upstream main channel.

On the unregulated rivers, the spatially-averaged value of median grain size downstream of the junction more closely resembles that on the upstream mainstem and on the tributary. For example, no significant difference exits between the median grain size below the WB-White junction (5 cm) and that of the upstream mainstem (4 cm, $p = 0.38$) and tributary (7 cm, $p = 0.09$) (Fig. 6C). At Winhall, the downstream median grain size (11 cm) is not significantly different from the median grain size in the tributary (13 cm, $p = 0.15$) and only marginally significantly different from that along the upstream mainstem (15 cm, $p = 0.04$) (Fig. 6D).

5. Discussion

5.1. Geomorphic impact of tributaries

Recent work by Benda et al. (2004a,b) highlights the importance of tributary characteristics (size, drainage density, gradient, etc.) in controlling the geomorphic impact of tributaries. They find that in unregulated systems, ratios of tributary to main channel drainage areas of ca. 0.6 or higher are generally needed for tributaries to have a significant geomorphic impact. However, we observe significant geomorphic effects, including on-going changes in channel width, bar area and particle size, at our regulated mainstem confluences despite their having drainage area ratios of ~0.2 (Table 1). The specific geomorphic impact of the tributaries on the regulated mainstem differs above and below the confluence.

Below the regulated confluence we observe narrowing of the channel that is clearly related to bar growth downstream of the junctions (Fig. 3). Consistent with previous studies, our results (Fig. 6A,B) indicate that tributary sediments dominate the sediment distribution downstream of a regulated confluence (Andrews, 1986; Graf, 1980; Petts, 1984; Petts and Thoms, 1987), reflecting the continued input of tributary sediment into the mainstem post-regulation. Over the same time period, no similar bar growth or dominance of tributary sediment is observed downstream of unregulated junctions (Fig. 6C,D).

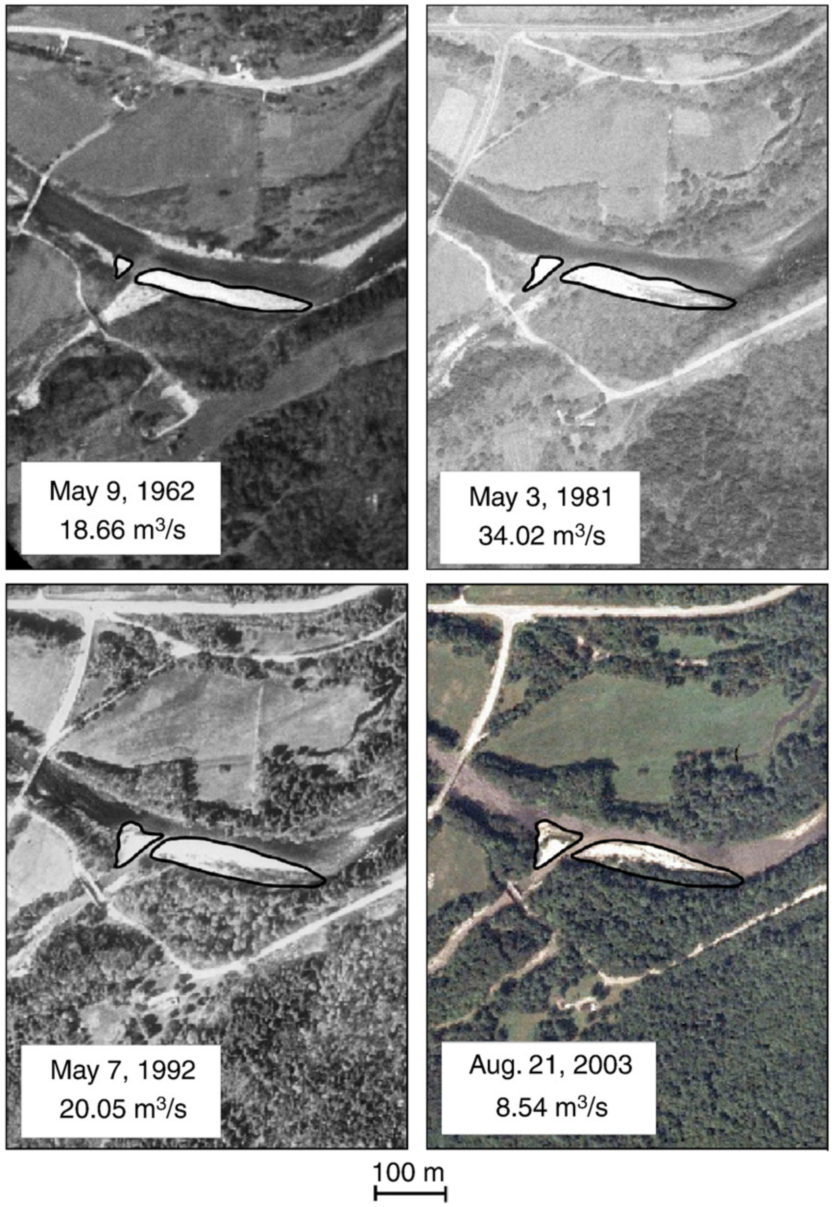

Fig. 3. Historical aerial photographs of Wardsboro Brook with the date and discharge of the West River immediately above the tributary junction indicated. Tributary bar extent is highlighted. Flow direction is left to right.

In contrast, we observe no significant narrowing of the mainstem above the confluence, but here the channel grain size is significantly finer than observed below the confluence or in the tributary. Although

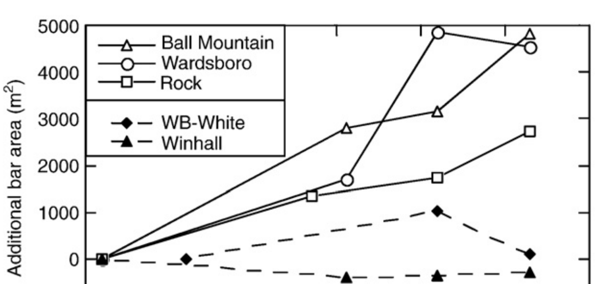

Fig. 4. Increase in tributary bar area at the three regulated tributary junctions (solid lines) and the two unregulated tributary junctions (dashed lines). Regulation began in 1961.

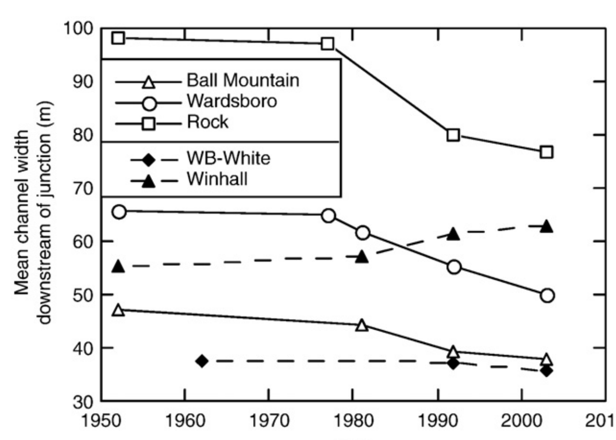

Fig. 5. Mean mainstem channel width over a 1.5-km reach immediately downstream of the regulated (solid lines) and unregulated (dashed lines) tributary junctions. At all regulated sites, channel narrowing accelerates ~20 years after the onset of flow regulation in 1961.

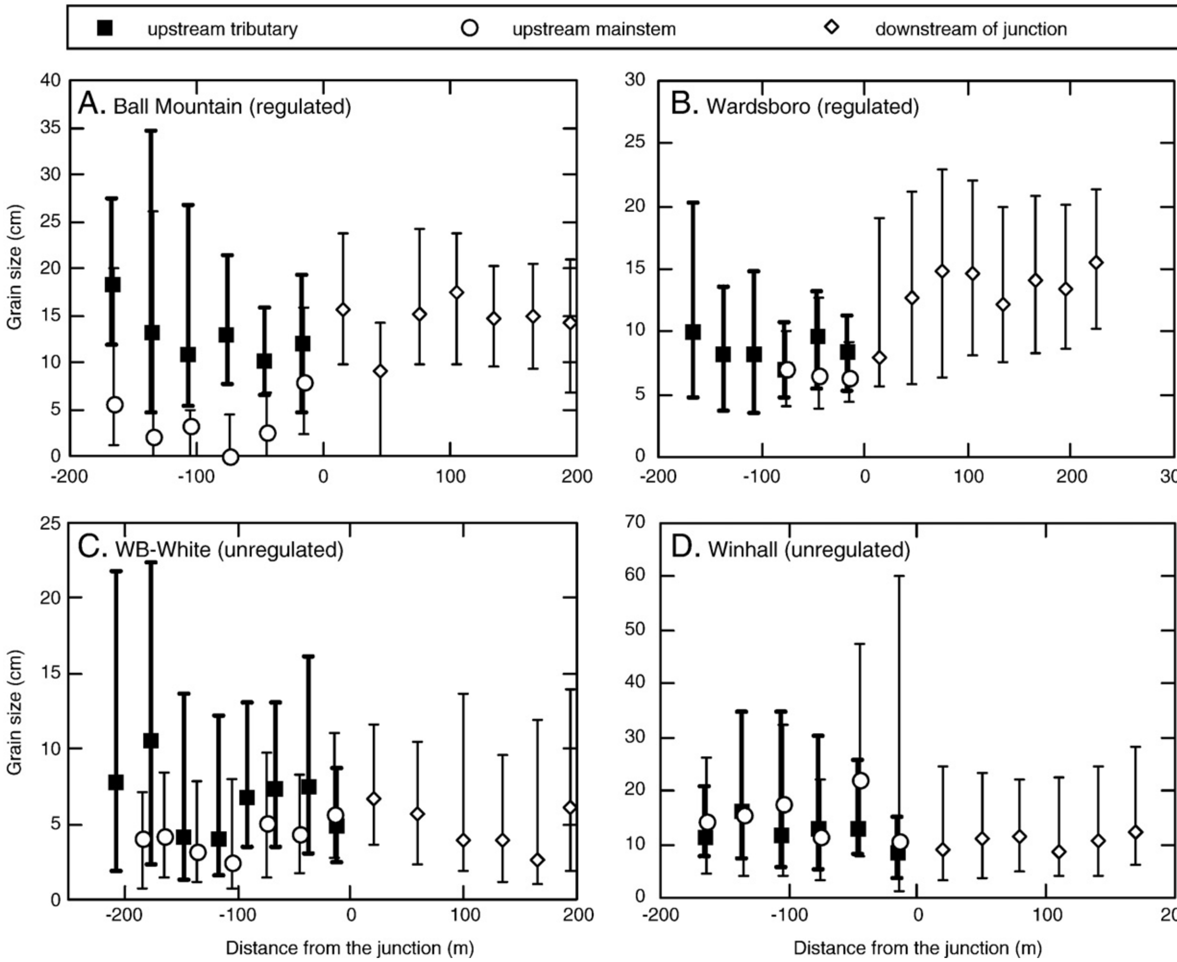

Fig. 6. Median channel grain size d_{50} as a function of distance from tributary junction at (A) Ball Mountain, (B) Wardsboro, (C) WB-White, and (D) Winhall. Error bars indicate the 25% and 75% grain size quartile.

the pre-dam channel grain size is unknown, we note that at the two unregulated tributary junctions the grain size along the mainstem upstream of the junction is similar to that both downstream of the junction and along the tributary (Fig. 6C,D). If this were also true at the regulated junctions prior to the construction of the dam, then significant reductions in channel grain size along the mainstem upstream of the junctions have occurred post-regulation.

5.2. Covariation in channel properties

Our results are consistent with those of Williams and Wolman (1984) in that when considered in terms of individual channel properties, there is no systematic response of a river to flow regulation. Along the mainstem we observe channel narrowing below the confluence and possibly bed fining above. In our case the differences in channel response likely reflect the impact of sediment supplied by the tributary. Thus to understand the geomorphic effects of flow regulation we need to consider the covariant responses of channel properties to changes in water and sediment flux.

Within coarse-bedded streams dominated by bedload transport, predictions for the sediment volumetric flux Q_s, such as the Meyer–Peter Mueller (MPM) equation, are generally of the form

$$\Psi \propto (\theta - \theta_{cr})^{a} \qquad (1)$$

where the dimensionless sediment flux $\Psi = Q_s / (\sqrt{g} d^{3/2} w)$ is a function of the gravitational acceleration g, the characteristic grain size of the sediment in transport d, and the characteristic channel width w. The constant a is equal to 3/2 in the MPM equation. The Shields parameter θ represents the ratio of the downstream shear force and the submerged weight of individual particles and, accordingly, is defined as (Julien, 2002):

$$\theta = \frac{Sh}{Rd} = \frac{1}{2R}\left(\frac{fQ^2S^2}{gw^2d^3}\right)^{1/3} \qquad (2)$$

where S is the downstream energy slope, h the characteristic channel depth, and R the relative excess density $(\rho_s - \rho)/\rho$, where ρ_s and ρ are the densities of the particles and fluid, respectively. Here a quadratic friction law with dimensionless coefficient f is used to eliminate flow depth (Julien, 2002). The critical value of the Shields parameter θ_{cr} corresponds to the onset of motion of noncohesive particles of characteristic size d.

Implicit in Eq. (1) is the assumption of sufficient sediment supply. This assumption is inappropriate immediately downstream of a dam with high trapping efficiency. But we find that in this region of abundant glacial till, the mainstem is quickly resupplied by sediment inputs from tributaries and relic bars, justifying the use of Eq. (1), in some cases, along reaches further downstream from the dam. We consider further the applicability of Eq. (1) in following sections.

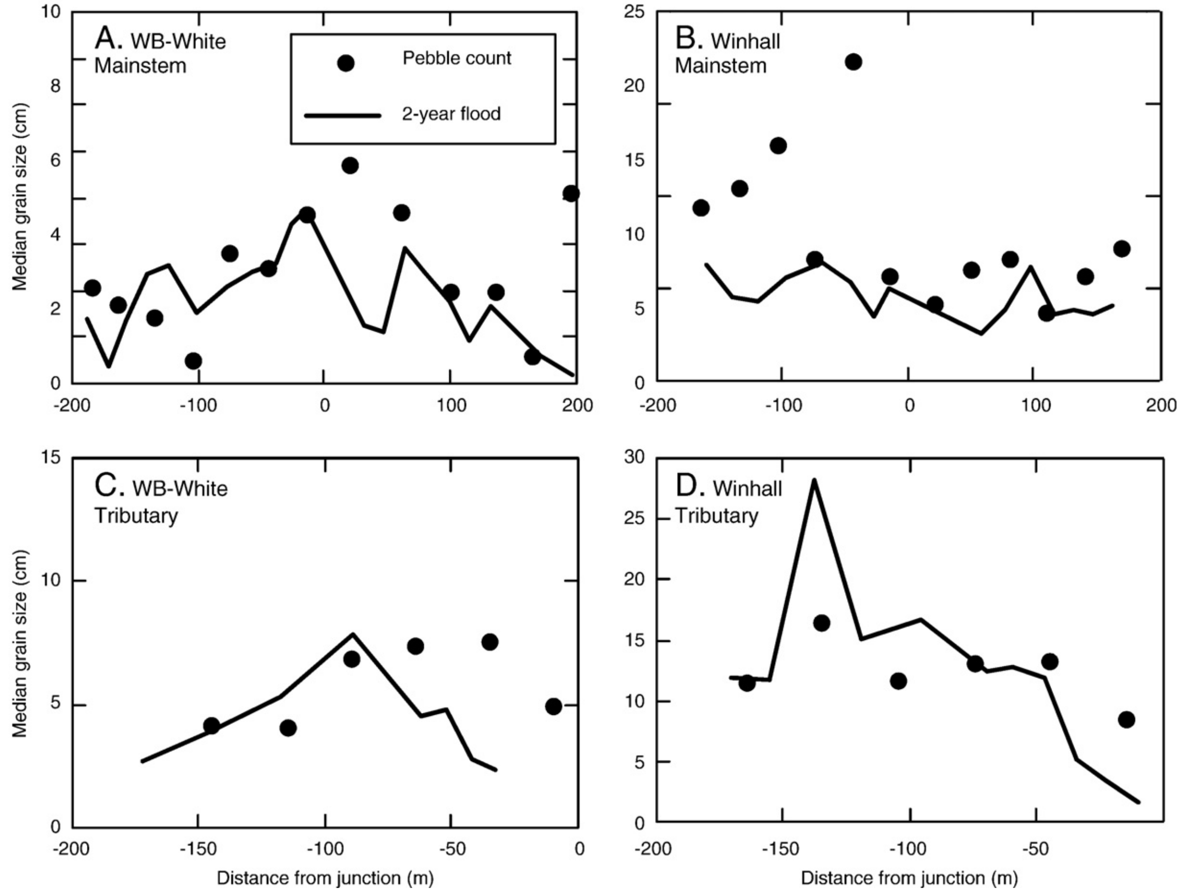

Fig. 7. Observed median grain size and estimated channel competence of 2-year peak discharge expressed as competent grain size d_c for the unregulated mainstems and tributaries: (A) WB-White mainstem; (B) Winhall mainstem; (C) WB-White tributary; and (d) Winhall tributary.

To quantify the impact of flow regulation on channel characteristics, we follow the approach of Schmidt and Wilcock (2008) and write Eq. (1) for the same reach under pre-dam and post-dam conditions. Taking their ratio gives

$$\Psi_*^{1/a} \propto \frac{(\theta_* - \theta_{cr^*})}{(1-\theta_{cr^*})} \tag{3}$$

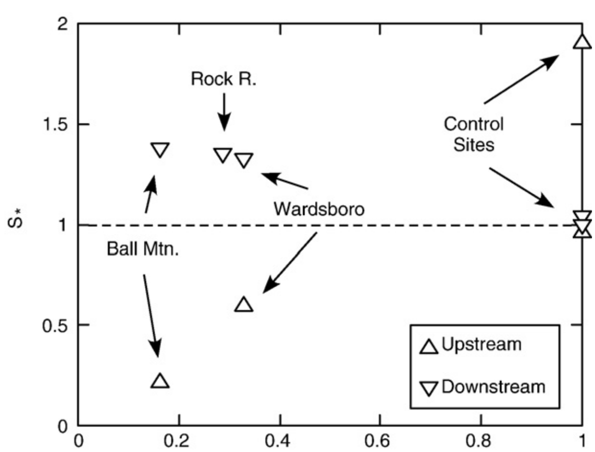

Fig. 8. Predicted changes in slope S_* along the mainstem above and below a tributary confluence as a function of normalized drainage area A_*.

where

$$\Psi_* = \frac{\Psi^{post}}{\Psi^{pre}} \; \theta_* = \frac{\theta^{post}}{\theta^{pre}} \; \theta_{cr^*} = \frac{\theta_{cr}}{\theta^{pre}} \tag{4}$$

where the superscripts pre and post indicate conditions before and after regulation, respectively.

Dade and Friend (1998) reviewed more than 120 observations of channel slope, depth, width, discharge, and grain size and found that values of the Shields parameters for rivers dominated by suspended-sediment transport generally exceed the value required for the mobilization of fine-grained sediment. Sediment transport competence, therefore, appears not to limit sediment transport in these systems, and channel geometry of fine-grained rivers is likely controlled by the sediment transport capacity of formative channel flows rather than their competence. In contrast, the Shields' parameters for coarse-sand and gravel-bed streams dominated by bedload transport (such as the West and White Rivers) are generally observed to be near the critical value required for the mobilization of the average size sediment in the bed, i.e., $\theta \approx \theta_{cr}$.

To confirm the applicability of Dade and Friend's observations to our sites, we used HEC-RAS flow modeling to estimate the Shields parameters for flooding flows at our unregulated control sites (Winhall and WB-White). To enable a direct comparison to measured field quantities, we express our modeling results as the competent grain size d_c corresponding to the critical Shields parameter $\theta = \theta_c$ (Eq. (2)), where for coarse-sand and gravel-bed channels, the critical value for motion of many particles is $\theta_c \approx 0.05$ (Julien, 2002). We also set $R = 1.65$ assuming that the majority of the sedimentary particles have the density of quartz. Finally, we use simulations of the post-dam

2-year peak discharge event to determine the characteristic energy grade slope and flow area and flow width, from which the mean depth is determined.

On the unregulated rivers and the tributaries considered here, the estimated competent grain size d_c (solid lines, Fig. 7) is generally similar to the observed median grain size (d_{50}) in the channel (points, Fig. 7), indicating that our control sites are similar to those observed by Dade and Friend in that the Shields parameters of formative flows are near the critical value required for the mobilization of the average size sediment in the bed, i.e., $\theta \approx \theta_{cr}$. The only exception is along the mainstem upstream of the Winhall junction where the estimated competence is much lower than the observed median grain size (Fig. 7B). This may be a consequence of the fact that along this reach, unlike at all our other sites, the mainstem channel is strongly confined by resistant bedrock; field observations and the surficial geology map of Vermont (Doll, 1970) indicate that this is the only reach with significant exposed bedrock. There are no recent alluvial deposits or glaciofluvial gravels immediately upstream of the Winhall tributary junction and the resistant bedrock may additionally limit the supply of fine bedload sediment to this reach.

Based on the observations of Dade and Friend and our own similar observations at our control sties, we speculate that prior to the construction of the dams, the Shields parameters of the formative flows at our regulated tributary junctions (Ball Mtn., Wardsboro and Rock River) were likely near the critical value required for the mobilization of the average size sediment in the bed, i.e., $\theta^{pre} \approx \theta_{cr}$, or, equivalently, $\theta_{cr*} \approx 1$. If so, then from Eq. (3), the constraint $\theta_{cr*} \approx 1$ requires that $\theta_* \approx 1$. This result implies that regulation causes the channel to regrade through some combination of adjustments in slope, grain size, and flow depth such that the Shields parameter is again near the critical value required for the mobilization of the channel bed. We note that it also follows that regulation causes the channel to regrade to maintain the condition $\Psi_* \approx 1$. In the following sections we use the results from our field surveys to explore the implications of this analysis.

5.3. Impact of flow reduction

Substitution of the definitions of Ψ and θ allows for the constraint that $\theta_* \approx 1$ to be written as

$$\theta_* = \frac{\theta^{post}}{\theta^{pre}} = \left(\frac{Q_* S_*}{W_*}\right)^{2/3} D_*^{-1} \approx 1 \tag{5}$$

where

$$Q_* = \frac{Q^{post}}{Q^{pre}}\ S_* = \frac{S^{post}}{S^{pre}}\ W_* = \frac{w^{post}}{w^{pre}}\ D_* = \frac{d^{post}}{d^{pre}} \tag{6}$$

We approximate Q_* as the ratio of the estimated post- and pre-dam peak two year discharges. Appropriate values for the pre- and post-regulation channel widths are determined from the pre-dam and most recent aerial photographs (Fig. 5). The post-regulation characteristic grain size d^{post} is estimated as the spatially-averaged value of the median grain size along each reach (Fig. 6).

No direct observations are available to constrain d^{pre}. Consequently, we estimate d^{pre} by noting the strong similarity at both unregulated and regulated tributary junctions between the grain sizes in the tributary and in the mainstem downstream of the confluence (Fig. 6). This similarity reflects the debouching of sediment from the tributary into the mainstem and, at the regulated junctions, is consistent with previous studies demonstrating that tributary sediments dominate the sediment distribution downstream of regulated confluences (Graf, 1980; Petts, 1984; Andrews, 1986; Petts and Thoms, 1987). Regulation of the mainstem does not impact either the character of the sediment in the tributary or the debouching of this sediment into the mainstem. Thus, downstream of the confluence, regulation has had only minor impact on the sediment supplied to the mainstem and, correspondingly, the mainstem channel grain size. Further, at our regulated control sites we observe a strong similarly between grain sizes above and below the confluence. Thus, we estimate d^{pre} along the mainstem, both upstream and downstream of the confluence, as equal to the modern spatially-averaged median grain size downstream of the confluence. While we recognize the uncertainty inherent in this assumption, we also note that the potential variability in D_* below the confluence is limited by the role of the tributary in restricting possible changes in grain size below the tributary junction. Thus this assumption provides a reasonable and pragmatic first approximation for d^{pre} that allows us to proceed with further analysis.

Because we have even fewer constraints on the pre-regulation channel slopes S^{pre} at our sites, we treat S_* as an unknown and rearrange Eq. (5) as

$$S_* = \frac{W_* D_*^{3/2}}{Q_*} \tag{7}$$

In Fig. 8 we plot the estimated changes in channel slope as a function A_*, the drainage area below the nearest dam normalized by the drainage area above the dam

$$A_* = \frac{A - A_{dam}}{A} \tag{8}$$

The sampled reach of the mainstem channel upstream of a confluence is sufficiently close (<200 m) to the tributary junction to be impacted by the delivery of sediment from the tributary. For example, the deposition of sediment at the mouth of the tributary necessarily results in a reduction in the energy grade slope along the mainstem for some distance upstream of the junction, reducing the competence of the mainstem channel flows upstream of the confluence (Hanks and Webb, 2006). Because the mainstem just upstream of a tributary junction is impacted by delivery of sediment from the tributary, we define A_* for the mainstem just upstream of the confluence as including the drainage area of the tributary.

Otherwise, the significance of the A_* is as follows. Very small values of A_* indicate little unregulated, below-dam drainage area contributing to a mainstem channel; in contrast values of A_* that approach unity indicate increasing unregulated, below-dam drainage area contributing to a channel.

Inspection of Fig. 8 indicates that estimated values of S_* are near unity at all the control sites ($A_* = 1$) except along the mainstem upstream of Winhall where, as noted above, the grain size of the channel is impacted by the exposed resistant bedrock (Fig. 6). Along the regulated mainstem, in contrast, estimated changes in slope S_* are greatest nearest the dam ($A_* \to 0$) and systematically approach $S_* = 1$ as $A_* \to 1$. This trend reflects the diminishing impact of regulation with increasing distance from the dam. Note that while the Rock River tributary junction is located much further downstream from the nearest dam than either the Ball Mountain or Wardsboro tributary junctions (Table 1), because of the larger watershed of the Townshend dam, A_* at Rock River is intermediate between those of Ball Mountain and Wardsboro (Table 1). Thus, the change in slope S_* at Rock River is intermediate between the greater change at Ball Mountain and the lesser change at Wardsboro.

Also of note is the observation that the changes in slope differ up and downstream of the confluence; slope decreases above the confluence ($S_* < 1$), but increases below ($S_* > 1$). As noted above, this difference likely reflects the deposition of tributary sediment at the confluence because the downstream mainstem lacks sufficient competence to mobilize the sediment being supplied by the tributary. To demonstrate this, we again used HEC-RAS flow modeling of the post-dam 2-year peak flow to estimate the competent grain size d_c corresponding to the critical Shields parameter $\theta=\theta_c$ (Eq. (2)). Results are given in Fig. 9 and indicate that the 2-year peak discharge is generally sufficient to mobilize the median grain size in the upstream mainstem. However, the median grain size along the mainstem below the regulated junctions is consistently greater than the predicted competence of formative flows. For example, at Ball Mountain (Fig. 9A), the observed grain size d_{50} is about 7 cm greater than the grain size d_c potentially mobilized by the post-dam 2-year peak flow. Similarly at Wardsboro, the observed grain size is 5 cm greater than the predicted competence of the post-dam 2-year peak flow (Fig. 9B). The similarity in grain size between that in the tributary and that downstream of the junctions (Fig. 6) suggests that the tributaries are the source of the immobile sediment in the main channel.

Upstream in the tributary the channel grain size is generally consistent with the channel competence. However, the competence of the tributary drops below the observed grain size as the junction is approached, reflecting backwater effects at the junction; the high flows along the main channel reduce the energy grade slope along the tributary near the junction. The backwater effect diminishes stream power near the junction, thus locally reducing the competence.

Taken together, these observations are consistent with the deposition of tributary sediment at the confluence. As the bed of the mainstem aggrades at the confluence due to the deposition of tributary sediment, the channel slope along the mainstem upstream of the confluence is reduced while downstream of the confluence the slope increases and bars are enlarged (Figs. 4 and 8). Upstream of the confluence the grain size and channel competence are consistent with the requirements of Eq. (1). Downstream of the confluence the enlargement of the bars is narrowing the channel, increasing competence. However, Fig. 9 demonstrates that the narrowing of the channel is not yet sufficient to increase the competence to match the caliber of the sediment being supplied by the tributary. This mismatch between sediment supply and transport downstream of the confluence violates the implicit assumption of Eq. (1) and therefore the actual slope changes downstream of the confluence may differ from those shown in Fig. 8. However, steepening of the slope downstream of the confluence is plausible even if the magnitude of the steepening uncertain. And the mismatch between sediment supply and transport will result in continued narrowing as more tributary sediment is deposited. In the next section we explore this idea further by considering the impact of flow regulation on sediment flux.

5.4. Impact of sediment trapping

If regulation causes a channel to regrade to maintain the condition $\Psi_* \approx 1$, then it follows that

$$\Psi_* = \frac{\Psi^{post}}{\Psi^{pre}} = \frac{Q_{s^*}}{W_* D_*^{3/2}} \approx 1 \tag{10}$$

Average specific sediment flux Q_s/A, where A is the drainage area, typically is observed to decrease with drainage area. However, this decrease is slight; typically less than an order of magnitude for a five to ten order of magnitude increase in drainage area (Dendy and

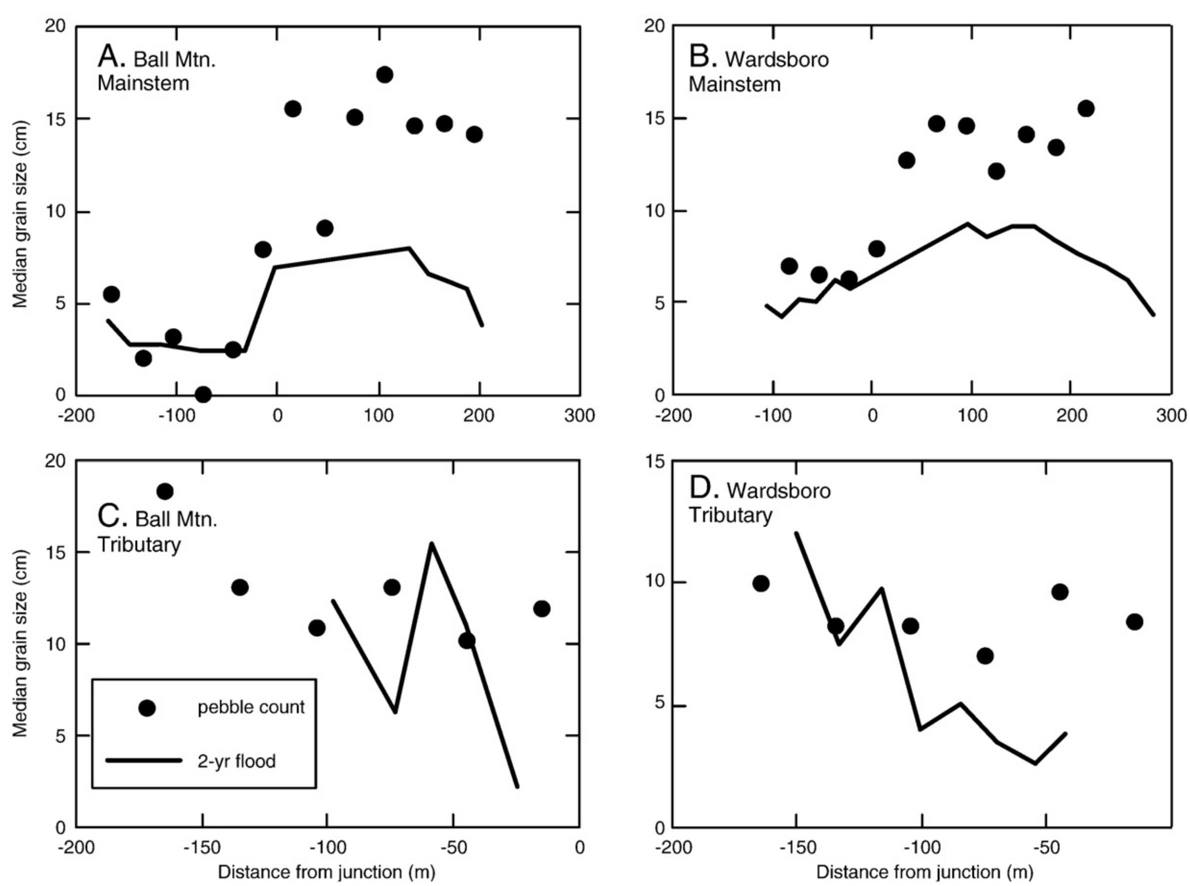

Fig. 9. Observed median grain size and estimated channel competence of 2-year peak discharge expressed as competent grain size d_c for the regulated mainstems and tributaries: (A) Ball Mountain main channel; (B) Wardsboro main channel; (C) Ball Mountain tributary; and (D) Wardsboro tributary.

Bolton, 1976; Walling, 1983). Thus for drainage areas of similar order, the average specific sediment flux is nearly constant. It follows that if a dam has perfect sediment trapping efficiency, the average sediment flux downstream of the dam is reduced by an amount proportional to the drainage area upstream of the dam A_{dam} and $Q_{s*}\approx A_*$ For unregulated reaches or reaches upstream of a dam, $A_{\mathrm{dam}}=0$ and $Q_{s*}\approx 1$. Substitution into Eq. (10) gives

$$A_*\approx W_* D_*^{3/2} \tag{11}$$

The channel changes predicted by the above analysis are evident on the West River; since the construction of the Ball Mountain and Townshend dams, significant channel narrowing has occurred downstream of regulated tributary junctions and, we argue, significant fining has occurred along the mainstem upstream of the junctions. More specifically, in Fig. 10 we plot A_* versus $W_*D_*^{3/2}$ for all our sites. As for S_* (Fig. 8), estimated values of $W_*D_*^{3/2}$ are near unity at all the control sites ($A_*=1$) except along the mainstem upstream of Winhall where, as noted above, the grain size of the channel is impacted by the exposed resistant bedrock (Fig. 6). Along the regulated mainstem, estimated values of $W_*D_*^{3/2}$ are approximately equal to A_* along the mainstem upstream of the confluence, as predicted by Eq. (11). However, downstream of the confluence the factor $W_*D_*^{3/2}$ is consistently greater than A_*, suggesting, as noted above, that the channel is not in equilibrium with the supplied sediment; further reduction in W_* and/or D_* is required. As noted earlier, a reduction in D_* is unlikely as the grain size is set by the sediment being supplied by the tributary. Thus this analysis predicts further reductions in channel widths, a conclusion consistent with the trend observed in our measurements of channel widths over time (Fig. 5).

As an aside, it interesting to estimate, given the current channel widths, the grain size required for the downstream channel to be in equilibrium. This can be estimated by rearranging Eq. (11) to give

$$d^{\mathrm{equil}}=d^{\mathrm{pre}}\left(\frac{A_*}{W_*}\right)^{2/3} \tag{12}$$

Fig. 11 compares the equilibrium grain size calculated using Eq. (12) to the spatially-averaged competent grain size d_c determined using the HEC-RAS simulations (lines in Figs. 7 and 9). The strong correlation ($r=0.93$) between the equilibrium grain size and the competent grain size d_c indicates that Eq. (12) provides a good approximation of the competent grain size. Downstream of the confluence where the channel grain size is fixed by the caliber of sediment supplied by the tributary, we expect the channel to continue to narrow until the competent grain size $d_c\approx d^{\mathrm{equil}}\approx d^{\mathrm{pre}}$, or equivalently, $W_*\approx A_*$. In Fig. 12 we plot the observed changes in W_* downstream of our regulated confluences versus years since the onset of flow regulation. Also shown for each regulated tributary junction is the estimated time, based on the current rate of narrowing, at which $W_*\approx A_*$. From this analysis we expect, if the current rate of narrowing continues, for narrowing downstream of the regulated tributaries to continue for about a century after the onset of regulation.

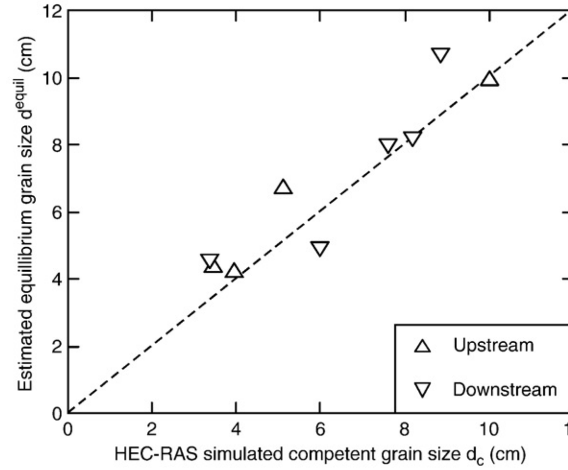

Fig. 11. Spatially-averaged grain size corresponding to the critical Shields parameters θ_{cr} along the mainstem above and below tributary junctions versus the equilibrium grain size predicted using Eq. (12).

5.5. Impact of controlled releases

The U.S. Environmental Protection Agency describes the West River between the two flood control dams as impaired due to aquatic degradation from increased sedimentation of fines (Vermont DEC, 2004). Elsewhere it has been proposed that regulated floods may redistribute fine sediment from the channel bed to its banks (e.g., Webb et al., 1999). By combining the two constraints that follow from the assumption that $\theta_{cr*}\approx 1$, we can explore the expected impact of

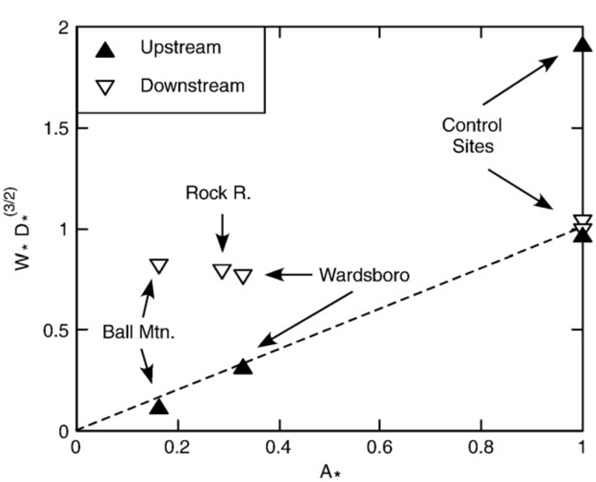

Fig. 10. Product of changes in mean channel width and median grain size along the mainstem above and below tributary junctions as a function of normalized drainage area A_*. Dashed line indicates scaling predicted by Eq. (11).

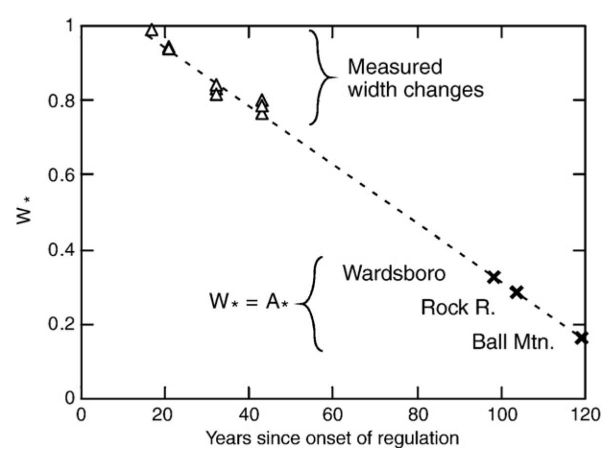

Fig. 12. Normalized changes in mainstem width downstream of regulated tributary junctions as a function of years since regulation. Bold X's indicate, for each tributary junctions, values of normalized widths corresponding to the normalized drainage area A_*.

controlled floods on bedload-dominated rivers such as the West River. Specifically, combining Eqs. (7) and (11) gives

$$S_* = \frac{A_*}{Q_*} \tag{13}$$

Eq. (13) indicates that the long term effect of changing the post-dam formative flow Q_*, such as through regulated floods, is to change the slope of the channel, assuming no change in the sediment trapping efficiency of the dam. That is, any increase in Q_* results in a proportionate decrease in S_* such that $W_* D_*^{3/2}$ remains constant (Eq. (7)). Of course, this conclusion only holds if the river is free to adjust its slope; i.e., it is not confined by bedrock.

6. Conclusions

As noted by Williams and Wolman (1984), when considered in terms of individual channel properties, there is no systematic response of a river to flow regulation. On the West River, we observe channel narrowing below the confluence and inferred fining of the bed of the mainstem immediately above the confluence. Tributaries to the regulated section of the West River are inducing significant geomorphic effects, including on-going changes in channel width, bar area and particle size, despite their having drainage area ratios much less than those generally required for tributaries to have a significant geomorphic impact on unregulated rivers (Benda et al., 2004a,b). We propose that the differences in channel response upstream and downstream of confluences reflect the impact of sediment supplied by the tributary and show that they can be understood in terms of the covariant responses of channel properties to changes in both water and sediment flux.

Because our analyses of the impact of flow regulation on water and sediment flux are based on a prediction for bedload transport, they are only valid for coarse-bedded rivers where, when unregulated, the Shields parameter of the formative flows is near the critical value required for the mobilization of the average size sediment on the bed. Within this context, our results show that the drainage area ratio A_* appears to provide a useful metric for assessing the relative impact of flow regulation at different locations. By extension, the drainage area ratio also predicts the rate at which the impacts of flow regulation on channel geometry are ameliorated with increasing distance downstream from the dam. The impacts of flow regulation on channel geometry will diminish as the drainage area ratio approaches unity.

Our analyses suggest that in coarse-bed rivers the long term impact of regulated floods is to change channel slope, assuming the river is not confined by bedrock. A possible alternative mitigation strategy for mobilizing fine sediment from the channel that follows from our analysis is to accelerate the narrowing of the channel. However, whether naturally induced such as by the influx of tributary sediment or anthropogenically accelerated, channel narrowing may have implications for the consequent ecological adjustments. As the channel narrows to re-establish an equilibrium shape and profile, there is less bed area for benthic macro-invertebrates (less food for fish) to colonize and there are changes to the velocity profile which may shift benthic community structure. Thus, what may be "good" for channel stability following flow regulation may not be good ecologically.

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