Sediment Dynamics and the Hydromorphology of Fluvial Systems (Proceedings of a symposium held in Dundee, UK, July 2006). IAHS Publ. 306, 2006.

Evaluating the impacts of impoundment on sediment transport using short-lived fallout radionuclides

FRANCIS J. MAGILLIGAN[1], NIRA L. SALANT[2],
CARL E. RENSHAW[3], KEITH H. NISLOW[4],
ARJUN HEIMSATH[3] & JAMES M. KASTE[3]

1 *Department of Geography, Dartmouth College, Hanover, New Hampshire 03755, USA*
magilligan@dartmouth.edu

2 *Department of Geography, University of British Columbia, Vancouver, British Columbia V6T 1Z2, Canada*

3 *Department of Earth Sciences, Dartmouth College, Hanover, New Hampshire 03755, USA*

4 *US Department of Agriculture Forest Service, University of Massachusetts, Amherst, Massachusetts 02125, USA*

Abstract Dams greatly influence water and sediment discharge regimes and can have significant impacts on channel morphology and sediment storage. By using the short-lived fallout radionuclide ^{7}Be ($t_{1/2}$ = 53.4 days) as a tracer of fine (~0.25–2 mm) bed material load transport, we capture the sedimentological and geomorphic impacts of the Union Village Dam, located on the Ompompanoosuc River, in eastern Vermont, USA. We measured ^{7}Be activities in approximately monthly samples from streambed sediments in a regulated stream and an unregulated control stream. In the regulated stream our sampling spanned an array of 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. Because sediment stored behind the dam during the winter quickly became depleted in ^{7}Be activity, it became possible to track this plug of "dead" sediment as it moved downstream. Measured average sediment transport velocities (30–80 m day^{-1}) exceed those typically reported for bulk bed-load transport and are remarkably constant across varied flow regimes, possibly due to corresponding changes in the bed sand fraction. Results also show that the length scale of the downstream impact of this dam management (winter pool and summer run-of-the river with minimal sediment trapping efficiency) on sediment transport can be short (~1 km); beyond this distance the sediment trapped by the dam is replaced by new sediment from point bars, tributaries and other downstream sources. The benthic community structure indicates significantly greater abundance of caddisflies downstream of the dam due primarily to a lack of bed disturbance following impoundment.

Key words dams; radionuclides; sediment; tracers

INTRODUCTION

Flow regulation by dams can have profound and significant impacts occurring across the array of geomorphic, hydrological, and ecological systems. Most of the initial work on evaluating the impacts of dams focused on either the geomorphic adjustments, such as channel capacity and channel shape (Gregory & Park, 1974; Graf, 1980; Petts & Pratt, 1983; Williams & Wolman, 1984; Andrews, 1986), or the hydrological shifts associated with reservoir storage and dam management (Chien, 1985; Benke, 1990).

Driven by a contemporary global concern for maintaining ecological integrity within the channel and riparian zone, these early efforts have expanded into an extensive research agenda that aims to capture the broader eco-geomorphic shifts to help manage river systems impacted by dams (cf. Poff *et al*., 1997; Graf, 1999, 2001; Magilligan *et al*., 2003; Magilligan & Nislow, 2005). This intensification in research on dams is now coinciding with another major advancement in the study of surficial processes—the fingerprinting of sediment and the detailed geochemical analyses of fine-grained sediment, especially the use of short-lived radionuclides such as ^{7}Be (Walling & Woodward, 1992; Hassan & Ergenzinger, 2003). In this paper we couple these recent approaches to evaluate the impacts of impoundment on the downstream pattern of sediment storage and transport and the concomitant role of sediment dynamics on the ecological community structure.

Study area

The Ompompanoosuc River is regulated by the Union Village Dam, located in Thetford, Vermont, USA, ~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 ~6 m^{3} s^{-1}, the gradient is <0.1%, the bed width averages ~6 m, and the median grain size of the bed surface (D_{50}) is ~100 mm. Two small tributaries contribute water and sediment to the Ompompanoosuc River well below the dam during large storm events and spring high flows.

A US Army Corps of Engineers streamgauging station located directly below the Union Village Dam on the Ompompanoosuc River (at Site 3) provides hourly discharge and precipitation data. The dam transitions from a flood-control to a run-of-the-river facility during late spring. During winter months, the dam gate levels are low (i.e. restricted open gate), discharge through the dam is controlled, 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.

METHODS

Sampling began in February 2004 and continued monthly through late summer 2004. Sampling timing and frequency were modified during large storms and during the opening of the dam gates on the Ompompanoosuc River in order to specifically monitor the effects of these events. Three sites at increasing downstream distance from the dam were sampled: Site 3 (~200 m from dam), Site 2 (2.1 km from dam), and Site 1 (~3.1 km from dam). Moreover, two unregulated control sites upstream of the dam were also sampled: Site 4 (~2 km from dam and upstream of its backwater effect) and Site 5 (~3 km from dam). At each bed load sampling site, ~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. Replicate samples were collected at various locations within the stream channel periodically throughout the year to determine the degree of spatial variability. At all sites, the most surficial layer of sediment was collected to capture the most recently deposited sediment. Immediately after collection, samples were dried and sieved.

Sieved (<2 mm) sediment samples were packed in plastic 105-ml containers for radionuclide analysis via gamma-ray spectrometry. We used Broad Energy Intrinsic Ge Detectors (Canberra) that are equipped with low-background Pb shields and have sufficient resolution (800 eV FWHM at 122 keV) to quantify the ^{210}Pb photopeak (46 keV), the ^{7}Be photopeak (478 keV), and other pertinent gamma-emitting radionuclides in the ^{238}U and ^{232}Th series. 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% or less. We calibrated the efficiency of the Ge detectors over a range of energies using certified standard solutions (Isotope Products) and certified U ore from the Canadian Reference Materials Project. These standards were packed in an identical matrix and geometry as the sediment samples that we analysed, and we carefully accounted for the self-attenuation of the 46 keV ^{210}Pb photon using the procedures outlined by Hussain *et al.* (1995). Sediment samples of typically 150 g were counted for 90 to 180 ks. We accumulated at least 125 counts at the 477 keV photopeak to keep the statistical error associated with decay counting <10%; at 46 keV and other regions of interest total counts accumulated was usually >1500. Here we report radionuclide activities in Bq kg^{-1}, as we normalized our count rates to the detector efficiency and the gamma-ray efficiency for each nuclide. Detector efficiency was 7–12% for the ^{210}Pb photon and 3–4% for the ^{7}Be photon, depending on sample mass and the specific detector. Peak areas and background corrections were calculated using Canberra Genie2k spectrum analysis software.

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} watershed. Furthermore, Bonniwell *et al.* (1999) found that normalizing the ^{7}Be activity by the activity of the longer-lived fallout nuclide ^{210}Pb ($t_{1/2}$ = 20.2 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, spatial variations in relative ^{7}Be/^{210}Pb activity generally reflect differences in the time since the sediment was last exposed to atmospheric input.

Benthic macroinvertebrates were sampled at multiple locations within each site. At each location, two sub-samples were taken using a 0.36-m diameter Hess sampler (250-µm mesh) and hand water pump. The two sub-samples were then pooled for analysis and preserved in 70% ethanol for counting. Large samples (>300 individuals) were sub-sampled to reduce counting error. All individuals were identified to family level and categorized by functional feeding group. Substrate embeddedness was measured at each location using five standard methods, the results of which are fully described by Sennatt *et al.* (2006); only one method is presented herein.

RESULTS

The effects of the Union Village Dam on sediment transport and storage depended on the seasonal management style and on the distance downstream of the dam. Because the dam operates as a run-of-the river during the summer months, most of the sediment stored behind the dam during maximum flow storage is flushed downstream in spring. Because this sediment has been trapped during the winter, ^{7}Be has decayed to negligible levels (^{7}Be/^{210}Pb of ~0.05). Moreover, because this sediment differs significantly in ^{7}Be activity, it is possible to measure its downstream transport (Fig. 1).

The pattern of tagged "dead" sediment suggests variable sediment transport throughout the year and the role of tributaries in mitigating the effects of impoundment (Fig. 1). For example, at the site immediately downstream of the dam (Site 3), the initial spring release flushes considerable fresh sediment into the system. This sediment is relatively dead in ^{7}Be and is stored immediately at Site 3 while the downstream sites (Sites 2 and 1) receive the influx of recently tagged sediment high in ^{7}Be (Fig. 1), primarily from tributary runoff. Subsequent competent flows entrain this dead sediment from immediately below the dam (Site 3) and mobilize it downstream such that the plug of dead sediment is deposited at Site 2 by the middle of May. This "dead" sediment appears at the most downstream site by mid-to-late June (Fig. 1) while the site immediately downstream of the dam (Site 3) is simultaneously receiving new sediment mobilized from exposed and recently tagged point bars behind the dam.

Using the distance between sampling sites and the spatio-temporal pattern of the flux of dead sediment from spring releases, we calculate sediment transport velocities through the ~3 km sampling reach. These distances and measured activity levels suggest an average transport velocity of ~30–80 m day^{-1}. These measured values lie between those typically reported for bed load sediment (0.3–4.5 m day^{-1}) (Beechie, 2001) and suspended sediment (150–600 m day^{-1}) (Bonniwell *et al*., 1999). There may

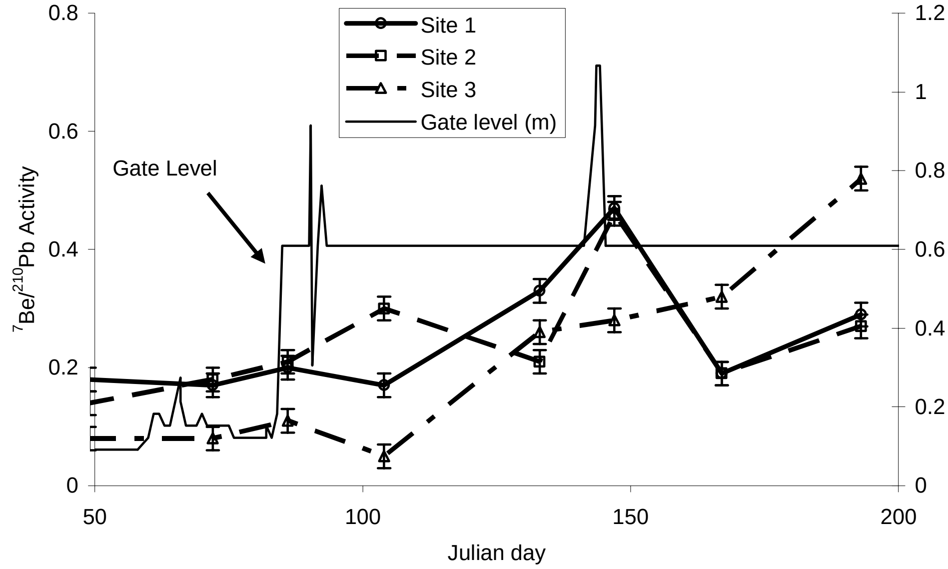

Fig. 1 Change in 7Be/210Pb activity over time at the site immediately downstream of the dam(Site 3), a site ~ 2.1 km from dam (Site 2), and at the most downstream site ~3 km (Site 1) from the dam. Gate level (surrogate for discharge) shown in black (no symbols). Error bars are the standard error around the mean.

be several explanations for the faster measured transport rates obtained by this study, compared to those typically reported for bed-load transport. The bed-load transport rates from Beechie (2001) were determined from bed-load annual travel distances, measured by tracer particles or measurement of sediment “wave” movement (Madej & Ozaki, 1996), and represent a range of stream characteristics, including drainage area, bankfull discharge, slope, channel width and bed composition that span those for the Ompompanoosuc River. Despite the range of stream characteristics encompassed in the Beechie (2001) review, bed-load transport rates are still consistently one to two orders of magnitude less than our ^{7}Be-derived rates, indicating that site specific effects cannot fully explain the difference in transport rates. One simple explanation for the different transport rates may be that, while the previously reported rates are averaged over the entire year, our ^{7}Be-derived rates reflect the comparatively faster transport that occurs during high seasonal flows.

An alternative explanation 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.

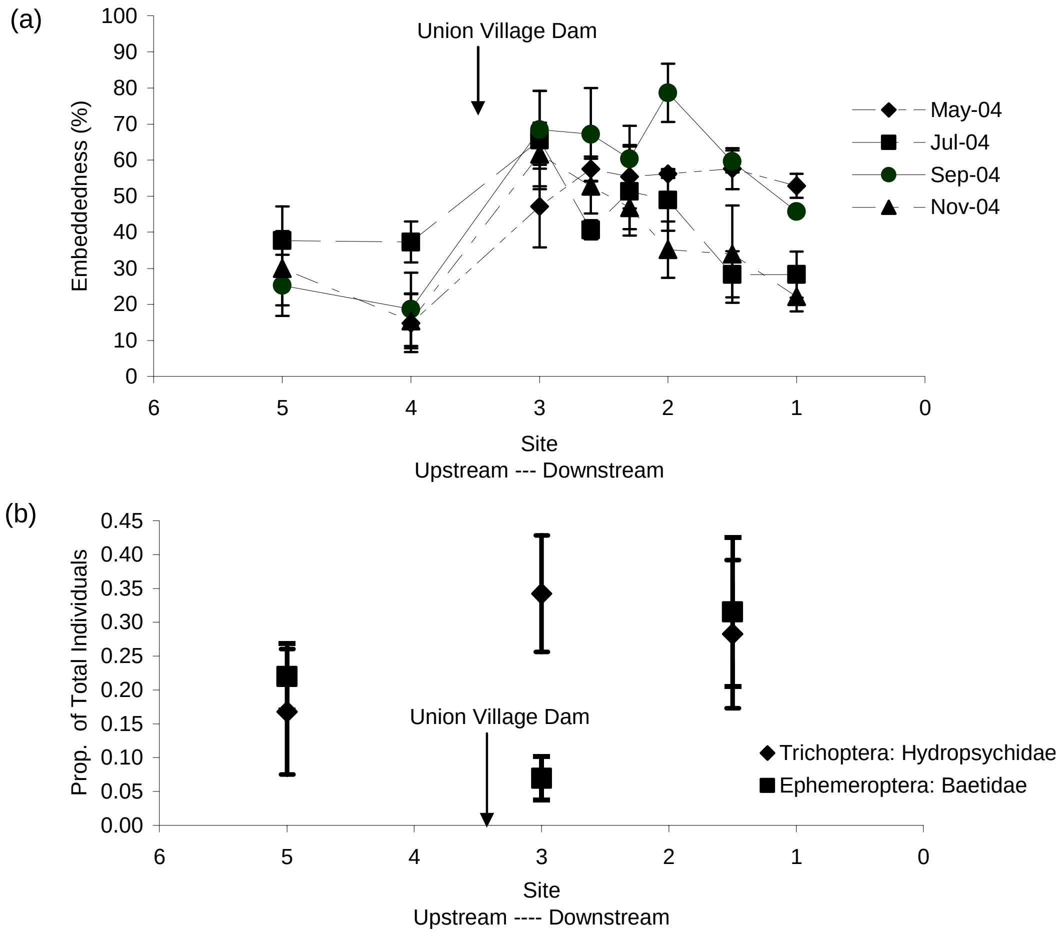

Fig. 2 (a) Changes in embeddedness over time at each site revealing the increased embeddedness immediately downstream of the dam. (b) Proportion of total individuals for mayflies (Ephemeroptera) and caddiflies (Trichoptera) at each site in September 2004.

Because the particle size of the transitional load is smaller than bed load, it should move more rapidly.

The large fluxes of sediment tracked by ^{7}Be are further manifest in the bed composition and benthic community structure of regulated sites. These large fluxes overwhelm stream transport capacity, resulting in increased embeddedness downstream of the dam (Fig. 2) (Sennatt *et al.*, 2006). Surprizingly, the community composition of benthic macroinvertebrates suggests that this increased sedimentation has not impacted filter feeders but has decreased substrate heterogeneity. High densities of filter feeding caddisflies (Hydropsychidae) downstream of the dam (Fig. 2) may be explained by decreased disturbance frequency and increased substrate stability (Salant *et al.*, 2006), which allows these sedentary species to proliferate. Decreased substrate mobility and increased sediment deposition may homogenize the substrate, reducing biofilm growth (Cardinale *et al.*, 2002) and thus food availability for Ephemerellidae mayflies, hence decreasing their population at regulated sites (Fig. 2).

CONCLUSIONS

Our results suggest that, in the Ompompanoosuc River, the translation of fine bed material load is rapid even though some degree of dispersion may occur in the coarser fraction. This study further demonstrates that fallout radionuclides may offer a simple and efficient method for directly measuring transport rates of fine bed-material load, improving the study of sediment dynamics in both scientific and applied fields.

Acknowledgements This research was funded in part by the National Science Foundation (BCS-0322850) by the Geography and Regional Science Program (Magilligan, Renshaw, Nislow and Heimsath) and the Arthur D. Howard Award from the Quaternary Geology and Geomorphology Division of the Geological Society of America (Salant).

REFERENCES

Andrews, E. D. (1986) Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah. *Geol. Soc. Am. Bull.* **97**, 1012–1023.

Beechie, T. J. (2001) Empirical predictors of annual bed load travel distance, and implications for salmonid habitat restoration and protection. *Earth Surf. Processes Landf.* **26**, 1025–1034.

Benke, A. (1990) Perspective on America's vanishing streams. *J. N. Am. Benthol. Soc.* **9**, 77–88.

Bonniwell, E. C., Matisoff, G. & Whiting, P. J. (1999) Determining the times and distances of particle transit in a mountain stream using fallout radionuclides. *Geomorphology* **27**, 75–92.

Cardinale, B. J., Palmer, M. A., Swan, C. M., Brooks, S. & Poff, N. L. (2002) The influence of substrate heterogeneity on biofilm metabolism in a stream ecosystem. *Ecology* **83**, 412–422.

Chien, N. (1985) Changes in river regime after the construction of upstream reservoirs. *Earth Surf. Processes Landf.* **10**, 143–159.

Graf, W. L. (1980) The effect of dam closure on downstream rapids. *Water Resour. Res.* **16**,129–136.

Graf, W. L. (1999) Dam nation: a geographic census of American dams and their large-scale hydrologic impacts. *Water Resour. Res.* **35**, 1305–1311.

Graf, W. L. (2001) *Dam*age control: restoring the physical integrity of America's rivers. *Ann. Assoc. Am. Geogr.* **91**, 1–27.

Gregory, K. J. & Park, C. (1974) Adjustment of river channel capacity downstream from a reservoir. *Water Resour. Res.* **10**, 870–873.

Hassan, M. A. & Ergenzinger, P. (2003) Tracers in fluvial geomorphology. In: *Tools in Fluvial Morphology* (ed. by G. M. Kondolf & H. Piegay), 397–423. John Wiley & Sons Inc., New York, USA.

Hussain, N., Kim, G., Church, T. M. & Carey, W. (1995) A simplified technique for gamma-spectrometric analysis of ^{210}Pb in sediment samples. *Appl. Radiat. Isot*. **47**, 473–477.

Madej, M. A. & Ozaki, V. (1996) Channel response to sediment wave propagation and movement, Redwood Creek, California, USA. *Earth Surf. Processes Landf.* **21**, 911–927.

Magilligan, F. J. & Nislow, K. H. (2005) Changes in hydrologic regime by dams. *Geomorphology* **71**, 61–78.

Magilligan, F. J., Nislow, K. H. & Graber, B. E. (2003) A scale-independent assessment of discharge reduction and riparian disconnectivity following flow regulation by dams. *Geology* **31**, 569–572.

Petts, G. E. & Pratt, J. D. (1983) Channel changes following reservoir construction on a lowland river. *Catena* **10**, 77–85.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E. & Stromberg, J. C. (1997) The natural flow regime. *BioScience* **47**, 769–784.

Salant, N. L., Renshaw, C. E. & Magilligan, F. J. (2006) Short and long-term changes to bed mobility and bed composition under altered sediment regimes. *Geomorphology* **76**, 43–53.

Sennatt, K. M., Salant, N. L., Renshaw, C. E. & Magilligan, F. J. (2006) Assessment of methods for measuring embeddedness: application to sedimentation in flow-regulated streams. *J. Am. Water Res. Assoc.* (in press).

Walling, D. E. & Woodward, J. C. (1992) Use of radiometric fingerprints to derive information on suspended sediment sources. In: *Erosion and Sediment Transport Monitoring Programmes in River Basins* (ed. by J. Bogen, D. E. Walling & T. Day), 153–164. IAHS Publ. 210. IAHS Press, Wallingford, UK.

Williams, G. P. & Wolman, M. G. (1984) Downstream effects of dams on alluvial rivers, *US Geol. Survey Prof. Paper 1286*.