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Flow dynamics and bedload sediment transport around paired deflectors for fish habitat enhancement: a field study in the Nicolet River

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ABSTRACT: Schemes to restore fish habitat in rivers often involve installing instream structures such as current deflectors to create and maintain riffle-pool sequences. However, there is a lack of field studies on the impact of these structures on flow dynamics and bed topography. The objective of this research is to characterize flow dynamics and sediment transport around paired deflectors used to enhance fish habitat in the Nicolet River (Qc). Bed and bank topography surveys were taken with a total station, and velocity and bed shear stress estimates were obtained from an Acoustic Doppler Velocimeter. Bedload sediment transport was assessed by two methods: tracer rocks (painted particles and PIT tags) and sediment traps. Results show marked differences in bedload sediment transport patterns between the left and the right bank downstream of the deflectors. This is surprising considering that paired deflectors should produce a relatively symmetrical disruption to the flow field on each side. More high-flow dynamics data during overtopping conditions are required to understand the complex interactions between these instream structures and bedload transport.

Key words: Stream restoration, pool, bedload transport, RFID, PIT tags, field work, deflectors, fish habitat

INTRODUCTION

Several factors play an important role in defining the quality of physical fish habitat in rivers. Fish species show preferences for certain hydraulic values (flow velocity, depth) and substrate element size (Gore and Judy 1981; Maddock 1999; Mäki-Petäys et al. 2002). Models of quantitative estimates of habitat suitability in a stream reach have already been developed for shear stress, velocity, water depth, and discharge (Lamouroux et al. 1992, 1995, 1998a, 1998b, Leclerc 2005). A healthy fish habitat is typically described as containing riffle-pool sequences, which play a key role in the fish's life cycle (Thompson 2002a, Thompson 2006). These successions of shallow and deep areas play an essential role in water oxygenation, fish reproduction, feeding, and rest. In many areas, human activities affect the original morphology of rivers resulting in a deterioration of the riffle-pool sequences (Thompson 2002a). Because of the importance of recreational fishing, a large number of restoration projects focus on fish habitat enhancement, particularly on salmon and trout habitats which are of vital economic importance for the sport fishing industry.

Stream deflectors are one of the most successful instream-structure methods for restoring or enhancing low-gradient channels for trout (Hunter 1991, Thompson 2002b) and are in widespread use in stream restoration projects for salmonids (Brookes and Shields 1996, Roni et al. 2002). As for any other type of instream structures, though, their placement needs to take into account channel morphology, flood plain, hydraulic and sedimentological conditions in order to be successful. These in-stream structures constrict the channel section, and by consequence increase flow velocity, causing an increase in bed shear stress. The outcome is a local scouring of the bed, creating a pool (Thompson, 2006) and an accumulation of sediment downstream of the scour pool which forms the riffle (Booker et al. 2001). Many deflectors, however, are installed in rivers on a "trial-and-error" basis (Brookes and Shields 1996). Recently, some laboratory studies have shed more light on the complex flow dynamics and resultant bed topography around deflectors (Biron et al. 2004a). They compared design of deflectors with different angles, heights and lengths and provide useful design recommendation for paired deflectors.

To improve the success rates of restoration projects, however, field monitoring studies are required. Natural rivers, unlike laboratory flows, exhibit many additional complexities such as varying planform geometry and heterogeneous bed sediments, which need to be taken into account when implementing instream structures. With a few isolated exceptions (e.g. Thompson 2002a), there is very limited, if any, field data available on flow velocity and sediment transport around deflectors in natural rivers. These data are required if attempts are made to model the complex three-dimensional flow dynamics around these instream structures. Three-dimensional numerical models have been used extensively over the last few years in rivers (e.g. Lane et al. 1999, 2002, Nicholas and Smith 1999, Ferguson et al. 2003). These models, however, require detailed spatially distributed datasets of three dimensional flow variables to be validated (Ferguson et al. 2003, Lane et al. 2005).

This study is part of a larger project which involves three phases: monitoring fluid dynamics and sediment transport data for the existing deflectors in the Nicolet River (Québec, Canada), designing a three-dimensional numerical model for this field site using the software PHOENICS (from CHAM), and testing and validating the 3D model in order to maximize deflector efficiency and success rate for future implementation. The ultimate goals of this project are to develop numerical modeling tools for river management and guidelines on optimal location of dug pools when installing flow deflectors in rivers. This paper will provide a detailed description of the field methodology used to monitor fluid dynamics and sediment transport data around the existing deflectors in the Nicolet River, and will describe results obtained after two years of field data acquisition.

METHODOLOGY

The Nicolet River, near Victoriaville (Québec, Canada), is located within the Nicolet sub-basin that covers an area of 265 km^2, which is part of the Arthabaska watershed. Founded in 1988, the "Corporation de gestion des rivières des Bois-Francs" (CGRBF), has the task to restore the physical habitat of the Nicolet River for sport fishing. The rehabilitation work began in 1993 and included two 300 m reach bank stabilizations, construction of four paired stream deflectors, four solo stream deflectors, and fish stocking. Sixty nine fish shelters were installed in the river bed to protect fish from the sun. Three trout species (Brook, Brown and Rainbow trout) are stocked on a weekly basis during the fishing season. Furthermore, forty thousand trees were planted to reduce erosion, keep the water cooler, and filter pollutants. The purpose of the stream deflectors is to reduce the bank erosion, maintain the depth of the pool, and eventually re-establish the riffle/pool sequence. The first structure, a pair of wooden deflectors oriented downstream, was built in 1994 at a cost of $25,000 (CDN). This project was unsuccessful, due to the structural failure of the wooden deflectors after the passage of a large flood which occurred only a few years after their implementation. In 1997, eleven sets of paired boulder deflectors oriented upstream were installed at a cost varying between $10,000 and $25,000 each (dependent on boulder availability). This project has been successful up to now, but long-term monitoring remains necessary.

Field work in this study includes topography surveying, velocity measurement and methods to estimate bedload sediment movement in a 250m long reach on the Nicolet River. The reach includes 2 sets of paired deflectors (Figure 1) and detailed measurements were made for the downstream deflector. This reach is characterized by a highly heterogeneous bed with a median diameter (D_{50}) of 90 mm, and a D_{84} (where 84% of the particles are finer) of 180 mm. It has a width of around 35 m, and a discharge varying from about 0.6 m^3/s at low flow to 30 m^3/s at bankfull. Repeated detailed bed and bank topography surveys were taken with a total station to monitor bed morphology changes and the dynamics of the riffle-pool sequences. Three permanent benchmarks have been installed to allow comparison between surveys. Bed topography and water surface were measured at several cross-sections, with a higher density of points where change was the greatest. The flow stage was monitored with a pressure transducer recording at a 15 minute sampling interval. The discharge at the pressure transducer's cross section was calculated from velocities measured by a vertically-mounted axis propeller current meter. A stage-discharge rating curve of the reach between June and August 2004 was obtained from the discharge measurements (0 – 5 m^3/s). For higher discharge, another rating curve was developed, based on discharge obtained at a gauging station around 65 km downstream (Environment Quebec station # 030103) on the Nicolet River. The ratio of watershed areas between the downstream station and the field site was used to estimate high-flow discharge at the field site from the station discharge. These data were then used to convert flow stage to discharge data for flow stage greater than 0.7 m, which corresponds to 5 m^3/s.

Three-dimensional velocity measurements were taken with a Sontek Acoustic Doppler Velocimeter (ADV). The ADV provides single-point measurements in a small sampling volume located 5 cm below the probe at frequencies of 25 Hz. Bed shear stress estimates were calculated from the velocity data obtained by the ADV between 5 and 10 cm from the bed for two different flow stages. Each set included an average of 65 points well distributed upstream and downstream of the downstream deflectors. Based on results from Biron et al. (2004b) who compared different methods of estimating bed shear stress in a complex flow field around deflectors, the Reynolds shear stress (Eq. 1) and Turbulent Kinetic Energy (TKE) (Eq. 2) methods were used to estimate bed shear stress (τ_0):

[1] $$\tau_0 = -\rho < u'w' >$$

[2] $$\tau_0 = C_1\left[0.5\rho(< u'^2 > + < v'^2 > + < w'^2 >)\right]$$

where *u'*,*v'* and *w'* are the velocity fluctuations of the streamwise, lateral and vertical component of velocity, ρ is mass density, C_1 is taken as 0.19 and < > indicates a time average.

Two-dimensional surface velocities were also obtained in this project through the adaptation of Particle Image Velocimetry (PIV), typically used only in laboratory flumes (Grant 1997), for natural rivers. Four docking stations for a camera were built; two on each bank at the downstream deflector level and at the riffle level downstream of the deflectors. Movies were taken with a Panasonic digital camcorder equipped with a polarized lens to avoid reflection. The methodology and first results are presented elsewhere (Carré et al. in review), where PIV data are used to obtain higher density velocity measurements for the purpose of validating a three-dimensional numerical model.

Bed topography surveys are used to quantify yearly bedload transport changes by comparing pre-existing topography datasets obtained between 1999 and 2005. Bed load sediment transport was also assessed in more detail using two methods: sediment traps and tracer rocks. Three sediment traps were installed downstream of the downstream deflector in a riffle cross-section to obtain estimates of the bulk rate of bedload sediment movement. In addition, two hundred painted particles were deployed in 2004 at two cross-sections divided in five zones in order to investigate the sorting of sediment, thickness of the active layer and distance moved for individual particles. The individual particles were positioned upstream of the second boulder deflector and downstream of the second boulder deflector on the riffle (Figure 2). To investigate differential transport rates as a function of grain size, five size groups were selected: < 42.5mm (1), < 64mm (2), < 90.5mm (3), < 128mm (4), and < 256mm (5). The number of rocks for each size range were choosen proportionaly to the grain size distribution found at each cross section. To easily recognize each rock, the coding system used had a principal color for each zone and a secondary color for each size.

The tracer rocks were monitored after each significant flood in 2004 (Figure 3). Overall, six complete surveys of the particles were taken. During the successive monitoring, the percentage of recovery decreased due to several factors, such as sediment and algae deposition on the painted rocks, and particle~~s~~ burial by sand or under the active layer. It was therefore decided to use an alternative method in 2005: the Radio Frequency Identification (RFID) system with Passive Integrated Transponder (PIT) tag. PIT tags have been used extensively to monitor the movement of fish (Zydlewski et al. 2001, Bruyndoncx et al. 2002). Recently, this method has been successfully used for tracking individual particles in gravel-bed rivers (Nichols 2004, Lamarre et al. 2005). In this study, we have used a technology similar to that used by (Nichols 2004), with the transponder implanted in natural particles and with a series of improvements, mainly in terms of optimisation of the field coverage, and easy identification of particles with color coating.

We used PIT tags developed by TIRIS (Texas Instrument Registration and Identification System) technology and distributed by Texas Instruments. We chose 32mm glass Transponders with read and write capabilities, with a Reader Frequency of 134.2 kHz (Figure 4a). The range is less than or equal to 1.0 m, depending of the tag position and the size of the rock. The coding was done by using a TIRIS Series 2000 Reader S251B also manufactured by Texas Instruments, as well as a PC using a program called S2000 Reader Software, from TI. The power is supplied to the reader in the form of two 6V lantern batteries connected in series. Attached to the reader was a Series 2000 Stick Antenna (Texas Instruments), which was programmed to read off the transponder ID. This antenna was placed at the end of a 2-meter long clear plastic tube with an attached buzzer connected to the reader that alerted the reading of a tagged rock (Figure 4b). The tube was sealed at one end and capped at the other, allowing the antenna and its wire to be easily removed. Similarly, a modified Series 2000 medium Gate Antenna (Texas Instruments) was used interchangeably with the Stick Antenna, depending on the distribution of the rocks, and whether they were located below the armour layer, or covered with sand and algae (Figure 4b). The Stick antenna provides a focused read zone and an ability to separate between transponders in close proximity whereas the multidirectional antenna is used in locations where the reading field coverage needs to be maximized.

110 rocks were collected and sorted into the following four size categories: < 64mm (2), < 90mm (3), < 125mm (4), and < 250mm (5). Their dimensions, a, b, and c, were also taken, with the convention being that a > b > c. Their volume was determined from the displacement volume of the particle in a container of water and used to calculate the density in kg/m^3. They were soaked overnight, washed, brushed and dried in the laboratory. All 110 rocks, as well as a few additional ones, were given three coats of fluorescent orange paint, drilled, properly air-dried, and glass tags were implanted and sealed with resin (Figure 4c). The fluorescent paint was used as a means of easily identifying the drilled rocks from the surface of the water. They were programmed once sealed inside the rocks, and were given coded ID's ranging from 1 to 110.

The machine used for the drilling of all rocks was a Cleereman Drill Press, used at a speed of 150 revolutions/minute. A ¾ inch (19.1 mm) diameter self-cleaning diamond coring bit, with a wall thickness of $^1/_8$ inch (3.2 mm) was used. The ¾ inch drill bit was attached through an adapter to a water supply, and lasted for all 110 rocks drilled. Drill time varied with rock size, ranging from 1 or 2 minutes to roughly 7 minutes, for the smallest and largest sizes respectively. To hold the rocks down, two large metal screws secured a hollow metal pipe that forced the rocks against the bottom of a plastic container used to catch the excess water and material. Once the drilling was complete and the rocks loosened from their supports, their core was removed with a small chisel and hammer. To seal the holes and securely fix the transponders, Bondo Fibreglass Resin with Hardener was used. Once completed, all rocks were weighed using an electronic balance.

The rocks were then transported to the river, and placed randomly along two different cross-sections of the river: 50 upstream and 60 downstream of the downstream deflectors of the study reach (Figures 2 and 4d). The cross-sections were 21-metre wide, and successive rocks were placed at approximately 0.25 m distance, measured from centre-to-centre. The initial positions of every individual tracer rock were taken with a Leica Total station and recorded on a database with their corresponding ID. After every significant flood, a tracer-rocks survey has been taken. However, since the interest is the sediment movement around the deflectors, once any given rock on the downstream cross section moved more than 15 meters downstream of its initial location, it was moved and placed again upon the original position. Maps of bed topography and of the rock positions relative to the river were created with ESRI ArcGIS 8.2 software.

RESULTS

Repeated detailed bed and bank topography surveys taken between 1999 and 2005 to monitor bed morphology changes and the dynamics of the riffle-pool sequences. The pool zones were defined as areas below a fixed elevation threshold (corresponding to the average bed height) obtained from the total station measurements. Results show that the pool of the upstream deflectors became larger with time (Figure 5a). In comparison, the pool of the downstream deflectors only experienced minor changes over that time period (Figure 5b). Long-term monitoring, however, is required to determine whether this trend will continue and how major floods will affect the interaction between deflectors and pools.

Velocity data obtained at low flow with the ADV around the downstream set of deflectors reveal a marked decrease in flow velocity in the recirculation zone downtream of the deflectors (Figure 6a). Both methods of bed shear stress estimates reveal larger values where the channel is constricted by deflectors, as well as further downstream in the centre of the channel (Figure 6b,c). Both velocities and bed shear stress reveal a relatively symmetrical disruption to the flow field on each side of the deflectors.

Figure 7 shows the position of the particles after the passage of floods. Both the painted rocks (Figure 7a) and the PIT tag tracers (Figure 7b) show marked differences in bedload transport patterns from the left to the right bank downstream of the deflectors. The PIT tag tracers had a recovery rate of close to 100%, and allowed the recovery of fine particles at large distances downstream (around 100 m) that would have been lost using the painted rock method (Figure 7b). Furthermore, particles can be recovered even when buried under 0.60 m of sediment. Particles were recovered from depths of 0.25 to 0.45 m under sand and gravel layers, which also gives an indication of the depth of the active layer. From the painted rock results, it appears that there is an increasing downstream movement from the right to the left bank (looking downstream). The PIT-tag observations, however, provide a somewhat different interpretation of bedload pattern. Although there is clearly more transport occurring on the left side, some particles on the right side were also transported for long distances downstream after the first big flood. Because each particle was coded in 2005, it is possible to see that bedload transport is actually occurring on each side of the pool, and that particles are then entrained towards the centre of the channel (Figure 7b).

Results from the three sediment traps also indicated a lateral variation in both the volume of transport and grain size. Particles found in the right-bank trap (looking downstream) were mostly sand and gravel, whereas those in the left-bank trap were coarser gravel, with no sand. In 2004, flow conditions were particularly high compared to previous years. Each flood completely filled the sediment traps and further analysis was not possible for most of the floods. In 2005, the trap openings were reduced to avoid the complete filling of the traps during a flood to allow transport rates to be estimated. For the flood of September 1, the volume was 2.5 times larger in the left trap (0.170 m^3) than in the right trap (0.068 m^3), with an intermediate value in the middle trap (0.117 m^3).

Different flow patterns will occur depending on whether the flow overtops or goes around the deflectors. Overtopping flows start at approximately 8 m^3/s for the second set of deflectors. In 2004, there was no clear relationship between the maximum discharge and the travel distance of tracer particles (Figure 8a). For example, the third flood, with a maximum discharge of 22.71 m^3/s (overtopping flow), moved particles for distances similar to the fourth flood, which only reached a maximum discharge of 8.06 m^3/s. Only the last flood was able to move particles for considerable distances. With the exception of the period from 6 to 20 August 2004, the expected decrease in travel distance with increasing size was also not observed (Figure 8a). This seems to be related to the low recovery rate of painted particles, particularly of the smallest size, which was in the order of 85% at the beginning of the field season, and decreased to about 50% at the end. In contrast, the recovery rate was 97% for the PIT tags used in 2005 (107 out of the 110 initial rocks), and did not decrease with successive floods. There is a clearer relationship between maximum discharge and travel distance in 2005 using PIT tags (Figure 8b). There is also a marked difference in tranport between the upstream and downstream cross-sections, with travel distances on average (for the four grain sizes) of 5.0 m downstream of deflectors compared to only 1.8 m upstream during the first flood (Figure 8b). The average travel distance for the June 21, July 4 period (discharge of 21.1 m^3/s – about 70% bankfull, overtopping flow) was 8.5 m for the smallest size, and 1.7 m for the largest one, whereas it was only 0.30 m and 0.08 m for the smallest and largest sizes, respectively, for a discharge corresponding to about half bankfull (14.1 m^3/s, overtopping flow, Table 1). The lack of movement generated by the latter flood is surprising. It may indicate that an armour layer was formed after the first flood, and that only a very important flood will be able to move particles.

DISCUSSION

Flow and sediment transport dynamics around paired deflectors are much more complex than that often presented in stream restoration guidelines (Hey (1996), Figure 6.9). For example, a symmetrical disruption of the flow field, resulting in a symmetrical bedload pattern, would be expected downstream of paired deflectors (Hey 1996). Indeed, mean velocity and bed shear stress patterns (Figure 6) revealed a symmetrical distribution. This, however, is in contrast with the observed particle movement where more transport occurs on the left. This suggests that during high flow conditions, where water flows above the deflector height, bed shear stress patterns might be asymmetrical at the Nicolet River. Flows above approximately 8 m^3/s start to overtop the deflectors, therefore producing different flow patterns. Asymmetrical scouring processes near paired obstructions were also observed by Thompson (2006) in a laboratory flume. The differences in scour of paired pools were attributed to minor variations in local turbulence generation and sediment transport, producing a feedback with the final morphology (Thompson

2006). More flow dynamics observations during overtopping conditions, such as those obtained by Thompson (2002b), are clearly essential for the understanding of the complex flow dynamics and sediment transport around these structures.

There are many difficulties in obtaining a detailed field dataset on flow and sediment transport dynamics in a river of the size of the Nicolet, which is too small to be easily surveyed by boat, and too large to collect information during high flow stage. Methods need to be developed to remotely obtain as much information as possible. PIT tags are very promising in terms of particle movement assessment, with a near-to-perfect recovery rate despite some deeply buried particles (up to 0.60 m). Nichols (2004) also reported high recovery rates using the PIT-tag technology on spherical concrete particles after four runoff events (98% and 94% in two gravel-bed channels, respectively), whereas the recovery rates of Lamarre et al. (2005) were 96% and 87% after the first and second event, respectively. The lower recovery rate in the latter case was attributed to particles buried too deeply within the substrate, particles too close together, or particles that had moved outside of the sampling section. More detailed information on particle movements are hoped to be obtained by placing PIT tag particles on five cross-sections (two upstream, two downstream of deflectors and one between deflectors).

The major difficulty lies in bed velocity and bed shear stress estimates at the reach scale. Point measurements such as those collected with an ADV are difficult and time-consuming to collect, which means that flow stage cannot necessarily be maintained constant between during the sampling period. The Acoustic Doppler Profilers (ADPs) technology would allow entire vertical profiles to be collected simultaneously. However, they are not well-suited for shallow environments. Pulse-Coherent ADPs can be used in shallower flows, but the level of error has been shown to be high in zones with high levels of turbulence (*A. Roy, pers. comm.*), such as that typically observed around deflectors. Particle Image Velocimetry (PIV) seems a promising method to obtain high-density, simultaneous, two-dimensional velocity data in natural rivers (Carré et al. in review), but more tests are required to assess the impact of seeding, light, water surface irregularities, etc.

The long-term field monitoring programme initiated in 1999 on the rehabilitation work of the Nicolet River which began in 1993 in is an invaluable tool to assess the stability of instream structures, as the majority of restored reach evaluations gauge the success of these projects less than five years after completion (Thompson and Stull 2002). If, following Platts and Rinne (1985), one assesses the success of a restoration scheme based on the ability of the structures to remain stable in the channel, the Nicolet River project would be considered successful. Based on discharge data from a gauging station 65 km downstream of the study reach, the return interval of the largest flood since the first structures were installed was only 12 years. However, less than 10-year return interval floods have been observed to cause more than 50% of the habitat structures to fail in coastal Oregon and Washington streams (Frissel and Nawa 1992). Our repeated bed morphology surveys also reveal that the downstream pool size and shape is relatively stable (Figure 5b). However, the upstream pool shape has been much more variable with fluctuating annual flows (Figure 5a), indicating the river is still adjusting to reach a dynamic equilibrium (Schmetterling and Pierce 1999). Note that the upstream pool and deflectors are located in the downstream section of a meandering reach, whereas the river is very straight further downstream (Figure 1a). This further complicates the dynamics around these upstream deflectors.

Considering the large number of failed restoration projects, a more scientific approach to channel-restoration design is required (Thompson and Stull 2002). Three-dimensional numerical modelling will clearly play a growing role in representing complex flow situations in the context of habitat studies (Leclerc 2005). In the case of the Nicolet River, where future restoration schemes are envisaged, such models would allow testing of different scenarios of deflector angles and length prior to their expensive implementation in the field. For these models to be calibrated and validated, extensive field data are required. It is therefore essential to properly plan field data collection so that the density of information is compatible with the output of these models.

CONCLUSION

Although there is a clear need for more detailed field research on how instream structures interact with the river flow dynamics and sediment transport patterns, results of this research show that these types of data are difficult to obtain, which might explain why most studies on flow deflectors are done in a laboratory setting. Results on velocity and bed shear stress obtained at low flow in this study showed an expected symmetrical pattern around paired deflectors – high values of bed shear stress and velocity in the centre, low values on either side. This, however, did not match well the observed bedload transport pattern corresponding to high flows which indicated more movement on the left side. The use of PIT tag tracers has greatly improved our understanding of bedload transport around deflectors since it is possible to follow individual particle paths. This has revealed that bedload transport seems to occur on both sides of the pool, and is redirected towards the centre of the channel. More data at high flow, when water is overtopping deflectors, are required to fully understand the complex flow dynamics around these structures. Nevertheless, the near-bed shear stress and bedload transport measurements obtained in this study will be very helpful in assessing the accuracy of three-dimensional numerical simulations, which will hopefully improve the success rate of future stream restoration projects.

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REFERENCES

Biron, P.M., Robson, C., Lapointe, M.F., and Gaskin, S. 2004a. Deflector designs for fish habitat restoration. Environmental Management **33 (1)**: 25-35.

Biron, P.M., Robson, C., Lapointe, M.F., and Gaskin, S. 2004b. Comparing different methods of bed shear stress estimates in simple and complex flow fields. Earth Surface Processes and Landforms **29 (11)**: 1403-1415.

Booker, D.J., Sear, D.A., Payne, A.J. 2001. Modeling three-dimensional flow structures and patterns of boundary shear stress in a natural pool-riffle sequence. Earth Surface Processes and Landforms **26 (5)**: 553-576.

Brookes, A., Knight, S.S. and Shields Jr., F.D. 1996. Habitat enhancement, pp. 103-126 *in* Brookes, A. and Shields Jr., F.D. [eds.], River Channel Restoration: Guiding principles for sustainable projects. John Wiley and sons, New York.

Bruyndoncx, L., Knaepkens, G., Meeust, W., Bervoets, L. and Eens, M. 2002. The evaluation of passive integrated transponder (PIT) tags and visible implant elastomer (VIE) marks as new marking techniques for the bullhead. Journal of Fish Biology, **60**: 260-262.

Carré, D.M., Biron, P.M. and Gaskin, S.J. in review. A three-dimensional model of flow dynamics around paired deflectors for fish habitat enhancement. River Flow 2006.

Ferguson, R.I., Parsons, D.R., Lane, S.N. and Hardy, R.J. 2003. Flow in meander bends with recirculation at the inner bank. Water Resources Research, **39(11)**: 1322-1334.

Frissel, C.A. and Nawa, R.K. 1992. Incidences and causes of physical failure of artificial habitat structures in streams of western Oregon and Washington. North American Journal of Fisheries Management, **12**: 182-197.

Gore, J.A., Judy, R.D. 1981. Predictive Models of Benthic Macro invertebrate Density for use in Instream Flow Studies and Regulated Flow Management. Canadian Journal of Fisheries and Aquatic Sciences, **38 (11)**: 1363-1370.

Grant, I. 1997. Particle Image Velocimetry: A review. Proceedings of the institution of mechanical engineers. Journal of Mechanical Engineering Science, **211 (1)**: 55-76.

Hey, R.D. 1996. Environmentally sensitive river engineering (Chapter 6). In: Petts, G. and Calow, P. (Eds.) River Restoration. Blackwell Science, Oxford.

Hunter, C.J. 1991. Better Trout Habitat. Island, Washington, D.C.

Lamarre, H., McVicar, B. and Roy, A.G. 2005. Using passive integrated transponder (PIT) tags to investigate sediment transport in gravel-bed rivers. Journal of Sedimentary Research, **75, 4**, 736-741.

Lamouroux, N., Statzner, B., Fuchs, U., Kohman, F., Schmedtje, U. 1992. An unconventional approach to modeling spatial and temporal variability of local shear-stress in stream segments. Water Resources Research **28 (12)**: 3251-3258.

Lamouroux, N., Souchon, Y., Herouin, E. 1995. Predicting velocity frequency-distribution in stream reaches. Water Resources Research **31 (9)**: 2367-2375.

Lamouroux, N. 1998a. Depth probability distributions in stream reaches. Journal of Hydraulic Engineering, ASCE, **124 (2)**: 224-227.

Lamouroux, N., Capra, H., Pouilly, M. 1998b. Predicting habitat suitability for lotic fish: Linking statistical hydraulic models with multivariate habitat use models. Regulated Rivers-Research and Management, **14 (1)**.

Lane, S.N., Bradbrook, K.F., Richards, K.S., Biron, P.M., Roy, A.G. 1999. The application of computational fluid dynamics to natural river channels: three-dimensional versus two-dimensional approaches. Geomorphology **29 (1-2)**: 1-20.

Lane, S.N., Bradbrook, K.F., Richards, K.S., Biron, P.M., Roy, A.G. 2000. Secondary circulation cells in river channel confluences: measurement artefacts or coherent flow structures? Hydrological Processes **14 (11-12)**: 2047-2071.

Lane, S.N., Hardy, R.J., Elliott, L., Ingham, D.B. 2004. Numerical modeling of flow processes over gravelly surfaces using structured grids and a numerical porosity treatment. Water Resources Research **40 (1)**.

Lane, S.N., Hardy, R.J., Ferguson, R.I. and Parson, D.R. 2005. A framework for model verification and validation of CFD schemes in natural open channel flows. In: Bates, P.D., Lane, S.N. and Ferguson, R.I. (eds.). Computational Fluid Dynamics: Applications in Environmental Hydraulics. Wiley, 169-192.

Leclerc, M. 2005. Ecohydraulics: A new interdisciplinary frontier for CFD. In: Bates, P.D., Lane, S.N. and Ferguson, R.I. (eds.). Computational Fluid Dynamics: Applications in Environmental Hydraulics. Wiley, 429-460.

Maddock, I. 1999. The importance of physical habitat assessment for evaluating river health. Freshwater Biology, **41**: 373-391.

Mäki-Petäys, A., Huusko, A., Erkinaro, J. and Muotka, T. 2002. Transferability of habitat suitability criteria of juvenile Atlantic salmon (*Salmo salar*). Canadian Journal of Fisheries and Aquatic Sciences, **59**: 218-228.

Meselhe, E.A., Peeva, T., Muste, M. 2004. Large scale particle image velocimetry for low velocity and shallow water flows. Journal of Hydraulic Engineering, ASCE, **130 (9)**: 937-940.

Nicholas, A.P., Smith, G.H.S. 1999. Numerical simulation of three-dimensional flow hydraulics in a braided channel. Hydrological Processes, **13 (6)**: 913-929.

Nichols, M.H. 2004. A radio frequency identification system for monitoring coarse sediment particle displacement. Applied Engineering in Agriculture, **20 (6)**: 783-787.

Platts, W.S. and Rinne, J.N. 1985. Riparian and stream enhancement management and research in the Rocky Mountains. North American Journal of Fisheries Management, **5**: 115-125.

Roni, P., Beechie, T. J., Bilby, R. E., Leonetti, F. E., Pollock, M. M. and Pess, G. R. 2002. A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific northwest watersheds. North American Journal of Fisheries Management, **22**: 1-20.

Schmetterling, D.A. and Pierce, R.W. 1999. Success of instream habitat structures after a 50-year flood in Gold Creek, Montana. Restoration Ecology, **7 (4)**: 369-375.

Thompson, D.M. 2002a. Long-term effect of instream habitat-improvement structures on channel morphology along the Blackledge and Salmon Rivers, Connecticut, USA. Environmental Management **29 (1)**: 250 65.

Thompson, D.M. 2002b. Channel-bed scour with high versus low deflectors. Journal of Hydraulic Engineering, **128 (6)**: 640-643.

Thompson, D.M. 2006. The role of vortex shedding in the scour of pools. Advances in Water Resources, **29**: 121-129.

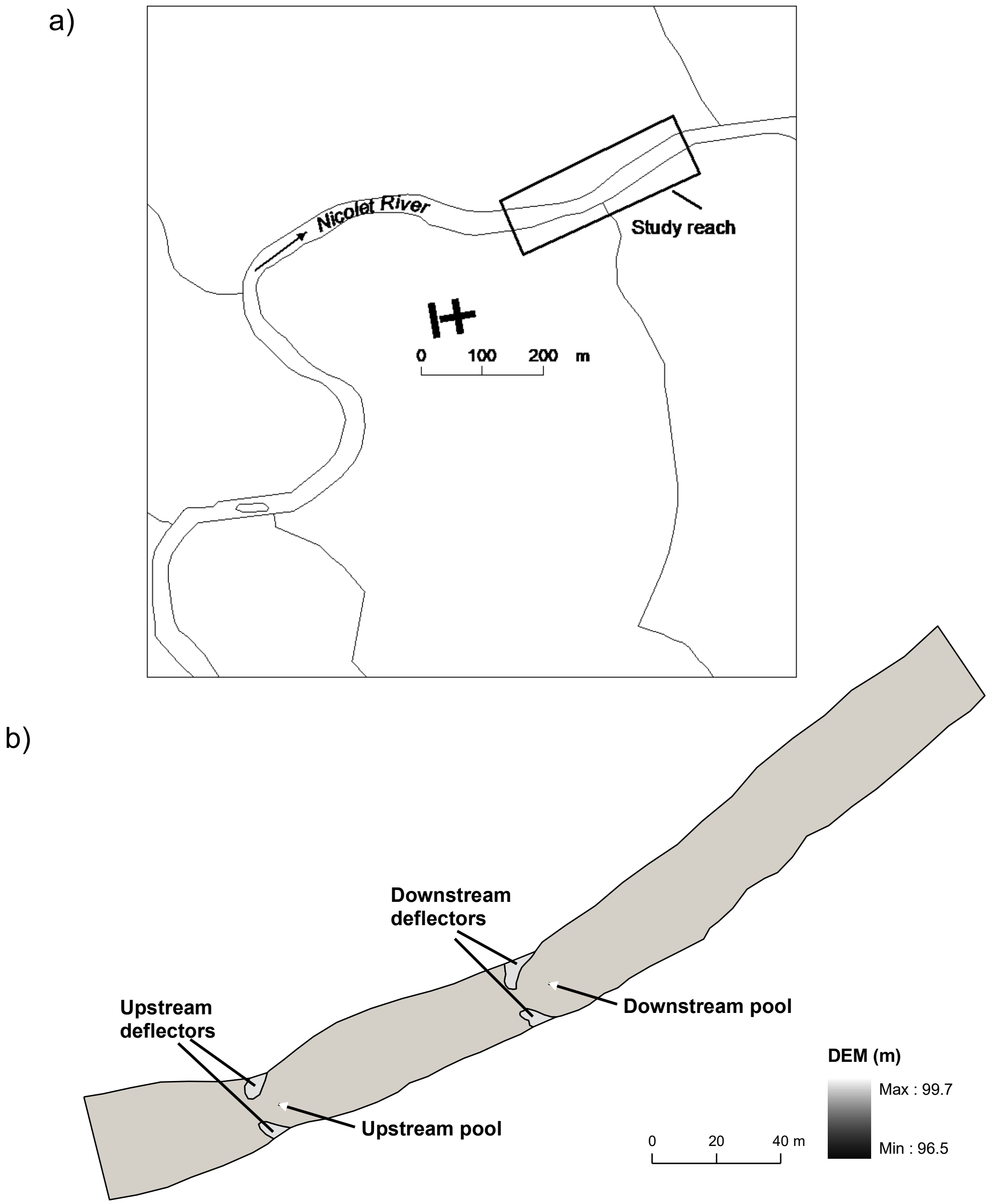
Thompson, D.M. and Stull, G.N. 2002. The development and historic use of habitat structures in channel restoration in the United States: the grand experiment in fisheries management. Géographie physique et Quaternaire, **56 (1):** 45-60.

Zydlewski, G.B., Haro, A., Whalen, K.G. and McCormick, S.D. 2001. Performance of stationary and portable passive transponder detection systems for monitoring of fish movements. Journal of Fish Biology, **58**: 1471-1475.

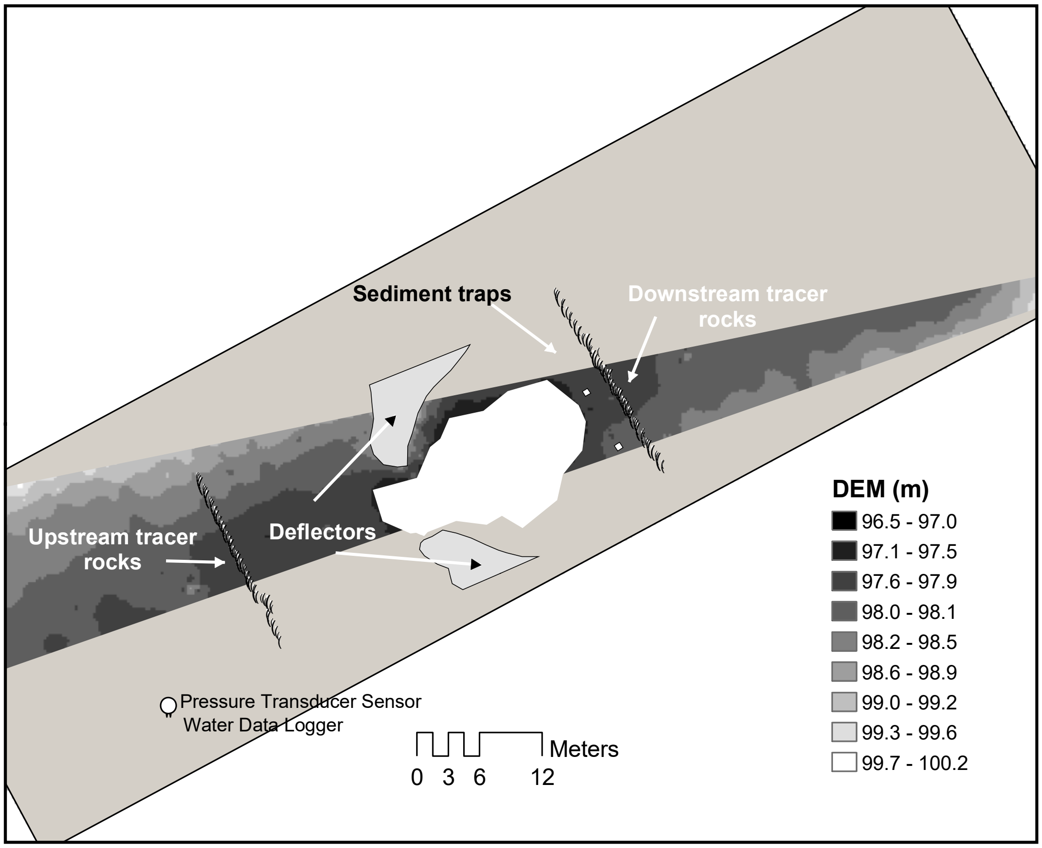
Table 1. Average and maximum travel distances for PIT tag tracers for three floods in 2005.

Period	Max discharge of flood (m^3/s)	Size	Average Distance (m)	Max distance (m)
21 June – 4 July	21.1	2	8.33	97.28
		3	2.09	19.22
		4	2.00	11.98
		5	1.68	12.42
July 4 – August 3	8.0	2	0.04	0.20
		3	0.04	0.26
		4	0.23	4.83
		5	0.04	0.18
August 3 – Sept. 5	14.1	2	0.30	3.42
		3	0.17	2.32
		4	0.07	0.39
		5	0.08	0.44

List of Figures

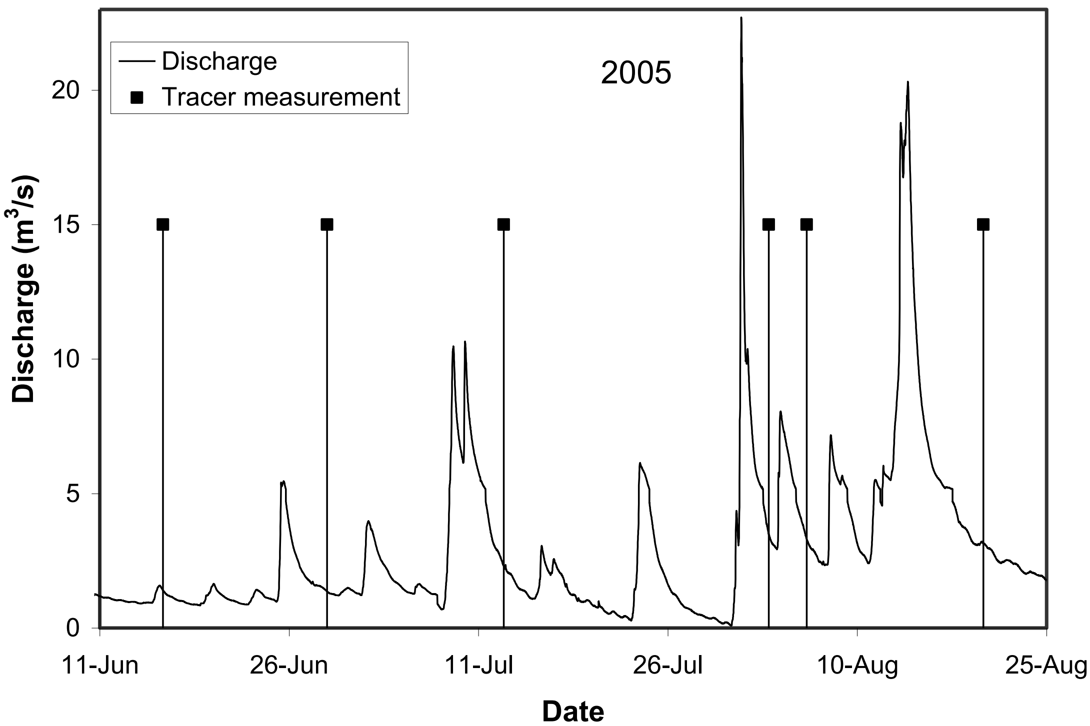


a)
Nicolet River
Study reach
0 100 200 m
b)
Downstream deflectors
Downstream pool
Upstream deflectors
Upstream pool
DEM (m)
Max : 99.7
Min : 96.5
0 20 40 m

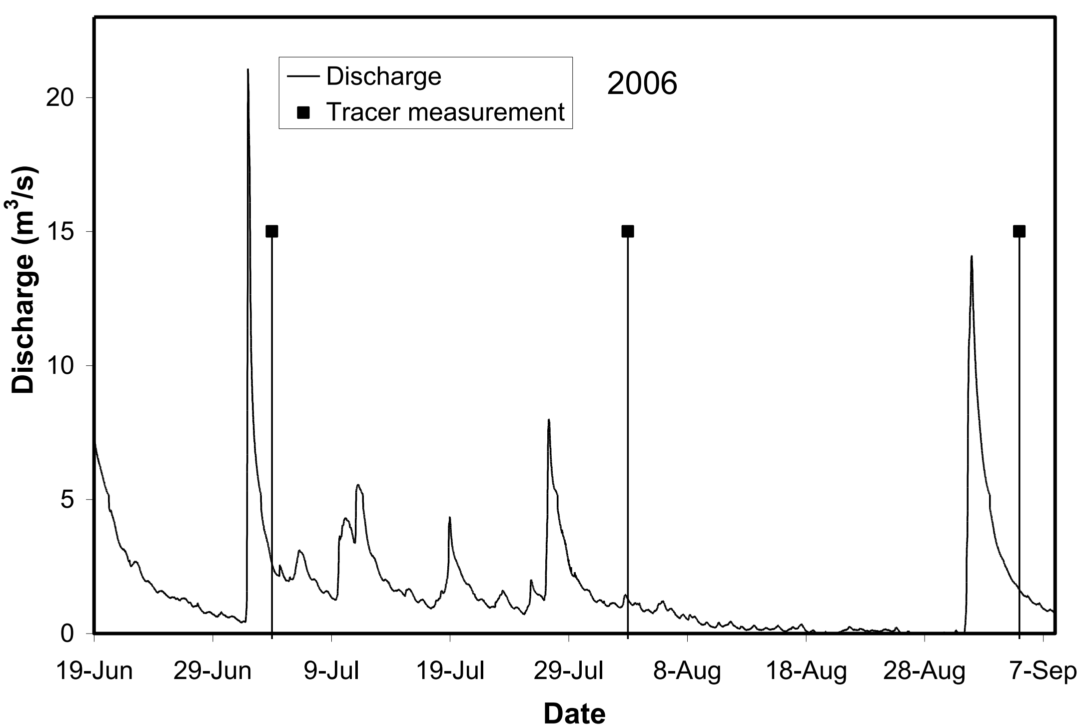


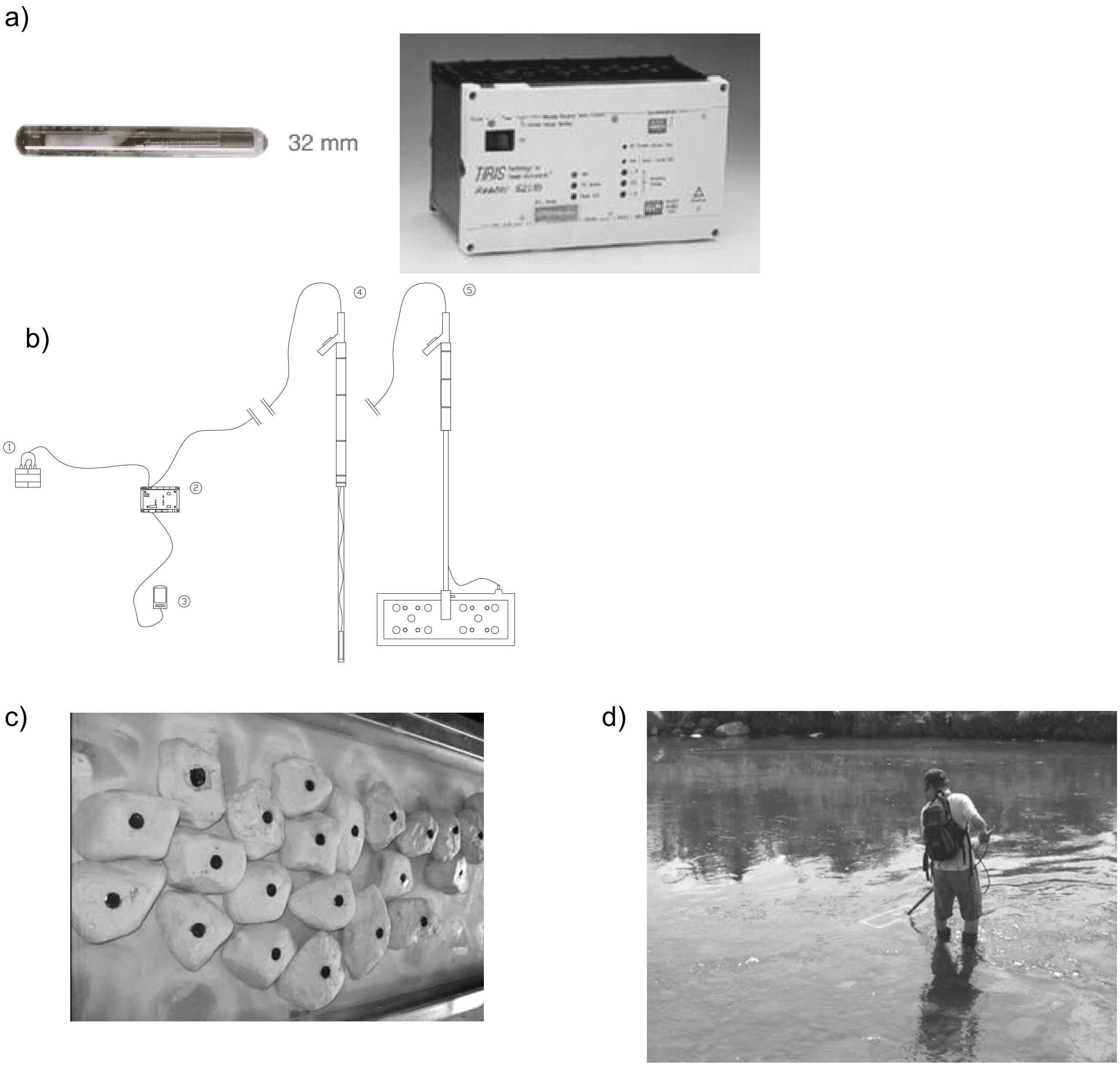
Sediment traps
Downstream tracer rocks
Upstream tracer rocks
Deflectors
DEM (m)
96.5 - 97.0
97.1 - 97.5
97.6 - 97.9
98.0 - 98.1
98.2 - 98.5
98.6 - 98.9
99.0 - 99.2
99.3 - 99.6
99.7 - 100.2
Pressure Transducer Sensor
Water Data Logger
Meters
0 3 6 12

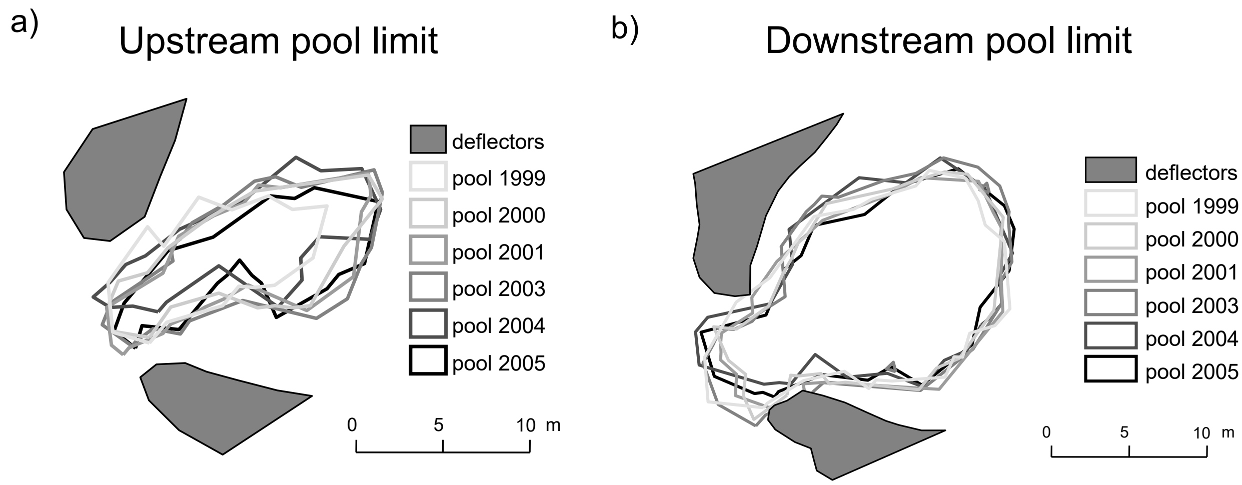
a)

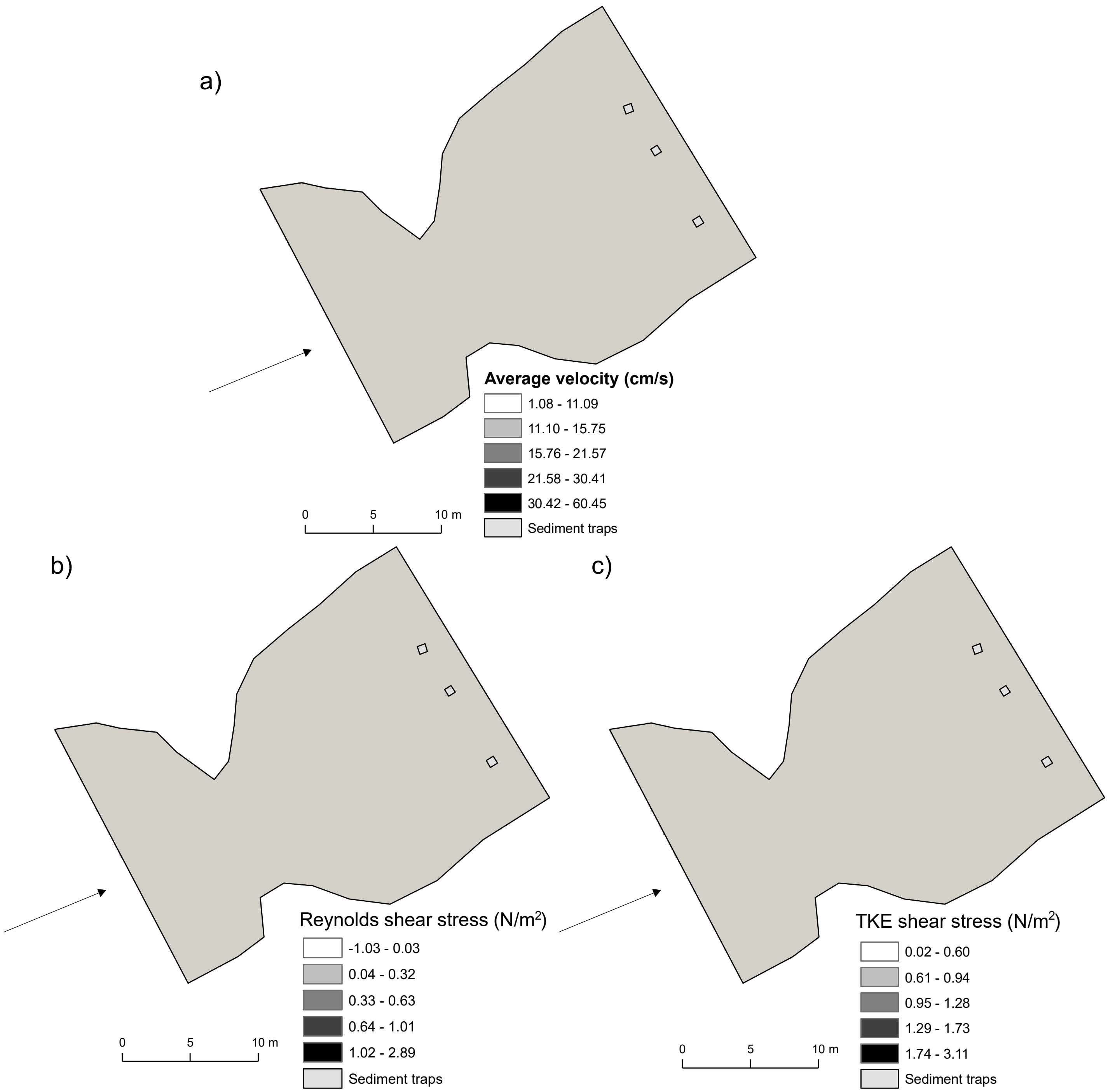

Discharge
Tracer measurement
2005
Discharge (m3/s)
0
5
10
15
20
11-Jun
26-Jun
11-Jul
26-Jul
10-Aug
25-Aug
Date

b)


Discharge
Tracer measurement
2006
Discharge (m3/s)
0
5
10
15
20
19-Jun
29-Jun
9-Jul
19-Jul
29-Jul
8-Aug
18-Aug
28-Aug
7-Sep
Date

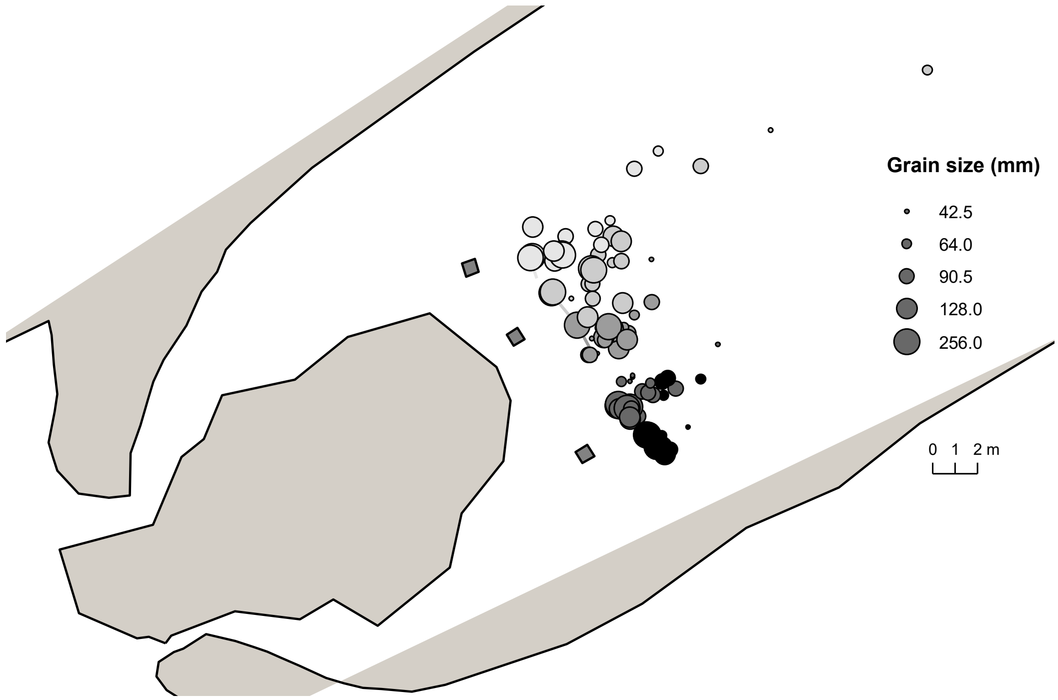

a)
32 mm
TIRIS
b)
①
②
③
④
⑤
c)
d)


a)
Upstream pool limit
deflectors
pool 1999
pool 2000
pool 2001
pool 2003
pool 2004
pool 2005
0
5
10
m
b)
Downstream pool limit
deflectors
pool 1999
pool 2000
pool 2001
pool 2003
pool 2004
pool 2005
0
5
10
m

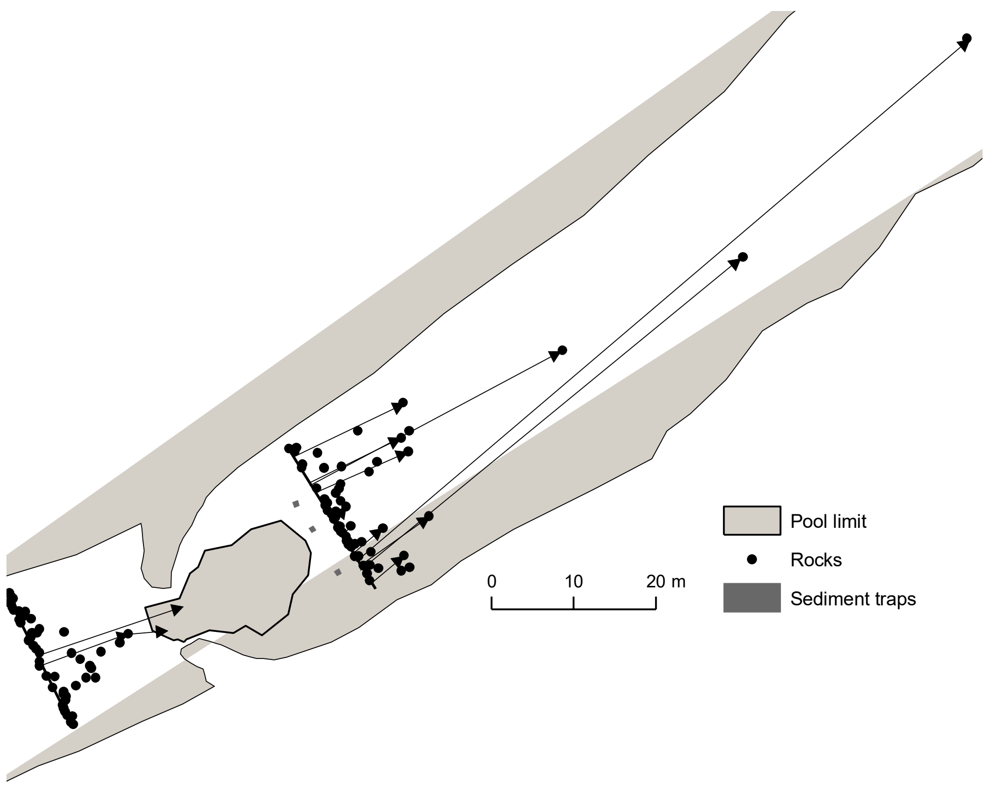


a)
Average velocity (cm/s)
1.08 - 11.09
11.10 - 15.75
15.76 - 21.57
21.58 - 30.41
30.42 - 60.45
Sediment traps
0
5
10 m
b)
Reynolds shear stress (N/m2)
-1.03 - 0.03
0.04 - 0.32
0.33 - 0.63
0.64 - 1.01
1.02 - 2.89
Sediment traps
0
5
10 m
c)
TKE shear stress (N/m2)
0.02 - 0.60
0.61 - 0.94
0.95 - 1.28
1.29 - 1.73
1.74 - 3.11
Sediment traps
0
5
10 m

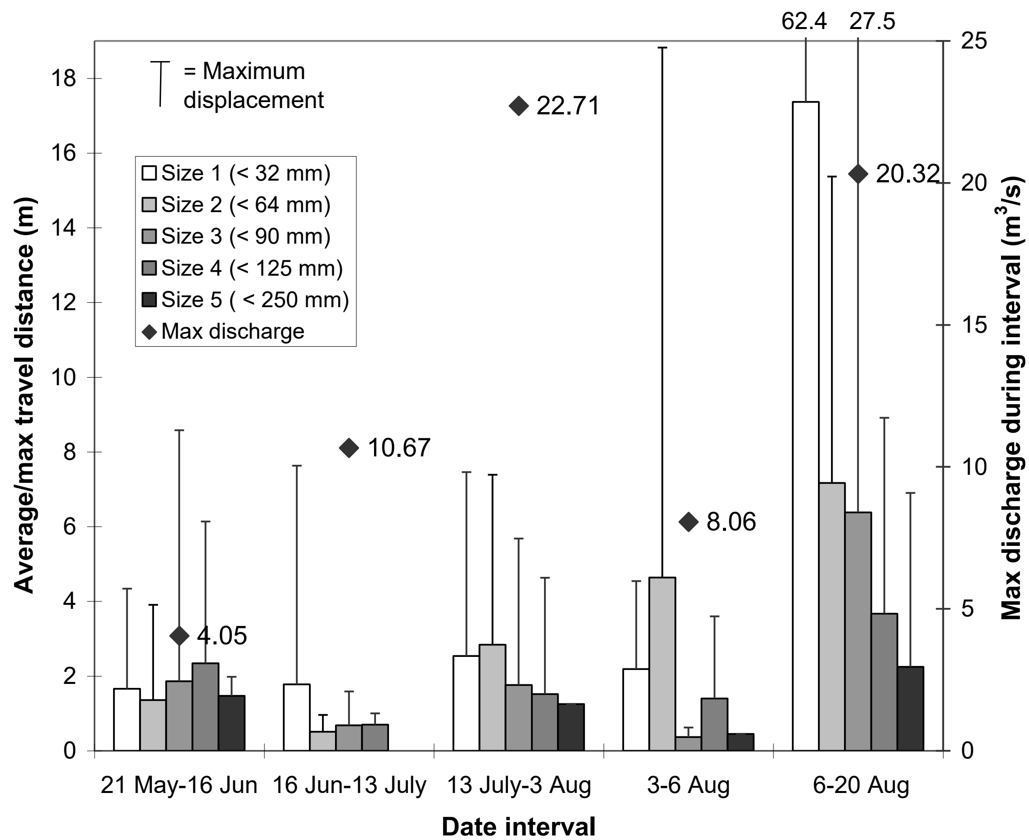
a)


Grain size (mm)
42.5
64.0
90.5
128.0
256.0
0 1 2 m

b)

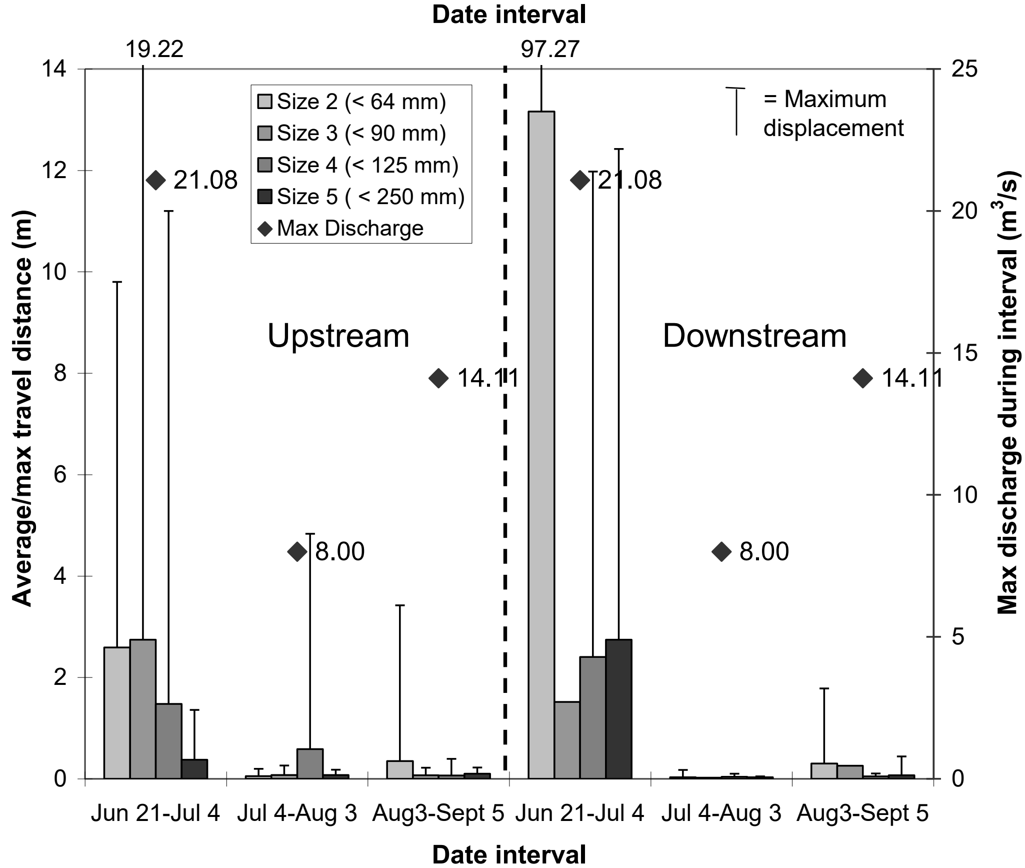

Pool limit
Rocks
Sediment traps
0 10 20 m

a)



= Maximum displacement
Size 1 (< 32 mm)
Size 2 (< 64 mm)
Size 3 (< 90 mm)
Size 4 (< 125 mm)
Size 5 (< 250 mm)
Max discharge
Average/max travel distance (m)
Max discharge during interval (m^3/s)
Date interval
21 May-16 Jun
16 Jun-13 July
13 July-3 Aug
3-6 Aug
6-20 Aug
62.4
27.5
22.71
20.32
10.67
8.06
4.05

b)



Size 2 (< 64 mm)
Size 3 (< 90 mm)
Size 4 (< 125 mm)
Size 5 (< 250 mm)
Max Discharge
= Maximum displacement
Upstream
Downstream
Average/max travel distance (m)
Max discharge during interval (m^3/s)
Date interval
Jun 21-Jul 4
Jul 4-Aug 3
Aug3-Sept 5
Jun 21-Jul 4
Jul 4-Aug 3
Aug3-Sept 5
19.22
97.27
21.08
21.08
14.11
14.11
8.00
8.00