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Flow and sediment regimes at tributary junctions on a regulated river: impact on sediment residence time and benthic macroinvertebrate communities

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Abstract:

Tributaries may either ameliorate or exacerbate the geomorphic and ecologic impacts of flow regulation by altering the flux of water and sediment into the flow-regulated mainstem. To capture the effects of tributary influences on a flow regulated river, long-term discharge and cross-sectional data are used to assess the geomorphic and hydrologic impacts of impoundment. In addition, the use of the short-lived cosmogenic radioisotope ^{7}Be (half-life 53·4 days) to link sediment transport dynamics to benthic macroinvertebrate community structure is evaluated. It is found that the ^{7}Be activity of transitional bed load sediment is highly seasonal and reflects both variations in activity of sediment sources and limited sediment residence time within the junction. Benthic communities also exhibit a strong seasonal variability. In the spring, neither the ^{7}Be activity of the sediment, nor benthic communities exhibit clear relationships with sample site location. In contrast, during the late summer the ratio of Ephemeroptera (mayflies)/Trichoptera (caddisflies) decreased significantly below tributary junctions. This decrease in benthic community ratio was driven by increases in caddisfly abundance and was strongly correlated with the presence of recently ^{7}Be tagged transitional bedload sediment. These observations are probably associated with the presence of coarse, stable, and unembedded substrate downstream of tributaries and the rapid turnover of sediment that may also be associated with a rapid flux in nutrients or seston. The results show that tributaries are impacting the flow-regulated mainstem and that these impacts are reflected in the benthic community structure and in the ^{7}Be activity of transitional bed load sediment. Moreover, the observed reduction in competence and capacity of the mainstem following flood control suggests that these spatial discontinuities may be a consequence of impoundment.

KEY WORDS flow regulation; dams; isotopes; macroinvertebrates; tributary junctions

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INTRODUCTION

Flow regulation by dams drives riverine ecological changes by directly altering downstream water quality, including, for example, dissolved oxygen levels, water temperature, and suspended sediment loads (Caduto, 1990; Lytle and Poff, 2004). Dams may also indirectly impact downstream ecosystems through the effects of altered flow regimes on sediment transport. Numerous studies have documented significant hydrogeomorphic changes associated with flow regulation (Petts, 1980; Petts and Greenwood, 1985; Andrews, 1986; Magilligan and Nislow, 2001, 2005) while a host of other studies have documented riverine ecological changes resulting from flow regulation (Erskine *et al*., 1999; Collier, 2002; Osmundson *et al*., 2002). However, the specific linkages between hydrology, geomorphology and ecological functions have been difficult to discern (Yarnell *et al*., 2006). To understand these linkages better, it is critical to focus research on locations where impacts are likely to be pronounced.

Because dams interrupt the downstream transport of water and sediment, tributary junctions, by re-supplying the mainstem with water, nutrients, organic matter and sediment, may serve as important buffers on further downstream ecological impacts (Rice *et al*., 2001a, 2001b). In unregulated rivers, tributary junctions can be 'hotspots' of productivity and diversity for benthic invertebrates and fishes (Rice *et al*., 2001b; Fernandes *et al*., 2004; Kiffney *et al*., 2006) and be major nodes of geomorphic adjustments (Germanoski and Ritter, 1988; Storey *et al*., 1991; Benda *et al*., 2004a, 2004b; Ferguson *et al*., 2006). Because of their high productivity and possible role in buffering flow regulation impacts, tributary junctions may amplify linkages between dam-induced hydrogeomorphic responses and ecological impacts, making them more manifest and easier to quantify.

Here we seek to quantify flow regulation-induced changes in sediment transport and channel bed morphology at tributary junctions downstream of the Ball Mountain and Townshend Dams on the West River in eastern Vermont, USA. Specifically, we investigate the

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use of the short-lived fallout radionuclide beryllium-7 (^{7}Be; $t_{1/2} = 53{\cdot}4$ days) as an indicator of sediment transport dynamics, including sediment residence time, at tributary junctions. By comparing the temporal dynamics of sediment transport to changes in the ecological communities at these locations, we seek to better understand the extent to which sediment transport may drive ecological responses.

This study focuses on sand sized material. Because of the granitic terrain of New England, the abundant till, and lack of loess, fines (silts and clays) are lacking in this region, generating some of the lowest sediment concentrations in the USA with values generally less than 200 mg L^{-1} (Rainwater, 1962). Sites are thus fines-limited and so the focus is on 'transitional load'. Sediment transported both in suspension and as bed load is referred to as mixed or 'transitional' load, often defined as having a fluid shear velocity to particle settling velocity ratio (u_*/w_s) between 0·4 and 2·5 (Julien, 2002). In previous work, it has been shown that ^{7}Be activity of streambed sediment in New England traces the movement of transitional bed load (Salant *et al*., 2006b).

Selectively tracing transitional bed load may offer significant advantages for linking sediment transport dynamics to benthic community responses. Fine sediment such as silts and clays are often carried in suspension and, therefore, interact less frequently with the bed and streambed biota. In contrast, larger particles that roll and saltate along the bed as bed load have longer residence times in the streambed, but are less strongly associated with contaminants or water quality impacts. The boundary between these two transport modes is transitional; depending on flow magnitude, medium and coarse sand (0·25–2 mm) may move either short distances in suspension or roll along the bed as bed load. While both sand and silt have been shown to have deleterious ecological effects, the effects are different; essentially, silt affects the biota directly, while sand changes the habitat (Wood and Armitage, 1997, 1999).

To correlate possible ecological responses with changes in transitional bed load sediment dynamics as reflected in ^{7}Be activity, the benthic ecological community structure, both up- and downstream of tributary junctions, is assessed. Changes in the relative abundance of benthic invertebrates may be particularly useful for evaluating the impact of flow regulation on riverine ecosystems (Collier, 2002; Townsend *et al*., 1997). For example, previous studies (Wooton *et al.* 1996) found that both case-building and net-spinning caddisflies (Insecta: Trichoptera) increase in abundance in habitats with stable, unembedded substrate. In contrast, the morphological, behavioural and life-histories of mobile grazers such as many mayfly (Insecta: Ephemeroptera) species permit their populations to be both resistant and resilient with respect to scouring floods (Nislow *et al*., 2002). As a result the ratio of mayflies to caddisflies may be a sensitive metric linking transitional bedload dynamics to ecological response (Townsend *et al*., 1997).

In this study, we compare, at tributary junctions on a regulated mainstem, benthic community structure (focusing on the relative abundance of caddisflies and mayflies) with coarse sand-sized sediment residence times as reflected in temporal changes in short-lived radionuclide activity of transitional bedload sediment. The results from this work help better constrain the type and magnitude of ecological impacts due to flow regulation as well as quantify the length scale over which this impact occurs.

SITE DESCRIPTIONS

The West River begins in the foothills of the Green Mountains and flows south-east for 74 km to Brattleboro, Vermont, USA, where it discharges into the Connecticut River (Figure 1). The US Environmental Protection Agency describes the West River as impaired due to aquatic degradation from increased sedimentation and elevated temperatures between the two flood control dams on the river, the Ball Mountain and Townshend Dams (Vermont DEC, 2004).

The US Army Corps of Engineers constructed the Ball Mountain and Townshend Dams in 1961 as part of a network of flood control projects in the Connecticut River Basin. The Ball Mountain Dam is located 48 km upstream from the junction with the Connecticut River. Just below the dam, the drainage basin is 464 km^2, the mean annual discharge is $\sim$11 m^3 s^{-1}, the average gradient $<$1% and the typical bankfull channel width measures $\sim$25 m. The Townshend Dam is located 14 km downstream of Ball Mountain. Just below the Townshend Dam the drainage area is 730 km^2, the mean annual discharge is $\sim$17 m^3 s^{-1}, the average channel gradient is $<$1% and the typical bankfull channel width is $\sim$30 m. Wardsboro Brook is the second, and furthest downstream,

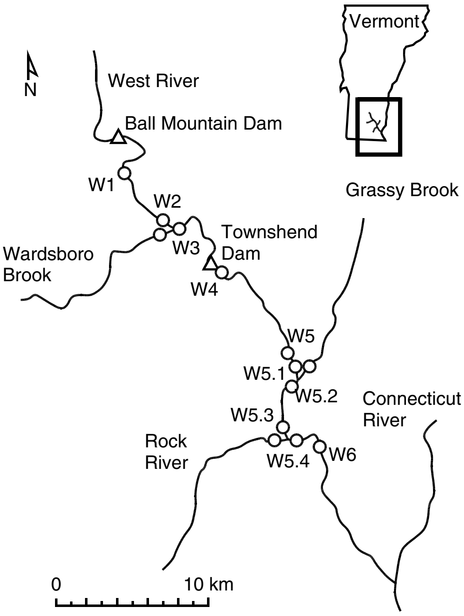

Figure 1. Location of sampling sites, dams and tributaries on the West River, Vermont

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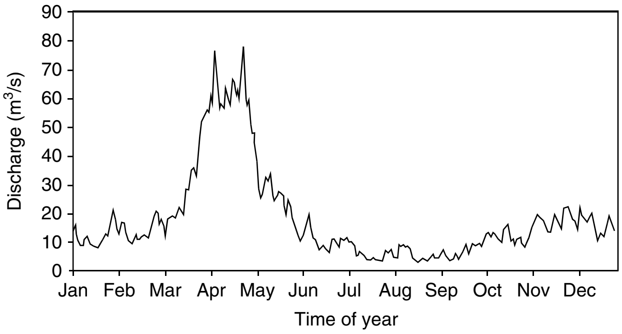

Figure 2. Post-dam (1961–1989) average daily discharge for the West River, Vermont measured below the Townshend Dam

of two major tributaries joining the West River between the two dams. The yearly hydrograph of the West River post impoundment shows that the highest flows occur during the spring, while the lowest flows occur in the late summer/early fall (Figure 2).

The US Geological Survey (USGS), in coordination with the U.S. Corps of Engineers, maintains stream flow gauging stations downstream of both dams. Daily discharge data and stage height for each gauging station and approximately bi-monthly direct measurements of channel cross-sectional area, channel width, mean water depth and discharge are available for both gauges. Records for the original gauge located below the Townshend Dam in Newfane, Vermont, date back to the year 1919. Only the data collected before 1989 are considered here because the Newfane gauge was moved approximately 9 km upstream to a site directly below the Townshend Dam after 1989. Records for the Ball Mountain gauge, which is located ~4·5 km below the dam, date back to its original construction in 1946. Management of both dams is coordinated and primarily designed for flood control. Both dams maintain reservoirs and have water intakes near the bottom of the dams. Storage behind the Ball Mountain Dam varies with season; the typical summer stage of ~20 m is lowered to ~8 m during the winter. The Townshend Dam maintains a more constant year-round reservoir stage of ~6 m. Each year there are three scheduled daylong high releases of ~42 m^3 s^{-1} for recreational purposes: two occur in April and the third in September.

To assess the impact of tributaries on the flow-regulated river, we focused on the confluences of three major tributaries of the West River—the Wardsboro Brook between the dams and two tributaries located downstream of both dams, Grassy Brook and Rock River (Figure 1). Just above their respective confluences with the West River, Wardsboro Brook has a bankfull channel width of ~20 m, a channel gradient <2%, and a watershed area of 91 km^2. Grassy Brook, the smallest of the three tributaries, has a bankfull channel width of ~5 m, a low channel gradient <1%, and a watershed area of 38 km^2. Rock River has a bankfull channel width of ~15 m, a gradient of ~1% and watershed area of 149 km^2. The median grain size and summer water temperatures measured upstream and downstream of each tributary junction are shown in Table I.

Table I. West River tributary median grain size (D_{50}) and summer water temperature

Tributary	D_{50} (mm)		Summer water temperature (°C)	
	Upstream	Downstream	Upstream	Downstream
Wardsboro Brook	110	140	24·5	25·0
Grassy Brook	50	80	27·2	27·9
Rock River	100	160	27·9	28·8

The sample sites were selected with consideration for large-scale and local geomorphic characteristics. Sediment and macroinvertebrate sampling occurred within riffles at all sites except for site 5·1, the mainstem site above the Grassy Brook confluence where no riffles were apparent. With regard to sites above and below tributary confluences, we selected the riffles closest to the confluences based on local geomorphic and habitat homogeneity.

METHODS

Gauge station data

To quantify changes in channel bed morphology as a result of flow regulation, the bi-monthly cross-section data from the gauging stations were used to determine the mean water depth and bed elevation for each cross-section measurement in the pre-dam and post-dam periods. In addition, annual peak stream flow data for each station were used to calculate the flood recurrence interval for pre-dam and post-dam periods using the Log-Pearson Type III distribution.

Fallout radionuclides

Beryllium-7, created by spallation from cosmic rays in the atmosphere, enters the ecosystem primarily through wet deposition where it strongly sorbs onto fine particles (Brown *et al.*, 1989); fixation is rapid and not easily reversible (Karamanos *et al.*, 1976; You *et al.*, 1989). The surface layer of sediment exposed to the atmosphere on surface soils, point bars, and banks receives a regular input of ^{7}Be—this sediment is considered 'new' or 'tagged'. Upon entering the river, this sediment is no longer exposed to the atmosphere and the ^{7}Be activity begins to decay. The longer the sediment remains in the river, the less active it becomes—this sediment is considered 'old' or 'dead'.

Previous studies have used ^{7}Be to fingerprint sediment sources and to quantify the mixing of suspended sediment with the channel bed (Olley *et al.*, 1993; Bonniwell *et al.*, 1999; Rowan *et al.*, 2000; Walling *et al.*, 2003). More recently, Salant *et al.* (2006b) used ^{7}Be as a tracer of transitional bed load. In a similarly sized regulated river, also located in the Upper Connecticut

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River Valley, they calculated average sediment transport velocities for five sites downstream of the Union Village Dam with sediment collected from early to late spring. They observed average transitional bed load sediment transport velocities (30–80 m day^{-1}) that exceeded those typically reported for bulk bed load transport and were remarkably constant across varied flow regimes. The inverse of average sediment transport velocity is one way to quantify sediment residence time.

Sampling of transitional bed load for radionuclide analysis began in November 2004 and continued through November 2005. Samples were collected mid-month from November 2004 to March 2005 and from September 2005 to November 2005. From April to August 2005, sediment samples were collected near the beginning of each month with bimonthly sediment samples collected mid-month in April and May 2005. This collection schedule sought to capture the temporal changes in sediment radionuclide activity associated with varying seasonal flow regimes and short-term high discharge events. Therefore, although the sediment sample collections were scheduled at regular monthly or bi-monthly intervals, the actual collection date varied slightly depending on weather and flow conditions. One grab sample of approximately 500 g of sand-sized sediment was collected from the top 5 cm of streambed sediment halfway between the bank and thalweg at each sample site. Sediment close to the surface was collected to ensure collection of only the most recently deposited sediment. Because of the time required to analyse each sample, it was not feasible to analyse replicate samples at each site or to analyse multiple samples from different locations in the reach. Previous work (Salant *et al.*, 2006b) has demonstrated that variations in ^{7}Be/^{210}Pb across a channel are generally small ($<10\%$) in these watershed and the variation in ^{7}Be activity from replicate samples at the same location much less.

After collection, the sediment was placed in a plastic bag for transport to the laboratory. At the laboratory, the sediment was oven dried at 29 °C and sieved to collect the fraction between 62·5 µm and 2 mm (Salant *et al.*, 2006b). This fraction was packed into a plastic container and weighed in preparation for analysis. A high purity germanium detector was used to determine the activities of ^{7}Be and ^{210}Pb via decay counting over 90 ks to 170 ks. Values were corrected for weight, time elapsed since collection, time counted, and detector efficiences. The measurement errors associated with decay counting are a function of both the uncertainty due to photon emission statistics and uncertainty due to the background subtraction. Uncertainty due to photon emission statistics is a function of the total number of decays or 'counts' (n) detected, where the standard error $\sigma_n = \sqrt{n}$. We typically accumulated 200–400 net counts in the 477–478 keV region for ^{7}Be. Decays in the 46–47 keV region corresponding to ^{210}Pb were collected simultaneously, with net counts in this region typically > 1000. The uncertainty due to the background subtraction was determined based on a linear fit of the Comptom Continuum near the photopeak regions. Specifically, the standard deviation was calculated for the best fit regression line by calculating the average distance of the residuals in the background region: the total propagated measurement errors for ^{7}Be activity were 5–13%. Detector efficiencies were determined by counting certified standards of the same weight and geometry as the samples. Because of the low energy of the ^{210}Pb photon, each sample was corrected for self-attenuation using direct measurements of gamma transmission from a ^{210}Pb point source (Cutshall *et al.*, 1983).

Previous studies (Bonniwell *et al.*, 1999; Salant *et al.*, 2006b) demonstrated that normalizing ^{7}Be activity by the activity of the longer-lived fallout nuclide ^{210}Pb ($t_{1/2} =$ 22 years) partially corrects for differential radionuclide sorption between samples due to compositional differences and differences in grain size distributions. Consequently, changes in the ^{7}Be/^{210}Pb activity ratio primarily reflect the extent of decay, not sorption or grain size effects. Variations in relative ^{7}Be/^{210}Pb$_{\text{total}}$ activity ratios are reported and it is assumed they generally reflect differences in the time since the sediment was last exposed to atmospheric input. Higher values of the isotope ratio represent recently (days to weeks) introduced surficial sediment and lower values reflect sediment that has been underwater or buried for a longer time (months to years).

The ^{210}Pb$_{\text{total}}$ measured in sediments is a function of the ^{210}Pb supported *in situ* by ^{222}Rn decay and atmospherically-derived ^{210}Pb. In the fluvial sediment, it was found that excess (atmospheric, unsupported) ^{210}Pb is generally low to zero; so supported ^{210}Pb is the dominant component of ^{210}Pb$_{\text{total}}$. Furthermore, quantifying the level of ^{210}Pb that is truly unsupported by ^{222}Rn in a fluvial environment is nearly impossible because of advection and diffusion of gas in these dynamic systems. In companion studies (Ericsson, 2006), it is shown that radium concentrations increase with increasing surface area (and decreasing particle size). Since radium directly supports ^{210}Pb, the ^{7}Be/^{210}Pb$_{\text{total}}$ activity ratio will have some particle-size correction. Experiments were run comparing normalization techniques (Fisher *et al.*, in review) using the BET method to measure specific surface area of samples. It was observed that in stream sediments Pb$_{\text{total}}$ activity is more strongly correlated to total surface area, and hence compositional difference, than Pb$_{\text{excess}}$. The goal of normalization is to best account for grain compositional effects, and it was found that Pb$_{\text{total}}$ is a better proxy for these effects than Pb$_{\text{excess}}$.

Grain size and embeddedness

Surface grain distributions were determined at sampling sites upstream and downstream of each tributary confluence using Wolman pebble counts (Wolman, 1954). In addition, since previous studies have linked a high degree of embeddedness to changes in the structure of macroinvertebrate communities (Collier, 2002; Weigelhofer and Waringer, 2003), embeddedness was measured monthly at each site from May 2005 through August

2005. To allow for comparisons between sites, only riffles were sampled. Numerous methods have been proposed for quantifying embeddedness. In a recent comparison of methods, Sennatt *et al.* (2006) found that the method proposed by the US Environmental Protection Agency (Peck *et al.*, 2000) best reflected the sediment regime on a nearby and similarly-sized flow regulated river. Accordingly, this method was employed. The embeddedness was measured by examining all particles larger than sand size in a 10 cm diameter circle at four transects at each sampling site. Along each transect, measurements were taken at 0, 25, 50, 75 and 100% of the wetted channel width. The embeddedness was estimated by the percentage (to the nearest 10%) of the upper surface area of gravel or larger rocks surrounded by sand or finer sediment. Sampling points with only sand size and smaller particles were classified as 100% embeddedness. Two sites were added for greater resolution in the embeddedness measurements—Site 0, located several kilometres above Ball Mountain Dam, and Site 3·5, located between Site 3 and the Townshend Dam.

Benthic macroinvertebrates

Benthic macroinvertebrates were randomly sampled at nine mainstem sites (site 5·0 was excluded due to its proximity to site 5·1, the site directly above the Grassy Brook confluence) and the three tributary sites in late May/early June 2005 and August 2005. Only riffles were sampled (except for site 5·1 which did not contain a riffle). Two collections were taken at each transect and four random transects covered in order to capture within-site variability. The samples were collected away from the banks, but without further consideration for habitat features. The macroinvertebrates were collected using a 0·36 m diameter Hess sampler (250 µm mesh). The benthic macroinvertebrates from each transect were rinsed into a labelled plastic container and preserved using 70% ethanol for transport to the laboratory. In the laboratory, the macroinvertebrate samples were classified to order and counted. Large samples (>600 invertebrates) were subsampled using a wheel sample splitter and at least 300 organisms were counted for each sample. The data were then pooled across samples for each sample date in order to calculate total invertebrate abundance, and abundance of mayflies and caddisflies for each site. In a subset of samples, macroinvertebrates were classified to family level and categorized by functional feeding group.

RESULTS

Channel morphology

Below the Townshend Dam the magnitude of the 2-year flood declined by ~50% following impoundment and the discharge post-dam has never reached the pre-dam 2-year flood (Figure 3). This major change in the hydrologic regime has resulted in adjustments to the channel geometry as reflected in the measured channel bed cross-sections below the Ball Mountain and Townshend Dams. The cross-sections reveal a stabilization of bed elevation variability following the construction of the dam (Figure 4). Below the Townshend Dam, the variance in bed elevation decreased by ~40% from its pre-dam levels (1919–1960) during the first 15 years after dam construction (1961 to 1975) and decreased again by ~50% over the period 1976 to 1989. The variance in bed elevation below the Ball Mountain Dam decreases similarly following dam construction, although the initial decrease is less.

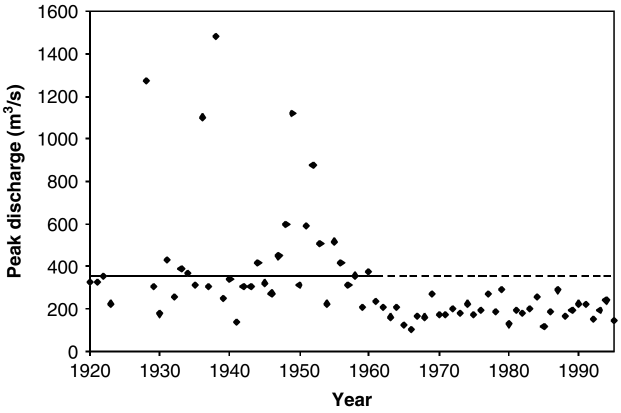

Figure 3. Annual peak discharge recorded at the Newfane gauge on the West River, Vermont. The horizontal line indicates pre-dam 2-year flood discharge before impoundment in 1960

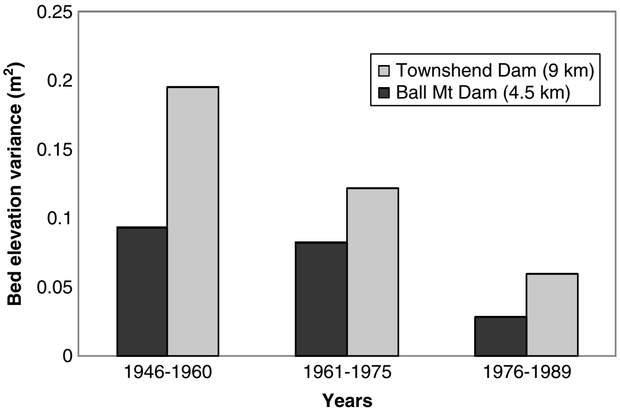

Figure 4. Variance in bed elevation for pre-dam period (1946–1960) and post-dam periods (1961–1989) at two gauging stations along the West River, Vermont. Distances in legend represent downstream distance between respective dam and gauge. The graph bars for the Ball Mountain gauge represent these data points for each period: (1946–1960) = 152 observations, (1961–1975) = 102 observations, (1976–1989) = 75 observations. The graph bars for the Newfane gauge below the Townshend Dam represent these data points for each period: (1946–1960) = 170 observations, (1961–1975) = 101 observations, (1976–1989) = 87 observations

In addition to decreased peak flows, part of the decreased variability in bed elevation appears to be due to the bed becoming more difficult to mobilize. Channel scouring, defined as decreases in the bed elevation measured at the gauge, of more than 1 m between two consecutive cross-section measurements occurred 35 times in the 29 years before the construction of the dam (~1·2 year^{-1}) and occurred even when the maximum

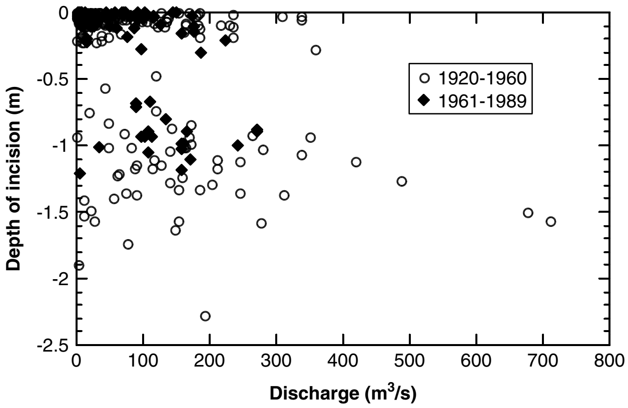

Figure 5. Depth of channel scouring versus maximum discharge between bed elevation measurements at the Newfane gauge below the Townshend dam for pre-dam (1920–1960) and post-dam (1961–1989) time periods for the West River, Vermont

discharge between cross section measurements was as low as 3 $m^3 s^{-1}$ (Figure 5). Following impoundment, large bed scouring events are less frequent; channel incisions greater than 1 m occurred only six times in the 29 years after the construction of the dam (~0·2 $year^{-1}$) with no such events after 1973. Although post-dam flows have reached discharges associated with significant incision events prior to the construction of the dam (e.g. greater than 3 $m^3 s^{-1}$), the channel cross-section measurements indicate that the channel has become more resistant to incision and consequently bed elevation has stabilized.

The bed elevation measurements below the Ball Mountain and Townshend Dams on the West River are compared with those on the nearby, similarly sized, flow regulated Black River (Salant *et al.*, 2006a), measured 1 km below the North Springfield Dam (Figure 6). The bed elevation increases post-dam on the West River at both gauging stations, 4·5 km below Ball Mountain dam and 9 km below the Townshend Dam. In contrast, the bed elevation measured 1 km below the North Springfield Dam decreases ~15 cm in the 30 years after impoundment, indicating channel bed scouring in response to flow regulation in this dam proximal location.

Channel embeddedness

Channel embeddedness decreased below each of the three major tributaries (Figure 7). This may result from the increased sediment transport capacity provided by the additional discharge entering the confluence. This increased transport capacity may winnow fine sediment from the bed below the confluence, resulting in decreased embeddedness. The region of decreased embeddedness appears to be limited; further downstream of all three confluences the average embeddedness increases, although the increase below Rock River is not statistically significant.

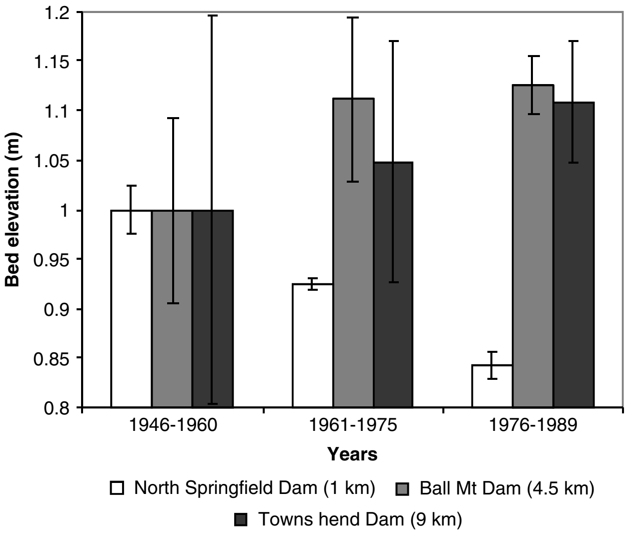

Figure 6. Bed elevation for the pre-dam period (1946–1960) and post-dam periods (1961–1989) for the West and Black Rivers, Vermont. The data were measured on the West River ~4·5 km below Ball Mountain Dam and ~9 km below Townshend Dam. Data were measured ~1 km below the North Springfield Dam on the Black River, Vermont. All elevation data are shifted by a constant factor for each gauge such that the average elevation in the pre-dam period is 1·0 m. Error bars indicate bed elevation variance

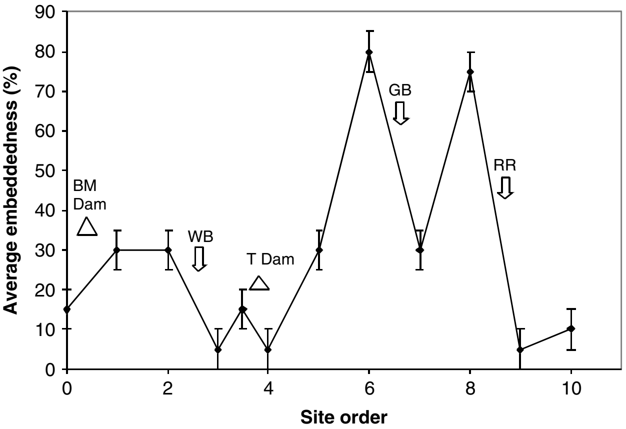

Figure 7. Embeddedness measurements versus site order for the West River, Vermont. The dams and tributaries are labelled with their initials. Error bars indicate standard errors

As expected, the measured embeddedness below the dams is generally low, reflecting sediment trapping efficiency of the dams that maintain year-round reservoirs. However, the embeddedness below the Ball Mountain Dam is not as low as below the Townshend Dam or as low as observed on the nearby Black River below the North Springfield Dam (Sennatt *et al.*, 2006). The reason for the relatively high embeddedness below the Ball Mountain Dam may be an artefact of the embeddedness being measured ~4·5 km below the dam, whereas embeddedness measurements were collected immediately below the Townshend and North Springfield dams.

Fallout radionuclides

The yearly average $^{7}Be/^{210}Pb$ ratio (solid line) along with the average ratio during spring and summer (dashed lines) for each sampling site are shown in Figure 8. The activities were grouped in spring (April/May/early June) and summer (July/August) time periods based on the yearly hydrograph. The average sediment activity in

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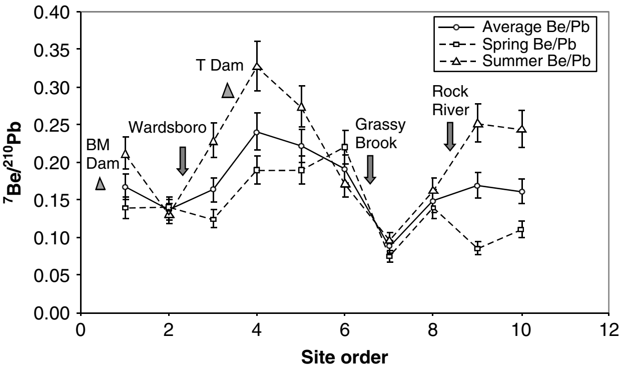

Figure 8. Solid line indicates yearly average sediment ^{7}Be/^{210}Pb activity ratios versus site order on the West River, Vermont. Dashed lines show average ratios for the spring (April, May and June 2005) and summer (July and August 2005) time periods. Error bars indicate +/− one standard error in average activity ratio measured during each time period. The arrows indicate tributary confluences and the triangles represent the dams

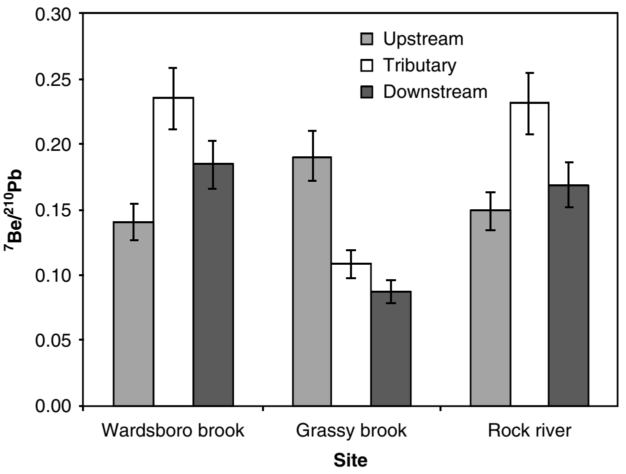

Figure 9. The average ^{7}Be/^{210}Pb activity ratio for the May to August time periods versus location at the tributary junctions on the West River, Vermont. Error bars indicate standard errors

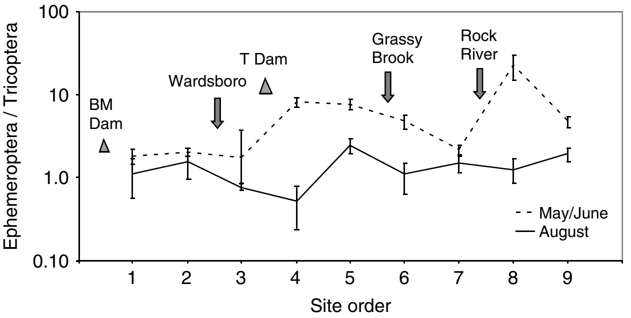

Figure 10. Ephemeroptera (E) to Trichoptera (T) ratios for the May/June and August sampling dates versus site order (increasing downstream) on the West River, Vermont. Error bars indicate +/− one standard error in average E/T ratio measured along four different transects at each site

the mainstem consistently decreases below each tributary confluence in the spring, although a pooled t-test for change between upstream and downstream confluence sites is only marginally statistically significant ($P = 0{\cdot}08$). In contrast, there is an increase, albeit marginally significant, in activity (t-test indicates $P = 0{\cdot}11$) below the Townshend Dam. During the summer, the mainstem activity increases below the dam and below the two largest tributaries (pooled t-test for change below dam or large confluence yields $P < 0{\cdot}01$). The activity below the Grassy Brook confluence is higher in the summer than in the early spring, but still remains less active than observed elsewhere along the mainstem and there is still a clear decrease in contrast to the larger tributaries.

In addition to the spring and summer normalized activity, Figure 8 shows the average normalized sediment activity for the year. Yearly average normalized sediment activity increases below the Townshend Dam and then falls to a minimum after the confluence with Grassy Brook before increasing again further downstream. There are no systematic increases or decreases in yearly average activity downstream of the dams or confluences. The yearly average activities of the tributary confluences and up- and downstream mainstem West River are consistent with mixing between the mainstem West River and the two largest tributaries, Wardsboro Brook and Rock River. The average ^{7}Be/^{210}Pb activity ratio in the West River below these confluences is intermediate between the upstream mainstem activity and the activity in the tributary, although the Rock River results are not outside the error (Figure 9). For the Grassy Brook tributary the relationship between ^{7}Be/^{210}Pb activity ratio in the tributaries and mainstem differs in comparison with the larger tributaries, since Grassy Brook appears to dilute rather than enrich the upstream mainstem activity. However, the downstream ^{7}Be/^{210}Pb activity ratio is lower than both the upstream mainstem and tributary sediment activity. These results indicate that although the tributaries impact the mainstem through water and sediment fluxes, the ^{7}Be/^{210}Pb activity ratio in the mainstem depends on many factors.

Macroinvertebrate community structure

The ratio of total abundance of Ephemeroptera (E) to Trichoptera (T) showed almost two orders of magnitude variation among sites and seasons, ranging from $\sim 0{\cdot}1 - 10{\cdot}0$. E/T ratios were consistently higher in the May collections, across all sites (Figure 10). For the summer samples that were classified to the taxonomic family level and assigned to functional feeding groups, at most sites the majority (>60%) of caddisflies (families Hydropsychidae and Philopotamidae) were net-spinning species belonging to the filter feeding functional group, while the remainder were case-building species (families Limnephilidae and Lepidostomatidae) belonging to the shredder functional feeding group. At the Grassy Brook confluence, this order was reversed, with the dominant functional feeding group being the shredders followed by the filter feeders. E/T ratios did not reflect any consistent variation at tributary junctions during the spring. The late spring ratios are approximately constant between the two dams and then increase sharply after the Townshend Dam. E/T ratios then gradually decrease until the confluence with Rock River where they again rise sharply.

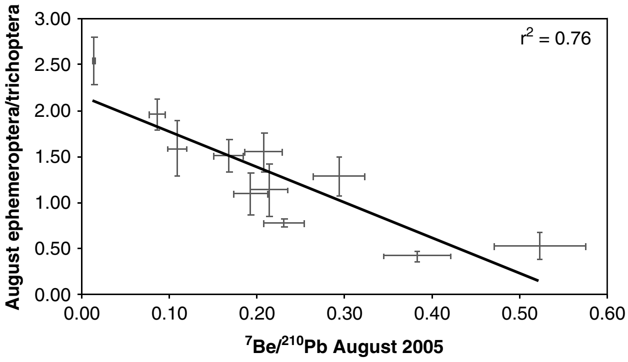

Figure 11. Ephemeroptera/Trichoptera ratio for the August benthic collection versus ^{7}Be/^{210}Pb activities of the August 6 sediment samples for the West River, Wardsboro Brook and Rock River, Vermont sites. Error bars represent standard error

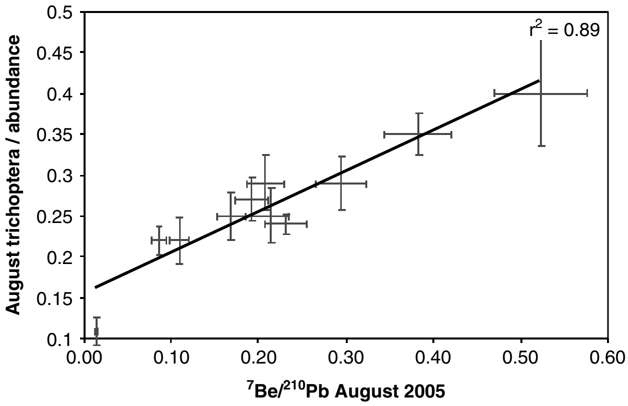

Figure 12. Trichoptera abundance normalized by total abundance of macroinvertebrates for the August benthic collection versus ^{7}Be/^{210}Pb activities of the 6 August sediment samples for the West River, Wardsboro Brook and Rock River Vermont sites. Error bars represent standard error

In contrast, in the late summer collection, we observed a significant relationship between E/T ratios, location, and sediment radionuclide activity. E/T ratios consistently decrease significantly below tributary confluences (pooled t-test for change below confluence $P < 0{\cdot}01$), and below Townshend dam ($P = 0{\cdot}07$). At the same time, summer normalized radionuclide activity increased below the two largest tributaries and below Townshend dam (Figure 8). Overall, a significant relationship was observed between radionuclide activity level (measured in the two weeks before invertebrate sampling) and August E/T ratio (Figure 11). Further, this relationship is the result of increased caddisfly abundance ($r = 0{\cdot}94$), $P < 0{\cdot}0001$) (Figure 12), with little effect on the abundance of mayflies. There was no relationship between E/T ratio and sediment activity for the spring season, or integrated across seasons.

DISCUSSION

Hydrologic disruptions and sediment transport

Although river characteristics such as discharge, channel width, and bed sediment size are often described as functions of longitudinal distance downstream, at intermediate ($10^{0}-10^{2}$ km) scales, longitudinal trends in geomorphic and hydrologic features are locally modified by water and sediment inputs from tributaries and by impoundment from dams (Rice *et al.*, 2001b). At this more local scale rivers may better reflect a series of downstream links disrupted by influxes of water and sediment from tributaries or by water and sediment regulation at dams. The specific impacts of these hydrologic disruptions along the mainstem depend on many factors, including the size of the tributary or impoundment relative to the mainstem, biophysical features of the watershed, and dam management style (Storey *et al.*, 1991; Rice *et al.*, 2001b; Poff and Hart, 2002; Magilligan *et al.*, 2003; Benda *et al.* 2004a,b; Salant *et al.*, 2006b).

The construction of the Ball Mountain and Townshend Dams on the West River hydrologically disrupted the mainstem West River by eliminating the pre-dam 2-year flood discharges associated with historical bankfull discharge and channel maintenance (*cf* Williams, 1978; Andrews, 1980; Magilligan *et al.*, 2003, 2008). As a result, the channel beds at the gauging stations, located 4·5 km downstream of the Ball Mountain Dam and 9 km below the Townshend Dam, have both aggraded and stabilized (i.e. reduced variation in bed elevations), as reflected in the decrease in bed elevation variability and increase in minimum discharge required for significant bed incision events. This stabilization has continued to occur decades after the construction of the dams.

Salant *et al.* (2006b) found a similar increase in bed stability immediately below the North Springfield Dam on the Black River, a comparable flow-regulated river in central Vermont. Like the Ball Mountain and Townshend Dams, the North Springfield Dam is managed as a constant reservoir flood control facility and hence has a high sediment trapping efficiency. However, in contrast to what is observed at the gauges along the West River, the channel bed at the gauge on the Black River has degraded since the dam was constructed. This difference probably reflects the fact that whereas the Black River gauge is located less than 1 km below the dam, the gauges below the Ball Mountain and Townshend Dams on the West River are located 4·5 and 9 km downstream of the dams, respectively. It is likely that immediately below the Ball Mountain and Townshend Dams the sediment trapping efficiencies of the dams have resulted in channel bed degradation similar to that observed below the North Springfield Dam. However, at some point downstream on the West River, sediment influxes from tributaries exceed the reduced transport capacity of the flow regulated river and the impact of the dam changes from bed degradation to bed aggradation. This shift represents an important transitional length scale of dam impact. These results indicate that for the Townshend and Ball Mountain Dams the transitional length scale where sediment influx overprints the sedimentological control of the dam is less than 4·5 km and probably greater than 1 km.

The aggradation of the channel beds at the gauging stations requires a net influx of sediment into the active channel below the dams. Although it would be difficult to quantify net sediment influx on the West River, the three largest tributaries as shown on Figure 1 are probably primary sources of sediment. This conclusion is supported by the prevalence of extensive sand bars near tributary junctions on the West River (*cf* Topping *et al.*, 2000; Powell, 2002). In addition, there are several smaller tributaries, as well as other lateral sediment sources such as eroding banks and point bars along the mainstem, that probably also supply lower amounts of sediment.

Further evidence of the disruptions provided by the tributary junctions comes from the low embeddedness values observed in the mainstem West River below each tributary and below the Townshend Dam. However, the primary cause for these decreases in embeddedness probably differs between the dam outlet and the tributary confluences. As noted above, the decrease in embeddedness below the dam is probably due to the high sediment trapping efficiency of the dam. In contrast, the decrease in embeddedness below the tributary confluences probably reflects the decreased capacity of the mainstem to mobilize all the sediment supplied by the tributaries. With the reduction in the frequency and magnitude of high discharge events, the sediment competence and capacity of the West River has been decreased, preventing the mainstem from transporting all the sediment the tributaries supply. With the limited transport competence and capacity available, finer material, such as sands, from the tributaries is more mobile than the coarse substrate and therefore less likely to remain at the confluence (Rice *et al.*, 2001b), resulting in the observed low embeddedness (Richardson and MacKay, 1991). Wolman pebble counts provide further evidence of substrate coarsening after the tributary confluences. The change in median particle size across the confluences clearly indicates that the mainstem bed undergoes large increases in average substrate size at the tributary junctions (Table I). This resulting coarsening of the channel bed at the tributary junctions combined with the decreased competence of the regulated mainstem results in greater bed stability at the confluence.

Sediment activity

The relative radionuclide activity levels of the mainstem and tributaries are strongly seasonal. In the spring, old sediment predominates at all sites. The seasonal effect may reflect differences in sourcing of sediment and/or the seasonal variation in the meteoric supply of ^{7}Be. Bank collapse preferentially occurring post-winter may be one cause of temporal changes in sediment sourcing; for example, in a 5 year study of the sinuous channel of Watts Branch in eastern Maryland, Wolman (1959) found that 85% of the bank erosion and 65% of the suspended sediment transport occurred during the winter due in part to frost action and subsequent bank collapse. Sediment derived from bank collapse generally comes from below the zone of highest ^{7}Be activity, which is limited to the top few cm of the soil (Blake *et al.*, 1999). In addition, any ^{7}Be in the river channel has decayed during the winter (Bonniwell *et al.*, 1999). Sediment derived from bank collapse and in-channel decay would present the seasonal low in ^{7}Be/^{210}Pb activity ratio that occurs at most sites during the early spring. Moreover, the low activities in the early spring also may reflect the variations in atmospheric supply of fallout radionuclides. Because snow is less effective at scavenging aerosols and convective storms are less common in late winter and early spring, the fallout of ^{7}Be diminishes in these months compared with summer, where tropospheric and stratospheric exchanges more commonly occur (Ross and Granat, 1986; Ishikawa *et al.*, 1995).

During the summer, the opposite trend is generally observed with regard to the relative ^{7}Be/^{210}Pb activities of the tributaries and mainstem. The ^{7}Be/^{210}Pb ratios are higher at all sites during the summer period indicating the input of more recently ^{7}Be tagged sediment. The seasonal increases in ^{7}Be/^{210}Pb activity ratio at sites during the summer months may be due to increases in ^{7}Be deposition on exposed sediment that is washed into the channel during precipitation events. Since ^{7}Be is held in the top few millimetres of the exposed sediment (Blake *et al.*, 1999), sediment eroded from the surface contains higher ^{7}Be activities than sediment located below the surface.

Discontinuities in mainstem ^{7}Be activities during the sampling periods may be explained by an influx of sediment from the tributaries. In the spring, the ^{7}Be/^{210}Pb ratio of the mainstem decreases below each tributary, reflecting the input of older sediment that has not been recently exposed to the atmosphere. This dead sediment may originate from the tributaries, although this was not examined directly and therefore one can only speculate on the source. However, evidence collected during the summer sampling period strongly suggests that tributaries are a source of sediment for the mainstem. Figure 9 indicates that the activity of the sediment below the biggest tributaries reflects a mixture of the activities of the sediment in the tributary and upstream mainstem. The figure suggests that the mainstem sediment activity is enriched or diluted by the sediment activity of the tributary.

In addition, the activity of the mainstem increases immediately downstream of the largest tributaries during the summer sampling period. The observed change in activity coupled with the low embeddedness, indicating little sediment storage, imply that the residence time of the transitional bedload sediments at the junctions therefore must be on the order of, or less than, the decay timescale ($\sim$100 days) for one to capture this temporal change. The 'newer' sediment found below the confluence occurs during the low flow periods; however, the sampling sites are never exposed during this time. Therefore, the tagged sediment may reasonably be assumed to stem from tributary inputs or bar inundation during higher flows at the confluence. Sediment from the tributary may be exposed during the low summer flows and then washed downstream into the mainstem during precipitation events. In addition, large sand bars located at the mouth of these tributaries are susceptible to surface erosion during the summer rain events. Several extensive bars are also present below the Townshend Dam. Summer precipitation events may transfer the tagged sediment into the mainstem channel. The high activity of sediment derived from these bars coupled with the trapping of upstream, less active sediment by the dam likely are responsible for the very high ^{7}Be/^{210}Pb summertime activities found below the dam.

The lack of a summertime increase in ^{7}Be/^{210}Pb ratio below Grassy Brook possibly is related to the fact that Grassy Brook is the smallest tributary with the lowest gradient. Rice *et al.* (2001b) and Benda *et al.* (2004) suggest that the biophysical impact of tributaries varies as a function of tributary size relative to the mainstem. Alternatively, observed dam-building activities by beavers just upstream of the confluence may have released buried, ^{7}Be-dead sediment into the channel, causing a decrease in the ^{7}Be/^{210}Pb ratio in both the tributary and the downstream mainstem. Palmer *et al.* (2000) have shown that beavers exert important influences on aquatic sediments in streams through their dam-building activities. The beaver-induced bioturbation of old sediment into the channel is consistent with the observation that downstream of the Grassy Brook confluence consistently has the lowest ^{7}Be/^{210}Pb activity ratio among all sites on the West River.

Macroinvertebrates

The changes in embededdness and the normalized ^{7}Be/^{210}Pb activity ratio below the tributaries discussed above reflect disruptions in bed sediment character which may drive changes in benthic macroinvertebrate community structure (Rice *et al.*, 2001b). However, ecosystems are sensitive to many factors, including stream size, substrate, vegetation cover, temperature and stream discharge, and thus channel bed sediment character and/or hydrologic disruptions often may not be the dominant factor controlling community structure. This is evident in the late spring where no consistent trend in E/T ratio is observed across the tributary junctions. In contrast, the summer E/T ratio consistently decreases below tributary junctions and below the Townshend Dam. Distinct winter/spring and summer taxonomic changes related to physical and chemical changes associated with flow-alteration and macroinvertebrate life cycles are well known and reflect both life cycle variations and hydrological redistribution (Linke *et al.*, 1999; Reece *et al.*, 2001; Beche *et al.*, 2006). Since the spring season is a period of emergence and reproduction for many aquatic invertebrates, as well as usually being the season with the highest yearly flows, sampling during the spring may give inconsistent assessments of benthic communities. The data indicate that summer benthic community structure is more reflective of the bed sediment character than the spring. For this reason the focus here is on the summer data.

Increased caddisfly abundance below tributary confluences in the summer is probably the result of mainstem-tributary interactive effects on substrate conditions. Salant (2005) observed high filter-feeding caddisfly densities below the Union Village Dam that could not be accounted for by changes in seston quality, as the dam did not maintain a pool during the period of study. Instead, Salant (2005) argued that increases in filter feeding Trichoptera abundance reflect increased bed stability due to reduced disturbance frequency associated with the flow regulated river. Since filter feeding Trichoptera attach nets and retreats to the substrate, bed stability is important for maintaining their position and their filtering apparatus in the higher velocity flows necessary for seston capture (Rice *et al.*, 2001a). It is suggested that the combination of coarse sediment inputs (gravel and cobble size) and subsequent winnowing of fine sediments by tributary flows results in stable, unembedded substrate below tributary junctions. Although they differ with respect to feeding strategy and morphology, case-building caddisflies would also be expected to benefit from stable substrates that are not embedded with fine sediment (and therefore able to provide interstitial space) (Wooton *et al.*, 1996). As a result, general increases in caddisfly abundance associated with these habitat conditions can be predicted, in spite of the variation in functional feeding group representation across sites.

The presence of a large stable substrate at the tributary confluences is supported by the physical data and changes in radionuclide activity. Wolman pebble counts indicate coarse sediment stability below the tributary junction. In addition, the decrease in embeddedness observed below the tributary junctions is consistent with a stable channel bed where incoming transitional sediment is quickly removed. During the summer, the 'newer' sediment below the tributary junction suggests a rapid flux of sediment and a large stable substrate. Results show that at tributary junctions the ratio of Ephemeroptera to Trichoptera is well correlated with the sediment ^{7}Be/^{210}Pb activity ratio during the summer when the E/T ratio decreases with increasing ^{7}Be/^{210}Pb ratio. It is likely that Trichoptera are not directly responding to an influx of 'new' sediment, but rather that the 'newness' of the sediment is indicative of other favorable habitat features.

It might be argued that focusing on a single metric is not sufficient to capture the suite of changes in benthic community structure. To investigate this potential limitation, these results were compared with the Vermont Department of Environmental Conservation's (DEC) benthic macroinvertebrate assessments on the West River from 1992 to 2003. The DEC repeatedly evaluated four sites—two sites in Dummerston, Vermont, one site below the Townshend Dam and one site below the Ball Mountain Dam—for a total of nine macroinvertebrate community assessments. The DEC classified the macroinvertebrates to species and completed community assessments using standard metrics, including density, richness, Ephemeroptera-Plecoptera-Trichoptera

Table II. DEC community assessments on the West River from common macroinvertebrate metrics compared to the E/T ratio for each sample date

West River Site	Date	E/T	DEC Community Assessment
Jamaica below BM Dam	Oct 1997	2·66	Excellent
Dummerston above bridge	Sept 1998	1·93	Excellent
Jamaica below BM Dam	Oct 1991	1·93	Excellent
Dummerston above bridge	Oct 1992	1·37	Very good
Dummerston below bridge	Oct 1994	0·88	Good
Dummerston above bridge	Oct 1995	0·81	Good
Dummerston below bridge	Sept 2003	0·70	Good
Dummerston above bridge	Sept 2003	0·70	Good
Below Townshend Dam	Oct 2003	0·40	Very good

(EPT) richness, percentage Oligochaeta and PPCF-F1 (Pinkham-Pearson coefficient of similarity) (Pinkham and Pearson, 1976). Based on these metrics, the DEC summarized the ecological state at each site as 'good', 'very good', or 'excellent'. As shown in Table II, in general the late August E/T ratio correlates very well with the DEC community assessment except for the site directly below the Townshend Dam which has high caddisfly abundance. This relationship suggests that the E/T ratio captures more general attributes of macroinvertebrate community structure.

It was initially hypothesized that transitional bedload sediment residence time at tributary junctions would impact both ^{7}Be/^{210}Pb activity ratio and macroinvertebrate community structure. Therefore, sediment ^{7}Be/^{210}Pb activity ratio might be a proxy for macroinvertebrate community structure. The picture that now emerges is more complex as both the macroinvertebrate community structure and the sediment activity display a strong seasonality. During the spring season, the ^{7}Be/^{210}Pb values are low at all the sites, suggesting a depleted ^{7}Be source perhaps associated with bank collapse, the *in situ* decay of the short-lived isotope during winter low flows, and less effective scavenging of atmospheric ^{7}Be during winter. Sites that have the shortest residence times, i.e. below the confluences, also have the lowest sediment activities, suggestive of an influx of dead sediment to these regions over the seasonal time scale. The suggestion of a limited transitional bedload sediment residence time at these locations is further supported by the fact that during the summer, the ^{7}Be/^{210}Pb activity ratio at the larger tributary junctions and below the dam increases significantly. Such a rapid increase in activity requires both an influx of newly-tagged sediment and a high ratio of sediment flux to in-channel sediment storage that permits this rapid shift in bulk activity. Since the embeddedness decreases at each tributary junction in this study, the in-channel storage at these sites is low. Therefore, the two junctions with high late summer activities (below the Wardsboro and Rock River confluences) must be sites with short sediment residence times. The short residence times may reflect an environment which provides favourable conditions for the filter feeders such as a clean, stable substrate and low fine sediment storage. In addition, the rapid turnover of sediment may also be associated with a rapid flux in nutrients or seston. However, it is acknowledged that there may be other biological and physical factors that could influence the macroinvertebrate distributions along the mainstem.

In contrast, the lower late summer sediment activity below the Grassy Brook tributary confluence reflects either a continued input of dead sediment from the tributary and/or a very slow sediment flux at this site. The lack of new sediment may be due to the smaller size of the Grassy Brook tributary and/or upstream bioturbation of the sediment supply. Whatever the cause of the low sediment activity, the sediment transport dynamics at this junction may reflect differences in environmental conditions. Differences in environmental condition such as embeddedness, substrate size, or nutrient flux could explain the dominant Trichoptera families belonging to the shredder feeding group, not the filter feeding group at this site.

CONCLUSION

The Ball Mountain and Townshend Dams have altered the downstream hydrologic regime of the West River by reducing the annual peak flows. The consequent reductions in downstream competence and capacity have resulted in significant changes in the channel bed, including bed aggradation and a reduction in bed elevation variability at the stream gauges located 4·5 km downstream of the Ball Mountain Dam and 9 km downstream of the Townshend Dam. Closer to the dam the high-sediment trapping efficiency of the dams probably has resulted in bed degradation. Thus at some distance less than 4·5 km from the dam there is a transition from bed degradation to bed aggradation. This is termed the transitional length scale of the dam.

The transition from bed degradation to bed aggradation occurs, in part, because tributaries assist in the mainstem recovery from impoundment by providing an influx of water and sediment. Due to its reduced capacity and competence, tributaries downstream of the dams are no longer graded with the mainstem. The mainstem can no longer transport all the sediment delivered by the larger tributaries, resulting in the observed bed aggradation as well as the formation of extensive, large cobble and sand bars, and the preferential transport of finer sediment below the tributary confluences.

Despite the influx of sand-sized sediment from the tributaries, the mainstem embeddedness consistently decreases below tributary confluences, implying that fine sediment entering the confluence has a short residence time. During the spring, bed sediment below the tributaries has very low radionuclide activity, indicating a source depleted in ^{7}Be, possibly the eroded sediments from winter/spring bank collapse and sediment whose ^{7}Be activity has decayed during the winter. High spring flows in the non-regulated tributaries may carry

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this 'dead' sediment into the mainstem. In contrast, fine sediment at the confluence during the summer has high radioisotope activity, indicating a recently exposed source. It is speculated that summer precipitation events raise the mainstem, washing 'tagged' sediment from the tributary banks and confluence bars into the mainstem channel. This sediment is continually renewed by an influx of water and sediment from the tributaries.

Caddisflies benefit from the habitat conditions at the tributary confluences. However, the seasonal variations in benthic population and radioisotope signals confound the relationship between invertebrates and sediment in the spring. The late summer Trichoptera abundance and Empheroptera/Trichoptera ratios show a strong relationship with the sediment radionuclide activity, suggesting that Trichoptera prefer habitats with a low transitional bedload sediment residence time. Since the mainstem bed remains uniformly stable due to flow regulation, high caddisfly abundance at the tributary junctions and below the dam suggest that filter feeding and shredder Trichoptera are most successful at stable mainstem sites with a constant influx of new sediment and water. Ultimately, this shift in benthic community structure may affect the entire riverine food web, since Trichoptera have been recognized as a less desirable energy source for aquatic fish (Wooton *et al.*, 1996).

Understanding the role of tributaries in modifying the downstream effects of flow regulation is critical for elevating the analysis of dams away from a primarily singular case toward a more comprehensive evaluation of the hydro-geomorphic effects of dams at the scale of the watershed encompassing an array of dam types and operation strategies. At the watershed scale, tributaries have generally been thought to buffer the effects of impoundment by re-supplying water and sediment to a regulated mainstem. However, due to the reduced capacity and competence of the regulated mainstem, the sediment load supplied by the tributaries may exacerbate, rather than ameliorate, the effects of impoundment (*cf* Andrews, 1986). With the tremendous interest in environmental flows and adaptive management scenarios, these results indicate that a watershed scale perspective is necessary to mitigate the effects of mainstem impoundments as tributaries may have significant effects on the mainstem eco-geomorphology.

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