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The use of short-lived radionuclides to quantify transitional bed material transport in a regulated river

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Abstract

We investigate the use of the short-lived fallout radionuclide beryllium-7 (^{7}Be; $t_{1/2} = 53{\cdot}4$ days) as a tracer of medium and coarse sand (0·25–2 mm), which transitions between transport in suspension and as bed load, and evaluate the effects of impoundment on seasonal and spatial variations in bed sedimentation. We measure ^{7}Be activities in approximately monthly samples from point bar and streambed sediments in one unregulated and one regulated stream. In the regulated stream our sampling spanned an array of flow and management conditions during the annual transition from flood control in the winter and early spring to run-of-the-river operation from late spring to autumn. Sediment stored behind the dam during the winter quickly became depleted in ^{7}Be activity. This resulted in a pulse of 'dead' sediment released when the dam gates were opened in the spring which could be tracked as it moved downstream. Measured average sediment transport velocities (30–80 metres per day (m d^{-1})) exceed those typically reported for bulk bed load transport and are remarkably constant across varied flow regimes, possibly due to corresponding changes in bed sand fraction. Results also show that the length scale of the downstream impact of dam management on sediment transport is short (*c.* 1 km); beyond this distance the sediment trapped by the dam is replaced by new sediment from tributaries and other downstream sources.

Keywords: beryllium-7; dams; flow regulation; sand; sediment transport

Introduction

Fine (<2 mm) sediment can severely impact aquatic systems (Angradi, 1999; Lowe and Bolger, 2000; Nerbonne and Vondracek, 2001; Richards and Bacon, 1994; Waters, 1995; Weigelhofer and Waringer, 2003). In addition, as an often significant component of the overall sediment transport budget (Meade, 1990), the discharge regime of fine sediment is an important agent of geomorphic change; reduced sediment loads enhance streambed incision and armouring (Dietrich *et al.*, 1989), while increased sediment deposition leads to streambed aggradation. These effects are of particular concern in flow-regulated streams where reduced discharges can decrease transport capacity and increase sedimentation with increased distance from the dam (Andrews, 1986).

The impact of sedimentation will depend on the frequency and magnitude of sediment deposition and its subsequent residence time in the bed. Numerous studies have demonstrated the deleterious effects of increased finesediment storage on aquatic ecosystems, decreasing invertebrate density and abundance (Angradi, 1999; Richards and Bacon, 1994; Waters, 1995; Weigelhofer and Waringer, 2003) and degrading benthic habitat (Lowe and Bolger, 2000; Nerbonne and Vondracek, 2001; Waters, 1995). These problems should be expected to worsen with less frequent transport and longer storage times. The extent to which fine sediment interacts with the bed is also important because of its high association with pollutants in river sediments (Allan, 1979; Bonzongo *et al.*, 1996; Karickhoff and Brown, 1978).

Previous studies have primarily focused on the mode of fine sediment transport; whether fine particles are transported in a series of steps and jumps (Jobson and Carey, 1989; Verhoff and Melfi, 1978; Verhoff *et al*., 1979, 1982) or travel the length of a river in a single hydrograph (Cahill *et al*., 1974; Partheniades, 1972). This study complements this earlier work by investigating a novel technique for assessing the bed residence time of sand in mixed-load rivers with small proportions of sand in the bed.

Sediment residence time, or conversely, sediment transport rate, is a function of particle size and discharge. Generally, fine particles such as silts and clays are carried in suspension; therefore, under normal flow conditions they are unlikely to frequently interact with the bed or have long residence times in the stream. In contrast, larger particles roll and saltate along the bed as bed load (Knighton, 1998) and have longer residence times, but are less strongly associated with contaminants or biotic 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. For this reason, 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). It is highly conceivable that transitional load will have the greatest impact on stream ecosystems because, like suspended load, it can carry a significant sorbed contaminant load and, like bed load, it has a long residence time and frequent interactions with the bed. However, to our knowledge, this has not been extensively tested due to the inherent difficulty in measuring this component of the sediment load. Thus the ability to quantify transitional load transport is critical for accurate analyses of the interactions between sediment transport and stream ecosystems.

In the field, suspended sediment transport rates can be determined from samples of suspended load taken from the water column (Lewis *et al*., 2001; Nistor and Church, 2005; Pfannkuche and Schmidt, 2003), but these measurements mostly represent particles that rarely interact with the bed. Bed load sediment transport rates are typically measured using hand-held samplers or pit and slot traps extending across the entire river width (Emmett, 1980; Hassan and Church, 2001; Kuhnle, 1992). However, hand-held samplers often require large numbers of samples or long sampling times in order to obtain reliable estimates (Bunte and Abt, 2005; Emmett, 1980; Gomez, 1991; Sterling and Church, 2002; Vericat *et al*., 2006) and slot traps can be prohibitively expensive to install and operate. Transport rates for larger bed load particles can be directly determined by measuring the displacement of magnetically tagged or painted particles (Church and Hassan, 2002; Hassan and Ergenzinger, 2003). However, no similar methodology has been developed for directly tracing the transport of transitional sediment.

In this study, we investigate the use of the short-lived fallout radionuclide beryllium-7 (^{7}Be; $t_{1/2} = 53·4$ days) as a tracer for transitional bed load transport. 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 – we consider this sediment '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 – we consider this sediment 'old' or 'dead.'

Previous studies have used radionuclides to fingerprint sediment sources in terrestrial and aquatic environments (Olley *et al*., 1993; Walling and Woodward, 1992), but their application to fluvial systems has been limited (Blake *et al*., 2002). Bonniwell *et al*. (1999) used ^{7}Be to trace the downstream transport and channel bed mixing of suspended sediment in an unregulated stream. Their results indicated that suspended fine particles have short residence times and travel long distances in a high gradient stream during high flow periods, but they acknowledged that rivers of varying size, slope, climate and land use may exhibit very different dynamics.

This study seeks to better understand the dynamics of ^{7}Be as a tracer of transitional bed load and evaluate its ability to measure the geomorphic effects of impoundment, where changes to discharge, sediment transport and bed morphology may be profound. Specifically, we characterize the source, distribution and composition of ^{7}Be-tagged sediment in unregulated and regulated streams and track seasonal trends in the ^{7}Be activity of transitional bed load. We use an unregulated stream to assess the spatial and temporal variations in the ^{7}Be activity of source and bed sediment in the absence of anthropogenic influence. We then monitor a flow-regulated stream where dam operation transitions between highly regulated and unregulated conditions so that we can capture the effects of both seasonal and operational changes in flow.

Site Description

The White and Ompompanoosuc Rivers are mixed gravel–sand tributaries of the Connecticut River in eastern Vermont (Figure 1). Because of the primarily coarse-grained local geology and abundant sandy-textured Pleistocene

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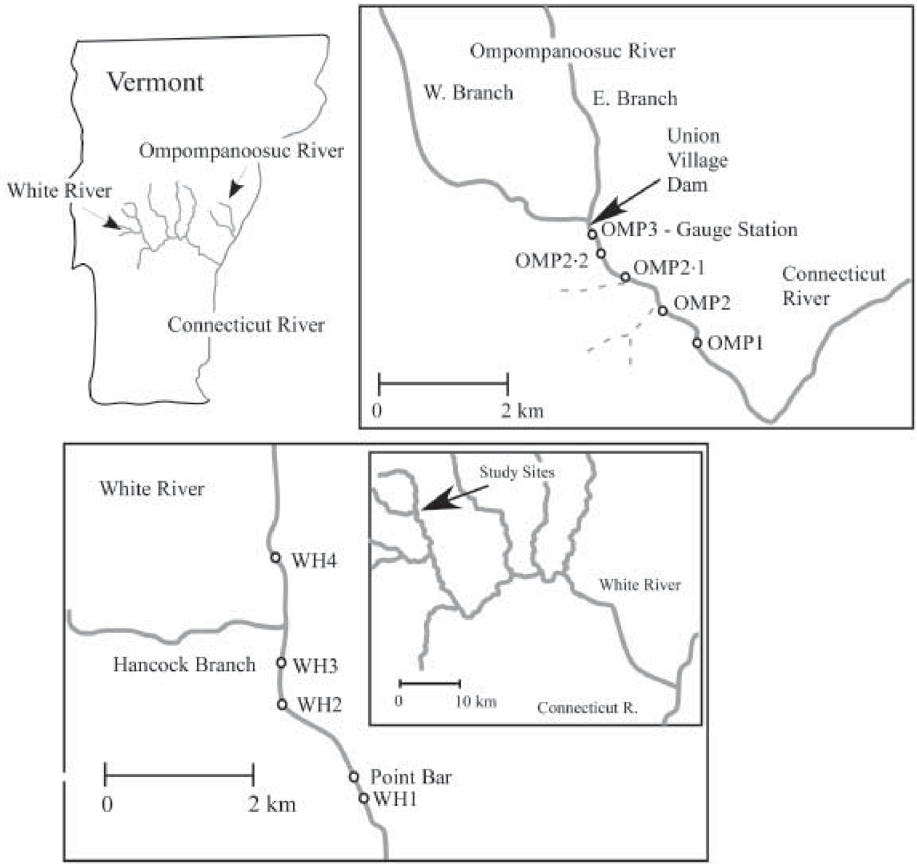

Figure 1. Location of sample sites on the White and Ompompanoosuc Rivers, tributaries of the Connecticut River in eastern Vermont. Sites on the White River were located up and downstream of the Hancock Branch tributary. Sites on the Ompompanoosuc River were located downstream of the Union Village Dam. Also indicated are the locations of the two small, ephemeral tributaries of the Ompompanoosuc River downstream of the dam.

deposits, fine-grained material is poorly represented in the total sediment discharge regime, and Vermont catchments tend to have some of the lowest suspended sediment loads in the USA, generally with concentrations <200 mg l^{-1} (Rainwater, 1962).

At the selected study reaches on the unregulated White River, the drainage basin area ranges from 80 to 140 km^2, the gradient is <0·1 per cent, the bed width averages *c*. 11–21 m, and the median grain size of the bed surface (D_{50}) is *c*. 10–11 cm. The Ompompanoosuc River is regulated by the Union Village Dam, located in Thetford, Vermont, *c*. 5 km upstream from the junction with the Connecticut River and just downstream of the East Branch tributary. Just below the dam, the drainage basin area is 103 km^2, the mean annual discharge is *c*. 6 $m^3 s^{-1}$, the gradient is <0·1 per cent, the bed width averages *c*. 20 m, and the median grain size of the bed surface (D_{50}) is *c*. 10 cm. Two ephemeral tributaries contribute water and sediment to the Ompompanoosuc River below the dam during large storm events and spring high flows.

A US Geological Survey (USGS) stream gauging station on the White River provides hourly discharge data. A US Army Corps of Engineers stream gauging station located directly below the Union Village Dam on the Ompompanoosuc River (at Ompompanoosuc River site 3, OMP3) provides hourly discharge and precipitation data. The dam transitions from a flood-control to run-of-the-river facility during late spring. During winter months, the dam gate levels are low, discharge through the dam is restricted, and water pools behind the dam. During non-winter months, the gate levels are higher, generally allowing for run-of-the-river conditions and the release of sediment from behind the dam. During spring high flows, despite higher gate levels, discharge is restricted and water is temporarily stored in the reservoir. Overlaying the hydrograph on the gate level and the precipitation record (Figure 2) demonstrates the relationship between these factors. While the gate level generally correlates with flow throughout the sampling

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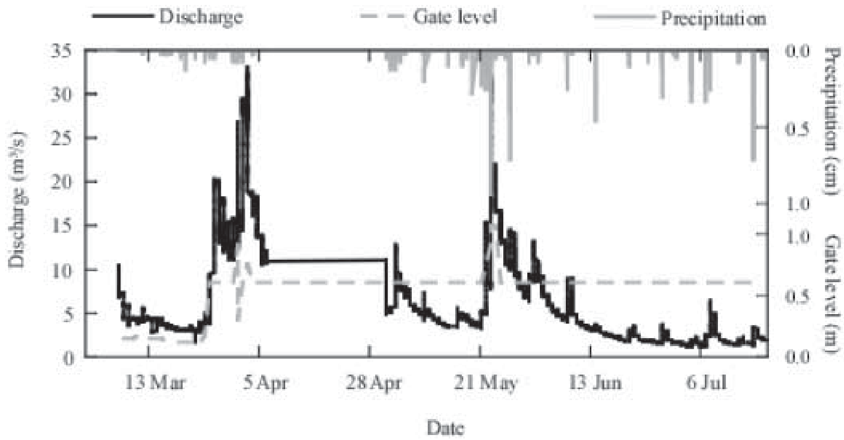

Figure 2. Hydrograph below the Union Village Dam on the Ompompanoosuc River for the period from February 2004 to July 2004 (black line) plotted against the level of the flood-control gates of the Union Village Dam (dashed line) and the precipitation record (gray line) for the same time period.

period, precipitation and flow do not correlate early in the sampling period, indicating that increases in flow in mid- and late spring are due to snowmelt and the opening of the dam's gates.

Sampling sites on the White River included a gravel–sand point bar and four bed sediment sampling sites, located up- and downstream of the Hancock Branch tributary (Figure 1). Bed sediment sampling sites on the Ompompanoosuc River were selected to represent a downstream progression of regulation impact. OMP3, directly below the dam, represents the highest level of regulation. OMP1, farthest downstream, represents the last free-flowing section of river before the backwater effect of the regulated Connecticut River. Additional sites were spaced between OMP1 and OMP3 with a finer scale of spatial resolution closest to the dam, for a total of five sites.

Methods

Sediment sampling

Approximately monthly sediment sampling began in February 2004 and continued through late summer 2004. Sampling timing and frequency were modified during large storms and during the opening of the dam's gates on the Ompompanoosuc River in order to specifically monitor the effects of these events. All sites on the White and Ompompanoosuc Rivers were sampled throughout the entire time period with the exception of Ompompanoosuc River sites 2·1 (OMP2·1) and 2·2 (OMP2·2), added in early May to capture the fine-scale spatial and temporal dynamics of the spring release.

At each bed load sampling site, *c.* 500 g of sand-sized sediment was grab-sampled from the top 5 cm of the streambed at a location half-way between the bank and the thalweg. At four sites on the Ompompanoosuc River, replicate samples were collected at various locations within the stream channel periodically throughout the year to determine the degree of spatial variability (Table I, Figure 3). Because of the time required to analyse each sample, it was not feasible to analyse replicate samples each time a site was sampled. At all sites, the most surficial layer of sediment was collected to capture the most recently deposited sediment. White River point bar samples were taken from an area within *c.* 1 m of the water's edge.

Radionuclide and grain size analysis

Immediately after collection, samples were dried and sieved. The <2 mm fraction was then packed into plastic containers and weighed. Samples from White River site 1 (WH1) and Ompompanoosuc River site 1 (OMP1) in early March were further sieved into three additional size fractions for radionuclide analysis to determine relative activity as a function of grain size: <0·25 mm, 0·25–1 mm and 1–2 mm. In addition, the weighted grain size distribution was determined for all ten samples from the Ompompanoosuc River site 3 (OMP3) by sieving with a Sonic Sifter into representative size classes and weighing each class.

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Table I. Variability in the $^{7}Be/^{210}Pb$ ratio of replicate sediment samples taken from the Ompompanoosuc River, Vermont. Samples for which $n = 2$ were taken near both the right and left banks; samples for which $n = 3$ where taken near both banks and near the right bank *c.* 20 m upstream; samples for which $n = 4$ were taken near both banks and near the right bank *c.* 20 m upstream and downstream (see Figure 3)

Date	Site	*n*	Mean $^{7}Be/^{210}Pb$ (SE)	SE/<x> (%)
22 October 2003	OMP3	3	0·19 (0·007)	3·5
10 November 2003	OMP1	2	0·09 (0·001)	1·0
10 November 2003	OMP2	2	0·39 (0·003)	0·8
10 November 2003	OMP3	2	0·09 (0·006)	0·7
7 August 2004	OMP1	4	0·30 (0·042)	17·0

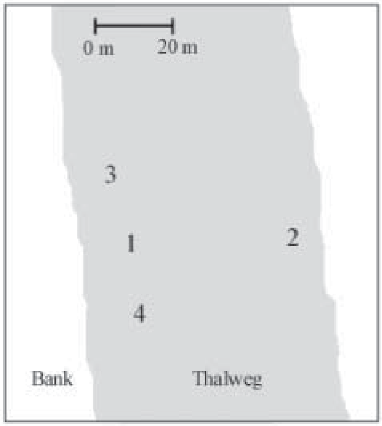

Figure 3. Schematic of stream channel indicating where samples were taken from the streambed, represented by a number that equals the total number of replicates taken for that site and date. Samples for which $n = 2$ were taken near both the right and left banks; samples for which $n = 3$ where taken near both banks and near the right bank *c.* 20 m upstream; samples for which $n = 4$ were taken near both banks and near the right bank *c.* 20 m upstream and downstream.

A high-purity germanium detector was used to determine the activities (Bq kg^{-1}) of ^{7}Be (477·6 keV) and ^{210}Pb (46·5 keV) in each sample via gamma counting. Activities were calculated by correcting for sample mass, decay since collection, time counted, and detector and photon efficiencies. The analytical error associated with photon counting is a function of the total number of decays or 'counts' (n) detected, where $\sigma_n = \sqrt{n}$. All samples accumulated at least 100 counts, thus our counting error is 10 per cent or less. 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, a self-attenuation correction was made based on the mass of the sample (Hussain *et al.*, 1995).

The use of ^{7}Be as a tracer of sand-sized sediment requires the assumption that ^{7}Be adsorbs and tags sediment in the range of 0·25–2 mm, thus permitting the tracing and measurement of transport for particles of this size. There is ample evidence to support this assumption. The sand-sized sediment that we collected for this study is dominated by quartz, feldspar, micas, and lithic fragments. The divalent cation $^{7}Be^{2+}$ is a very reactive atom and will adsorb strongly to surfaces on all of these grains. Although quartz has a framework structure of SiO_4 tetrahedra that are linked entirely by oxygen sharing (each tetrahedron shares all of its oxygen atoms with adjacent silica atoms), these crystal lattices are not infinite. At grain boundaries the oxygen atoms are not linked to other silica atoms; they are left with an 'unsatisfied' outer electron shell. Because $^{7}Be^{2+}$ is electronegative, it will tend to form strong covalent bonds with oxygen atoms at these grain boundaries. Direct evidence of trace metal adsorption to inorganic silica, alumina and iron mineral surfaces is given by numerous X-ray studies (Cheah *et al.*, 1998, 2000; Chen *et al.*, 2006)). Furthermore, You *et al.* (1989) measured the partitioning coefficient (K_d) of ^{7}Be on a range of natural substances, including river sands (presumably dominated by quartz and feldspar), lake muds, soils, crushed carbonate mineral separates, and crushed beryl mineral separates. They showed that ^{7}Be favoured the solid (adsorbed) phase over the dissolved (aqueous) phase

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by at least a factor of 1000 on all of these surfaces. Our sediment samples are best characterized as individual grains, not as aggregates, thus it is reasonable to assume that the ^{7}Be in our samples is tagging the sand-sized sediments.

While the absolute amount of ^{7}Be depends upon the atmospheric flux, depth of penetration and specific sorption processes, we assume that the spatial variations in these processes are small relative to variations in activities due to decay. This assumption is supported by the observations of Bonniwell *et al*. (1999) who found little variation in the total ^{7}Be inventory in soils sampled throughout a 389 km^2 catchment. Furthermore, Bonniwell *et al*. (1999) found that normalizing the ^{7}Be activity by the activity of the longer-lived fallout nuclide ^{210}Pb ($t_{1/2} = 20{\cdot}2$ years) partially corrected for compositional differences. Consequently, changes in the ^{7}Be/^{210}Pb activity ratio primarily reflect the extent of decay, not sorption or grain size effects. Thus, we assume that spatial variations in relative ^{7}Be/^{210}Pb activity generally reflect differences in the time since the sediment was last exposed to atmospheric input.

We acknowledge that the use of total ^{210}Pb, rather than 'excess' ^{210}Pb, is potentially problematic because total ^{210}Pb contains both atmospheric ^{210}Pb and ^{210}Pb due to the decay of ^{226}Ra in the local regolith. However, 'excess' ^{210}Pb is difficult to accurately determine in river sediments, because it is actually impossible to quantify the level of ^{210}Pb that is truly 'supported' by ^{222}Rn in fluvial systems. In soils, this can be accomplished with less uncertainty because diffusion is the dominant ^{222}Rn transport process, and this can be addressed with a simple model (Nozaki *et al*., 1978). However, the amount of disequilibrium that might occur between ^{210}Pb and ^{226}Ra from ^{222}Rn escape through advection in sediment pore-water could have a considerable range (Benoit *et al*., 1991). To report 'excess' ^{210}Pb, one could measure ^{226}Ra and ^{210}Pb and subsequently estimate the amount of ^{222}Rn gas that escapes in this part of the decay series in a natural fluvial system. Total ^{210}Pb is a function of ^{226}Ra content and atmospheric inputs, both of which will increase with decreasing grain size. Since our main goal is to normalize ^{7}Be for particle-size effects (higher adsorption affinity of smaller grain sizes), we feel that total ^{210}Pb is appropriate, and more transparent. The reporting of 'excess ^{210}Pb' will require a set of assumptions that will be very difficult to justify in this or any other fluvial system.

Results and Discussion

Spatial variability of ^{7}Be/^{210}Pb activity in streambed sediment

The ^{7}Be/^{210}Pb activity ratios of samples collected at different locations within the channel (Figure 3) at a given reach are generally similar; the standard error between multiple samples collected at the same reach ranges from 1 to 17 per cent with an average of 7 per cent and a median of 4 per cent (Table I). This variation is within the range expected for the uncertainty due to instrumental error (10%). For comparison, the seasonal variability of ^{7}Be/^{210}Pb at a given reach was generally 50 to 100 per cent of the annual mean. Thus within our analytical precision, no significant spatial variation in activity ratio exists at a particular sampling site.

Grain size analysis

The lack of significant spatial variability in activity ratio at a particular site indicates that the measured sediment is well mixed across the channel. Smaller particles, because they are more easily moved, are likely to be better mixed than larger particles. The lack of significant spatial variability thus suggests that the bulk sediment activity of the samples may primarily reflect the activity of the finer fraction of sediment. To further investigate this concept, we determined activity as a function of grain size in select samples.

The ^{7}Be and ^{7}Be/^{210}Pb activities of from OMP1 and WH1 as a function of grain size class are presented in Figure 4. Activities are normalized by the activity of the bulk (<2 mm) sample. At both sites ^{7}Be activity is highest (around twice bulk activity) in the smallest (<0·25 mm) size fraction, reflecting preferential sorption onto smaller grains. As suggested by Bonniwell *et al*. (1999), normalizing ^{7}Be activity by the longer-lived ^{210}Pb activity (dashed lines) partially corrects for compositional effects, although some variation with grain size remains.

While the finest (<0·25 mm) grain sizes have the highest activity, their contribution to the bulk activity of the sample is limited because they, on average, only comprise *c*. 16 per cent of the total sediment mass (Table II). The larger size fractions (0·25–1 mm and 1–2 mm), while less active, are more abundant. To determine the net contribution of each size fraction to the bulk activity, we weighted the activity level of each size fraction by its percentage weight (Figure 4c). For both rivers, the 0·25–1 mm size fraction dominantly controls the bulk activity of the sample. These results demonstrate that despite preferential sorption of ^{7}Be onto the fine fraction, the ^{7}Be/^{210}Pb measured in the bulk sample mostly traces the activity of the 0·25–1 mm size fraction, which is typically transported as transitional load. For example, discharges on the Ompompanoosuc River used to calculate the u_*/w_s for 0·25, 1 and 2 mm sediment demonstrate that throughout the study period, most of this sediment is carried as transitional load, defined by

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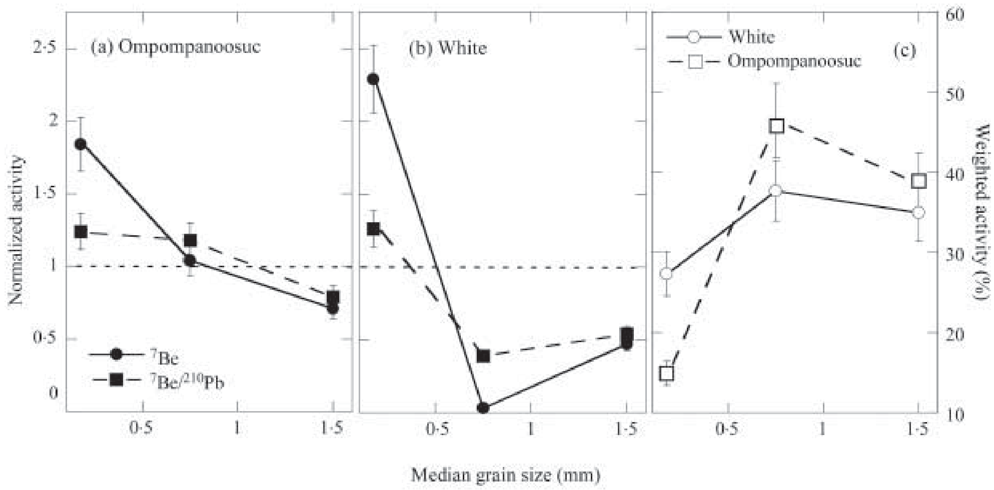

Figure 4. Grain size analysis and distribution for bed sediment samples from the Ompompanoosuc and White Rivers, Vermont. Beryllium-7 and $^7Be/^{210}Pb$ activities of particle size classes (<0·25 mm, 0·25–1 mm and 1–2 mm) of bed sediment samples from sites (a) OMP1 and (b) WH1, normalized by the activities of the bulk (<2 mm sample) and (c) $^7Be/^{210}Pb$ activities of particle size classes (<0·25 mm, 0·25–1 mm and 1–2 mm) of bed sediment samples from OMP1 and WH1, weighted by the percentage weight of each size class in the bulk sample. Error bars are a representative standard error of per cent of the mean; in some cases, figure markers are larger than error bars.

Table II. Percentage weight of three particle size fractions for ten bed sediment samples from site 3 on the Ompomanoosuc River (OMP3), Vermont, located directly below the Union Village Dam.

		Weight (% of total)		
Site	**Date**	**<0·25 mm**	**0·25–1 mm**	**1–2 mm**
OMP3	20 Feb 04	30·6	45·5	23·9
OMP3	13 Mar 04	9·8	16·1	74·1
OMP3	27 Mar 04	6·8	93·0	0·2
OMP3	15 Apr 04	36·0	32·9	31·1
OMP3	14 May 04	11·4	82·9	5·7
OMP3	28 May 04	34·9	50·9	14·1
OMP3	18 Jun 04	5·6	9·9	84·5
OMP3	14 Jul 04	10·2	12·1	77·7
OMP3	7 Aug 04	7·3	15·7	77·0
Average (SE)		15·9 (3·8)	37·6 (9·1)	46·5 (10·4)

$u_*/w_s \approx 0{\cdot}4$–$2{\cdot}5$ (Figure 5). Only the high flows in late March and late May resulted in fully suspended transport of the finest fraction ($u_*/w_s > 0{\cdot}4$).

Sources of ^7Be-tagged sediment

Figure 6 summarizes the $^7Be/^{210}Pb$ activities of the White River point bar and bed sediment from the site directly downstream of the point bar (WH1). Overlaying the hydrograph for the same time period illustrates the enrichment and mobilization of sediment sources to the stream. Both point bar and bed sediment activities are generally low (*c*. 0·2) prior to, during and immediately following the high flows in the late winter and early spring. Low point bar activities reflect that the point bar is partially snow-covered at this time and that the flux of ^7Be is at a minimum during the winter (Bachuber and Bunzl, 1992; Koch *et al*., 1996). There are three main reasons for this: (i) snow is not as efficient at scavenging aerosols from the atmosphere as rain, therefore radionuclide concentrations in snowfall are low (Ishikawa *et al*., 1995; Ross and Granat, 1986); (ii) stratosphere–troposphere exchange, the main mechanism by which atmospheric ^7Be increases, is minimal in the winter (Feely *et al*., 1989); and (iii) thunderstorms, which because

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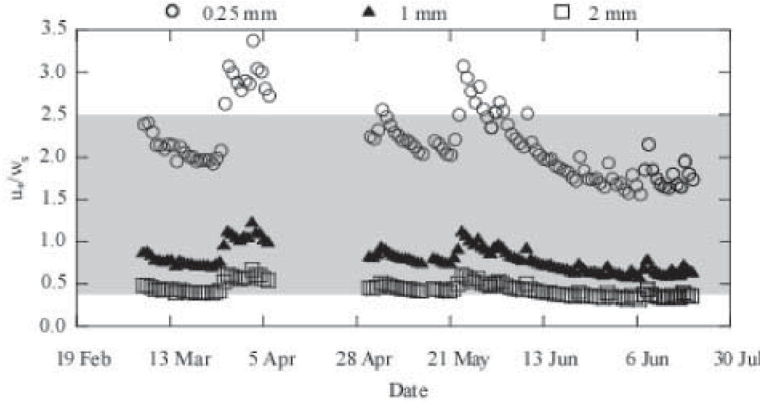

Figure 5. The shear velocity to settling velocity ratio (u_*/w_s) of 0·25, 1 and 2 mm particles for discharges measured below the Union Village Dam on the Ompompanoosuc River, Vermont, during the study period. Particles with a u_*/w_s between 0·4 and 2·5 are referred to as mixed or 'transitional' load, transported both in suspension and as bed load.

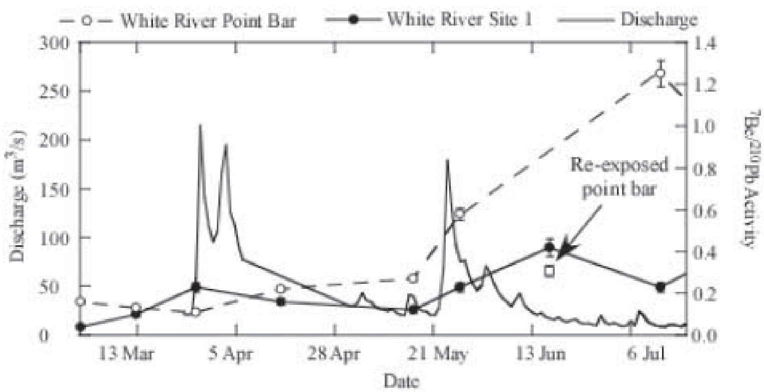

Figure 6. The $^7Be/^{210}Pb$ activities of the White River point bar (open symbols) and bed sediment from site WH1 (closed circles) directly downstream, overlaying the hydrograph (black line) for the same time period. The 18 June point bar sample (open square) was taken from an area of the point bar flooded during the late May storm and is therefore differentiated from the area of the point bar exposed during the storm. Error bars are a representative standard error of 10 per cent of the mean; in some cases, figure markers are larger than error bars.

of their large volume and contact with the troposphere are a major source of ^7Be deposition, occur rarely during the winter. In addition, any ^7Be that is deposited with winter snowfall will partially decay before it enters the stream as spring melt. Thus spring melt flows generally have only low to moderate concentrations of ^7Be (Bonniwell *et al*., 1999). The slight increase in bed sediment activity that occurs at the start of the spring flood at the end of March may reflect of the release of the small portion of the annual input of radionuclides stored in the snowpack. While early spring high flows likely mobilize point bar sediment into the stream and remobilize stored bed sediment, both sediment sources are low in ^7Be activity. Thus the observed increase in bed sediment activity at the end of March is small relative to the increases observed after high flows later in the year that mobilize newly tagged sources of sediment.

Throughout the spring, point bar $^7Be/^{210}Pb$ activity increases as rainfall enriches the exposed sediment with ^7Be; immediately following a large rainstorm in late May, the activity of the exposed point bar is observed to increase significantly (Figure 6; open circles) and it continues to increase with additional rainfall. This is due to the high aerosol-scavenging efficiency of rainfall (Ishikawa *et al*., 1995; Ross and Granat, 1986) which results in an annual peak concentration of ^7Be in rainfall during late spring and early summer (Bachuber and Bunzl, 1992; Brown *et al*., 1989; Olsen *et al*., 2001) and is consistent with the strong correlation between annual rainfall and ^7Be flux observed elsewhere (Vogler *et al*., 1996; Whiting *et al*., 2005). Although not sampled, it is likely that exposed bank sediment and surface soils similarly increase in activity over the same time period.

On 18 June, as the hydrograph receded, a portion of the point bar was sampled that had been flooded during the late May storm. The activity of this re-exposed point bar sediment (Figure 6; open square) is lower than that of sediment

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from the unflooded part of the point bar sampled earlier at the end of May (open circle). This decrease in activity is more than expected from the *in-situ* decay of the unflooded point bar sediment sampled at the end of May. Over the same time period the bed sediment activity increases (solid circles), indicating that some newly tagged sediment, possibly mobilized from the areas of the point bar flooded during the storms, entered the stream during the end-of-May storm as well as the two smaller storms at the beginning of June. Thus the lower activity of the re-exposed point bar sediment may be partially attributed to the removal of enriched point bar sediment during storm events. The similarity in activity levels of re-exposed point bar and bed sediment on 18 June is likely due to the mixing of sediment in the active channel during the storm, supporting our earlier assertion that streambed sediment is readily and easily mixed.

As the hydrograph recedes after mid-June, the $^{7}Be/^{210}Pb$ activity of the bed sediment decreases (Figure 6, solid circles) because, in the absence of high flows, no newly tagged sediment is mobilized into the stream and the existing bed sediment in the stream decays. Assuming only first-order decay, the *c*. 0·4 activity ratio measured for the bed sediment in mid-June should decrease to *c*. 0·25 by mid-July, which is similar to the bed sediment activity ratio observed at this time. In contrast, the activity level of the point bar sediment increases considerably during this period (Figure 6, open circles), reflecting the accumulation of precipitation inputs (Figure 2) throughout the summer, as discussed above.

Temporal variations in ^{7}Be activity of transitional bed load below a dam

We now apply our understanding of the source, distribution and composition of ^{7}Be-tagged point bar and streambed sediment in an unregulated stream to evaluate the temporal dynamics of transitional bed load transport in a regulated stream and the role of dam management on channel bed sedimentation. The radionuclide activity in bed sediment downstream of the Union Village Dam on the Ompompanoosuc River allows us to assess the effects of both seasonal and operational changes in flow on sediment transport and deposition. To more easily interpret and present the temporal variation of radionuclide activity in the Ompompanoosuc River, we segment our analysis into three distinct flow periods: early spring high flows with highly regulated dam management, mid-spring high flow with partially regulated dam management, and late spring low flows with run-of-the-river dam management.

Highly regulated flow: Early spring Like the White River, the $^{7}Be/^{210}Pb$ activity at all sites is low (*c*. 0·2 or less) during the winter and early spring (Figure 7a). Although not sampled during this time period, we expect the sediment stored behind the dam to be even less active because the reservoir begins filling prior to persistent snow cover. The dam gates were lowered on 9 December 2003 and opened again on 27 March 2004, a span of 109 days or slightly more than two ^{7}Be half-lives.

The opening of the gates in late March, coupled with a rain event in early April (Figure 2), flushed accumulated sediment from behind the dam. The input of this 'dead' sediment is reflected by the large (*c*. 50%) decrease in the $^{7}Be/^{210}Pb$ ratio at OMP3 immediately below the dam observed on 15 April (Figure 7a).

It is possible that compositional effects could explain this decrease in activity below the dam. The grain size analysis of ^{7}Be activity demonstrates that normalizing by ^{210}Pb corrects for most, but not all, of the effects of preferential sorption onto fine particles (Figure 4). Consequently, the measured decrease in $^{7}Be/^{210}Pb$ activity in bed sediment observed at OMP3 on April 15 (Figure 7a) might reflect the preferential transport of fines out of the bed during the high flows. However, the percentage of fine particles at this site on this date actually increases (Table II), which would lead to an increase in $^{7}Be/^{210}Pb$ activity if solely due to compositional effects. A measured decrease in $^{7}Be/^{210}Pb$ activity combined with an increase in the fine fraction of the bed sediment indicates that the activity of these fine particles has decayed to low levels. Thus the release of old sediment from behind the dam and subsequent deposition on the streambed provides a more plausible explanation for the decrease in the activity of bed sediment.

In contrast, the $^{7}Be/^{210}Pb$ ratio further downstream either increases (OMP2) or does not change significantly (OMP1). Based on our results from the White River, we hypothesize that the increase at OMP2 could be due to new sediment mobilized from two small, ephemeral tributaries located upstream of the sampling site (Figure 1). These tributaries remain dry for most of the year, exposing the channel sediment to a regular input of ^{7}Be. Flooding of the tributaries during the increased flows from the opened gates and the early April rain event likely mobilized this enriched sediment into the main channel.

Partially regulated flow: mid-spring After the initial plug of dead sediment passes site OMP3 just below the dam in mid-April, a steady increase in $^{7}Be/^{210}Pb$ is observed that continues throughout the rest of the sampling period (Figure 7b and c). By mid-April the reservoir behind the dam had fallen to about half of its typical mid-winter depth. As for the point bar sediment from the White River, shown in Figure 6, the exposed loose sediment deposited behind the dam during the winter quickly became enriched in ^{7}Be. For example, a sample taken from an exposed sand bar directly behind the dam during the summer had a $^{7}Be/^{210}Pb$ ratio of 0·88, similar to the activity ratio measured on the White

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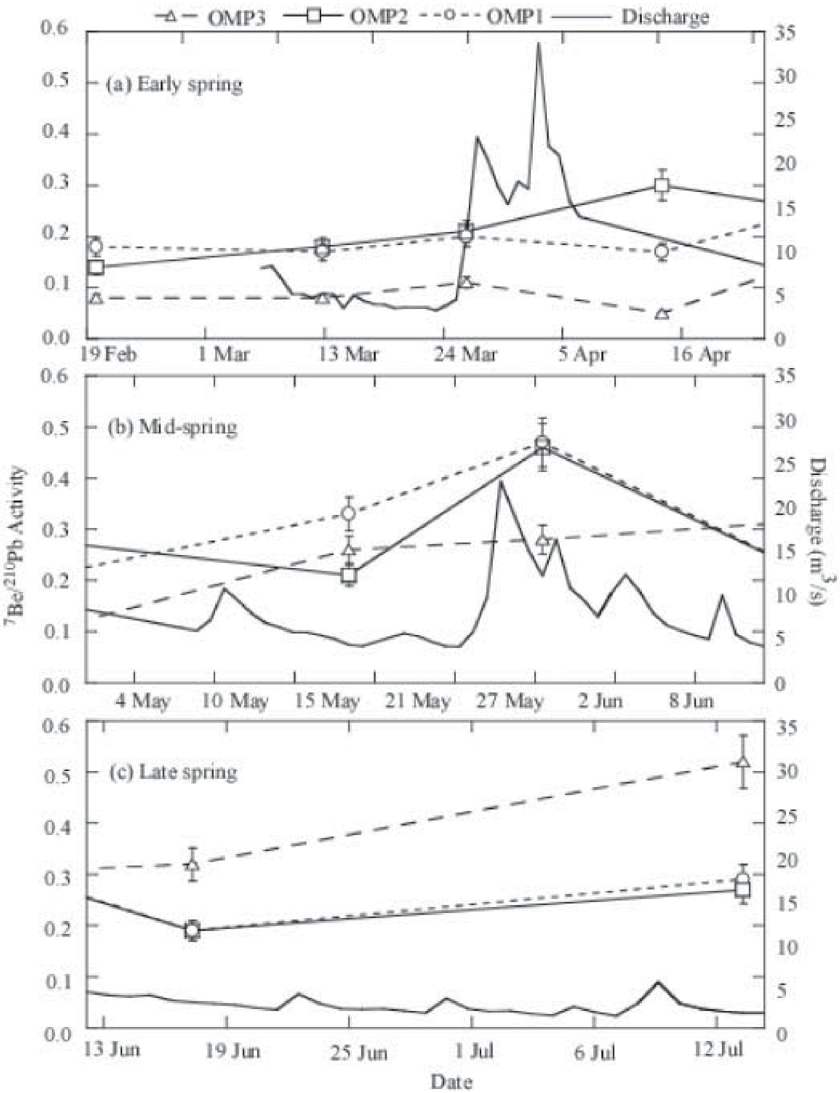

Figure 7. The hydrograph downstream of the Union Village Dam on the Ompompanoosuc River for the period from February to July 2004 (black line) and the $^{7}Be/^{210}Pb$ ratio of bed sediment samples for (a) 19 February to 25 April 2004 (early spring), (b) 25 April to 13 June (mid-spring), and (c) 13 June to 18 July (late spring/early summer). Sites are listed in downstream order: OMP3 is located directly below the Union Village Dam; OMP1 is the farthest downstream site; OMP2 is located mid-way between OMP3 and OMP1 (see Figure 1).

River point bar during the summer. During rain events, it is likely that some of this enriched, easily eroded sediment entered the river, increasing the ^{7}Be activity in the bed sediments directly below the dam.

A similar steady increase in activity ratio during this time period is also observed at the furthest downstream site, OMP1 (Figure 7b). We speculate that this increase is due to the input of newly tagged sediment from tributaries, exposed point bars and banks, as well as surface soils eroded during the late April and May rain events (Figure 2).

However, the typical springtime recovery of the $^{7}Be/^{210}Pb$ ratios observed at OMP1 and OMP3 is interrupted at OMP2 during mid-May (Figure 7b). Instead of increasing, the $^{7}Be/^{210}Pb$ ratio at this site decreases. By this time the ephemeral tributaries had ceased flowing, thus they are not likely to be responsible for the decrease in $^{7}Be/^{210}Pb$ activity. Instead, we interpret this decrease in activity as reflecting the passage of the plug of dead sediment previously evident at OMP3 in early April (Figure 7a). If this interpretation is correct, then in the 47 days following the opening of the gates at the end of March, the plug of sediment travelled at least 2·1 km downstream. That the furthest downstream site remains unaffected by the pulse of dead sediment (its activity increases) provides an upper bound on

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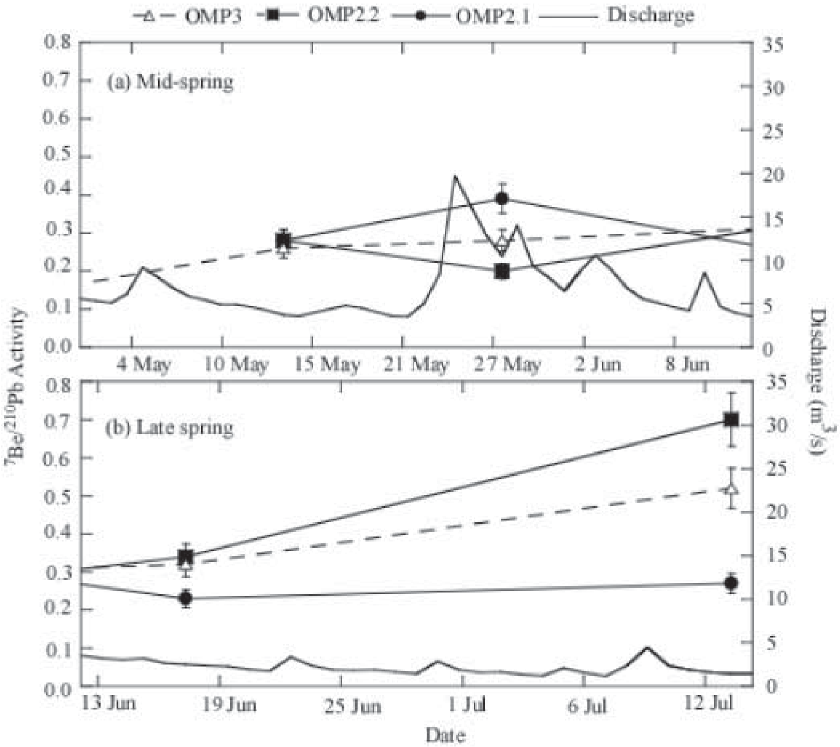

Figure 8. The hydrograph downstream of the Union Village Dam on the Ompompanoosuc River for the period from April to July 2004 (black line) and the ^{7}Be/^{210}Pb ratio of bed sediment samples of the three most upstream sites for (a) 25 April to 13 June (mid-spring) and (b) 13 June to 18 July (late spring/early summer). Sites are listed in downstream order: OMP3 is located directly below the Union Village Dam; OMP2·2 and OMP2·1 are located between OMP2 and OMP3 (see Figure 1). Error bars are a representative standard error of 10 per cent of the mean; in some cases, figure markers are larger than error bars.

the sediment transport, constraining average transport velocity to be in the range of 40–60 m d^{-1} (Table II). We note, however, that the actual transport of the sediment is probably episodic and mainly occurs during high flow at rates much faster than the average value given here.

The seasonal increase in ^{7}Be/^{210}Pb activity at OMP2 resumes with the large rain event that occurs at the end of May. This rain event is also associated with an increase in activity at all of the downstream sites except the two immediately below the dam (OMP3 and OMP2·2; Figures 7b and 8a). As before, we interpret the increased activity at the further downstream sites as likely due to the flooding and mobilization of newly tagged bank and point bar sediment and surface soils.

That the radionuclide activity remained unchanged at OMP3 and decreased at OMP2·2 (Figure 8a) suggests that the dam reduced new sediment input to these sites during the storm event. Figure 2 shows that the gate level was raised from 0·6 to 1·1 m during the storm in order to accommodate the larger flows. However, the pool depth behind the dam also doubled during this time, indicating that the dam still restricted flow and trapped sediment. As a result, it is likely that discharge at the sites immediately downstream of the dam did not transport newly tagged sediment from behind the dam, but instead remobilized older sediment from the bed. In fact, the activity ratio at OMP2·2 (0·20) is consistent with the simple transport and decay of the sediment at OMP3 prior to the storm (0·26). Further downstream, both flow and sediment sources increased (e.g. flooding of the ephemeral tributaries below OMP2·2), contributing new sediment to the streambed. This is seen by the progressive increase in activity from OMP2·1 to OMP2 and OMP1 (Figures 7b and 8a). The similar activities at OMP2 and OMP1 suggest that the impact of the dam during this time period did not affect distal locations. The intermediate activity level at OMP2·1 may indicate a mixture of dam and bank/tributary effects. Thus the downstream impact of the dam on sediment transport during the storm appears limited to sites OMP3, OMP2·2 and OMP2·1, with a total reach length of *c*. 1 km.

The plug of dead sediment released with the opening of the dam gates was either overwhelmed by the input of new sediment during the end-of-May storm or, more likely, transported beyond OMP1 during the storm. The former

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Table III. Sediment transport velocities (m d^{-1}) for three time periods in the Ompompanoosuc River, Vermont

Date	^{7}Be velocity	Two-fraction velocity*		Sand fraction (F_s)
		Sand	Gravel	
31 March–14 May	40–60	39–59	0·62–0·8	0·099–0·10
31 March–28 May	40–60	36–62	0·62–0·8	0·099–0·10
28 May–18 June				
below dam	30–60	33–60	0·44–0·80	0·14–0·15
downstream	60–80	60–75	0·80–1·0	0·15

* Wilcock and Kenworthy (2002). Parameters used in two-fraction model: A = 115, ϕ' = 1·27, χ = 0·923, D_s = 0·001 m, D_g = 0·075 m, $(\tau^*_{rg})_0$ = 0·035, $(\tau^*_{rs})_1$ = 0·065, $(\tau^*_{rg})_1$ = 0·011, α = 1, Manning's *n* = 0·05, slope = 0·001.

conclusion is supported by the similarity in $^{7}Be/^{210}Pb$ ratios at OMP1 and OMP2 after the storm (Figure 7b). Assuming the plug of dead sediment was transported beyond OMP1 during the storm, the average velocity of the sediment through the entire reach is estimated as 40–60 m d^{-1}, similar to that estimated prior to the late-May event (Table II). This estimation also assumes that the transported material had minimal interaction with the bed and uniformly low activity. These are both reasonable assumptions. First, this type of transport mostly involves the movement of sand particles over a static bed, with negligible water column and streambed mixing. Secondly, all sediment was stored behind the dam for an equivalently long (>3 month) period and thus probably decayed to uniformly low activity levels.

Unregulated: late spring A series of three smaller rain events occurred in the three-week period following the large flows at the end of May (Figure 7c). Unlike the case during the large flows of late May, the dam did not restrict flows during these smaller events and thus ^{7}Be-enriched sediment from behind the dam was entrained, causing the $^{7}Be/^{210}Pb$ ratio at OMP3 to increase (Figures 7c and 8b). This increase is not due to an increase in fine fraction; the percentage of fine particles between these dates actually decreases (Table II). As noted before, while compositional differences may somewhat affect changes in the $^{7}Be/^{210}Pb$ activity of bed sediment, this effect appears to be minimal, so that changes in activity mostly reflect the influx and transport of new or old sediment.

Assuming the increase in $^{7}Be/^{210}Pb$ ratio at OMP2·2 (Figure 8b), located approximately 0·6 km from the dam, is at least partially due to sediment from behind the dam, then the transport velocity for this sediment is at least 30 m d^{-1} and may be as high as 60 m d^{-1}.

The decreases in $^{7}Be/^{210}Pb$ ratios at OMP1, OMP2 and OMP2·1 in mid-June (Figures 7c and 8b) from their high levels at the end of May is somewhat surprising in that it is the opposite to the increase in bed sediment activity observed for the White River after these storms (Figure 6). Under unregulated conditions, we would expect the high flows associated with these storms to mobilize newly tagged sediment from point bars and banks and increase bed sediment activity, as occurs on the White River. If these storms did mobilize newly tagged sediment, the amount of sediment was either small or entirely transported out of the river by the storm events. The latter is consistent with the observation that the decrease in activity at these sites significantly exceeds those predicted by simple *in-situ* decay of the ^{7}Be. This implies that enriched ^{7}Be sediment from the end-of-May rain event was transported out of the reach by the smaller storms in early June. In fact, the $^{7}Be/^{210}Pb$ ratios (0·19) at OMP1 and OMP2 can be explained by assuming that the sediment present at site OMP3 at the middle and end of May (0·26–0·28) decayed and was transported to these sites by the early June events. This, in turn, implies an average transport velocity for the lower reach of 60–80 m d^{-1}, similar but slightly faster than previous estimates (Table II).

Sediment transport velocities

The average transport velocities measured in this study (30–80 m d^{-1}) are between those typically reported for bed load sediment (0·3–4·5 m d^{-1}) (Beechie, 2001) and suspended sediment (150–600 m d^{-1}) (Bonniwell *et al.*, 1999). That our bed material transport rates are slower than those for suspended sediment is not surprising. That our rates are faster than those typically reported for bed load transport has several possible explanations. The bed load transport rates from Beechie (2001) were determined from annual travel distances measured by tracer particles or sediment 'wave' movement (Madej and Ozaki, 1996) and thus are averaged over the entire year. In contrast, our ^{7}Be-derived rates only reflect the comparatively faster transport that occurs during high seasonal flows. These previously reported

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transport rates also represent a range of stream characteristics, including drainage area, bankfull discharge, slope, channel width and bed composition that differ from, but span, those for the Ompompanoosuc River. However, across the entire range of stream characteristics for which bed load transport rates are reported in the Beechie (2001) review, the rates are consistently one to two orders of magnitude less than our ^{7}Be-derived rates, suggesting that site-specific effects cannot fully explain our faster transport rates.

An alternative explanation for our faster transport rates involves the composition of the sediment being measured. Tracer particles are typically pebble- or cobble-sized, thus specifically measuring the movement of the larger components of bed load. Commonly used bed load traps, in contrast, measure the transport of total bed load and not a specific size fraction. Beryllium-7, however, specifically tracks the movement of transitional load sediment composed of the fine- to medium-coarse sand fraction (0·25–1 mm), as demonstrated by the grain size analysis of ^{7}Be/^{210}Pb activity weighted by sample composition (Figure 4). Because transitional load is smaller than bed load, it should move more rapidly.

The ^{7}Be-derived transport velocities for the transitional load remain fairly constant throughout the study period despite large variations in discharges (Figure 2, Table IV). This suggests that flow is not the only factor controlling transport rates in this system. For example, changes to the bed sand fraction will affect entrainment thresholds and the availability of sediment, thus modifying both sand and gravel transport rates (Lisle *et al*., 2000; Wilcock, 2001; Wu and Chou, 2004). The high transport rates during late summer low flows might be explained by an increase in bed sand fraction throughout the summer. An increase in sand fraction reduces the obstruction of sand-sized particles by larger particles and, consequently, the rate of sand transport is increased.

The effect of grain size interaction on transport rates can be demonstrated using sediment transport models formulated for many finely divided sediment size fractions. However, this approach requires specification of the full grain size distribution. A simpler approach is to assume that the bed is composed of two fractions, sand and gravel. In applying a two-fraction model (Wilcock and Kenworthy, 2002) to the Ompompanoosuc River, all of the required parameters are well-constrained by empirical data with the exception of the sand fraction (F_s). In the field we estimated the sand fraction as 10 (±5) per cent. However, the model is highly sensitive to this parameter; slight changes to this estimate result in order-of-magnitude differences in transport velocity. To demonstrate this sensitivity, we used the model to predict sediment transport velocities for the Ompompanoosuc River during early and mid-spring assuming first a sand fraction of 5 per cent and then a sand fraction of 15 per cent. We converted sediment flux predicted by the model to transport velocity by scaling the flux to particle size, or the depth of the bed load layer, assumed to be $2D_{50}$ (DeVries, 2002) of the site directly below the dam. Hourly discharge records for the time period of interest were converted to flow depth for use in the model by regressions based on monthly cross-sectional measurements (Salant, 2005). Using a sand fraction of 5 per cent for this time period results in an average transport velocity of 10^{-3} m d^{-1}, while a sand fraction of 15 per cent results in an average transport velocity of 3000 m d^{-1}. Our best estimate of the sand fraction (10%) results in predicted sand transport rates that closely approximate the rates measured in early and mid-spring periods (Table II). However, the same sand fraction underestimates the transport rate of the late spring period. To model the observed late spring transport rates a higher sand fraction is required. Both field observations and our qualitative interpretation of the measured ^{7}Be activities are consistent with increasing sand fractions throughout the spring and summer as sediment from behind the dam is transported downstream after the gates are opened. Treating the sand fraction as a fitting parameter, we find that increasing the sand fraction to 14–15 per cent during the late spring is sufficient to match the range of observed transport velocities.

Because the modelled transport velocities are highly sensitive to sand fraction, almost any plausible transport velocity can be modelled with only slight changes in the assumed sand fraction. Consequently, it is important to emphasize that these estimates of absolute sand fractions from the model are simply calibrated values and are not independent measures of the actual bed sand fractions. However, the relative increase in calibrated sand fraction needed to match the observed transport rates is consistent with field observations and demonstrates how slight changes in sand fraction (4–5 per cent) can offset larger changes in discharge to maintain average transport velocities.

Conclusion

This study presents a novel technique in which the short-lived fallout radionuclide ^{7}Be, expressed as a ratio of the longer-lived ^{210}Pb, is used to independently quantify transitional bed material load transport rates over short temporal and spatial scales. This study also demonstrates that on the regulated Ompompanoosuc River, the impact of the dam does not extend far downstream: under highly regulated conditions the two most downstream sites, >1 km from the dam, still responded to a large change in natural flow. This indicates that the length scale of the downstream impact of this dam management on sediment transport is short (*c*. 1 km); beyond this distance sediment from downstream

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sources such as point bars and ephemeral tributaries is efficiently mobilized and mixed with the bed. The small length scale results in part because of the lack of larger tributary inputs downstream, where additional sources of bed material would likely occur and perhaps lead to enhanced aggradation.

Although the use of short-lived radionuclides has been applied primarily to terrestrial systems, our results indicate that they also offer enormous potential for fluvial settings (Bonniwell *et al*., 1999) and for quantifying bed material transport. For example, in a recent study, Blake *et al*. (2002) measured ^{7}Be concentrations of fine sediment stored in the streambed in the River Clyst, UK. The measured activity level of resuspended bed sediment was slightly less than that of suspended sediment in the water column, demonstrating that the bed contained a mixture of recently deposited and previously stored sediment. High activity levels of surface sediment also indicated that this material was more readily mobilized than sediment stored within the gravel. Our study expands upon these findings by shifting the focus from suspended sediment (typically silt and clay), which has shorter bed residence times and frequent transport in the water column, to the longer-term storage and slower transport of sand-sized particles. The ability to independently measure transitional bed material load as distinguished from suspended and bulk bed load transport is critical for assessing the impact of increased sediment loads on aquatic systems. The application of this technique may help provide important information on the minimum transport velocity required to flush sediment from a system and the rate of sediment deposition into receiving bodies. In addition, these methods may be applied to studies of dam removal and concerns over the transport and deposition of contaminated sediment accumulated behind dams. Beryllium-7-derived estimates of sediment transport under regulated conditions may help modify dam removal techniques, so as to ensure that sediment is fully transported out of the system before full removal of the dam. Alternatively, these methods may be used to track sediment through a catchment and determine the extent of its impact on the aquatic ecosystem. Lastly, these methods may also be useful for determining short-term rates of mixing between the bed and the water column as well as the degree of streambed infiltration. Such an analysis may complement long-term estimates of erosion rates like those obtained from the much longer-lived isotope, ^{10}Be. This information will have highly practical applications, aiding assessment of fine sediment infiltration into spawning habitat, for example, and the conditions under which this material is mobilized.

The use of fallout radionuclides as bed material tracers as presented herein provides an innovative method to characterize sediment residence times both along a reach and over time, yet certain limitations exist for its extension to other sites. Due to the complexity of fluvial processes, the application of fallout radionuclides to fingerprint bed material particles requires robust sampling along the reach and over time to best identify the sources of both newly tagged and decayed sediment and to best constrain compositional effects. Future investigations should benefit from sampling at finer scales of temporal and spatial resolution in order to precisely track the movement of radionuclide-tagged sediment through the fluvial system. However, despite these sampling and interpretive limitations, our results show that the magnitude of the radionuclide signal both at a site and over time are large relative to the errors of this technique, demonstrating the large potential of this approach for quantifying sediment residence time and transport along a reach.

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