SCIENCE CHINA
Technological Sciences

Special Topic: Erosion and Sedimentation
• Article •

August 2014 Vol.57 No.8: 1512–1521
doi: 10.1007/s11431-014-5607-0

# Influences and drivers of woody debris movement in urban watercourses

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Received March 25, 2014; accepted May 25, 2014

It is recognised that the blockage of culverts by woody debris can result in an increased risk of infrastructure damage and flooding. To date, debris transport analysis has focused on regional fluvial systems and large woody debris, both in flume and field experiments. Given the social and economic risk associated with urban flooding, and as urban drainage design shifts away from subsurface piped network reliance, there is an increasing need to understand debris movement in urban watercourses. The prediction of urban watercourse small woody debris (SWD) movement, both quantity and risk, has undergone only limited analysis predominantly due to lack of field data. This paper describes the development of a methodology to enable the collection of accurate and meaningful SWD residency and transportation data from watercourses. The presented research examines the limitations and effective function of PIT tag technology to collect SWD transport data in the field appropriate for risk and prediction analysis. Passive integrated transponder (PIT) technology provides a method to collect debris transport data within the urban environment. In this study, the tags are installed within small woody debris and released at known locations into a small urban natural watercourse enabling monitoring of movement and travel time. SWD velocity and detention are collated with solute time of travel, watercourse and point flow characteristics to identify the relationships between these key variables. The work presented tests three hypotheses: firstly, that the potential for unobstructed or un-detained SWD movement increases with flow velocity and water level. Secondly, that SWD travel distance, and the resistance forces along this travel path, influence SWD transport potential. Thirdly, the relationship between SWD and channel dimensions is examined with the aim of advancing representative debris transport prediction modelling.

**woody debris transport, prediction, urban flood risk, blockage, solute dye tracing**

**Citation:** Allen D, Arthur S, Haynes H, et al. Influences and drivers of woody debris movement in urban watercourses. Sci China Tech Sci, 2014, 57: 1512–1521, doi: 10.1007/s11431-014-5607-0

## 1 Introduction

Debris movement and deposition are key elements in local urban flood management. Large woody debris has been extensively considered in large river and rural settings with scaled physical and empirical modelling [1–3]. This work provides some understanding of small woody debris (SWD) impact on infrastructure and flood risk in rivers but is not scaled for urban watercourse use. Whilst flows through small urban watercourses may be lower in volume, the potential impact from flooding due to blockage on housing, local urban infrastructure and community safety can be high. With increasing implementation of Sustainable Urban Drainage Systems, daylighting of historically piped surface drainage and incorporation of blue-green elements in urban design, the need to understand debris movement and associated flood risk in the local urban environment has increased.

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Small woody debris movement is thought to be influenced by SWD dimensions, channel and flow characteristics. Braudrick and Grant [1] theorised that travel distance increased as the woody debris length to channel width and the SWD diameter relative to buoyancy depth ratios decreased. Bocchiola et al. [4] quantitatively determined velocity, turbulence and detention potential (blockage) to influence effective transport showing the importance of flow conditions in woody debris movement analysis. Woody debris transport monitoring across large watercourses and non-urban areas has been achieved using aerial photography, ground survey, pinch point and video monitoring, Carbon-14 dating and transponder tracking [5].

The aim of the research presented in this paper is to test the passive integrated transponder (PIT) technology with regards to its effectiveness in monitoring SWD movement in an urban watercourse. Given the earlier evidence, debris data of key interest are the successful transportation, watercourse detention rates and SWD velocity. Field activities were designed to investigate potential relationships between SWD residency and velocity with flow and channel characteristics, including sinuosity, roughness coefficient and turbulence.

With regards to data collection, active transponders have been used successfully in previous studies to provide source to deposition information; however their shortcoming is their battery power requirement. This makes them less amenable for use in a waterway environment as there is a risk of electronic failure if the water tight seal is damaged and they have a limited field life. Furthermore, the weight of the battery can have an impact on the buoyancy of small debris. Thus passive transponders are used in this study. These are small (4 mm diameter, 23 mm length) glass vacuum capsules that withstand temperature fluctuation, submersion and mineral encasement [5,6]. PIT tags can withstand extended field exposure to provide meaningful field data-sets. The tags are not powered, but respond to the active (powered) antenna, therefore enabling individual tag monitoring and analysis [5]. In comparison with active transponders, they provide indefinite field exposure and tracing potential at a higher level of detail than video monitoring and aerial photography. Furthermore, PIT tag monitoring does not have a significant impact on the carrier (debris, fish or terrestrial mammal) and causes limited environmental disturbance.

## 2 Methodology

### 2.1 The study site

The study site is a minor watercourse (Murray Burn) located within the southern extent of Edinburgh, Scotland. The Murray Burn has been previously used for fieldwork [7,8], investigating Advection-Dispersion Equation, Transient Storage and Aggregated Dead Zone models [8–10].

The watercourse is hydraulically non-uniform [8] and as such does not have consistent hydraulic mixing or flow characteristics. The experimental reach extends 722 m upstream from a Scottish Environment Protection Agency (SEPA) gauging station. Watercourse flows have been recorded up to 3 $m^3$/s, with the months preceding the experiments showing a flow range up to 1 $m^3$/s (August-November 2012).

The upper reach is wooded with a decaying debris understory. It is transitional, turbulent, moderately sinuous and has a moderate bed slope of 13–14 m/km [8]. The central reach is also wooded but with a dense ivy understory, while the lower reach is landscaped and grassed. This lower section has fewer natural obstructions (large rocks, tree branches and bank encroachment) and channel bed slope of 8–9 m/km [8]. There are two artificial hydraulic structures in the study area (as shown in Figure 1), box culverts associated with road crossings, which are in good condition and without significant debris obstruction. The watercourse is least sinuous along the central and lower experimental reaches (the SWD monitoring stretch) and is the most modified without reaching canalisation. The channel bed width with varies from 3.2–4.5 m, with a wider channel bed occurring in the upper reach. Along the lower section of the Murray Burn, the watercourse has a trapezoidal cross section with very steep banks and undercutting. Vegetation overhang in front of this undercutting is extensive, and undercutting extends up to 400 mm in places.

Small woody debris sampling was completed across the monitored reach of the watercourse to define naturally

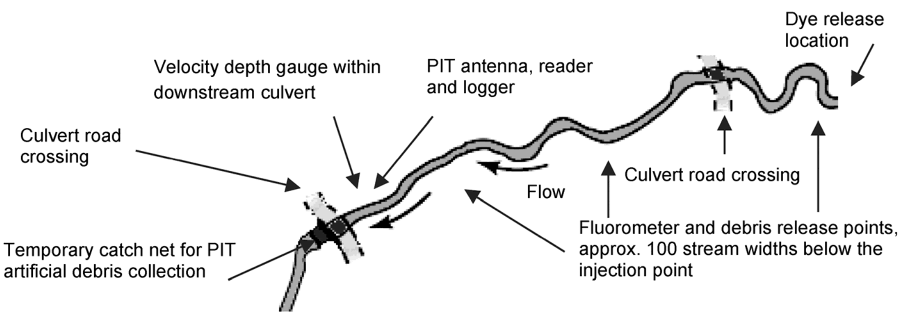


**Figure 1** Reach and field activity schematic (not to scale).

occurring SWD dimensions. The survey identified the predominant diameter of SWD on the bank and flood plains to be 10 mm, with the greatest sampled diameter of 35 mm. Woody debris was generally less than 1600 mm in length, with the majority extending no further than 800 mm. A simple variance analysis of grouped debris dimensions confirmed the most frequently occurring lengths were 200–400 mm followed by 0–200 mm and then 600–800 mm. Diameters of up to 15 mm, followed by 20–25 mm and 10–15 mm were most frequent. These groups determined the artificial SWD dimensions created for this transport analysis.

## 2.2 Experiment design

Artificial debris, representative of the reach SWD, was created using field sourced material. A selection of wood was trimmed to standard lengths, tagged and painted to enable field identification. Three lengths and diameters were used to achieve a representative sample diversity, (length: 150, 350, 750 mm; diameter: 10, 15, 25 mm) with 81 pieces created in total.

A looped antenna, depicted in Figure 2, was constructed in-stream enabling arrival time of each individual SWD element to be recorded. SWD arrival time and individual identity was collected via an electrical pulse send from the antenna, activating the PIT embedded in the woody debris.

Instantaneous Rhodamine dye release was used in sixteen experiments to determine the average flow velocity. At the downstream extent of the study area depth and velocity data was recorded for each experiment using a Greyline Stingray level-velocity. This setup enables the SWD transport velocity to be compared with the average flow velocity and mid-stream data collected by the Greyline Stingray device.

## 2.3 Data collected

Sixteen experiments were undertaken over a range of flows. Rhodamine dye was released from the upstream location and monitored at two downstream points (Monitoring Point (MP) 4 and an appropriate upstream point correlating to SWD release). Woody debris was released from three separate locations, increasing in distance upstream from the antenna (MP 1, 2 and 3) (Table 1). At each location, tagged SWD was released from the centre, left and right bank parallel to the flow at 30 s intervals with release order and time recorded.

Local water level and velocity was recorded for each experiment, using a point source level velocity meter, accounting for local climatic variations in conditions. Continuous fluorometry monitoring of the dye transport also provided detailed background fluorescent data and defined changes in reach specific flow velocity, natural lumines-

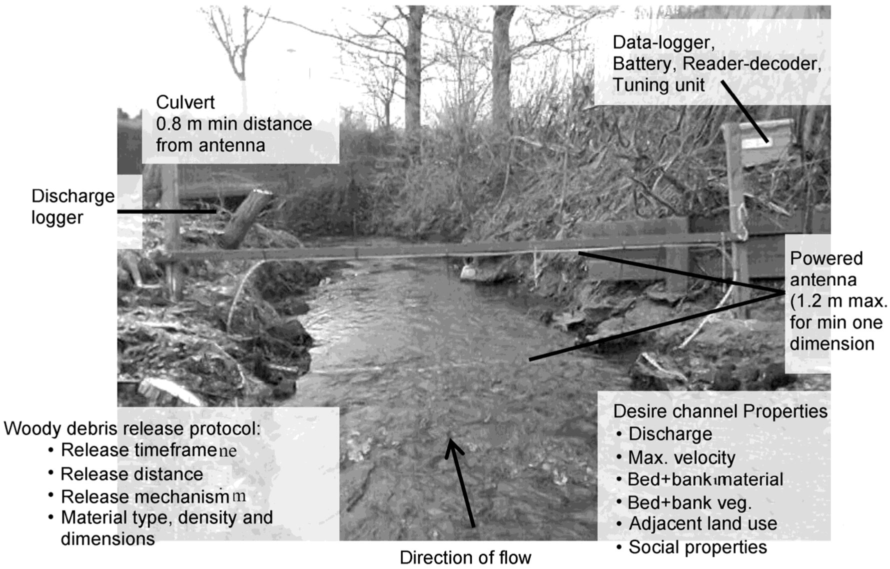


**Figure 2** Field equipment layout.

**Table 1** Monitoring location description

| Location | Distance from downstream monitoring point-MP4 (m) | Channel bed width (m) | Bank description |
|---|---|---|---|
| Dye release point | 722 | 4.2 | Moderately wooded, leaf litter and woody debris understory |
| MP3 | 353 | 4.5 | Moderately wooded, open ground and grass understory |
| MP2 | 267 | 3.5 | Moderately wooded, dense ivy understory |
| MP1 | 225 | 3.6 | Lightly wooded, grass flood plain banks |
| Antenna | 201 | 3.2 | Grass on left bank, garden bed on right bank |

cence, pH and turbidity.

Field work resulted in a comprehensive data set defining flow conditions and small woody debris movement within this urban watercourse. SWD transition time (SWD velocity, *Vs*), transport success rate (the potential for debris to move from entrainment location to the pinch point of interest) (*Ds*) and deposition rate (*Dt*) were extracted and analysed against flow velocity (*Vf*) and dye transition time (*Vc*).

Rhodamine dye concentration monitoring, undertaken at two locations using Cyclops 7 instrumentation, provided dye cloud transition curves (Figure 3(a) and (b)). The leading edge (Figure 3(a), line A), peak (B), centroid (C) and trailing edge (D) of the curves were identified and the dye velocity, concentration and mass loss over the monitored reach. Dye cloud velocity (time between the peaks) provided reach specific flow velocity for the time period during which field work was being completed.

Artificial woody debris was allowed three hours to reach the antenna, after which the detained debris was collected. Figure 3(b) shows an example of the raw SWD transport data which was used to calculate release location and experiment specific woody debris success rates and velocities. SWD detention, location and dam composition was recorded along the reach for each experiment, providing a dam composition database relative to flow conditions.

## 3 Results and analysis

A variety of factors with the potential to influence SWD movement were reviewed to identify any key influences that may define urban watercourse debris transport prediction. A range of experiment conditions, outlined in Table 2, were sampled over the course of the field work to identify the influence of water level, velocity and change in channel conditions on SWD transport.

### 3.1 Rhodamine dye movement

Released Rhodamine dispersed effectively over the 368 m mixing reach (the distance between release and upstream monitoring point). Dye was monitored from two locations, the upstream location concurrent with the debris release location and the downstream location close to the pinch point of interest. Dye reached the upstream monitoring point first, with a greater peak concentration and a shorter travel time for all dye to pass the monitoring point. Dye dispersion occurred over the monitored reach, resulting in a lower concentration peak at the downstream monitoring point but with a longer time for all dye to pass this point.

Locally specific flow characteristics were derived from

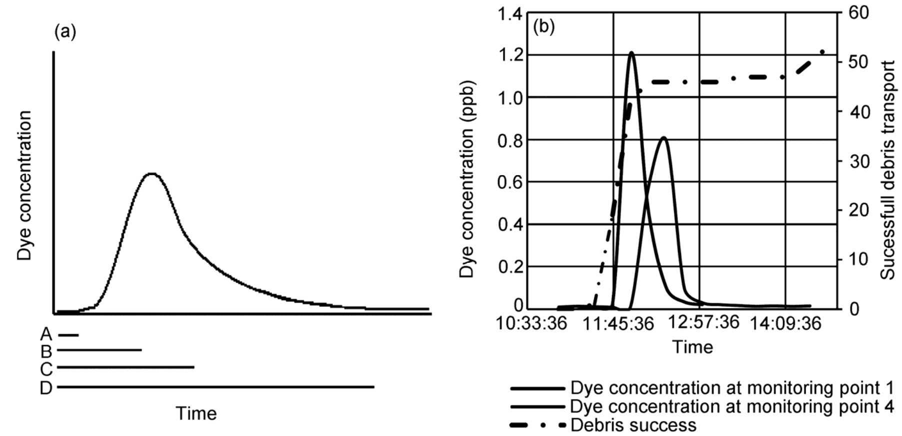


**Figure 3** Rhodamine dye transition (a) ([17], Figure 3 p255); an overview of the dye and SWD data collected from Experiment 1 (b).

**Table 2** Summary of experimental conditions

| Experiment | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| flow depth $z$ (m) | 0.130 | 0.129 | 0.130 | 0.130 | 0.129 | 0.113 | 0.113 | 0.113 |
| water velocity $Vf$ (m/s) | 0.437 | 0.423 | 0.431 | 0.445 | 0.445 | 0.445 | 0.409 | 0.407 |
| Flow rate $Q$ ($m^3$/s) | 0.065 | 0.122 | 0.075 | 0.122 | 0.122 | 0.056 | 0.056 | 0.04 |
| $Fr$ | 0.387 | 0.376 | 0.382 | 0.394 | 0.396 | 0.423 | 0.388 | 0.387 |
| $Re$ ($10^5$) | 1.25 | 1.22 | 1.28 | 1.24 | 1.23 | 1.12 | 1.03 | 1.02 |
| Experiment | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| flow depth $z$ (m) | 0.113 | 0.214 | 0.211 | 0.233 | 0.166 | 0.165 | 0.157 | 0.157 |
| water velocity $Vf$ (m/s) | 0.393 | 0.741 | 0.724 | 1.001 | 0.609 | 0.617 | 0.589 | 0.595 |
| Flow rate $Q$ ($m^3$/s) | 0.047 | 0.330 | 0.306 | 0.381 | 0.168 | 0.168 | 0.152 | 0.152 |
| $Fr$ | 0.373 | 0.511 | 0.503 | 0.662 | 0.478 | 0.485 | 0.474 | 0.479 |
| $Re$ ($10^5$) | 1.00 | 3.54 | 3.47 | 5.17 | 2.23 | 2.43 | 2.09 | 2.27 |

three separate data sources. Initial analysis of flow characteristics identified a good correlation between the site continuous depth/velocity monitor, SEPA gauge flow and flow calculated from dilution gauging (dye mass released/area under dye concentration profile) ($R^2$=0.80–0.93). Time taken for the dye cloud to pass decreased relative to an increase in flow velocity. The time between dye peak concentrations were used to calculate dye cloud velocity (*Vc*) relative to each experiment. The linear correlation between dye trace movement and flow velocity is illustrated in Figure 4.

Flow velocity was measured from the channel bed centre line rather than as a cross-sectional depth average and dye concentration was monitored 125 mm below the surface. Dye cloud velocity is an average centre line velocity for the length of the monitored reach and is therefore expected to differ from the point source monitored flow velocity.

The overall elevated flow velocities values are expected to occur due to instrumentation placement (proximity to the influence of a channel bend and culvert). When comparing the SEPA gauge, dispersion and monitored velocity/area calculated flows ($m/s^3$) it is noted that the monitored flow (and therefore velocities) were slightly high but reflected SEPA and dispersion calculated flow variations for all experiments.

### 3.2 Small woody debris dam constriction within the small urban watercourse

SWD became detained within the channel and along the banks of the watercourse during these experiments. The number and composition of dams (lodgment of three SWD or more) that occurred during the experiments were monitored. The frequency of dam occurrence was found to relate to dye cloud velocity and therefore flow velocity. As flow and dye velocity rises, dam frequency was observed to decrease. As expected, increase in distance between release location and the antenna resulted in a greater frequency of dam creation. The experiment average dam creation from the upstream monitoring point was approximately 70% greater than that of the downstream point, over a 150% distance increase.

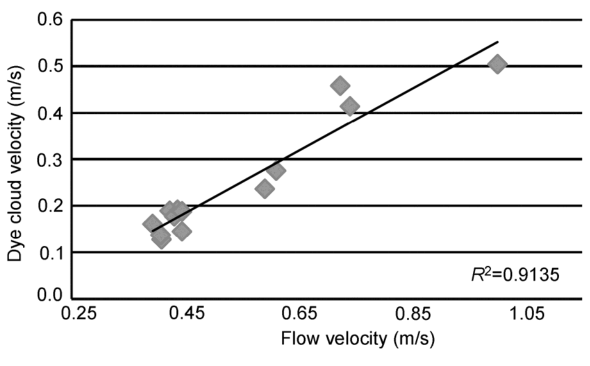


**Figure 4** Correlation between Rhodamine dye cloud and stream flow velocity.

The majority of dams comprised of less than 6 items, with exceptional experiments resulting in dam composition of up to 25 sticks. It was difficult to identify the initiating stick in these dams due to the tendency (noted visually during field work) for the initiating stick to become dislodged after dam creation. The first released stick within the dam was not found to follow a trend with debris dimension (*P*-values of 0.2–0.06). No specific SWD size was identified as key to dam initiation.

A greater number of shorter and smaller diameter woody debris was successfully transported and this is reflected in the dam composition. Figure 5 illustrates the dimensional trends in small woody debris occurring within the field experiment dams. There is a linear trend showing increasing frequency in SWD detention within a dam formation with increasing length and decreasing diameter dimensions. The influence of SWD length is stronger than that of diameter, suggesting SWD length as a more significant detention factor in transport prediction.

In addition, the location of release was found to have influence over the detention location, supporting the slight increase in right bank detention potential and the expected higher thalweg conveyance. A greater variance in deposition location was found in SWD released from the banks. However, it is evident that there is transport of woody debris into and out of the thalweg in smaller urban watercourses occurs, evident through the high *P*-values in significance analysis, and this process should be accounted for in future Ds modelling.

### 3.3 Transportation distance

A key initial finding was a distance limitation in SWD transport. Although the range of flow conditions sampled extended from 0.04 to 0.38 $m^3/s$, it was found that even during the upper extent of this range a very limited amount of SWD was transported through the whole study length (Figure 5). ANOVA analysis identified significant difference between the SWD velocities when comparing results from the three different upstream release locations (*P*-value 0.0074). As the release distance increased (the debris release location moved further upstream) there was greater opportunity for debris to become detained within the watercourse or along the banks. Temporary detention resulted in longer travel times, thus creating a slower average travel velocity. For the flow range studied, the distance between the antenna and MP3 (152 m) was found to be too great for debris from this location to significantly influence potential culvert blockage (at the antenna). Given a greater range of flows and further sample repetition, it is expected that a relationship relating channel characteristics, source distance upstream from the pinch point, experiment flows, and SWD transport success will emerge specific to this reach.

The travel distance limitation suggests there is a notional maximum travel distance, specific to the flow conditions

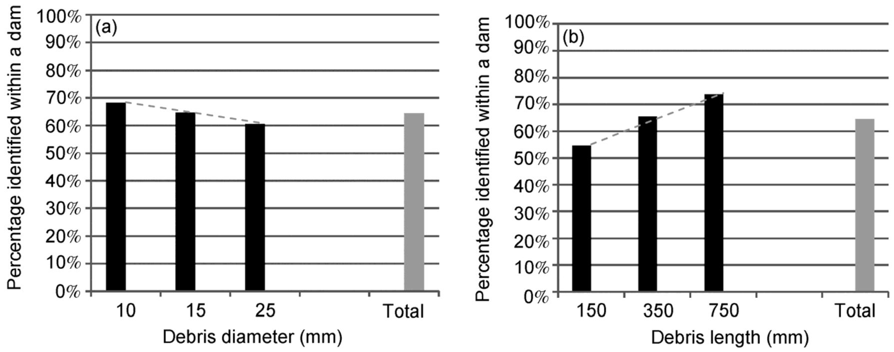


**Figure 5** Debris dimension influence on debris dam detention. (a) Illustrates debris diameter; (b) debris length influence on potential for dam detention.

and channel characteristics, beyond which debris is unlikely to travel. This distance will be dependent on the SWD length to channel width ratio, bank vegetation overhang, in-channel obstruction, channel sinuosity and slope. The impact of this transport limitation may be significant for urban watercourse maintenance and pinch point flood risk management. Within the examined watercourse reach, land use and maintenance of the vegetation along channel banks, up to MP2, would be expected to have significant influence on the potential for debris build up at the pinch point or culvert downstream. However, less influence may occur from works upstream of this maximum distance (near MP3 in these experiments). This distance relationship provides a critical length relating to SWD transport and pinch point deposition that may better inform flood risk management decisions and bank maintenance strategies.

### 3.4 Dimensions of successfully transported debris

Across the three monitoring locations there is a trend for shorter woody debris to travel more effectively, and transport success to increase slightly with increased woody debris diameter (Figures 4 and 5). The increase in transport success with SWD diameter is effective only until the floating threshold is no longer met [4] and rolling or sliding conditions result ($h^*<1$). This dimensionless floating threshold:

$$h^* = \rho w^* dw / \rho \log^* D \log, \tag{1}$$

incorporates water depth and SWD diameter and density to define the limits between flotation and alternative transport modes [4]. Floating conditions were reached in each experiment for all woody debris sizes ($h^*>5$) and SWD detention resulted from alternative influences (eddy, vegetative and in stream obstruction) rather than low $h^*$ values.

An average SWD velocity of 0.136 m/s (average watercourse velocity of 0.525 m/s) was calculated for the total dataset. The majority of SWD moved at between 0.05 and 0.25 m/s, 10%–48% of the flow velocity. This analysis confirms SWD velocity to be influenced by SWD dimension, displaying a positive relationship between SWD velocity and flow velocity (ratio of $Vs$:$Vf$) with increasing diameter and length.

Figure 7 illustrates a notable decrease in the variation of velocity as woody debris length and diameter increase. It is expected that this results from the decrease in SWD surface area and associated potential to become detained, supported by the debris success relative to dimension shown in Figure 4. It is also noted that median SWD velocities were consistently lower than the average debris velocity, suggesting a greater frequency of high velocity outliers and a greater range of velocities in the 3nd quartile. From this it can be inferred that debris moving at greater velocities (above the median) have a lower likelihood of temporary detention or achieve shorter detention periods within the reach in comparison to SWD travelling within the 2nd quartile velocity range.

Figure 7 illustrates the velocity variation when the entire dataset was considered. It was found that when the data was considered relative to the monitoring location (i.e. the total

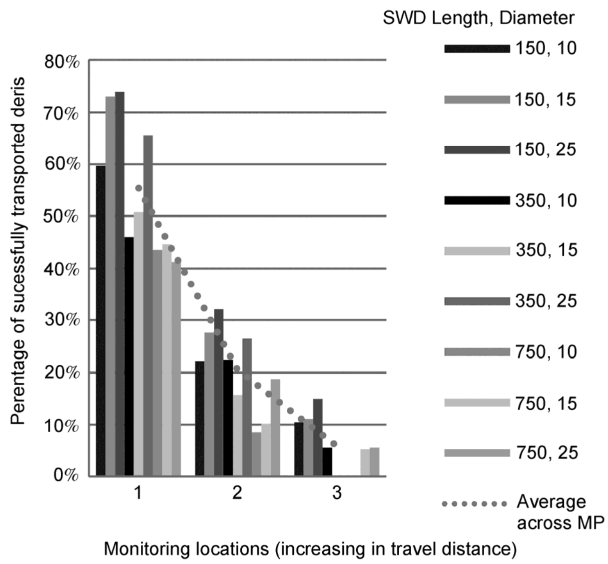


**Figure 6** Successfully transported small woody debris relative to release location.

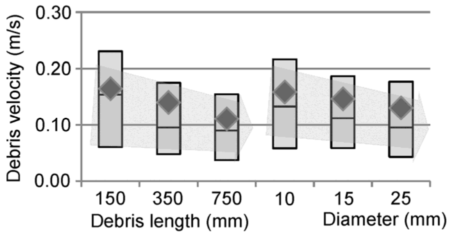


**Figure 7** SWD velocity variations according to dimensions.

dataset was split into 3 sets, one for each release location) similar trends were found. Regardless of the distance the SWD had to travel, SWD velocity variance generally decreased as debris dimensions increased. The majority of debris travelled slowly relative to the SWD velocity range (2nd and 3rd quartile are within the lower extent of the velocity range) and median *Vs* were generally lower than average *Vs*.

### 3.5 Influence of transverse debris release location on debris velocity

In general it was found that SWD released from the central location achieved greater velocities than those released at the right or left bank. This is due to lower potential vegetation and eddy influence on thalweg flows. The variance in the velocity range between the traverse release locations was limited at both release location MP1 and 2. Due to local resistance, there was insufficient data to accurately analyse traverse velocity variance at MP3.

### 3.6 Influence of stream and solute velocity on debris movement

Dye cloud velocity (*Vc*) is a function of stream velocity (*Vf*), acting to show effective channel flow through peak concentration movement. Cloud and flow velocity follow a similar but not parallel trend (Figure 8). Debris success rises and falls with the change in flow and cloud velocity, but with notable outliers. This suggests the influence of other local forces and resistance on SWD movement that require consideration. The relationship between flow velocity and debris movement was confirmed through *Fr* and *Re* relationships with debris transport success (relationship is not direct but linked through velocity and channel characteristics). As *Fr* and *Re* and strongly linked with velocity, this finding was expected and supports the SWD velocity results.

Physical modelling [4] has focused on depth and velocity as primary influences in woody debris movement. This field work has been conducted to help define whether small urban streams are influenced significantly by local resistance and movement forces, in conjunction with depth and velocity. On review of field data analysis, it was found that water depth and velocity have significant influence on SWD

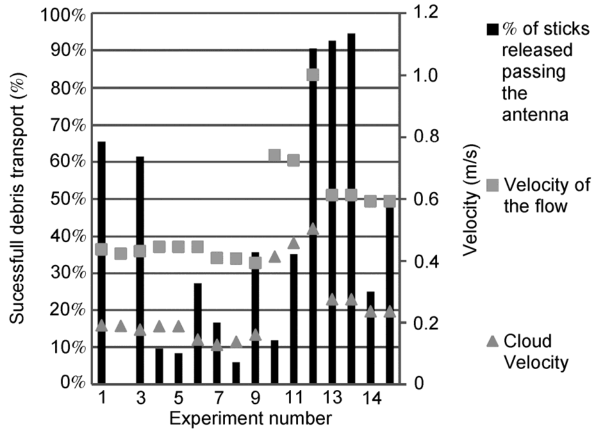


**Figure 8** Small woody debris transport rate relative to dye cloud movement.

debris movement when considered in conjunction with debris dimensions. However when considered individually the correlation was less significant ($Vf$=$R^2$<0.24, $Vc$ = $R^2$<0.14). Velocity is therefore a key influence on SWD transport but is not the sole predictor. This supports the inclusion of locally specific influences in urban watercourse SWD transport model design.

### 3.7 Influence of water level on debris transport success

The influence of water level was considered as distinct from flow velocity to determine whether water level has a specific and separate influence on SWD delivery success. A very small positive correlation was found between water level and debris transportation success (Figure 9). Water depth, flow velocity and debris delivery success field data, collected for each experiment run in the urban watercourse, was analysed to identify any significant influential trends. The scattered nature of the points plotted in Figure 9 illus-

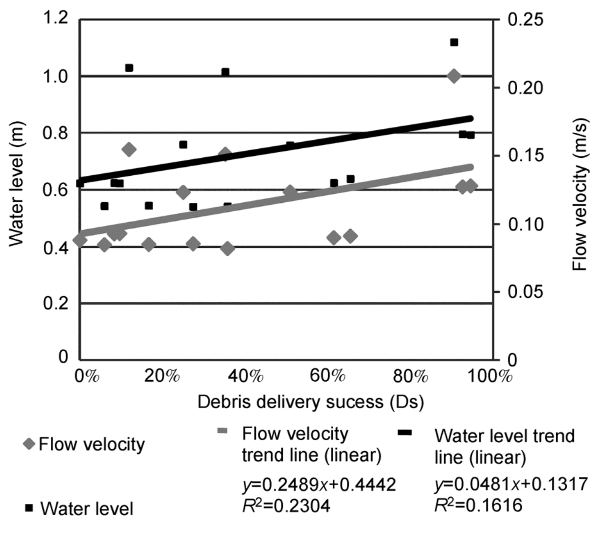


**Figure 9** Comparison of water level and flow velocity correlation to debris delivery success rate.

trates the limited direct influence both water level and flow velocity have on SWD transport success. The low $R^2$ is expected to result in part from the limited data set, but also due to the influence of local specific watercourse and woody debris characteristics. Analysis confirmed that water level and flow velocity appear to correlate with *Ds*, suggesting that *Vs* and *z* have a similar and relative influence on *Ds*.

Woody debris released from the right and centre bank locations were generally found to have greater transport success when flow depth was deeper. The positive influence of increased water level was found to have a lesser impact on SWD transport success from the left bank release location. Variation in flow velocity across the channel (relative to sinuosity) is expected to cause this decrease, in conjunction with vegetation proximity to the flow path and bank undercutting. Further field analysis is required to qualify this influence.

## 4 Debris predictive model analysis

There are numerous existing woody debris transport models that consider a limited number of influences on debris movement. Using the field data from the Murray Burn experiment, these equations were tested to determine their relevance and effective prediction within this urban watercourse and for small woody debris transport analysis.

Wallerstein and Arthur [12] provided a model that considered contributing stream length, upstream land use and socio-economic indices. The model provides monthly or seasonally relevant prediction of debris delivery potential (*Pd*), rather than experiment specific analysis. Comparison of field to predicted debris success data resulted in an $R^2$=0.44, complimented by $P$<0.005 and $F$>Fcrit, suggesting that *Pd* is a relevant and influential factor in debris transport success prediction.

Hydrodynamic force (*Fd*), the fluvial force pushing SWD downstream as described by Hygelund and Manga [13] considers debris drag coefficient and submerged area as key influences on debris movement. No clear correlation between hydrodynamic force and SWD transport success was found in the field data but a slight positive trend was found between *Fd* relative to SWD dimension (increased force resulted in greater transport success within each debris dimension data set). The lack of correlation may result from *Fd* reliance on flow velocity, without channel width and debris size consideration.

Debris roughness (DR) was used by Braudrick and Grant [1] in flume experiments to accurately predict blockage of large woody debris within a simulated river reach. The equation relates debris length to channel width and watercourse curvature in conjunction with debris buoyancy and channel depth. While this model may be effective for scaled large woody debris analysis, it was found to have a very low correlation with the field results from the Murray Burn ($R^2$=0.2). This may be due the lack of debris travel distance consideration. However, it may also be due to the construction of the numerical model as a summation of ratios which assume experiment reach consistency. Therefore, the low correlation may result from within reach local vegetative changes and their influence on debris transport success.

### 4.1 Blockage factor and debris transport prediction

Blockage, a factor in prediction of woody debris detention potential within a given reach, was calculated for individual debris elements using Bocchiola et al. [4] description,

$$B = D\,\log^{*}L\,\log/\,w^{*}z, \tag{2}$$

where *D* log and *L* log are SWD diameter and length, and *w* and *z* are channel dimensions. Hygelund and Manga [13] demonstrate the link between drag coefficient and blockage (modified equation), presenting a positive logarithmic relationship. *B* values were found to be low compared to previous studies [4], ranging up to 0.037. However, when viewed according to debris dimensions, there is a correlation between SWD transport success and blockage factor (Figure 10, $R^2$=0.56). As the blockage predictor increases, the success of debris transport falls showing *B* to be inversely linked to debris success rate (when averaged for debris dimension).

SWD dimension is the key driver to detention/success prediction using this blockage formula. *B* was averaged for each debris dimension across each experiment (allowing for consideration of the stable experiment specific characteristics, such as channel characteristics, distance upstream from the antenna and contributing upstream stream length). This created a data set of 16 points for each debris dimension. When plotted, the $R^2$ values for the logarithmic correlation (*Ds*:*B*) for specific experiments ranged from 0.38–0.64.

The moderate $R^2$ value provides a strong starting point in prediction analysis. As discussed in Bocchiola et al. [3] and Braudrick and Grant [5], SWD length to channel width ratio is a key indicator defined through their field and flume

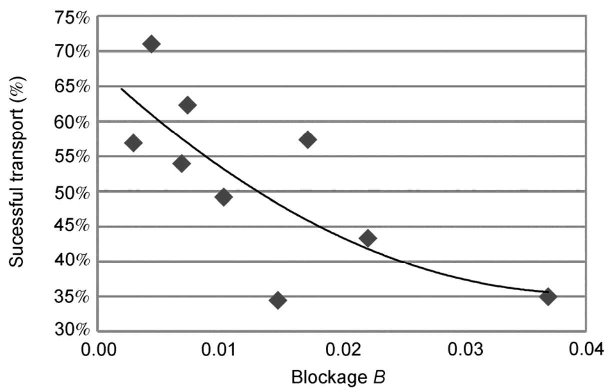


**Figure 10** SWD success relative to blockage potential.

debris transport analysis. The blockage factor takes this analysis a step further incorporating dimension ratios for both debris and channel.

### 4.2 Bank and bed roughness

Effective Mannings '*n*' for the channel was calculated using the velocity and depth data recorded on site and the Mannings '*n*' equation. Channel Mannings '*n*' values were calculated to range from 0.034–0.057.

Manning '*n*' was found to be inversely related to water depth. It should be noted that all experimental flows were within bank so flood plain influence was not able to be considered in detail. SWD transport success was not found to link strongly to effective Mannings '*n*'. Figure 11 illustrates the limited direct correlation between Manning '*n*' and woody debris delivery through the scattered nature of the data points ($R^2$=0.26). However, Manning '*n*' and Blockage were found to show a stronger correlation linking Blockage, SWD transport and Mannings '*n*' values to *Ds*. A logarithmic trend line has been used in Figures 10 to illustrate the scattered nature of the data. This trendline is chosen as alternative trend types (power, exponential and logarithmic trendline) show no stronger significant correlation. As descriptors of potential resistance to debris transport, is appears logical that Mannings values and blockage may relate, and that flow depth may be the interlinking function in within the relevant equations.

## 5 Conclusions

Passive integrated transponder tags have been found to function effectively in the field. The tags were easily imbedded within artificial debris and performed well in the watercourse environment. When combined with velocity, flow, water level information and local watercourse dynamics (through dye tracing) a detailed view of the water course small woody debris transport potential can be considered. Elevated water level and flow velocity resulted in increased SWD delivery success. However, the correlations between *Ds* and *Vf* or *z* are not strong, suggesting that velocity and water level are not the sole predictors or controlling factors in SWD delivery success

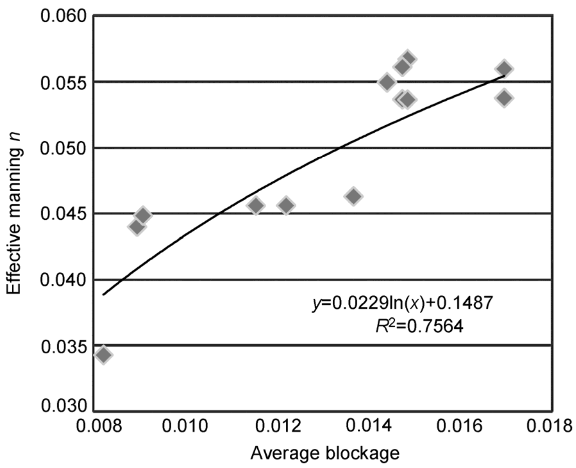


**Figure 11** Woody debris detention relative to Blockage relationship to Channel Mannings '*n*' correlation.

*Vc* was found to follow a similar trend to flow velocity. SWD delivery success increased as *Vc* increased. However, as found with *Vf*, the correlation was not strong, suggesting that the influence of further channel and debris characteristics be considered.

SWD travel distance was found to have a significant inverse influence on *Ds* (*Ds* increased as debris travel distance decreased). Data analysis suggests that there may be a critical maximum distance above which limited SWD transport will occur to a specified pinch point.

Mannings '*n*', as a description of channel roughness, has a low correlation with *Ds* when considered in isolation and is not shown to significantly influence *Ds*. However, a positive linear relationship was noted between Mannings '*n*' and *B* values, as depth calculated descriptors of channel resistance.

Statistical regression analysis of the experiment and total data set therefore identified several key factors in SWD transport prediction. These are,

$$Ds = \int (B, \mathrm{Dist}, Pb, z). \tag{3}$$

Regression analysis confirmed the importance of *Pd*, *B*, distance between release/source and the pinch point or blockage location (Dist), and water level (*z*). These four factors maintained significance throughout statistical interrogation of the data. While single factor review suggested a slight correlation between Mannings '*n*', blockage and SWD transport success, it was less significant when included in factorial analysis.

## 6 Future research

More extensive field data is required verify these findings for a greater range of urban watercourses and conditions. Field data needs to extend across a greater range of characteristic urban watercourses and flow conditions. To enable effective debris blockage risk assessment based on urban debris transportation potential, the suite of factors affecting urban debris transport need to be more clearly defined and tested, and this requires further field data.

There is potential to use conceptual simulation based on *Ds* to define high risk pinch points in the urban environment, and relate this risk to surrounding land use, watercourse and vegetation management. This can support more effective, flood resilient and sustainable urban design, flood risk and urban watercourse management in the future. It can also be used to identify existing high flood risk locations, areas where a modified maintenance regime, improved flood warning implementation or capital works improvements may improve the local level or frequency of inundation.

*This study was supported by the Engineering and Physical Sciences Research Council (Grant Nos. EPSRC EP/J501335/1 and EP/K50337X/1) and the Heriot-Watt University School of the Built Environment.*

1 Braudrick C A, Grant G E. Transport and deposition of large woody debris in streams: a flume experiment. Geomorphology, 2001, 41: 263–283

2 Mazzorana B, Hubl J, Zischg A, et al. Modelling woody material transport and deposition in alpine rivers. Natural Hazards, 2011, 56, 2: 425–449, doi:10.1007/s11069-009-9492-y

3 Wallerstein N P, Alonso C V, Bennett S J, et al. Distorted froude-scaled flume analysis of large woody debris. Earth Surface Processes and Landforms, 2001, 26, 1265–1283, doi: 10.1002/esp/.271

4 Bocchiola D, Rulli M C, Rosso R. A flume Experiment on the formation of wood jams in rivers. Water Resour Res, 2008, 44: W02408, doi: 10.1029/2006WR005846

5 MacVicar B J, Piegay H, Henderson A, et al. Quantifying the temporal dynamics of wood in large rivers field trials of wood surveying, dating, tracking and monitoring techniques. Earth Surface Proc Landforms, 2009, 34: 2031–2046, doi:10.1002/esp.1888

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

7 Wallis S G. Experimental Study of Travel Times in a Small Stream. Water Quality Hazards and Dispersion of Pollutants. New York: Springer, 2005

8 Ani E, Wallis S, Kraslawski A, et al. Development, calibration and evaluation of two mathematical models for pollutant transport in a small river. Environment Model Software, 2009, 24: 1139–1152

9 Lees M J, Camacho L A, Chapra S. On the relationship of transient storage and aggregated dead zone models of longitudinal solute transport in streams. Water Resour Res, 2004, 36: 213–224

10 Romanowicz R J, Osuch M, Wallis S G. Modelling of longitudinal solute transport in rivers under different flow rates: A case study without transient storage. Acta Geophys, 2013, 61: 98–125

11 Wilson J F. Time-of-travel measurements and other applications of dye tracing. Water Resources Division, US Geological Survey, Washington, DC Prepared for presentation at the 14th General Assembly, International Union of Geodesy and Geophysics, Berne, Switzerland, 1967

12 Wallerstein N, Arthur S. Predicting and managing flood risk associated with trash screens at culverts, FRMRC, www.floodrisk.org.uk

13 Hygelund B, Manga M. Field measurement of drag coefficients for model large woody debris. Geomorthology, 2003, 51: 175–185