South Hams River Improvement Projects

Restoration of the Upper Avon: Gravel Augmentation Monitoring Study

Final Report
December 2015

CATCHMENT AND RIVER SCIENCE WITH PLYMOUTH UNIVERSITY

Prepared for: Westcountry Rivers Trust
Rain Charm House
Kyl Cober Parc, Callington
Stoke Climsland, Cornwall PL17 8PH

Prepared by: Plymouth University
School of Geography, Earth and Environmental Sciences
Drake Circus
Plymouth, Devon PL4 8AA

Authors: Peter Downs PhD, FRGS, CGeog (Geomorph)
Claire Bithell BSc
Victoria Keele BSc

Table of Contents

List of Figures

List of Tables

1 Background

The impact of large dams on river systems is to fragment catchment fluxes of water, sediment and nutrients with potentially significant impact on native flora and fauna (Cairns 1995; Graf 2001). Of particular note, large dams totally disconnect the up-stream coarse sediment supply often resulting in progressive sediment exhaustion downstream and leading to channel incision, habitat simplification and an imbalance between volumes of coarse and fine sediment on the channel bed (*e.g.*, Petts 1979, 1982, 1984; Williams and Wolman 1984; Ligon *et al.* 1995). Approaches to offset this impact include the use of programmatic gravel augmentation, sometimes in combination with environmental flow releases (*aka* flushing flows), to both directly replenish spawning and rearing habitats downstream and to partially restore the sediment transport dynamics that are integral to the lifecycle requirements of sentinel species such as salmonids.

Programmes of gravel augmentation ideally require careful planning to maximise their potential for benefit, including:

- Knowledge of the lifecycle requirements of the target biological population such as preferred sediment sizes for spawning and rearing and the preferred flow regime;
- An evaluation of the best practicable locations for augmentation and preferred methods of instream placement of the gravel. These depend on physical factors related to the energetics of sediment transport processes and site-specific constraints on accessibility within the augmentation zone;
- An assessment of sediment volume and calibre required, and frequency of augmentation, in the context of the river's capacity for sediment transport and the resources available for obtaining sediment.

While techniques for the mitigation of the impact of large dams are well known and, in some regards, simple to implement, their systematic application and monitoring is far less well established and so the learning potential from previous projects is generally minimal. Further, it has long been understood that achieving a balance between the volume of material introduced and the capacity of the regulated flows to transport the material to meet habitat goals as efficiently as possible is technically very challenging (Kondolf and Wilcock 1996).

As part of a successful bid to the Catchment Restoration Fund, the Westcountry Rivers Trust (WRT) are undertaking an experimental programme whereby gravels in reaches below the Avon Dam have been augmented in order to improve salmonid spawning and rearing habitat in the upper reaches of the Devon River Avon. Augmentation of gravels, downstream of the 33-m high concrete structure that is the Avon Dam, is expected to partially offset interruptions in downstream coarse sediment connectivity caused by the sediment trapping capability of the dam which has been occurring since completion of the dam and its impoundment in 1957.

The goal of this project was to monitor the effectiveness of gravel augmentation practices during the first year following the implementation of pilot actions in two locations on the upper River Avon and its tributary Bala Brook.

Specific objectives of this study included:

1. Initial advice on the calibre, volume and location strategy for gravel augmentation for the upper River Avon.
2. Characterisation of the surface channel bed sediments and assess apparent morphological impacts of the dams on the upper River Avon.
3. Laboratory preparation and field distribution of a sample of RFID-tagged tracer gravels within the upper Avon pilot augmentation reaches.
4. Installation of three impact plate geophones in the bed of the upper Avon to provide corroboratory understanding of sediment transporting events.
5. Periodic tracking of RFID gravels following high flow events. Located tags will be left *in situ* to record further movements. Techniques will be refined as we better understand challenges associated with tracing in this upland channel.
6. Report on the apparent gravel mobility on the Avon based on a combination tracer movement, rates of transport indicated by the impact plate, and a record of instantaneous discharges obtained from the upper Avon gauge. The results will be used to provide further advice on best-practice augmentation for the Avon.

This report presents an assessment of tracer monitoring on the upper River Avon during Water Year 2015. The knowledge gained from this trial tracing period will, ideally, form the basis for designing a further monitoring programme intended to maximise the effectiveness of future gravel augmentation on the upper River Avon. There is, at present, only limited knowledge regarding the fundamental question of how to best augment gravels to benefit salmonid spawning habitat in bedrock-controlled, boulder-bedded fluvial environments like the upper River Avon. Central to the approach is an analytical understanding of dynamics of augmented gravel dispersion and subsequent deposition relative to the flows that are driving the dispersal.

2 Study Context

2.1 Catchment

The River Avon (or Aune as it is also known) is located in South Devon, where it rises 460 metres above sea level on the Aune Head mires in the southern half of Dartmoor (Figure 1). The River Avon catchment area extends over 110.5 km^2 and flows for approximately 40 km from source to sea passing through the Avon Reservoir, and the villages of South Brent, Avonwick, Loddiswell and Aveton Gifford before reaching the estuary mouth at Bantham and Bigbury on Sea. Major tributaries to the Avon include Bala Brook and Glaze Brook, both of which have their source on the moor (EA 2003). Geologically, the upper catchment is dominated by igneous granite. Land use within the catchment comprises of open moorland in the upper part on Dartmoor, which is used for extensive grazing by cattle, sheep and ponies. As the river flows from the open moorland, it flows through steep sided valleys, typically surrounded by small enclosures used for small-scale livestock farming (EA 2003).

The 33-m high Avon Dam, built in 1957 (Bogle *et al.* 1959), impounds the 1,313 ML Avon reservoir and is situated approximately 8km north of South Brent as the Avon River leaves Dartmoor. The reservoir serves as a public water supply to South Devon with an annual authorised abstraction of 7,683 ML, which has resulted in an altered and regulated flow of water (EA 2003). The upper River Avon consists largely of reaches characterised by large cobble and boulders and with significant areas of exposed bedrock. Boulder-sized material in the channels is presumed to derive from relict periglacial conditions (Ballantyne and Harris 1994), or possibly from glacial deposits (Evans *et al*. 2012). While the granite uplands of Dartmoor probably produce reasonably low rates of coarse sediment supply, the dam will have reduced sediment supply to the reaches below the dam with potentially deleterious effects on aquatic habitat. The extent of morphological impact of the dam on the downstream channel morphology is complicated by the bedrock-dominated reaches but by the mid-1970s was estimated to have resulted in (variable extents of) channel capacity contraction that extended some distance below the confluence of the Bala Brook tributary (Petts and Greenwood 1981).

The River Avon is currently home to a number of fish species, such as brown trout, sea trout and Atlantic salmon, but their numbers are falling (EA 2003). Juvenile salmon are present in satisfactory numbers throughout much of the main River Avon up to South Brent but, upstream of this location, habitat quality and quantity is suspected of being limited by the amount of available and suitable spawning habitats. In part this is due to naturally low rates of sediment supply from the upstream catchment but it is also assumed channel bed material has become more scarce and coarsened since construction of the Avon Dam. Because parts of the Avon catchment are currently failing to meet 'good' overall health due to a moderate or poor WFD fisheries classification (EA 2011), there is a desire to examine the utility of periodic gravel augmentation for improving spawning habitat quality and quantity.

Figure 1. Location of River Avon, Devon (source: N. Jackson 2014, unpublished MSc Dissertation)

2.2 Pilot Augmentation

Westcountry Rivers Trust (WRT) augmented approximately 30 tonnes of local quarry-derived granitic particles into the River Avon on the 13-14th October 2014 in a pilot approach to augmentation. Augmentation locations were chosen following discussions regarding areas of potential habitat suitability in combination with understanding of areas with suitable accessibility, shown in Figure 2. Approximately 5 tonnes of gravels were augmented on Bala Brook, and 24-28 tonnes on the main River Avon below Didworthy Bridge (Table 1). Augmentation at a third site, further upstream on the Avon main stem at Woolholes, is planned to commence late in 2015.

Tracer particles fitted with RFID tags were deployed in the pilot augmentation locations shortly after augmentation. Fifty each of particles drawn from of the augmented gravels and local 'native' gravels were tagged to provide a comparative assessment of mobility. On the regulated main stem sites, a further 50 particles sampled from above the dam were also added. The combination of augmented, local native and 'above dam' native tracer particles is intended to provide an indication of the relative mobility of the augmented gravels to natural rates of transport of local native sediments and pre-dam native sediments respectively. The tagged particles were subsequently traced using a hand-held RFID detector system.

Prior to augmentation, several impact plate geophones were installed in the bed of the channel below the primary augmentation locations at Didworthy, Bala Brook and Woolholes. The impact plates provide a means of continuously monitoring for coarse bedload transport (particles greater than ~10 mm). They thus provide an estimate of the relative volume of downstream sediment transport which, along with information regarding flow discharge, can be used to better contextualise the results from the RFID tags.

Table 1: Target sites for sediment tracing

Site name	River	Grid Reference	Site Description	Augmentation actions taken	Tracers deployed
Didworthy	Avon	268504, 61890	Approx. 300m downstream from Didworthy Bridge	Approx. 24-28 tonnes of gravels augmented on 13/10/14	28/10/14: 50 augmented gravels 50 'above dam' gravel-cobbles 06/11/14 50 local native gravel-cobbles
Bala	Bala Brook	267212, 62883	At footbridge, 80m downstream from weir	Approx. 5 tonnes of gravels augmented on 14/10/14	11/11/14: 50 augmented gravels 50 local native gravel-cobbles
Woolholes	Avon	268038, 64029	Downstream of Avon Dam, approx. 30m below weir	No gravels augmented during 1st inventory period	28/10/14: 50 above dam gravel-cobbles 06/11/14: 50 local native gravel-cobbles 50 augmented gravels

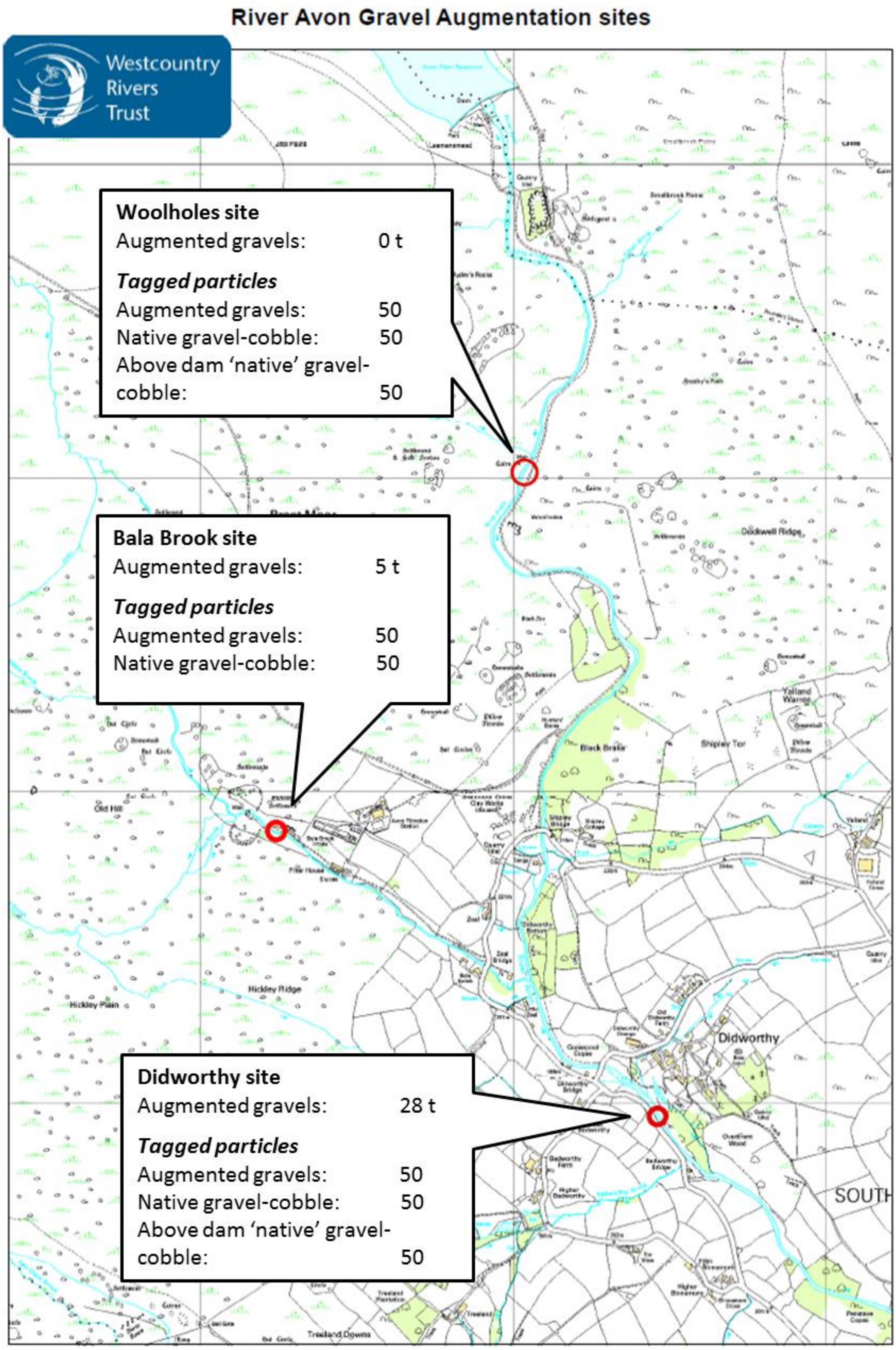


Figure 2. Overview of augmentation sites and tracer gravel locations.

3 Methods

This chapter outlines the field and laboratory methods undertaken to meet the objectives of the research project.

3.1 Reconnaissance: morphology, habitat and sediment

The contemporary channel condition in the upper Avon catchment is established from prior studies, including three previous Plymouth University Masters dissertations covering the geographic area of the upper Avon. Studies included catchment-wide assessment of factors limiting salmonid populations (Hedderson 2012) and factors affecting coarse sediment connectivity (Twohig 2014). The third was directed explicitly at establishing baseline conditions ahead of gravel augmentation (Jackson 2014).

Two of the studies (Jackson, Twohig) include measures of sediment characterisation in the upper Avon – the study of Jackson was used as the basis for establishing grain sizes for the tagging surveys, and sediments collected as part of this study were later tagged. Characterisation of coarse sediment on the surface of the channel bed was achieved using the 'Wolman method' (Wolman 1954, Figure 3) at multiple points on the Avon mainstem and Bala Brook tributary and include all of the locations in which gravels have been augmented (or have been targeted for augmentation). Further surface bed counts were conducted as part of this study.

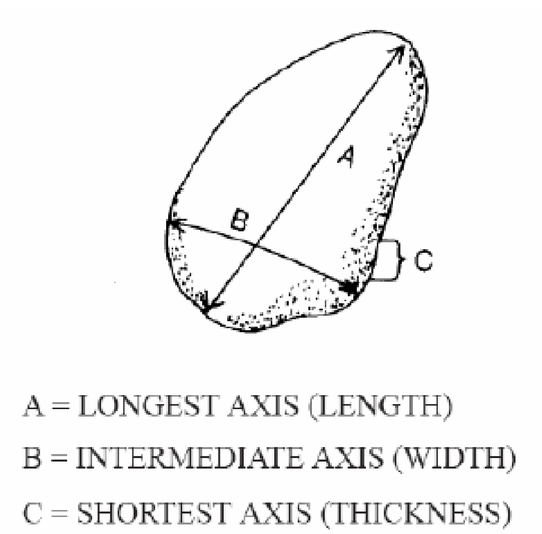


Figure 3. A, B and C axes of gravel (University of Wisconsin). By convention, gravel size is characterised by its b-axis, which is the axes that constrains sediment passing through a sieve.

3.2 Hydrological Characterisation

A measure of flow discharge is required to provide an indication of the 'driving force' responsible for the movement of tracer particles and the relative intensity of sediment transport. Information was drawn from the Environment Agency gauge recording 15-minute flow elevations on the River Avon at Didworthy. While not providing discharge directly, the flow elevations are correlated to flow discharge downstream at the Loddiswell gauging station and adjusted for area to provide an approximate indication of discharge at the Didworthy site. By using multi-year comparison of flow duration statistics, it is possible to characterise the flow year type during Water Year 2014-15 in comparison to other years extending back to 2003.

3.3 Bulk Bedload Sediment Transport - Impact Plates

To record the movement of bedload sediment transport, three 'Benson type' seismic impact plates were installed downstream of the three proposed augmentation sites in July 2014. The devices, based on a 150 x 130 x 6 mm steel top plate mounted onto a paving slab (for stability), are mounted flush to the channel bed and record an impact whenever a particle greater than ~10 mm strikes the plate. The plates are set to record at a maximum of 5 Hz (*i.e.*, 5 particles per second) and feature an integrated datalogger making them capable of continuously monitoring sediment movement over 64,000 pre-defined periods (maximum of 255 counts in each period) before the data loggers required downloading and re-setting. The plates were set here at 2.5 minute intervals and so require downloading at least every 3.5 months.

Impact plates thus provide a portable, non-intrusive continuous indication of the start, end and relative intensity of bedload movement. They can be compared directly to flow records to better understand the dynamics of sediment movement in comparison to received flows which is one of their two primary purposes here. The second is that they potentially provide a good indication of *when* the augmented gravels moved, information that can be combined with information about how far the augmented gravel has travelled obtained from recovering the RFID-tagged particles. Over extended time periods, this information can help understanding how much and how frequently to augment gravels.

The research team has gained considerable experience with impact plates while monitoring gravel movement in the lower Avon for the past three years (Downs *et al.*, 2015; Soar and Downs, *in preparation*). In comparison, the boulder-bedded upper Avon site presents a far more complex pattern of flow and morphology making the path of bedload movement far less predictable. Plates were situated where field judgment suggested that a reliable track of sediment might be observed, such as immediately downstream of sites where flow was forced by bedrock into one or two chutes that can be expected to concentrate moving bedload. However, errors in this judgment may cause sediment impacts be vastly underestimated (for instance, if sediment passes preferentially through a chute other than the one chosen, or if the plates are situated such that particle pass over them without hitting them). The plates were also situated in advance of final choices regarding the augmentation locations. Experience gained in the first year of monitoring may be used to refine plate position in future years.

3.4 RFID Sediment Tagging

Various techniques have been used to tag tracer stones for use in sediment transport studies and there is generally a compromise between the cost of the tagging and its accuracy and ease of retrieval. Radio Frequency IDentification (*i.e.*, RFID) technology has been increasingly popular in bedload movement studies in the last decade due to decreases in the cost of manufacturing and continuing technological improvements which have made the technique a plausible 'middle ground' technology combining relatively high rates of tracer retrieval (i.e., generally >60%) with relative low costs for the tags and the advantage of *in situ* detection. RFID technology consists of a transponder providing individual identification for the object of interest and a reader/control unit that contains a transmitter and receiver (Finkenzeller 2003). Active and passive transponders exist. As the name implies, passive integrated transponder tags (*i.e.*, PIT tags) do not require their own energy supply and are thus cheaper, and consist of a semiconductor chip, a capacitor and an antenna to send and receive signals housed inside a glass cylinders of 3.8mm in diameter and 12, 23 or 32mm in length (see Figure 4). Here, 23mm Half-Duplex (HDX) WMD PIT tags (TAG-H-234GL) were used in conjunction with a 'walker style' reader unit manufactured by Wyre Micro Design Ltd (model DEC-HDX-WALK-MK1) (see section 3.3.3).

3.4.1 Tracer Preparation

In the growing body of sediment studies, the PIT tags are frequently inserted into the rock by drilling an appropriately sized hole but this frequently results in shattering of rocks and breaking of drill bits. Conscious of the hardness of granite, and following advice from an experienced user (A. Schwendel, *pers. comm.,* and see Schwendel *et al.*, 2010), this study instead attached the tags to the outside of the rocks using dry curing epoxy-concrete. The tags were attached within natural grooves on the surface of the particle (where possible) in order to minimise their protrusion and thus any potential impacts on the hydrodynamics of rock transport. This was aided by the angular and sub-angular shape of both the augmented and native particles. Figure 5 shows a sample of augmented gravels fitted with RFID tags during preparation in the laboratory.

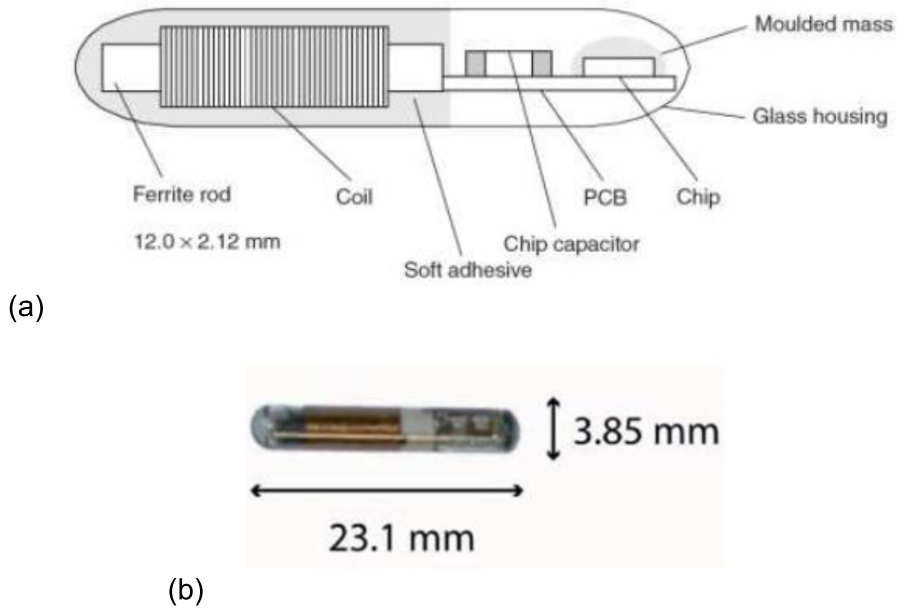


Figure 4. (a) Schematic diagram of a glass transponder (Finkenzeller, 2003) and (b) photograph of the tag used in this study

Figure 5. Tagged augmented tracer sediments during preparation

Particles were drawn from the mass of quarried gravels used for augmentation ('augmented' particles), and surface samples taken from the stream bed either at the intended augmentation location ('native' particles) or from upstream of Avon Dam ('above dam native' particles). The various sample populations were intended to enable comparisons between the mobility of the augmented particles in relation to the native particles conscious that the augmented particles are deliberately finer than the native bed sediments as an attempt to match spawning habitats which are presumed to have coarsened over time since dam closure. The above dam particles were intended to simulate potential particle size (and their mobility) in the absence of Avon Dam. In each case, samples sizes were measured and the tagged samples taken from the 50 central particles in the overall distribution (*i.e.*, between the 25th and 75th percentile of the size distribution). As such, each sample represents an approximate 'central tendency' of the sample population and avoids particularly large or small particles. Each particle was measured for it's a-, b- and c-axis dimensions, weighed and manually numbered.

3.4.2 Deployment

In tracing studies, the strategy for deployment generally involves a systematic approach to 'natural' placement of the tagged particle – basically simulating the natural positon of the particle so that its movement characteristics can be considered to be representative of untagged particles of the same size at that site. In fully alluvial rivers, 'seeding' is generally systematic, particles are placed according to a transect- or grid-based arrangement in order to ensure a wide variety of flow conditions and geomorphic units present within the stream reach are represented (*e.g.*, Bradley and Tucker 2012; Chapuis *et al*. 2015). The researcher removes a particle from the bed surface of the seeding location and replaces it with a tagged particle of similar size and shape.

Here, the deployment strategy was modified to suit the channel conditions which involve a 'semi-alluvial' channel morphology consisting of a very thin alluvial cover set in a framework of large cobbles and immobile boulders, and a consequently complex and chaotic pattern of flow hydraulics. Particles frequently occur in clusters between and in the lee of boulders. Tracers were distributed in an essentially systematic manner distributing 'augmented', 'native' and 'above dam native' particles (without the latter on Bala Brook which is not dammed) equally according to a visual 3 x 3 grid (Upper Left, Upper Middle, Upper Right, Mid- Left, Mid-mid etc.), taking care to place particles in a variety of the hydraulic flow types. Placement was as 'near natural' as possible but included placing particle next to clusters. Tracer particles in the augmented sections of the Didworthy reach were simply embedded into the augmented mass which is not fluvially-sorted in the first instance. In Bala Brook, where augmented sediments were placed in a low gradient area including the sill of a footbridge, tracer rocks were placed just upstream in a reach that appears to offer more 'typical' fluvial conditions.

3.4.3 Tracking

In common with most bedload studies, the study uses a portable reader for tracing PIT tags, rather than a point control station which records as tags pass the station (more common in studies of migrating fish). For a combination of practical and safety considerations, a minimum of two field staff are required. Surveys require low flow conditions as the head of the reader needs to pass within approximately 0.45 m of the tagged particle to enable detection. Tags that are standing on end are more difficult to trace than those lying horizontally and the read range may be only 0.20 m (Chapuis *et al*. 2014). One surveyor wades through the river with the reader and antenna system (Figure 6), scanning the bed for tracer particles, while the other records their locations from the bank using the GNSS (Global Navigation Satellite System) capacity of the Trimble Geo 7X handheld computer system. Tagged particles emit an audible 'bleep' in the headphones of the surveyor and the PIT tag's unique identification code, displayed on the screen of the reader, is called out to the bank and recorded using the handheld computer system (Terrasync software v5.61). Canopy cover restricts the accurate positioning of the instream tagged particle. Instead, we used the Trimble Flightwave™ rangefinder integrated in the Geo 7X, directing the rangefinder at the tracer particle from the bank: particle location is recorded automatically integrating the offset of the particle from the device. This enables the handheld computer system to be retained (in relative safety) on the bank where satellite reception is better while particle locations can be recorded up to 120 m away.

Figure 6. Field tracing of PIT tagged sediments at the Didworthy site. Within 0.45 m of the tagged particle, the reader sends an audible bleep to the headphones (avoiding the competing sound of water) while the tag identification is displayed on the reader around the surveyor's waist.

4 Results

4.1 Channel characterisation

The focal section of the Didworthy reach has an average gradient of 0.0236 and is morphologically similar to a 'cascade' reach type, despite having a lower gradient than classically observed for this type (Montgomery and Buffington 1997). Reaches with this gradient are more generally proposed to be of 'plane bed' or 'step-pool' type but the immobile boulder bed imparts a very high and variable relative roughness ratio to the reach resulting in a chaotic pattern of energy expenditure visually distinct from the relative uniformity of plane beds, or the organization inherent to a step-pool channel (although some partial bed steps exist). Gravel loss following impoundment may also have influenced the bed morphology. Gravels and sands congregate in the stoss and lee of boulders and in the channel margins where they are often deposited above low flow elevations. Patchy sediment storage and mild imbrication of gravels and cobbles suggests a supply-limited reach in which transport thresholds are characteristically bi-modal, meaning that gravel and small cobbles are mobilized during moderate recurrence interval events whereas coarser material requires far more infrequent floods for mobility.

The size distribution of the gravels on the channel bed was characterized using the 'Wolman' technique (Wolman 1954) taking samples at each of the augmentation locations, and above the dam. Sampling of 'native' river bed gravel deposits in the Woolholes reach immediately below the dam indicated a median (D_{50}) b-axis grain size of 78 mm whereas 'above dam' sediments have a characteristic D_{50} of 55 mm (see Table 2). Such results are suggestive of coarsening of the downstream channel bed following dam construction and imply loss of sediment storage. The Woolholes 'native' material is visibly much coarser in Figure 7. Conversely, the median particle size of particles in the Didworthy reach is the same as 'above dam' conditions at 55 mm (Table 2) but consists of a greater spread of particle sizes. Its visible distribution part way between 'above dam' and Bala Brook 'native' sediments may indicate that the reach is increasingly influenced by the input of sediment from the Bala Brook since the construction of Avon Dam. In contrast, the 'augmented' material consisted of well-sorted, sub-angular gravel obtained from a local quarry and sized to potentially benefit the spawning requirements of resident salmonids. The samples indicate a D_{50} of 40-43 mm and a far more restricted range of particle sizes (Table 2, Figure 7).

The RFID-tagged particles, drawn from 'native' bed samples and the augmented material replicate the D_{16} – D_{84} distribution of the above dam and augmented material faithfully (Table 3), but represent a narrower range of particle sizes than found in the contemporary Didworthy channel bed. Functionally, therefore, the tagged particles perhaps represent hypothetical 'pre-dam' sediment mobility ('above dam' and 'native' sediments, n = 100) versus the mobility of the distinctly finer augmented material (n = 49).

Table 2: Summary size parameters of tracer sediments

Site	Woolholes		Didworthy		Bala Brook		Above dam
Sediment type	Native	Augmented	Native	Augmented	Native	Augmented	Control
D_{min} (mm)	18	35	22	31	12	31	30
D_5 (mm)	27	36	24	34	22	32	35
D_{16} (mm)	47	37	36	36	31	35	40
D_{25} (mm)	60	38	40	38	38	35	47
D_{50} (mm)	**78**	**43**	**55**	**42**	**57**	**40**	**55**
D_{75} (mm)	97	46	69	45	79	44	60
D_{84} (mm)	106	47	78	46	92	46	68
D_{95} (mm)	123	50	92	49	125	49	84
D_{max} (mm)	165	56	143	50	160	56	90

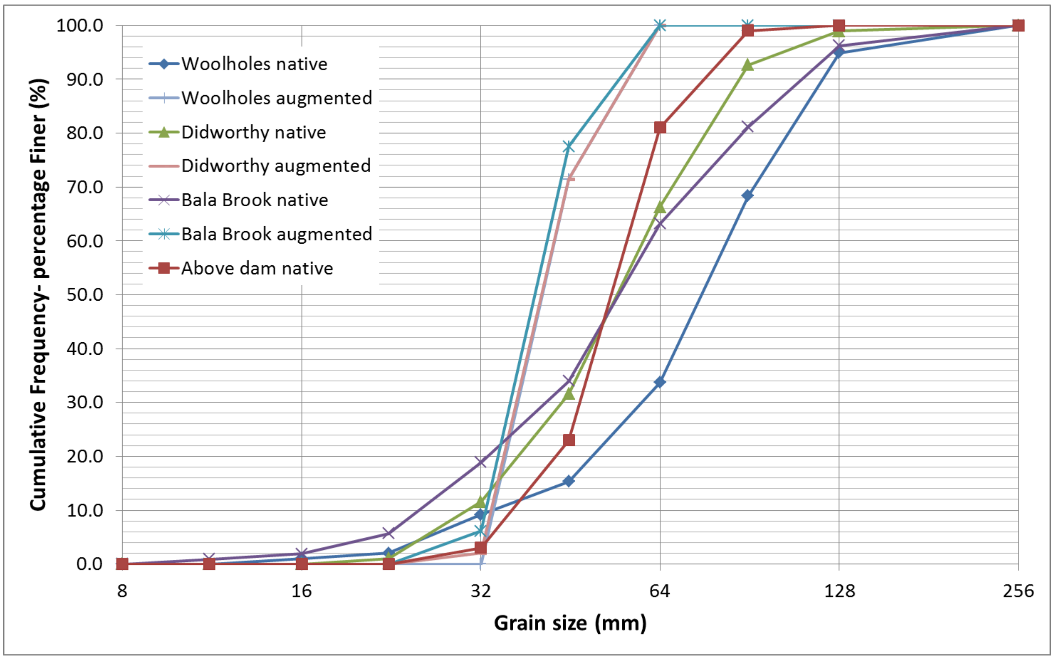


Figure 7. Grain size distribution of 'augmented', 'native' and 'above dam native' sediment samples

Table 3: Channel bed material size distribution from above the dam and in the Didworthy test reach and size distribution of RFID tagged samples. Wolman sampling method.

	Above dam		Didworthy reach		Augmentation material	
	Channel bed	RFID sample	Channel bed	RFID sample	Sample	RFID sample
D_{16} (mm)	40	41	36	48	37	36
D_{50} (mm)	**55**	**55**	**55**	**58**	**43**	**42**
D_{84} (mm)	68	70	78	70	47	46

4.2 Hydrology

Within the range of measures available to pursue river restoration (Downs and Gregory 2004), gravel augmentation is a method of 'prompted recovery' (Downs and Thorne 1998). Such measures represent a process-based approach to rehabilitation that works *within* existing river management constraints (*i.e.*, the continued existence of a large dam, in this case) but their effectiveness is dependent on a series of driving flow events in order to realize their potential (Downs and Kondolf 2002). For gravel augmentation projects where material is dumped into the channel and roughly spread across the channel bed, effectiveness implies receiving a series of flows sufficient to entrain and subsequently deposit the gravel in 'natural' locations. Flows of interest are thus those capable of generating sufficient shear stress to entrain the augmented material. This threshold flow and the extent it is exceeded during any one flow year determine the likely re-distribution potential of augmented gravels. Clearly, a Water Year characterized by few high flows is expected to result in 'less than average' gravel re-distribution whereas a year with many high flow events may be expected to transport augmented materials much greater distances than on the average.

The Didworthy gauge is situated immediately downstream of the augmentation area at Didworthy and at the confluence of Badworthy Brook. A twelve year record of daily mean flow elevations (the Didworthy gauge is not calibrated for discharge measurement) is compared in Figure 8. There is a minimum flow stage recorded by the gauge, which is occasionally adjusted, and it is evident that for about 50% of the daily mean flows that flow stage does not achieve the minimum stage. It is also noticeable in Figure 8 that the minimum recordable stage during WY2015 was far higher than in earlier years. This confounds a direct between-year comparison of flows received although it is notable that 2015 appears to be a relatively low flow year. The highest 20% of flow stages are magnified in Figure 9 and this highlights that 2015 may have been the one of the driest of the last twelve years, with only 2005 and 2011 being drier. The maximum recorded flow stage (0.89 m) is actually the lowest of this period, being marginally lower than those recorded in 2011 and 2012 (both 0.90 m).

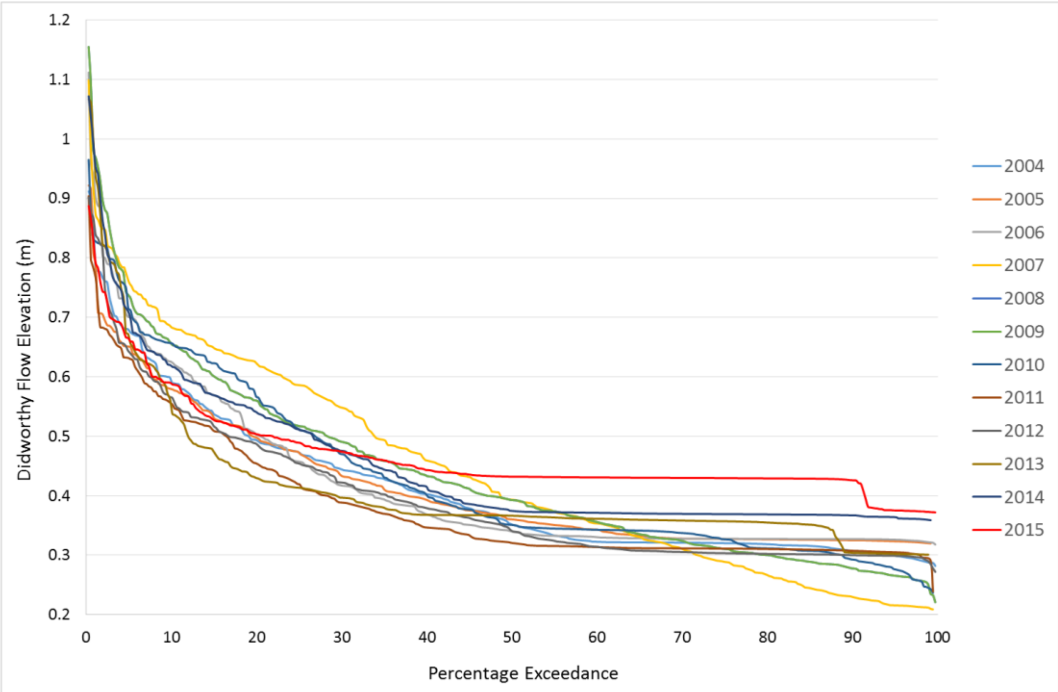


Figure 8. Flow duration curve of daily mean flow elevations above datum at the Didworthy gauge from Water Year 2004 to 2015, inclusive. Apparently different base levels for the gauge, especially during 2015 (red curve) complicate interpretation.

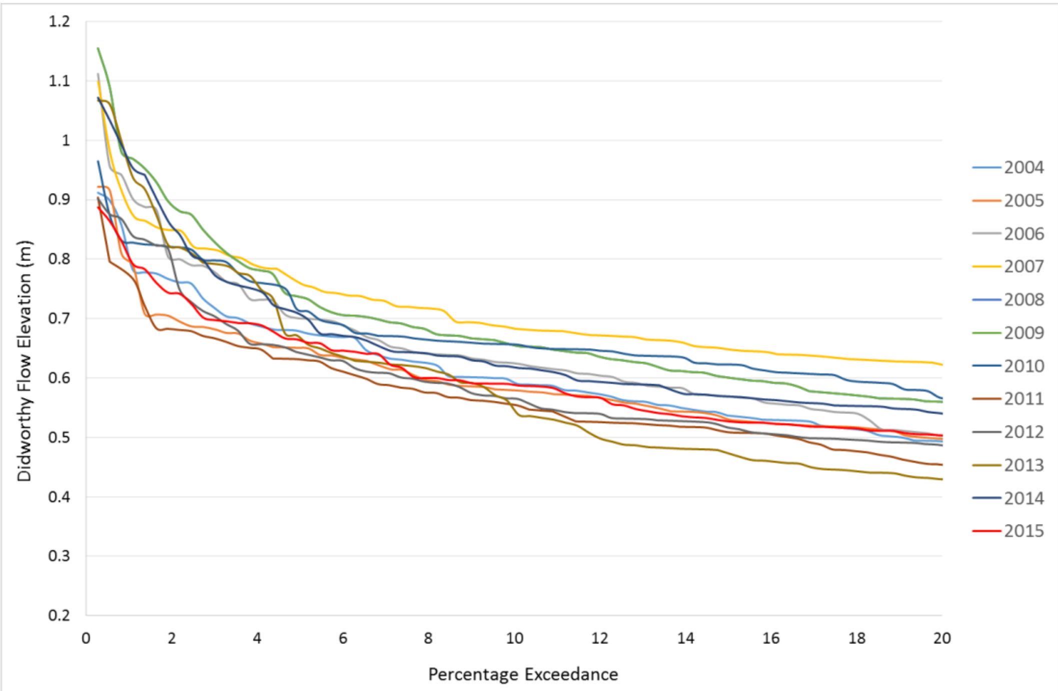


Figure 9. Flow duration curve of the highest 20% of daily mean flow elevations above datum at the Didworthy gauge from Water Year 2004 to 2015, inclusive.

Proving some additional confidence to these findings, there is a downstream gauging station at Loddiswell on the lower Avon. Plotting 15-minute flows at Loddiswell, for the period (October 2014 – July 2015) against 15-minute flow elevations at Didworthy reaches a best fit linear regression R^2 of 0.81 when 1.75 hours is added to the Didworthy gauge (to accommodate travel time of flows to the downstream gauge). The flow duration curve for Loddiswell shows far greater comparability of low flows between years (Figure 10a) and focusing on the highest flows only (inset Figure 10b) illustrates just how dry Water Year 2015 was relative to the three previous years. Overall, it appears likely that 2015 possessed relatively few high flows capable of significant transport of the augmented material.

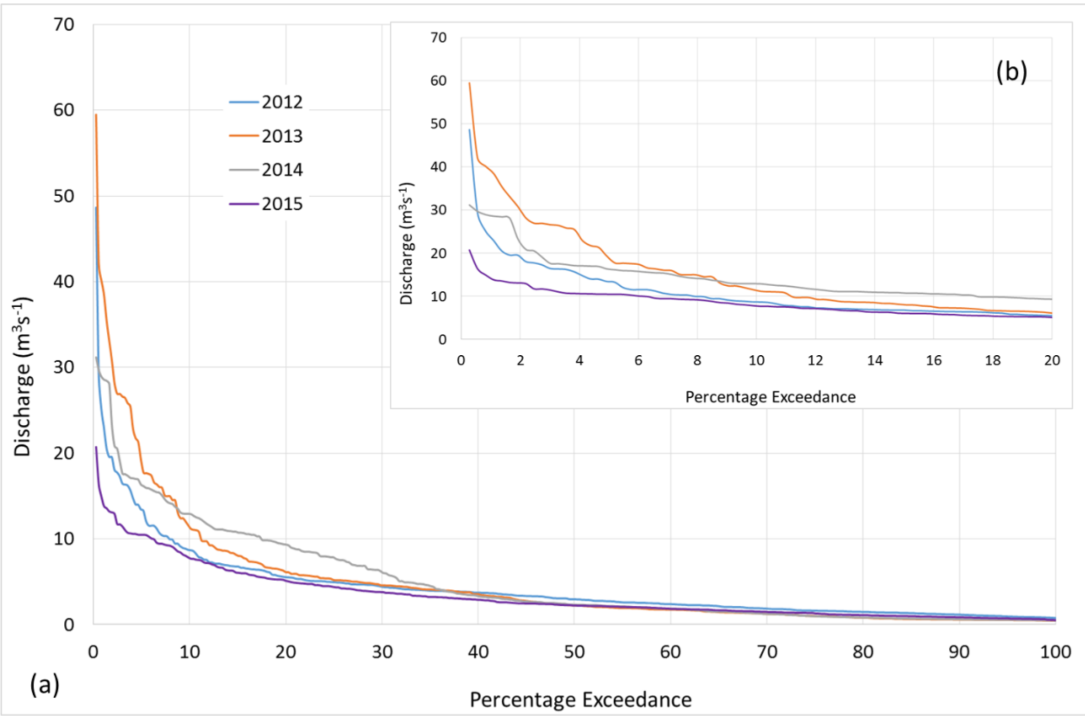


Figure 10. (a) Flow duration curve of daily mean flows at Loddiswell, on the lower River Avon, for Water Years 2012-2015. (b) Magnified illustration of the highest 20% of mean daily flows for 2012-2015.

4.3 Bedload Sediment Transport

Data from the three impact plates for the period October 2014 – September 2015 (Figure 11b-d) illustrate a clearly synchronised response of bedload transport relative to the 'forcing' by flow indicated by stage at the Didworthy flow gauge (Figure 11a). However, as evidenced by the very different y-axes in Figures 11b-d, there were considerable differences in the number of impacts with several orders of magnitude more impacts at the Didworthy site than at the other two sites. Over 168,000 counts were recorded at the Didworthy impact plate during this period, approximately 18,000 further upstream at 'Woolholes' on the main river and only 2,200 on the small tributary of Bala Brook. Caution must be applied in translating the results because impact counts reflect both the upstream site conditions but also the positioning of the plate in the channel (see Methods), but the results are interpreted as tentatively logical. Not only is the Didworthy plate the furthest downstream and the greatest distance from a dam or weir, but it is also immediately downstream of the primary augmentation site. Conversely, the Woolholes plate is downstream of both the Avon Dam and a weir that regulates coarse sediment and the Bala Brook plate is downstream of both a large regulating weir and a bedrock gorge that presumably reduces sediment input.

As possible corroboration of the meaningfulness of the numerical differences, during a largely dry test period (1/8/15 – 9/10/15) ahead of augmentation, the impact counts recorded at the two main river sites were comparable (432 at Woolholes versus 484 at Didworthy), suggesting that additional sediment supply was responsible for the higher counts at Didworthy. Further, with a mean mass of 90 g, there are around 11,000 particles per tonne of augmented gravel at Didworthy, or roughly 290,000 particles in the estimated 26 t of augmented material. The total impacts in the study period thus potentially represent ~58% of the augmented material which is considered reasonable considering the observed mobility of the tracers (even during a relatively low flow year) and the location of the Didworthy plate in the dominant chute for flow in its cross-section.

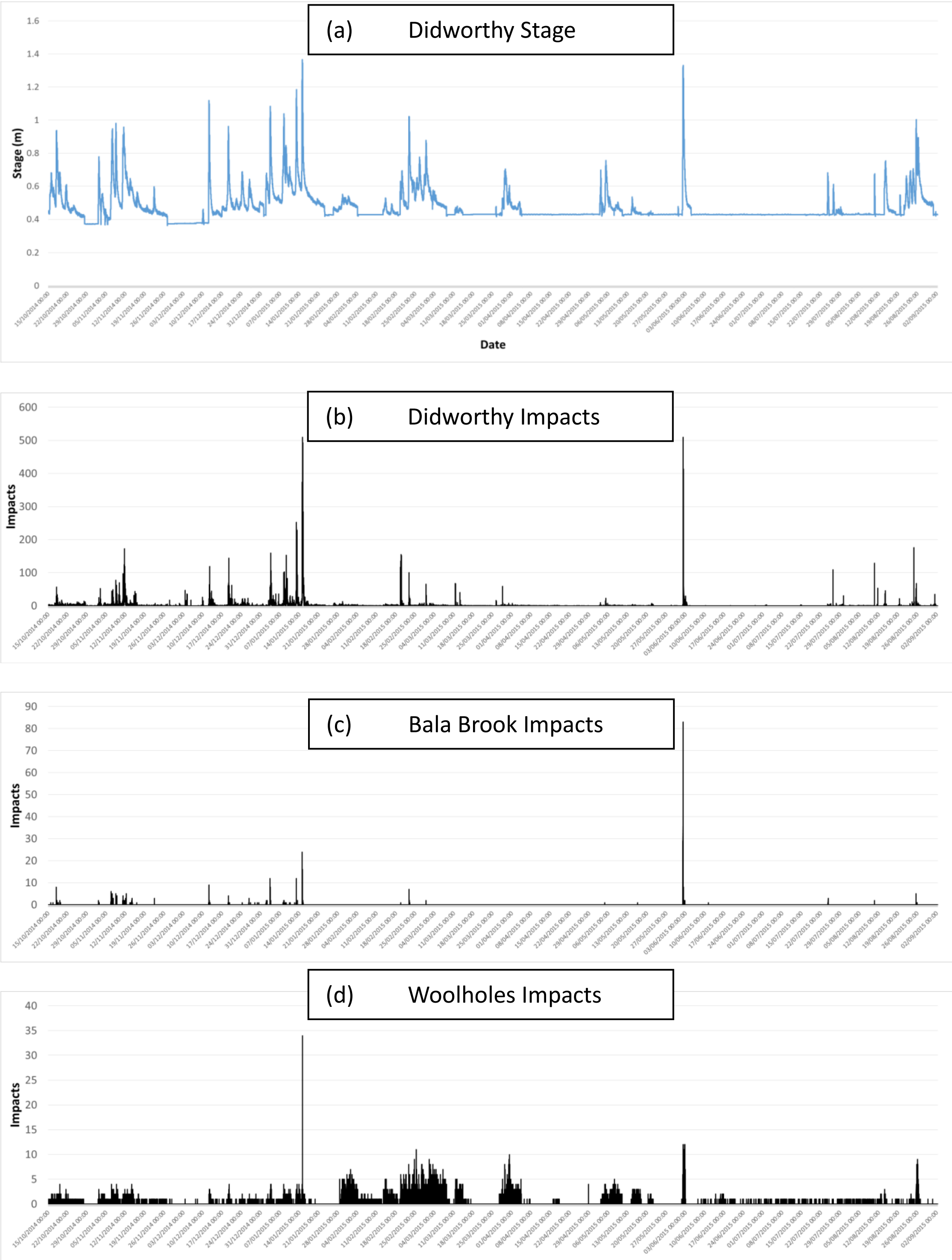


Figure 11. Records of sediment impact counts at each of the impact plates. The impact plates record sediment particles in excess of ~10 mm. Note difference in y-axis scale between each site.

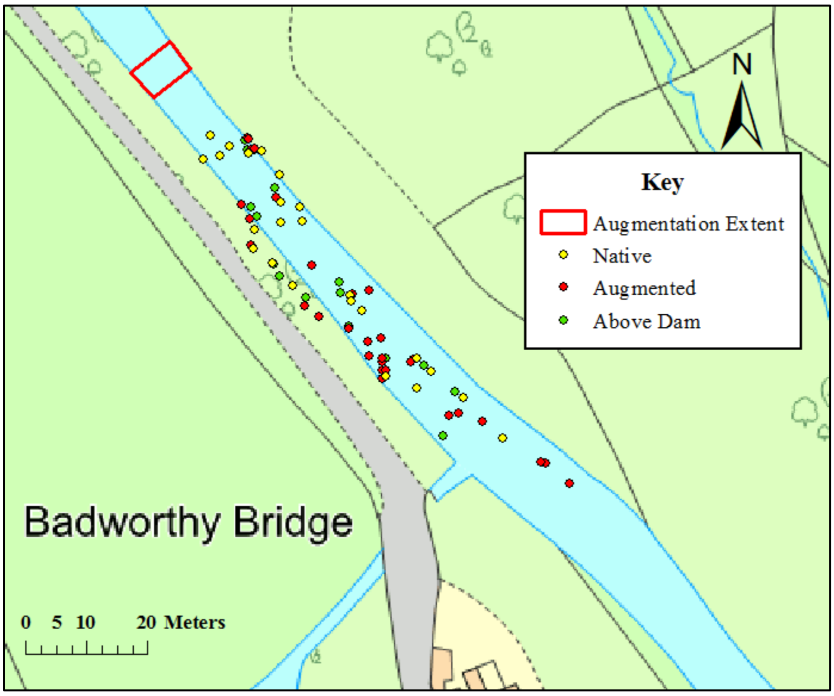
4.4 Dynamics of Tagged Particles

Water Year 2015 resulted in a series of flashy but not exceptionally large discharges. Peak instantaneous elevation at the Didworthy gauge was reached on the 15th January 2015 (1.367 m, 01:45) and a very similar stage reached on 2nd June 2015 (1.331 m, 01:30). The latter provided the marginally highest mean daily flow of the period (0.89 m). Other than the 2nd June event, and three far smaller peak flows, flows were perhaps uncharacteristically low from mid-March 2015 to mid-August. Tracing of tagged particles took place following the 15th January event at Didworthy (22 & 25/1/15), Woolholes (19/1/15) and later at Bala Brook (19/3/15). A second survey, focused on the Didworthy reach, took place on 2/9/15. Rates of particle recovery at each site during the first survey are outlined in Table 4. It is evident that in the larger, more complex reaches subject to greater particle entrainment (corroborated by data from the impact plates in Figure 11), recovery rates are far lower. Such results reflect a combination of the inherent likelihood of lower recovery rates when a larger surface area has to be surveyed, the physical difficulties of surveying a cascading reach, and the greater prospect that particles have been transported downstream of the survey area. Recovery rates for the Didworthy site may have been slightly higher if it had been possible to access the initial augmentation area but high flow velocities made this section of the channel unwadeable.

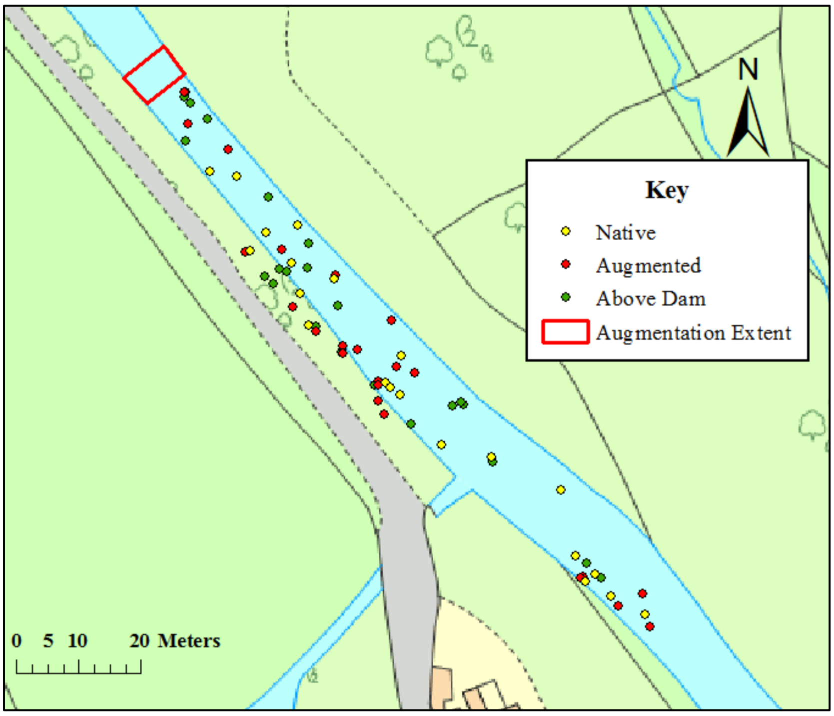
Table 4: Recovery rates from first tracer recovery

Site	Sediment type	Number of tracers	Number recovered	Percentage recovery
Didworthy	Above dam	50	23	46
	Native	50	26	52
	Augmented	49	30	65
	Total	**149**	**81**	**54**
Woolholes	Above dam	50	43	86
	Native	51	41	80
	Augmented	28	24	86
	Total	**129**	**108**	**84**
Bala	Native	50	50	100
	Augmented	49	49	100
	Total	**99**	**99**	**100**

There was very little particle movement recorded at Bala Brook and Woolholes during both surveys, and so our results focus on the primary augmentation site at Didworthy. The resting position of recovered particles at Didworthy is mapped in Figure 12 a and b, according to the two survey dates, and statistics related to the dynamics of the recovered particles following each surveys are outlined in Tables 5 to 8.



(a)



(b)

Figure 12. Distribution of recovered tracer particles below the Didworthy augmentation site (red box). (a) particle recovery in late January 2015, (b) particles recovery in early September 2015. Particles shown out of channel are in channel margins not well represented by the base map.

Table 5: Particle recovery statistics at Didworthy

Type	Tagged	1st survey		2nd survey		Recovered in both surveys	
	number	number	%	number	%	number	%
Augmented	49	30	61.2	20	40.8	13	26.5
Native	50	26	52.0	20	40.0	11	22.0
Above dam native	49	19	38.0	23	46.0	13	26.0
All particles	**149**	**75**	**50.3**	**63**	**42.3**	**37**	**24.8**

Table 6: Travel distance statistics for particles recovered following first survey

Type	Distance Travelled (m)			B-axis (mm)	Mass (g)	
	Minimum	**Mean**	Maximum	mean	mean	median
Augmented	15.7	**50.5**	92.7	41.9	93.7	87.9
Native	10.5	**36.0**	79.8	58.9	312.8	237.9
Above dam native	16.6	**42.3**	73.0	55.9	214.7	137.1
All particles	**10.5**	**43.4**	**92.7**	**51.3**	**200.3**	**129.7**

Table 7: Cumulative travel distance statistics for particles recovered following second survey

Type	Distance Travelled (m)			B-axis (mm)	Mass (g)	
	Minimum	**Mean**	Maximum	mean	mean	median
Augmented	6.6	**60.3**	116.2	41.8	94.4	88.5
Native	14.9	**60.0**	114.4	61.6	371.1	280.1
Above dam native	3.5	**44.4**	105.2	56.5	233.1	183.9
All particles	**3.5**	**54.4**	**116.2**	**53.5**	**232.9**	**137.1**

Table 8: Travel distance statistics for particles recovered in both surveys

Type	Distance Travelled (m)			B-axis (mm)	Mass (g)	
	Minimum	**Mean**	Maximum	mean	mean	median
Augmented	-1.9	**15.7**	54.8	41.4	93.8	86.0
Native	-0.9	**21.6**	70.5	61.3	372.8	253.7
Above dam native	-0.9	**9.5**	30.4	55.7	206.3	136.3
All particles	**-1.9**	**15.3**	**70.5**	**52.3**	**216.3**	**124.5**

It is clear that even with a lack of significant or sustained high flows during Water Year 2015, sufficient tractive forces were generated by those flows received to mobilise at least 50% of the tracer particles at Didworthy (Table 4), including particles from each tracer type. Unrecovered particles include those residing in areas of the channel that could not be accessed, those that may have travelled beyond the survey area, and those that were missed during survey (due either to operator error, loss of the RFID tag, burial, or by proximity to another tagged particle which can create difficulties in identifying both particles). Survey extent was approximately 100 m during the first survey, and approximately 180 m in the second survey. As indicated in Table 5, the number of recovered particles reduced in the second survey, and only half of the particles recovered in the first survey were found again in the second. This data, in conjunction with being able to access the initial augmentation area in the second survey and the position of some of the particles found in the channel thalweg at the downstream extent of the first survey (see Figure 12a), leads us to believe that many of the unrecovered particles have been transported downstream beyond the survey area. These may be found in later surveys but probability decreases with distance from source. As such, the transport distances outlined below should be considered minimums. Whereas there were a greater proportion (62%) of the augmented particles recovered during the first survey, recovery rates in the second survey were remarkably consistent across particle type.

Tables 6 to 8 outline selected transport statistics averaged over the first, second, and between survey periods, respectively. In general, particles travelled an average of 43 m from October 2014 to late January 2015, another 15 m between January and September 2015 for a cumulative average travel distance of 54 m. That the cumulative travel distance is not the summation of the two survey periods is further evidence that particles have travelled beyond the survey zone. The minimum, mean and maximum particle travel distances were greater during the first period than the second, irrespective on particle type (see Analyses). The indication of some ‘upstream movement’ of particles recovered during both surveys is a probable indication of the limits to our survey accuracy. Difficulties in using the rangefinder under canopy direct us to try to refine the method of particle positioning in future surveys. The minimum travel distances recorded in Table 8 suggest that our survey accuracy is probably in the range of ± 1-2 m.

Average transport distances appeared, after the first survey, to be somewhat related to particle size (and mass, Table 6), with the generally smaller and lighter augmented particles travelling farther than the larger ‘native’ and ‘above dam’ particles. Such size-related characteristics appears to disappear during the second survey (Table 7), although there is undoubtedly some prospect that a proportion of the augmented particles in particular, had travelled farther downstream than was practicable to survey. Overall, though, there is a suggestion, explored further below, that the particle size range encapsulated by the tagged particles were subject to tractive forces indicative of ‘equal mobility’ rather than ‘size selective’ transport dynamics.

5 Analyses

The analyses below explore the initial dispersal characteristics of the tracer particles (5.1) and their hydrological contextualisation (5.2), with the expectation that the analyses will be periodically updated and strengthened through further monitoring (funds permitting). It is also the intention to investigate the relationship of particle movement to resulting aquatic habitat following surveys provisionally planned for 2016. These sections will assist in answering questions related to the best-practice rate and frequency of augmentation, the effectiveness of augmented gravels in restoring spawning habitats of the upper Avon, and the overall regional potential for gravel augmentation to support such ecosystem service development. Clearly, periodic additions of tagged particles will be required to strengthen the data set.

5.1 Particle dispersal characteristics

Early indications of the relationship between particle travel distances and the particle size and mass are provided in Figures 13, illustrating particle travel distances following the late January 2015 surveys, and Figure 14 which indicates the total travel distances from recovered particles following the early September 2015 surveys. There is a mildly discernible relationship in evidence – in general, smaller, lighter particles have moved somewhat further than larger, heavier particles. However, the variance explained by the relationship is very weak (low R^2) depicting a large degree of variability in the travel distance by particles of similar sizes. Surprisingly, after the first survey, there was greater 'size selectively' in the distances travelled by smaller tracers characteristic of the augmented material (Figure 13c-d), than the larger tracers associated with the native and 'above dam' particles (Figure 13e-h) for which there is almost no size-based relationship. It is possible that larger particles may have been moved in a small number of the larger events that were capable of conveying all tracer particles regardless of size (under conditions closer to 'equal mobility' bedload transport wherein travel distance is governed primarily by the flow velocity rather than the particle mass), whereas some of the smaller augmented particles were additionally mobilised by a number of smaller flow events ('size selective entrainment' bedload transport) and thus moved further overall. However, by the time of the second survey, such size selectivity in the augmented particles has been significantly reduced with the particle size explaining less than 2% of the distance travelled (Figure 14 c) rather than 16% (Figure 13c). As such, the relationship of all particle sizes and types now explains generally less than only 3% of distance travelled (Figure 14a) rather than 10% (Figure 13a).

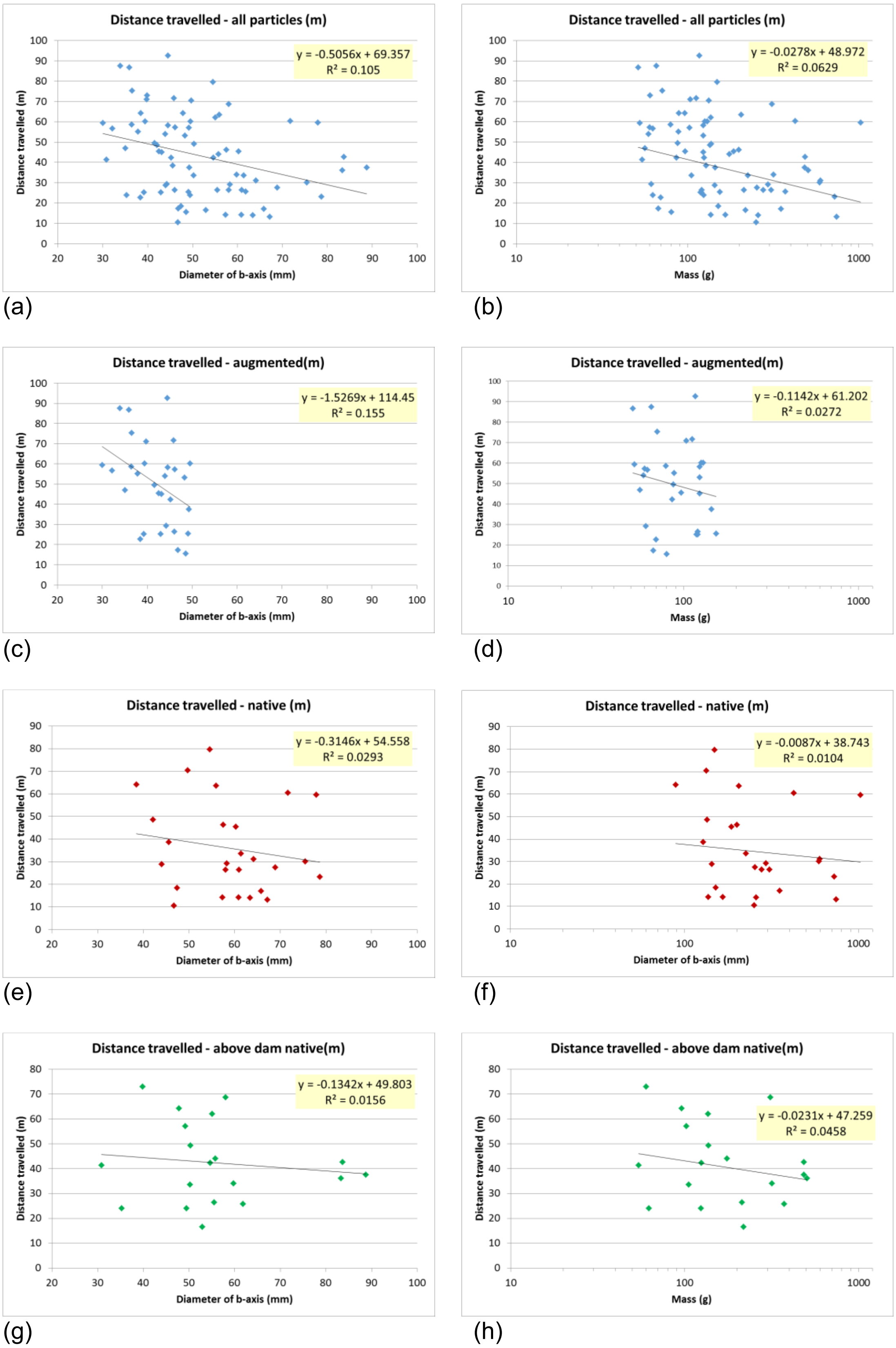


Figure 13. Relationship between particle travel distance and particle size (a, c, e, g) and mass (b, d, f, h) following first tracer recovery.

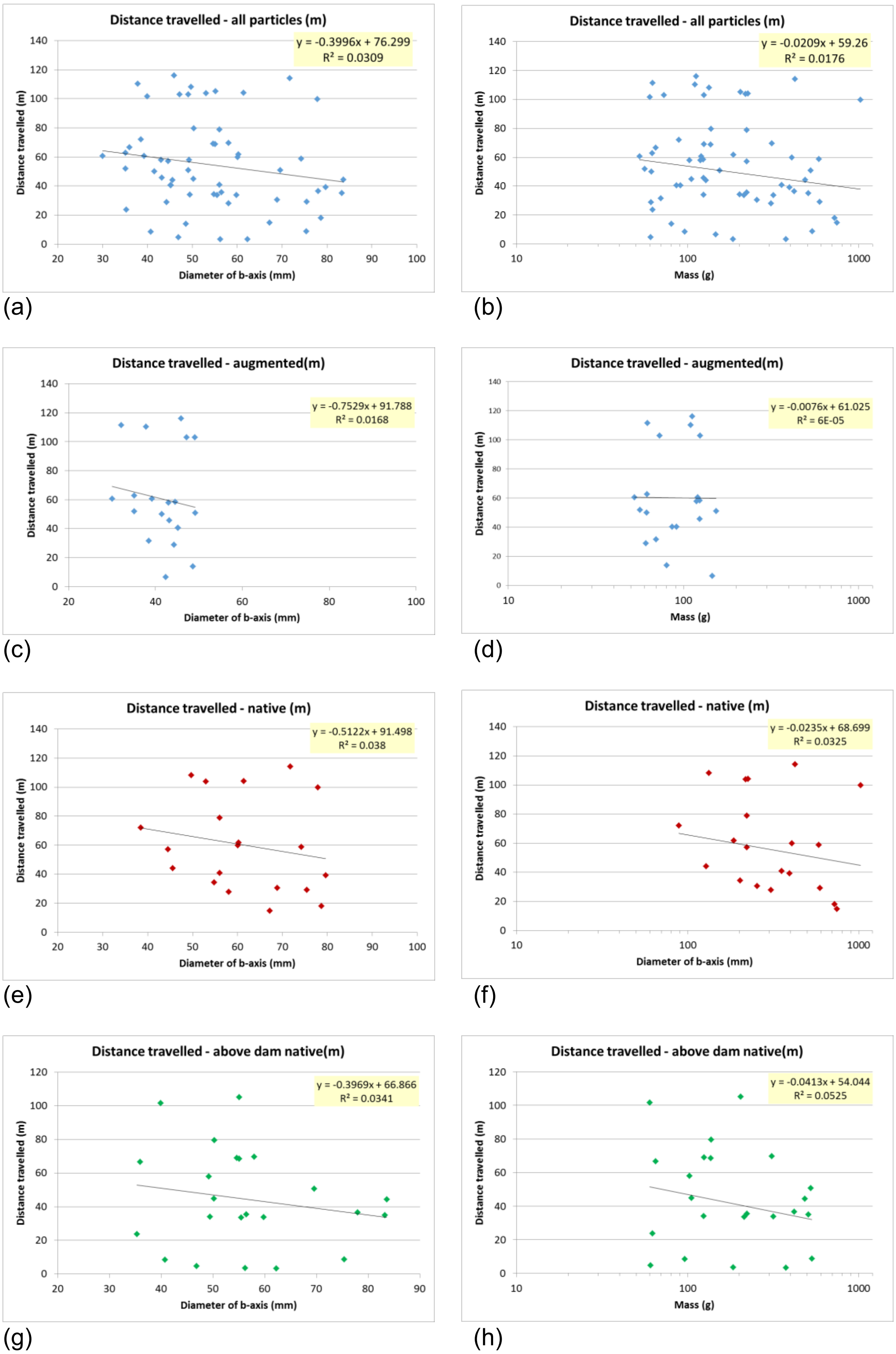


Figure 14. Relationship between total particle travel distance and particle size (a, c, e, g) and mass (b, d, f, h) following second tracer recovery.

It is noticeable also that the various plots of Figure 14 are now influenced by a cluster of particles deposited on a point bar near the building illustrated in Figure 12 (river curvature is far more distinct than indicated on the map). In particular for the augmented particles in Figures 14 c and d there were few particles recovered between 65 and 100 m downstream of the augmentation point. Such clustering may be evidence of the deposition of particles in natural depositional zones of the river, in this case the point bar caused by the meander bend, rather than their more 'random' deposition in the cascading reach just upstream. It should be expected that as the particles disperse further downstream, particle recovery is likely to be concentrated in such areas. The confounding effect of Badworthy Falls at the downstream extent of the second survey is as yet unknown.

Grouping particles by classic 'Wentworth Scale' size categories (30-45; 45-64; 64-90 mm) irrespective of origin emphasizes the difference in movement between survey periods. While the 2015 Water Year was, in general, very dry, the period from January to September consists of far fewer high flows events than the period from October to January. Figure 15 illustrates that those particles recovered in both surveys travelled far less distance, in general, in the second survey than they did in the first. It is often expected that tracer particles travel a shorter distance subsequent to their initial movement because the particles become better mixed with the general fabric of the channel bed. On initial placement, the tagged particles were integrated into the surface of a protruding mound of augmented materials and thus far more prone to movement. However, the period October 2014 – January 2015 also consisted of a far greater number of high flow events that during the later period, and so natal position of the tagged particles is unlikely to explain all of the difference between mean and median movement distances (see next section).

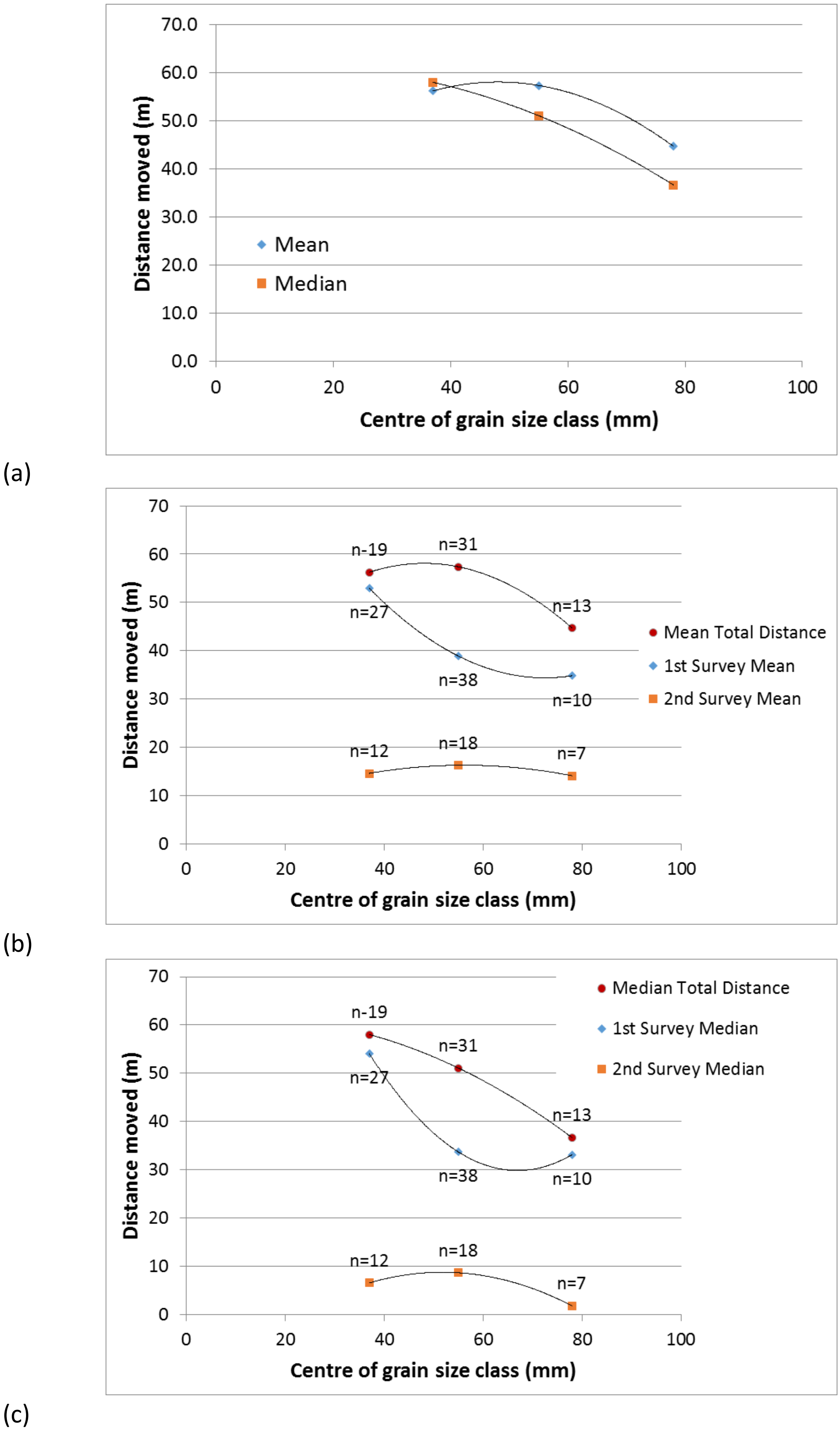


Figure 15. Relationship between particle travel distance and particle size (a, c, e, g) and mass (b, d, f, h) following first tracer recovery.

5.2 Event-based mobility of augmented gravels

Augmented gravels are unlikely to be transported the same distance in flood-poor years as they are in flood-rich years. Knowledge regarding sediment transport suggests the mobility of augmented gravels will reflect some measure of energy applied for bedload transport (*e.g.*, Mao and Lenzi 2007; Schneider *et al*. 2014), with more energy reflected in greater volumes and distances of gravel travel for a given grain size. Monitoring gravel movement over a sufficiently representative period thus brings the potential that some predictive capacity can be derived regarding the likelihood and distance of movement. Such prediction would allow better specification of sizes and volumes of gravel to augment per year to result in meeting specified habitat or channel morphology objectives. Assuming that such wet years cannot be predicted in advance, such knowledge might also form the basis for recommending mid-yearly augmentation if the preceding months have been sufficiently wet to risk significant loss of habitat during critical periods.

This section investigates the preliminary indications for such predictive relationships based the first year of monitoring. As the reach has no discharge data, the measurement of energy applied cannot be based on cumulative boundary shear stress or volume of flow (*cf.* Downs *et al*., 2015). It is necessary, instead, to rely on stage data at Didworthy which is less than ideal as discharge increases rapidly with stage as a function of the non-linear increase in average flow velocity with increasing flow depth. Further, because the measurement of baseflow stage appears to be variable between years (Figure 8) and sometimes within years (Figure 11), the consistency of flow stage readings is unknown. As a resolution, the investigation focused on cumulative impact of 17 'high flow events' within the (relatively dry) study period, as the variable representing the driving force for transport. The response variables include cumulative counts recorded by the seismic impact plates, as a surrogate for the total volume of gravel transport, and metrics related to tagged rock recovery as an indication of gravel transport distances. There are at present only three data points related to travel distance (see Figure 15), related to the survey period from October 2014 – late January 2015, from late January 2015 to the second survey in early September 2015, and to the total travel distances indicated by rocks recovered in both surveys.

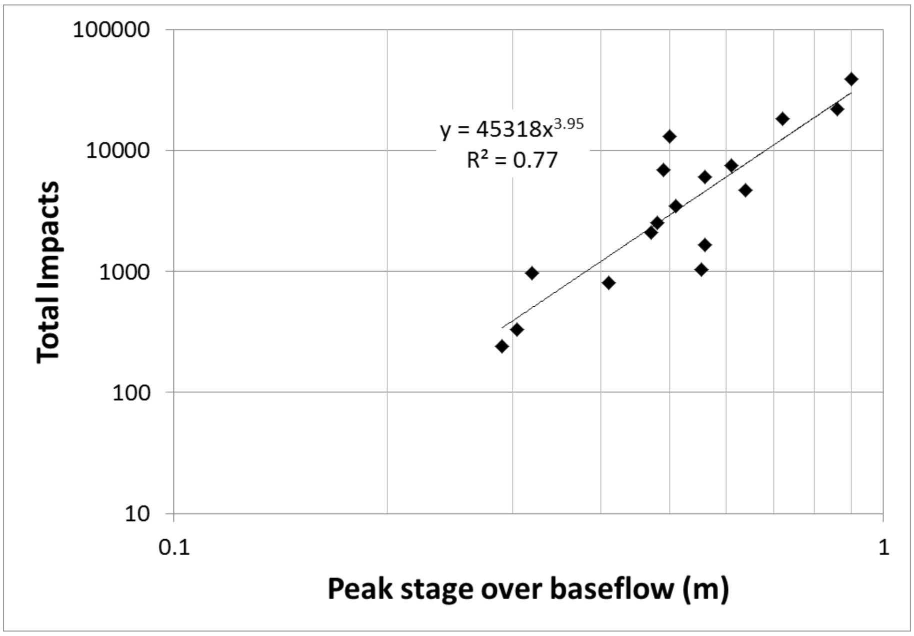
Regarding the volume of gravel transported by the flows received, the 17 high flow events occurred encompass 9.9% of the monitoring period but represent 77.7% (130,786 of 168,273) of the total number of impacts recorded. Clearly, as we might expect, there is a highly disproportionate transport of gravel during high flow events and our 17 events account for the large majority of recorded transport. We therefore assume that this event-based analysis has a similar representativeness for particle travel distances.

5.2.1 Sediment transport volume in relation to energy applied

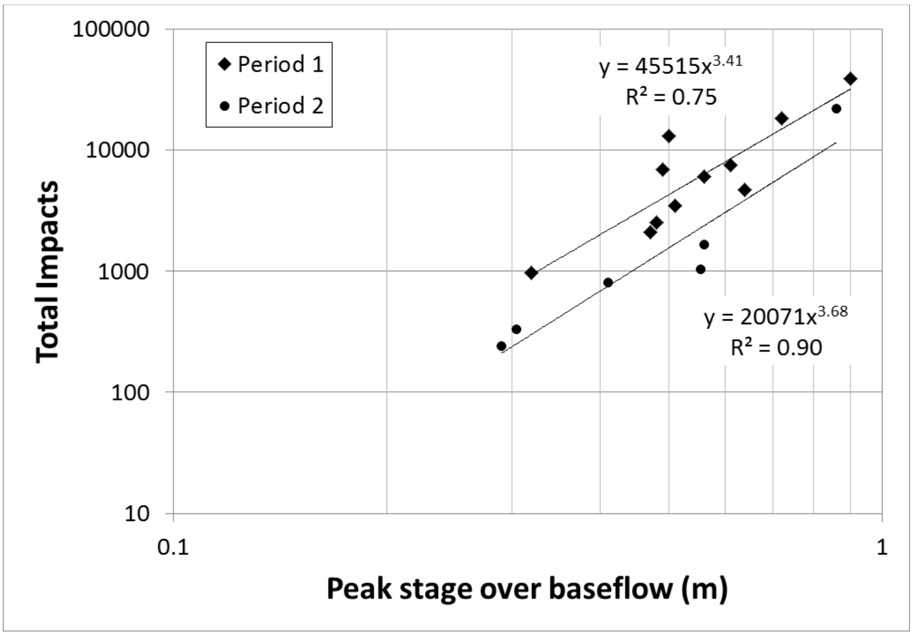
Figure 16a indicates a strong (R^2 = 0.77) and highly non-linear (exponent of 3.95) relationship of impacts recorded in individual events and 'peak stage over baseflow' (0.45 m) as a metric of energy applied. Experimentation indicated that this metric was the best surrogate for energy applied. Whereas a volumetric estimate of energy is preferred where the discharge is known (see Rickenmann *et al*. 2012, Downs *et al*. 2015), a 'volumetric' surrogate provided by the product of time and stage over baseflow ('stage seconds over baseflow') provided a much weaker relationship (R^2 = 0.25), emphasizing the extent to which energy (*i.e.*, discharge) increases non-linearly with stage. Using peak stage, instead, focuses the metric on the energy applied by the highest flows and thus inherently accommodates this non-linearity. Estimating peak stage *over baseflow* was used to accommodate the impact of the variable datum in the stage measurements, although the relationship obtained was barely any better than using the raw measurement of peak stage, again emphasizing the non-linear increase in sediment transport potential with increasing energy.

Of the high flow events, 11 occurred in the first monitoring period, and 6 in the second. Each contained one of the two highest peaks of the year (15/1/15, and 2/6/15) (see section 4.4) but the first period contains two-thirds of the total 'peak stage over baseflow' (6.2 m of 9.2 m), and higher average peak stage of baseflow (0.56 m compared to 0.50 m in the second period). This would suggest that more sediment transport should have occurred in the first period, and the event–based impact counts confirm that 80% of the total impacts occurred in the first period (67% of applied energy).

We might also assume that because the Didworthy reach has a very limited amount of sediment available for transport, the effect of gravel augmentation will be to accentuate the volume of material available for transport in the period immediately after augmentation, but that this effect will wear off as the store of augmented material is exhausted. As such, the relative concentration of bedload transport would be expected to drop from period 1 to period 2, irrespective of the peak flows received. Examination of the 8 data points that are greatest outliers in Figure 16a indicated that all four of the data points where significantly more impacts were counted than expected (*i.e.*, where the best-fit line under-predicts the count) occurred in the first period, and three of the four over-predictions occurred in the second, confirming this suspicion. Deriving best-fit relationships individually for the two periods (Figure 16b) numerically confirms the distinction, with the best-fit line for the second period plotting beneath that of the first. The constant indicates that, for instance, with a peak flow over baseflow of 1 m, we would have expected ≈45,000 counts in the first period, but only ≈20,000 in the second thus indicating a clear sediment 'exhaustion' effect. The prospects are that this occurs either because of a reducing stock of available gravel, or because the augmentation pile allowed very easy sediment entrainment in the period shortly after augmentation. As the exponents for each relationship is similar, indicating a similar rate of increase in impacts with peak stage, a preliminary conclusion is that the latter explanation is the most likely. Either explanation indicates that the volume of augmented material was far less than the 'saturated' transport capacity of the river, even during the dry year of 2015.



(a)



(b)

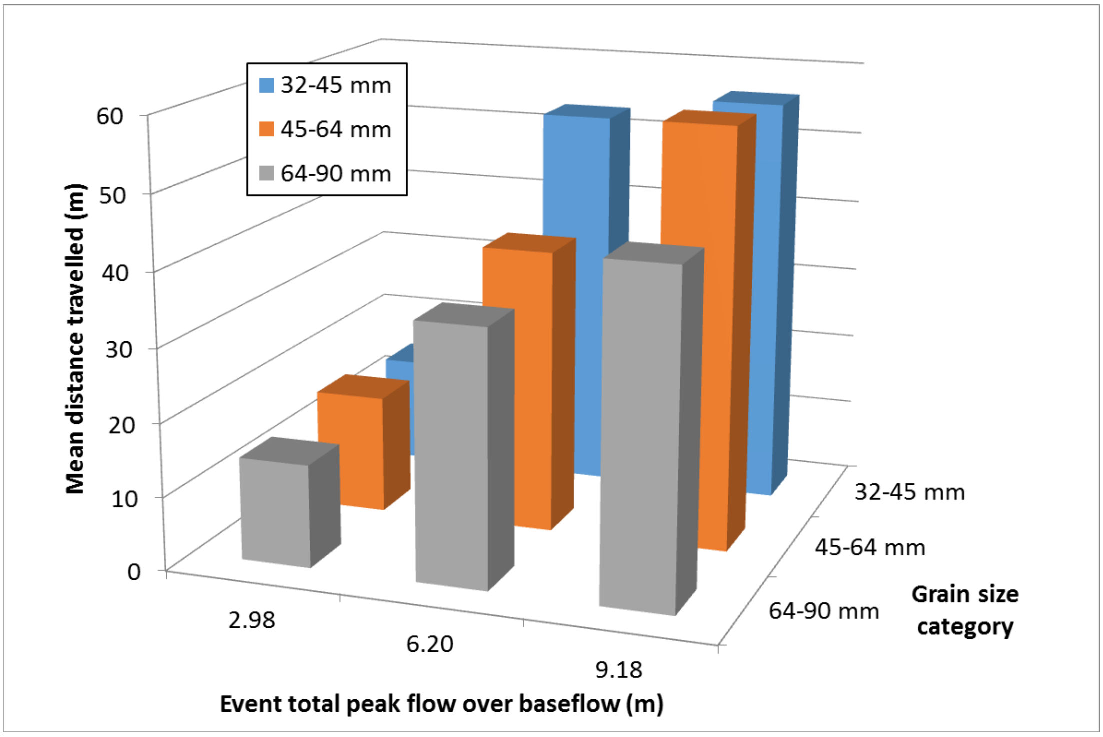
Figure 16. Event-scale bedload transport, expressed as total impacts, as a function of applied energy for sediment transport per event, expressed as peak stage over baseflow (m): (a) for the entire monitoring period, (b) for the period monitoring periods, separately.

5.2.2 Sediment transport distance in relation to energy applied

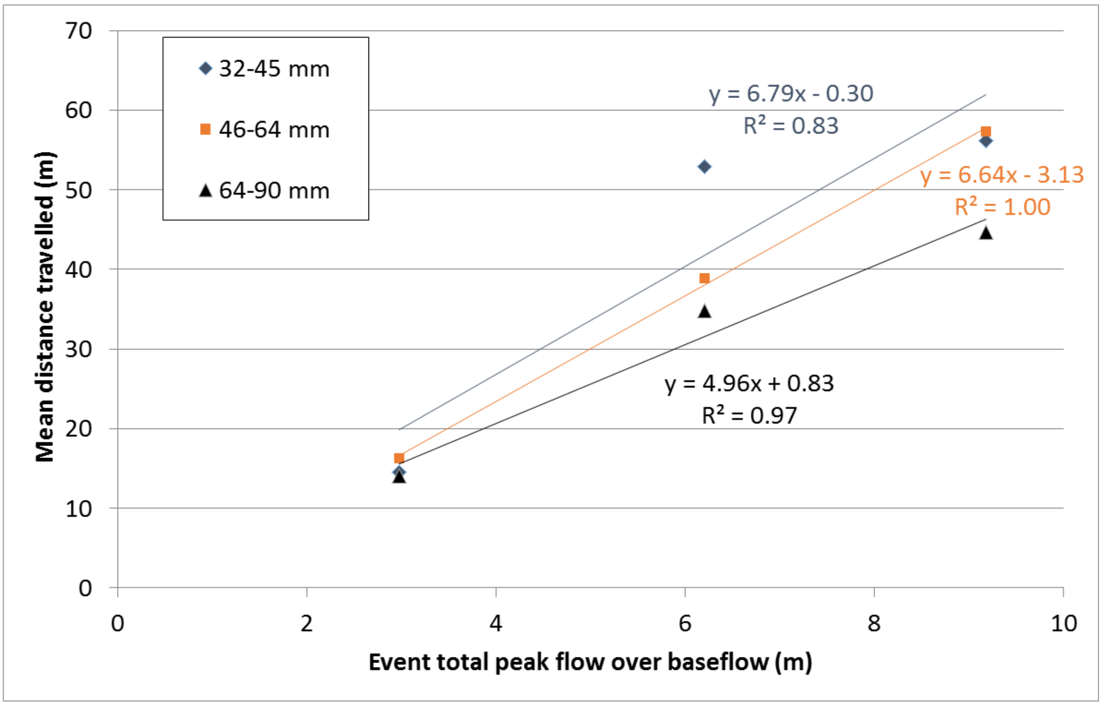
Data regarding sediment travel distances ascertained from RFID tagging were also related to applied energy ('peak stage over baseflow') for the two survey periods (Figure 17). Because we may expect a difference in particle mobility by grain size (see Figures 14 and 15), data was sub-divided by Wentworth grain size category. Note from Figure 15 (b and c) that sample sizes are relatively limited in this analysis.

Again we see clear trend of increasing distance with energy applied (Figure 17a). Some consideration must be given to the apparent 'exhaustion' effect (Figure 16a) that may accentuate the differences between the total peak stages of 2.98 (energy in period 2) and 6.20 (energy in period 1) and the cumulative peak stages between the two periods. Aggregating all sediment sizes, the mean travel distance of particles between periods one and two (15.3 m) is 35% of the mean travel distance in period one (43.4 m) when the energy applied is 48% indicating that transport distance, as well as transport volume was 'less efficient' in period 2. However, in general, the transport distances are reasonably proportional: Figure 17 b indicates the preliminary relationships between applied energy and transport distance by grain size for the study period. While analysis showed that the explained variance (*i.e.*, R^2) is slightly better when power relationships are defined (such as in Figure 16), the exponent in all cases is near to unity and so the linear plots are shown in Figure 17b for simplicity; relationships with mean travel distance are better than with median travel distance.

There are three notable elements in Figure 17b. First, the smaller grain sizes are predicted to move further than larger grain sizes, suggesting an element of size selectively to transport, as explored in section 5.1. Second, in very dry periods (*i.e.*, period 2) there is far less distinction of travel distance with grain size, probably emphasizing the non-linearity of sediment transport with increasing flow. This attribute may mean that with further monitoring that includes higher applied energies, a power law relationship will become a far better fit to the travel distance than a linear relationship. Third, it is apparent in Figure 17 that the travel distance of the 32-45 mm grain size class is significantly lower than might be expected for the combined ('full') monitoring period, that is, the mean travel distance at the end of the full monitoring period only just exceeds that achieved in the first period (56.2 vs 53.0 m). This relationship is provisionally interpreted as further confirmation that many of the gravels in this size class have been transported downstream of the survey area and that the best-fit relationship line for this grain size class should have been far steeper, and in which the second point is far less of an outlier. This last element is important because this grain size category consists of the majority of the augmented grain size class, thus suggesting that the augmented gravels are very readily transported beyond the application reach and may have only limited temporal benefits to habitat.



(a)



(b)

Figure 17. Event-scale transport distances, by grain size category, as a function of cumulative applied energy for sediment transport, expressed as total event peak stage over baseflow (m): (a) column chart highlighting individual data points, (b) scatter graph highlighting linear relationships.

5.2.3 Sediment transport distance in relation to sediment transport volume

As both sediment transport volume (section 5.2.1) and sediment transport distance (section 5.2.2) are highly proportional to the flow energy received, it is logical that transport volume and distance are highly related to each other. Figure 18 illustrates this relationship. The exponent of the relationship is less than one in all cases suggesting mean transport distance does not increase as quickly as transport volume. This is perhaps consistent with the notion that gravel transport consists of a progressive dispersal of sediment from the point of origin (Lisle *et al.* 2001; Cui and Parker 2005; Hassan *et al*. 2013) unlike the translating, attenuating dynamics of a fine sediment pulse. As such, the result provisionally indicates the potential for continued gravel accumulation to replenish sediment storage in the reach.

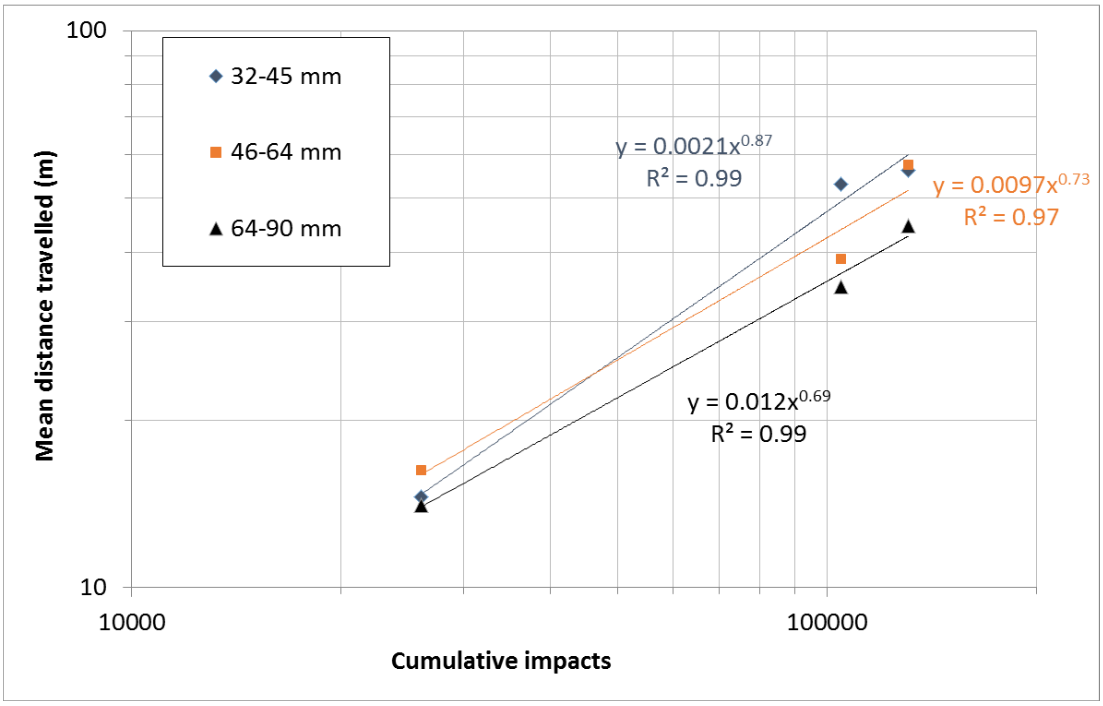


Figure 18. Event-scale transport distances, by grain size category, as a function of cumulative impacts representing bedload transport. Power relationships shown as powers depart from unity.

6 Observations and Provisional Recommendations

6.1 Methods

6.1.1 Impact Plates

The results from the impact plates provide an interesting and as yet uncontrolled account of different relative transport rates in the three sites that is a function of (a) natural setting, (b) plate situation, (c) human impacts and (d) proximity to augmentation. If possible, we will try to install a fourth impact plate in winter 2015-2016 to act as a control against some of these factors – for instance, by using a neighbouring site at Woolholes to assess to role of plate situation, or installing a plate just upstream of future augmentation at Didworthy to assess natural versus enhanced transport rates.

6.1.2 RFID tracers

Site conditions. The RFID tracers appear to have been quite robust following installation, but challenging to track in the upper Avon due to a combination of the complex flow hydraulics, highly irregular bed surface and flashy flow regime. The flashy discharge makes planning of surveys difficult and underpins the importance of deriving some measure of 'duration-over-threshold' flows for transport that integrate the sediment transporting effectiveness of multiple events, rather than summarising results from individual events which is possible in some other climates. Here, in the absence of discharge data, we found that a measure of 'peak stage over baseflow' provided the best relationship to the observed particle dynamics. The challenging site conditions have also resulted in planned iterations to our procedures and instrumentation during the surveys that should assist the efficiency of future surveys.

Recovery rates. The flashy flow regime also increases the prospect of tracing in sub-optimum conditions: the lower recovery rate for tracers in the Didworthy site during the January survey (50%, after adjustment for mis-registered particles) may have been partly related to high water levels that made some areas impossible to access. However, further reductions during the second survey (42% recovery) and low recovery rates for the same particles (25%) indicate both the challenging nature of surveying in the Didworthy reach, and may also point to particles being transported downstream of the survey area. There may also be issues related to particle clustering: when tagged particles cluster, the relatively large head of the portable reader (required to efficiently covering a large surface area) has difficulty distinguishing multiple particles in close proximity – one particle tends to dominate the reader response. This 'shadowing' effect has been noted in other studies (Bradley and Tucker 2012, Chapuis *et al*. 2014) and the use of an additional, far smaller, 'stick antenna' may help to obtain multiple readings. Clearly, too, installation of a stationary control reader at the downstream end of the survey reach would assist in confirming whether particularly long distance travel paths are occurring for some particles.

6.2 Tracer dynamics and lessons for augmentation

Despite the relatively flood-poor Water Year 2015 in comparison with recent years, it is clear that the majority of gravels augmented at the Didworthy site (October 2014) had dispersed from their placement position by the time of the second survey in September 2015. On average, the particles recovered during both surveys (n=37) had been transported 54 m (Tables 5, 7). Travel distance was weakly related to particle size such that the finer augmented particles had moved an average of 60 m overall (Table 7). Much of this movement was achieved during the flows received during the first survey period (equivalent to two-thirds of the flow energy received) with average travel distances of 43 m for all particles and 51 m for augmented particles (Table 6). Data indicates the potential that many particles in the 32-45 mm size category (including many of the augmented materials) may have been transported out of the augmented reach (Figure 17), accounting for the more rapid fall in second survey recovery rates for augmented particles than for the other types (Table 5). This would imply that the mean travel distances, of the augmented material in particular, is an underestimate. One implication is that coarser augmentation material may be required to provide some stability to marginal habitats.

Analysis indicated a weak relationship of particle travel distance to grain size (Figure 13, 14) that reduced after the second survey. This may point to 'equal mobility' dynamics of particles in the larger events received, with some additional movement of smaller particles in lower stage events. The second survey also began to identify particle clustering in a point bar at the downstream end of the surveyed reach. Such preferred deposition zones are important for habitat development and will be explored in more detail in future surveys.

There was a clear and strong relationship between the flow energy received, the volume of sediment transport (impacts recorded by the seismic impact plates) and sediment transport distance. Measured over 17 individual events, the sediment transport rate increases rapidly with flow energy (exponent = 3.95; Figure 16a). The volume of transport fell between the two monitoring periods independent of applied flow energy (Figure 16b) but the equivalent rate of increase with energy between the two periods may point to the ease of entraining of sediments from the augmentation 'pile' during the first period as the cause of this difference. In a similar way, particles were transported greater distances as greater flow energy was applied. Smaller particles are predicted to move somewhat further than larger particles although the extent of this difference may be masked by an apparent suppression of the total travel distance of the finer (32-45 mm) size class (Figure 17) which may be related to multiple particles moving beyond the downstream survey distance. The second monitoring period transported particles an average of only 35% of the distance in period 1 despite receiving 48% of the applied energy, which may emphasize differences in the 'ease' of sediment entrainment between the two periods, or underline the confounding effects of particles being transported downstream of the survey extent. Given that Water Year 2015 was relatively dry, the implication is that coarser particles are required to create more stable habitats.

Logically given earlier results, the volume of sediment transport is strongly related to sediment transport distance (Figure 18). The equation exponents of less than one for each size class may reflect the dominance of 'dispersal' as the mechanism of coarse sediment mobilisation from a point input, and it may indicate that continued augmentation of coarse sediment could potentially increase sediment storage in the reach.

All results and lessons for augmentation are highly provisional on further monitoring.

Stemming from this initial confirmation of particle mobility, further monitoring is required to establish:

- The extent to which dispersed particles become integrated into the fabric of native particles reducing their average movement rates in future years, and whether an average maximum dispersal length for particles can be established that defines a 'zone of benefit' from a single augmentation point;
- Whether particles become preferentially deposited in full or partial 'sink' locations that reduces their potential for benefit (and might lead to a revision in augmentation locations);
- And, whether, in general, the preferred pathways of dispersal create improved spawning habitat. Clearly, some particles will be transported to the channel margins during flood events where they may be of limited habitat utility but such dispersal mechanisms may change over time with repeat augmentation.

The estimate of particle mobility at Didworthy facilitated by impact plate data seems to confirm that annual rates of augmentation far higher than 24-8 t will be required to provide reach scale impact, and that multiple augmentation sites are likely to be required at least until the reach is 'saturated' with added gravel.

Both tracer movement and impact plate counts have been negligible at the Bala Brook and Woolholes sites. Rates of gravel supply in these locations is naturally low

(Twohig 2014) and the existence of dams and large weirs with upstream stilling basins in each reach may have further reduced the supply, such that only local contributions from bank erosion and channel bed sediment exist. As such, augmentation locations should probably be situated as close to potential spawning areas as possible, and there may be the need for additional raking and sculpting of augmented gravels to create suitable habitat in the context of limited expectation of movement. Conversely, these sites both have much smaller effective drainage areas than at Didworthy and it is possible that in wetter year discharges will exceed the threshold for effective sediment transport and rates of movement will be far closer in frequency to those at Didworthy. Further monitoring is required to investigate this prospect.

7 References

Ballantyne C.K. and Harris C. 1994. *The Periglaciation of Great Britain*, Cambridge University Press: Cambridge.

Bogle, J.M.L., Ross, R.M. and McMillan, T. 1959. The design and construction of the Avon Dam. *Proceedings of the Institution of Civil Engineers* 12: 83-106.

Bradley, D.N. and Tucker, G.E. 2012. Measuring gravel transport and dispersion in a mountain river using passive radio tracers, Earth Surface Processes and Landforms, 37: 1034–1045.

Cairns, Jnr. J. 1995. Ecological integrity of aquatic ecosystems, *Regulated Rivers, Research and Management*, 11: 313-323.

Chapuis, M., C. J. Bright, J. Hufnagel and B. MacVicar. 2014. Detection ranges and uncertainty of passive Radio Frequency Identification (RFID) transponders for sediment tracking in gravel rivers and coastal environments. *Earth Surface Processes and Landforms* 39: 2109-2120.

Chapuis, M., S. Dufour, M. Provansal, B. Couvert and M. de Linares 2015. Coupling channel evolution monitoring and RFID tracking in a large, wandering, gravel-bed river: Insights into sediment routing on geomorphic continuity through a riffle–pool sequence. *Geomorphology* 231: 258-269.

Cui, Y. and Parker, G. 2005. Numerical model of sediment pulses and sediment-supply disturbances in mountain rivers, *Journal of Hydraulic Engineering*, 131: 646–656.

Downs, P.W. and Gregory, K.J. 2004. *River Channel Management: towards sustainable catchment hydrosystems*, London, Arnold, 395pp.

Downs, P.W. and Kondolf, G.M. 2002. Post-project appraisals in adaptive management of river channel restoration, *Environmental Management*, 29: 477-496.

Downs, P.W. and Thorne, C.R. 1998. Design principles and suitability testing for rehabilitation in a flood defence channel: the River Idle, Nottinghamshire, U.K., *Aquatic Conservation: marine and freshwater ecosystems,* 8: 17-38.

Downs, P.W., Soar, P.J. and Taylor, A. 2015. The anatomy of effective discharge: the dynamics of coarse sediment transport revealed using continuous bedload monitoring in a gravel-bed river during a very wet year, *Earth Surface Landforms and Processes*, early view

Environment Agency, EA. 2003. The Rivers Avon and Erme Salmon Action Plan, Consultation Document. Environment Agency, Bristol, UK.

Environment Agency, EA. 2011. Waterbody Information Pack: Avon Waterbody, Draft Report. Environment Agency, Bristol, UK.

Evans, D.J.A., Harrison, S., Viel, A. and Anderson, E. 2012. The glaciation of Dartmoor: the southernmost independent Pleistocene ice cap in the British Isles. Quaternary Science Reviews, 45: 31–53.

Finkenzeller, K. 2003. *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification*, Chichester, J.Wiley & Sons Ltd, Second Edition.

Graf, W.L. 2001. Damage control: restoring the physical integrity of America's rivers. *Annals of the Association of American Geographers*, 91: 1-27.

Hassan, M. A., Voepel, H., Schumer, R., Parker, G. and Fraccarollo, L. 2013. Displacement characteristics of coarse fluvial bed sediment, *Journal of Geophysical Research – Earth Surface*, 118: 155–165.

Hedderson, L. 2012. An analysis of limiting factors for salmonid populations within the River Avon catchment, Devon, UK, unpublished MSc. Dissertation, Plymouth University, Plymouth UK.

Jackson, N. 2014. Impact of the Avon Dam on salmonid spawning habitat: potential for mitigation by gravel augmentation, unpublished MSc. Dissertation, Plymouth University, Plymouth UK.

Kondolf, G.M. and Wilcock, P.R., 1996: The flushing flow problem: defining and evaluating objectives. *Water Resources Research*, 32: 2589-2599.

Ligon, F.K., Dietrich, W.E. and Trush, W.J. 1995. Downstream Ecological Effects of Dams: a Geomorphic Perspective *BioScience*, 45: 183–192.

Lisle, T.E., Cui, Y., Parker, G., Pizzuto, J.E. and Dodd, A.M. 2001. The dominance of dispersion in the evolution of bed material waves in gravel-bed rivers. *Earth Surface Processes and Landforms*, 26: 1409–1420.

Mao, L and Lenzi, M.A. 2007. Sediment mobility and bedload transport conditions in an alpine stream, Hydrological Processes, 21: 1882–1891.

Montgomery, D.R. and Buffington, J.R. 1997. Channel-reach morphology in mountain drainage basins, *Geological Society of America Bulletin* 109: 596-611

Petts, G.E. 1979 Complex response of river channel morphology subsequent to reservoir construction, *Progress in Physical Geography,* 3: 329-362.

Petts, G.E. 1982 Channel changes in regulated rivers, in Adlam, B.H., Fenn, C.R. and Morris, L. (eds) *Papers in Earth Studies*, Norwich, Geobooks, pp.117-143.

Petts, G.E. 1984 *Impounded Rivers: perspectives for ecological management*, Chichester, J.Wiley & Sons, 326pp.

Petts, G.E. and Greenwood, M. 1981. Habitat Changes Below Dartmoor Reservoirs, *Report of the Devonshire Transaction of Advanced Science*, 113: 13-27.

Rickenmann D, Turowski JM, Fritschi B, Klaiber A, Ludwig A. 2012. Bedload transport measurements at the Erlenbach stream with geophones and automated basket samplers. *Earth Surface Processes and Landforms*, 37: 1000–1011.

Schneider, J.M., Turowski, J.M. Rickenmann, D., Hegglin, R., Arrigo, S., Mao, L.and Kirchner J.W. 2014. Scaling relationships between bed load volumes, transport distances, and stream power in steep mountain channels, J *Journal of Geophysical Research – Earth Surface*, 119, doi:10.1002/2013JF002874.

Schwendel, A.C., Death, R.G. Fuller, I.C. 2010. The assessment of shear stress and bed stability in stream ecology, *Freshwater Biology*, 55: 261–281.

Soar, P.J. and Downs, P.W. *in preparation*, Estimating bedload transport rates in a low-land gravel bedded-river using seismic impact plates.

Twohig, S. 2014. Assessing coarse sediment connectivity of the River Avon, Devon: a geomorphological conceptual model based on physical catchment characteristics, unpublished MRes. Dissertation, Plymouth University, Plymouth UK.

Williams, G.P. and Wolman, M.G. 1984. Downstream effects of dams on alluvial rivers, *U.S. Geological Survey Professional Paper* 1286, Washington DC, U.S. Geological Survey.

Wolman, M.G. 1954. A method of sampling coarse river-bed material. *American Geophysical Union Transactions,* 35: 951-956.