# Tracking log displacement during floods in the Tagliamento River using RFID and GPS tracker devices

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## Abstract

Large pieces of in-channel wood can exert an important role on the ecological and morphological properties of gravel-bed rivers. On the other side, when transported during flood events, large wood can become a source of risk for sensitive structures such as bridges. However, wood displacement and velocity in river systems are still poorly understood, especially in large gravel-bed rivers. This study focuses on log transport in a valley reach of Tagliamento River (Italy). Log displacement during flood events of different magnitude recorded from June 2010 to October 2011 have been analysed thanks to the installation of 113 radio frequency identification (RFID) tags and 42 GPS tracker devices in logs of different dimensions. Recovery rate of logs equipped with RFID and GPS

nalyse in details the log displacement and transport overtime, indicating a higher log entrainment during rising limb of hydrographs. The threshold for the entrainment of logs from low bars is around 40% of bankfull water stage. No clear relationship was found between the peak of flood and log displacement length and velocity. However, log displacement length and velocity appears significantly correlated to the ratio between the peak of flow and the water stage exceeding the flow duration curve for 25% of time (i.e. the ratio $h_{max}/h_{25}$ ratio). Log deposition was observed to occur at the peak flow, and logs transported during ordinary events are preferably deposited on low bars. This study reveals the potentials of GPS tracker devices to monitor the entrainment and movements of logs in large gravel-bed rivers during floods. These observations could be useful for better planning of river management practices and strategies involving the use of large wood pieces and could help calibrating wood budgets at the reach scale.

*Keywords:* wood transport; log displacement; wood characteristics; tracking systems; Tagliamento River; gravel-bed river

## 1.Introduction

The remarkable geomorphic effects of living plants in river systems (Gurnell, 2013) continue even after their erosion from the hillslopes and banks and transportation within the fluvial network. Dead or living pieces of wood can exert a tremendous influence on river erosion and sedimentation processes (e.g., Jeffries et al., 2003), channel morphology (e.g., Abbe and Montgomery, 2003), and channel hydraulics (e.g., Wallerstein et al., 2001). Wood has also been found to play a key role in the ecological diversity of river channels (Gurnell et al., 2002) by providing habitat for a range of fish and other riverine fauna and by regulating water temperatures, water turbulence, and nutrient fluxes (e.g., Van der Nat et al., 2003). Nevertheless, wood in-channel could be a threat to some human activities on rivers, including disruption of the navigation on large rivers and commercial marine operations (Piégay, 2003). Moreover, if wood is transported massively during high-magnitude flood events, it could represent a risk for sensitive structures such as bridge piers (Mazzorana et al., 2009; Rigon et al., 2012). Given the important positive and potentially very negative effects of wood in rivers, increasing attention has been given to the assessment of wood budget at the catchment and reach scales (Sedell and Froggatt, 1984; Palik et al., 1998; Piégay et al., 1999; Benda and Sias, 2003; Benda et al., 2003; Marcus et al., 2011; Schenk et al., 2013). Recently, Marcus et al. (2011) attempted to calculate an annual wood budget using a relation between the wood transport rate and the flow discharge. However, this approach is biased by the fact that wood transport dynamics (such as the log displacement length and velocity) is still poorly understood, mainly for lack of direct field observations (MacVicar and Piégay, 2012).

Field evidence is more easily obtained in small mountain rivers. Iroumé et al. (2010) reported that about 12% of tagged wood pieces in a small Chilean stream were transported during a period in which five floods exceeded the bankfull stage. Warren and Kraft (2008) found that 26% of tagged pieces moved during 4 years of survey in a small snowmelt-dominated stream in the USA, and Wohl and Goode (2008) reported yearly mobility ratio ranging from 16 to 23% in small streams of the Rocky Mountains, USA. These studies were conducted by marking single logs using metal tags. However, measuring log displacement in wide gravel-bed rivers is logistically more difficult and thus novel ways of tracking logs have been experimented with. Recently, Schenk et al. (2013) quantified the annual wood budget of the lower Roanoke River (North Carolina) using radio frequency identification tags (RFID) and metal tags installed to log pieces in order to track their movements during floods. Also, MacVicar and Piégay (2012) explored the relationship between wood transport rate and water discharge by using a streamside video camera in a wandering piedmont river, the Ain River in France. They confirmed the observations of MacVicar et al. (2009), who reported a higher wood transport rate during the rising limb than falling limb of hydrographs. Physical modelling under steady flow conditions revealed that log travel distance depends on the wood size and density, water depth and velocity, and the channel bed roughness (Braudrick and Grant, 2001; Haga et al., 2002). Additionally, field observations suggest that relatively small and loose wood pieces are easier to move than buried logs and/or pieces that are longer than the bankfull width (Gurnell, 2013). Moreover, mobile small pieces of wood have been observed as being trapped by large wood pieces (Seo and Nakamura, 2009; Welber et al., 2013).

The aim of this study is to assess log displacement length and velocity in a large gravel-bed river (Tagliamento River, Italy) during near-bankfull floods that occurred from June 2010 to October 2011. To achieve that, logs were tagged using radio transmitters and, for the first time, using GPS tracker devices, which collect GPS position data at high frequency resolution (1 s), and with RFID tags. Specific objectives are to verify the recovery rates of RFID tags after floods of different magnitude to test the use of GPS trackers to measure log entrainment and velocity, to assess the displacement length and velocity of logs in a braided river, and to quantify log mobility and velocity during floods.

## 2.Material and methods

### *2.1.Study site*

The Tagliamento River is a gravel-bed river located in northeastern Italy (Fig. 1). Its basin area is around 2871 km$^2$ and flows for 178 km from the southern Alps to the Adriatic Sea. Multiple-thread channel pattern and numerous islands characterize most of the river, although in some segments it is closely confined between flood embankments (Gurnell et al., 2001).

The Tagliamento River is influenced by intense and highly variable annual precipitation ranging from 1000 to 3100 mm. The flow regime is characterized by spring and autumn floods from snowmelt and long rainfall events, respectively (Tockner et al., 2003). Minimal management is applied to vegetation on islands and within the riparian forest. For this reason, fluvial processes and natural biological processes dominate the vegetation establishment and the erosion and deposition of vegetation and wood debris (Gurnell et al., 2001). As to the riparian areas, *Alnus incana* dominates on streams in the headwater (Gurnell and Petts, 2006), whereas *Populus nigra* and *Salix alba* are the most commons species on floodplains and islands in the wider reaches of the piedmont portions of the river (Francis et al., 2008; Bertoldi et al., 2013). The Tagliamento River is recognised as one of the most intact and less disturbed rivers in the Alps (Ward et al., 1999) as most of its longitudinal, lateral, and vertical biological and sediment connectivity are still preserved (Tockner et al., 2003). The selected study reach is located near the village of Forgaria nel Friuli (Fig. 1, hereon called Cornino). In this section the active channel is ~800 m wide and features a longitudinal slope of about 0.003 mm$^{-1}$ and an island-braided pattern. Three cross sections of this reach were surveyed with DGPS in 2010. On transects spanning ~200 m around the cross sections, single wood pieces and wood jams were surveyed (Mao et al., 2012). All wood pieces > 0.1 m in diameter and 1 m in length were measured, and volumes of logs and jams were calculated. Mao et al. (2012) reported that the average diameter and length of stranded logs were 0.16 and 4 m, respectively, being 2.4 and 22.7 m maximum diameter and length, respectively. The study reach featured a spatial density of large woods around 2.9 m$^3$ ha$^{-1}$, (1 and 1.9 m$^3$ ha$^{-1}$ as single logs and jams, respectively) and 4.7 jams/ha. Because ancillary information on log orientation to flow, state of decay, delivery mechanism, and position in the channel were collected, Mao et al. (2012) could infer that the dynamic of wood recruitment and transport is fast: more than 80% of logs were intact with complete bark and most of the original branches, more than 75% of isolated logs were oriented parallel to the direction of the flow, and up to 90% of isolated logs featured the rootwad facing upstream.

During the study period (from June 2010 to October 2011), 14 low-magnitude floods peaking at half the bankfull stage and a near-bankfull event occurred, as measured at the Villuzza gauging station located 8 km downstream of the study reach (Fig. 2). Bankfull stage was considered to be about 3 m as suggested in previous studies on the Tagliamento River (see Gurnell et al., 2002; Bertoldi et al., 2013).

### *2.2.Log tracking*

A total of 113 radio frequency identification tags (RFID) and 42 GPS tracker devices were installed in logs of different size. The most important characteristics of logs (e.g., length, diameter, presence and dimension of rootwads, presence and dimension of branches) were surveyed following the common standard size (10 cm in diameter and 1 m in length) of transported wood in Tagliamento River (Gurnell et al., 2000). The position of each tagged log was surveyed using a differential global positioning system (DGPS). Tagged logs were selected for having a size representative of logs lying in the study reach (Mao et al., 2012; Fig. 4) and for being relatively close to the main channel and lying on low and active bars. The morphological settings of the river in the specific site were surveyed as well.

An RFID tag is a device (purchased from RFcode Company) enclosed in a polycarbonate case measuring 47 x 34 x 12 mm (Fig. 3). The RFID tag is powered by a small battery and emits a signal at 443 MHz every two seconds (MacVicar et al., 2009). The signal can be read by a mobile receiver connected to an antenna, whose detection range is about 200 m. The RFID tags were implanted in holes scoured on the trunks of 113 logs and fixed using silicone caulk. Similar devices have been previously used in other environments for tracking logs in river systems (MacVicar et al., 2009; Schenk et al., 2013). During several field surveys (July, August, and December 2010, and then in March, April, May, July, August, and October 2011), the whole study site and ~18 km of the downstream area were explored with the RFID mobile antenna searching for tagged logs. Also, farther river reaches of easy convenient accessibility were explored downstream (e.g., around bridges) until the village of Latisana, located 60 km downstream from the study reach. When recovered, tagged logs were measured again, and their position was taken using DGPS in order to quantify precisely their displacement length.

On an additional 42 logs, a plastic box with a GPS tracker device inside was fixed to the trunks using a stain steel chain (Fig. 3). The GPS tracker devices (3100-EXT purchased from LandAirSea Company) are composed by a GPS antenna receiver, and a case (80 x 100 x 40 mm) hosting 4 AA batteries and data logger. When activated, the device acquires and stores in the data logger its position every second. The device activates with movement (warm start of 50 s) and has up to 300 hours storage-tracking capacity. In order to save the battery, the data logger stops collecting GPS position coordinates after the device remains immobile for more than 2 minutes. The devices were enclosed in waterproof plastic boxes. In order to help GPS recovery, an RFID tag was placed inside each plastic box.

The RFID and GPS were mainly installed on three different occasions during the study period (Fig. 2). Twenty-one GPS trackers and 63 RFID tags were installed in June-August 2010, 6 GPS trackers and 12 RFID tags in December 2010, and 15 GPS trackers and 31 RFID tags were installed in March 2011. In addition, 7 RFID tags were installed after June 2011. Apart from the first installation, which was carried out in summer 2010 when an extensive survey of volumes, type, degree of organization, and morphological effects of large wood took place (Mao et al., 2012), the other installation dates coincided with periods in which tagged logs were surveyed after floods.

Linear regressions were used to examine relationships between displacement lengths, virtual and mean velocities of logs as dependent variables, and the characteristics of transporting floods (water stage at the peaks and significant percentiles of flow duration curves) as independent variables. Regressions were considered statistically significant if $P \leq 0.05$.

## 3.Results

### *3.1.RFID tag and GPS tracker recovery rates*

From June 2010 to March 2011, 113 RFID tags and 42 GPS trackers were installed in single log elements (Table 1). The tagged LW elements have a median length of about 11.50 m and median diameter of 0.19 m, being the longest and thicker logs of about 21 and 2 m, respectively. Approximately 70% of tagged elements were trees with rootwad and branches, and about 30% were trunks with no branches. The recovery rates of RFID tags and GPS tracker devices range from 33 to 52% and from 20 to 81%, respectively, depending on the amount of time available for searching for the devices after floods. The overall recovery rate is around 43 and 42% for the RFID tags and GPS trackers, respectively. All logs, except one, were recovered on the edge of the channels or in low bars. The RFID and GPS trackers proved to perform fairly well over the study period, and no issues with low battery levels or filtration of water inside the device were noted. Because of that and because tagged logs were always searched on their last available position point, all unrecovered logs are very likely to have been transported from that position, farther downstream of the maximum extent of searching distance. More unlikely, unrecovered logs could have been submerged by water or buried by sediments to the extent that they could not have been detected by the portable antenna.

### *3.2.Log mobility during flood events*

Log mobility and displacement length during flood events that occurred during the study period have been analysed. The percentage of immobile tagged logs ranges from 15 to 50% depending on the flood events (Table 1). Considering the errors associated with GPS data and the fact that most logs were longer than 5 m, a minimum difference of 10 m between pre- and post- GPS position was assumed for considering that a log was actually displaced by a flood event. Taking this minimum displacement length into account, 20 logs tagged with RFID and 5 logs tagged with GPS were considered as transported.

Interestingly, because GPS devices were activated by movements, GPS trackers started registering point positions when water stage reached the logs that were attached by a steel chain. Overall, 15 GPS devices did not register any displacement but registered movements during flood events. The GPS devices were activated within a range of flow stages ranging from 0.20 to 1.80 m (as measured at the Villuzza gauging station), corresponding to 10 to 60% of bankfull stage, and the median value is ~40% of bankfull stage (Fig. 5). On the other end, the water stage needed to entrain and transport logs stranded on low bars for more than 10 m is higher than 40% of bankfull stage (Fig. 5).

### *3.3.Logs transport during flood events*

The mean distance travelled by entrained logs was about 13 km, with a minimum displacement length of 111 m for a tree tagged with an RFID (14 m long, 4.70 m wide considering the branches, and diameter of 0.33 m). The maximum displacement length was about 51.10 km, corresponding to a small log (1 m long, 0.15 m diameter) tagged with a GPS tracker device. Interestingly, both maximum and minimum log travel distances were caused by the same flood event that occurred on 19 June 2011, which reached ~70% of bankfull stage.

The peaks of floods that were competent enough to entrain and move tagged logs range from 1.91 to 2.90 m (63 to 96% of the bankfull stage). The log displacement lengths are positively correlated with the magnitude of the floods ($R^2 = 0.27$), but the correlation is not statistically significant ($p > 0.05$). In fact, because the peak might not be the only or most important parameter characterizing a flood event, the whole flow duration curve from installation (or last recovery) to recovery was calculated (Fig. 6). Significant percentiles of the flow duration curves were calculated as well, and their relevance in increasing the significance of the relationships between flow characteristics and log displacement lengths were tested. Flow percentiles close to the peak proved to be the most relevant descriptors of flow duration curves. In fact, the ratio $h_{max}/h_{25}$ ($h_{25}$ being the water stage exceeded for 25% of time) is better related to the displacement lengths ($R^2 = 0.42$; $p < 0.05$). Displacement lengths were used to define the transport velocity of logs. Naturally, logs moved only for a fraction of the time passed between their marking and recovery and because of that the velocity is considered virtual (*sensu* Wilcock, 1997). As expected, the correlation between the log velocity and the peak flow is positive ($R^2 = 0.20$) but poorly significant ($p > 0.05$). However, if the ratio $h_{max}/h_{25}$ is considered, the correlation increases and becomes statistically significant ($R^2 = 0.44$; $p < 0.05$; Fig. 7).

In order to avoid considering low flows that could not have been able to move logs in log velocity calculation, flow duration curves were recalculated considering only flows higher than a threshold of 1.20 m, corresponding to 40% of bankfull stage, that proved to be able to entrain logs (see Fig.

5). Even doing that, displacement length is only slightly better related to the ratio $h_{max}/h_{25}$ ($R^2 = 0.28$; $p > 0.05$), and a poor correlation with log velocity was found ($R^2 = 0.19$; $p > 0.05$).

Because RFID tags proved to provide measurements of virtual velocity that can be hardly related to the real log velocity during floods, the data provided by the GPS tracker devices was considered. Figure 8 shows the movement of four tagged logs during single flood events. Notably, logs were all entrained during the rising limbs of hydrographs at a water stage of ~1.20 m (apart from GPS tracker 2, which is entrained at 1.60 m). Also, logs stop near the peak of floods and are not entrained and transported any farther during the falling limbs. Mean log velocity during their actual transport ranges from 0.50 to 1.80 m $s^{-1}$, with an average value of around 1 m $s^{-1}$. Interestingly, the smaller log (1 m long, diameter 0.15 m) was transported with the highest velocity (1.88 m $s^{-1}$), whereas the largest tagged log (a tree 30 m long, diameter 0.45 m, with a canopy diameter of ~4.50 m) was transported with a mean velocity of 0.51 m $s^{-1}$. The smaller log was also transported for the higher distance, of ~51 km. A 16.70 m long log (0.26 m as diameter) tagged with the GPS2 (Fig. 8B) was entrained at a stage of 1.60 m and, after a stop of about 15 hours, was entrained again at a flow stage of 2.50 m. Even if transported at two different stages of the same hydrograph, its velocity is quite comparable, having being transported at 0.90 and 0.72 m $s^{-1}$ during the first and second displacements, respectively. Overall, LW velocity is not significantly related with the magnitude of the floods ($p > 0.05$). Instead, as expected, LW velocity is negatively and significantly correlated with the volume of logs ($p < 0.01$; Fig. 9). In order to compare the range of LW velocities with the average flow velocity during floods, the hydrographs registered at the Villuzza and Braulins gauging stations (the latter located 15.80 km upstream of the former) were used to calculate the celerity of the peaks between the two positions. Even if no significant relationship was found between log velocity and flood celerity ($p > 0.05$), logs moved at 40% of the floods celerity.

## 4.Discussion

### *4.1.RFID tag and GPS tracker recovery rates*

During the study period, which featured one near-bankfull and a few lower magnitude flood events, 25 over 155 tagged logs (113 RFID and 42 GPS) were entrained and transported. Recovery rate of transported logs is very similar for GPS trackers as for RFID tags, being 42 and 43%, respectively, because the recovery of GPS trackers was dependent on the RFID tag placed in the same box with the GPS tracker. These recovery rates are only slightly higher than what could be obtained using other LW tagging techniques (MacVicar et al., 2009). MacVicar et al. (2009) first used 51 RFID tags for LW tracking in the Ain River (France) using a fixed antenna. The system proved very promising, albeit certain issues could be experienced during flood events when transported logs are likely to be at least partially submerged and when RFID signals are absorbed by water. Schenk et al. (2013) inserted 290 RFID tags into the Roanoke River (USA) and used fixed and mobile antennas for surveying the transport of tagged logs up to 100 km, reporting a recovery rate slightly lower than 40%. Great novelty in this kind of study was carried out by using GPS trackers, in fact no attempts have been previously made to use GPS trackers for quantifying log transport. Because the devices used in this study are collecting position data inside the device, recruitment rate is obviously dependent on the RFID installed in the same log. However, GPS allows for following over time the transport of a single log in a manner that could not be achieved by any other devices tested in the field. In fact, it allows us to measure log movements overnight, where fixed cameras can experience serious difficulties, as recently reported by MacVicar and Piégay (2012) and Bertoldi et al. (2013). Similar devices have been successfully used in fluvial systems to measure surface flow velocities (Stockdale et al., 2007). In order to increase the recruitment rate, logs tagged with GPS could be additionally equipped with a GSM (Global System for Mobile Communications) transmitting system, which is able to send the GPS position over time. An experimental use of these devices is underway in the Piave River (southern Italian Alps) and is proving encouraging as it warrants recovery and continuous data collection (Ravazzolo et al., in preparation).

### *4.2.Log mobility and transport during flood events in the Tagliamento River*

Despite the importance of log transport for the morphodynamics of river systems (e.g., Bertoldi et al., 2014), only a little field evidence is available on the transport distance of logs during flood events. MacVicar and Piégay (2012) observed that logs tend to move when a certain threshold, needed to lift logs, is passed. The existence of this threshold has been confirmed in the present study. For the study reach of the Tagliamento River, this threshold has been identified as 40% of bankfull stage and corresponds to a discharge flooding secondary channels and low bars. The amount of logs stranded in low bars is relatively high, especially near the floodplains and densely vegetated islands. In previous research, Mao et al. (2012) conducted field surveys in 2010 of isolated and jammed logs along three cross sections located within the study segment revealing that main, secondary channels and low bars account for up to 0.40 $m^3$ $ha^{-1}$, which corresponds to ~30% of the total amount of wood on the river bed. This suggests that even ordinary flood events have a potential of entraining and transporting logs. Furthermore, in the same reach of the Tagliamento River, near-bankfull events proved to be able to erode banks (Picco et al., 2013) and islands, recruiting relevant volumes of wood in low bars (Bertoldi et al., 2013).

GPS trackers allowed to gain a proper insight on the movements of single logs during floods. Even if direct observations are limited to movements of four logs, their transport dynamics have been remarkably consistent. Logs were entrained during the rising limbs of hydrographs, and were deposited on bars at or shortly after the peak of the floods. This is consistent with observations of Bertoldi et al. (2013) who observed log transport in the Cornino field site using a fixed camera. The fact that logs stopped right at the peak of floods is likely related to the morphological conditions of the Tagliamento River, which is a wide and very dynamics multithread river. The main channel tends to switch position quite frequently (e.g., Welber et al., 2012; Picco et al., 2013), and logs are not necessarily transported along the thalweg as observed in the Ain River by MacVicar and Piégay (2012) and in flume experiments by Braudrick and Grant (2001). Instead, logs are transported above the bars as suggested by the travelling paths revealed by the GPS trackers (Fig. 10). As soon as discharge begins to reduce, the logs have much more chance of being deposited in a bar. In fact, braided rivers are very effective in retaining logs, as recently showed by Bertoldi et al. (2014) in a series of laboratory experiments involving log transport in a sand-bed braided channel. Interestingly, 50% of transported logs (considering both RFID and GPS tagged logs) have been recovered in high bars or in pioneering islands. Bertoldi et al. (2013) suggested that up to 50% of trees recruited from lateral erosion of densely vegetated islands and floodplains in the Tagliamento tend to be trapped locally or on the bar immediately downstream. If they resprout rapidly, this can lead to the development of a vegetated nucleus near floodplains and islands (Gurnell et al., 2005). However, logs that are already stranded in the active bars can actually be transported far downstream. Interestingly, half of the transported logs in the Tagliamento were deposited as individuals, and half were found trapped in a wood jam. Very stable jams and pioneering islands are probably more able to trap further logs if they are transported during events of higher magnitude, which are able to flood the entire floodplain (Mikus et al., 2012; Picco et al., 2014). Ordinary events are instead more likely to entrain and transport isolated logs.

Physical modelling of wood transport in braided rivers suggests that larger and thicker logs require higher discharge to be entrained and transported, if compared with smaller elements. Moreover, shorter and smaller logs tend to be transported for longer distances during flood events of comparable magnitude (Welber et al., 2013). However, in the present study we could not find any significant relationship between these variables, probably because of the relatively low and limited range of discharges that were analysed. A lack of relationship between these variables has been reported by Schenk et al. (2013) in the Roanoke River as well.

As to the relationship between the flood peak discharge and the displacement length, even if the ratio $h_{max}/h_{25}$ performs better than the $h_{max}$ itself, the relationship appears quite weak. An analogous weak relationship has been observed in flume experiments as well (Welber et al., 2013) and has been related to the fact that at relatively low flows the potential deposition sites are limited, thus conditioning the displacement lengths. In the study site, the reason for this weak relationship can be ascribed to the relatively limited data set and range of discharge. However, because GPS trackers proved that logs were deposited during the flood peaks, it is also likely that displacement length is related to the duration of the rising limb of hydrographs as it is to the magnitude. The relationship between displacement length, flood magnitude, and duration of rising limb is beyond the extent to which the current available data can be analysed, but would deserve future efforts to be properly explored. In fact, as also stressed by MacVicar and Piégay (2012), the shape of floods is likely to have a strong influence on wood recruitment and transport.

Because the wood balance of a certain river reach depends on the input from upstream, recruitment within the reach, output, and decay (Benda and Sias, 2003), the fluvial transport of wood into and out of the reach are important variables in the mass balance. The fluvial transport is usually derived from the mean transport distance of logs (Benda and Sias, 2003; Benda and Bigelow, 2014), but the velocity of logs could also prove useful in assessing the actual magnitude of log transport in and out of a reach. Very little evidence on log velocity during floods is available, with the notable exception of MacVicar and Piégay (2012) who showed that logs move at around 2.54 m $s^{-1}$ during a near-bankfull event and that average velocity of logs is comparable with the surface velocity in a single-thread wandering river. Because of its higher width/depth ratio in a wide braided river such as the Tagliamento, velocities during a near-bankfull event proved to be lower, ranging around 1 m $s^{-1}$, and this velocity was approximately half the celerity of the flood. Although preliminary, this type of evidence could help in the development of transport functions for logs to be introduced on wood balances.

## 5.Conclusions

This study attempts to provide a better understanding on the processes of entrainment, transport, and deposition of LW during floods in a gravel-bed river in Italy. Displacement length and velocity data have been analysed using active radio frequency identification (RFID) tags and GPS devices fixed to logs lying on low, active bars. Both devices operated reasonably well, allowing a recovery rate comparable with the study of MacVicar et al. (2009). Fixed antennas, especially if multiple, could provide even better insights on log dynamics, as GPS equipped with a GSM transmitting system could as well, being able to send to a receiver the GPS position of a transported log overtime. The GPS tracker devices allow us to collect data overnight and thus could complement data collected by video cameras as used by MacVicar and Piégay (2012). In the Tagliamento River, the log entrainment is higher during the rising limb of hydrographs. Even if wood transport distance is only weakly related with flood peak stage, a better correlation has been found between transport distance and the ratio $h_{max}/h_{25}$. Limited movements were recorded for GPS devices, but consistent dynamics were analysed and they indicate an entrainment threshold around 40% of bankfull stage in Tagliamento River.

Field observations on location where logs were deposited suggest that pioneer islands and stable jams probably play an important role in trapping logs transported during major flood events, whereas logs are more likely to be deposited on low bars during ordinary events. However, studies of this kind should be enriched by considering the species, density, and state of conservation of wood transported with the travel distance and velocity, along with the presence and dimension of rootwad and major branches. These studies could be necessary for supporting the choice of better river management practices and river ecology application, as wood transport is a possible key process for in-channel wood redistribution playing an important role to increase the number of habitat for different organisms.

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## List of references

Abbe, T.B., Montgomery, D.R., 2003. Patterns and process of wood debris accumulation in forest channels. Geomorphology 51, 81–107.

Benda, L., Bigelow, P., 2014. On the patterns and processes of wood in northern California streams. Geomorphology 209, 79–97.

Benda, L., Sias, J., 2003. A quantitative framework for evaluating the wood budget. Journal Forest Ecology Management 172, 1–16.

Benda, L., Miller, D., Sias, J., Martin, D., Bilby, R., Veldhuisen, C., Dunne, T., 2003. Wood recruitment processes and wood budgeting. American Fisheries Society Symposium 37, 49-73.

Bertoldi, W., Gurnell, A.M., Welber, M., 2013. Wood recruitment and retention: the fate of eroded trees on a braided river explored using a combination of field and remotely-sensed data sources. Geomorphology 180–181, 146–155.

Bertoldi, W., Welber, M., Mao, L., Zanella, S., Comiti, F., 2014. A flume experiment on wood storage and remobilization in braided river systems. Earth Surface Processes and Landforms. DOI: 10.1002/esp.3537.

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

Francis, R.A., Tibaldeschi, P., McDougall, L., 2008. Fluvially-deposited large wood and riparian plant diversity. Wetlands Ecology and Management 16, 371–382.

Gurnell, A.M., 2013. Wood in fluvial systems. In: Shroder, J., Wohl, E., (Eds.), Treatise on Geomorphology 9, Academic Press, San Diego, CA.

Gurnell, A.M., Petts, G., 2006. Tree as riparian engineers: The Tagliamento River, Italy. Earth Surface Processes and Landforms 31, 1558-1574.

Gurnell, A.M., Petts, G.E., Hannah, D.M., Smith, B.P.G., Edwards, P.J., Kollman, J.,Ward, J.V., Tockner, K., 2000.Wood storage within the active zone of a large European gravel-bed river. Geomorphology 34, 55–72.

Gurnell, A.M., Petts, G.E., Hannah, D.M., Smith, B.P.G., Edwards, P.J., Kollmann, J., Ward, J.V., Tockner, K., 2001. Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. Earth Surface Processes and Landforms 26, 31–62.

Gurnell, A.M., Piégay, H., Swanson, F.J., Gregory, S.V., 2002. Large wood and fluvial processes. Freshwater Biology 47, 601–619.

Gurnell, A.M., Tockner, K., Petts, G.E., Edwards, P.J., 2005. Effects of deposited wood on biocomplexity of river corridors. Frontiers in Ecology and Environment 3, 377–382.

Haga, H., Kumagai, T., Otsuki, K., Ogawsa, S., 2002. Transport and retention of coarse woody debris in mountain streams: an in situ field experiment of log transport and a field survey of coarse woody debris distribution. Water Resources Research 38, 1126.

Iroumé, A., Andreoli, A., Comiti, F., Ulloa H., Huber, A., 2010. Large wood abundance, distribution and mobilization in a third order Coastal mountain range river system, southern Chile. Forest Ecology and Management 260, 480-490.

Jeffries, R.J., Darby, S.E., Sear, D.A., 2003. The influence of vegetation and organic debris on floodplain sediment dynamics: a case study of a low-energy stream in the New Forest, Hampshire. Geomorphology 51, 61-80.

MacVicar, B., Piégay, H., 2012. Implementation and validation of video monitoring for wood budgeting in a wandering piedmont river, the Ain River (France). Earth Surface Processes and Landforms 37, 1272–1289.

MacVicar, B.J., Piégay, H., Henderson, A., Comiti, F., Oberlin, C., Pecorari, E., 2009. Quantifying the temporal dynamics of wood in large rivers: field trials of wood surveying, dating, tracking, and monitoring techniques. Earth Surface Processes and Landforms 34 (15), 2031–2046.

Mao L., Ravazzolo D., Picco L., Rigon E., Lenzi M.A., 2012. Types and volumes of in-channel wood in three Italian gravel-bed rivers suffering from different degrees of human disturbances. Proceedings, first international conference on Integrative Sciences and Sustainable Development of Rivers, 26–28 June 2012, Lyon, France.

Marcus, W.A., Rasmussen, J., Fonstad, M.A., 2011. Response of the fluvial wood system to fire and floods in northern Yellowstone. Annals of the Association of American Geographers 101, 22–44.

Mazzorana, B., Zischg, A., Largiader, A., Hubl, J., 2009. Hazard index maps for woody material recruitment and transport in alpine catchments. Natural Hazards and Earth System Sciences 9, 197-209.

Mikus, P., Wyzga, B., Kaczka, R.J., Walusiak, E. And Zawiejska, J., 2012. Islands in a European mountain river: linkages with large wood deposition, flood flows and plant diversity. Geomorphology 202, 115–127.

Palik, B. J., Golladay, S. W., Goebel, P. C., Taylor, B. W,. 1998 .Geomorphic variation in riparian tree mortality and stream coarse woody debris recruitment from record flooding in a coastal plain stream. Ecoscience 5, 551–560.

Picco, L., Mao, L., Cavalli, M., Buzzi, R., Rainato, R., Lenzi, M.A., 2013. Evaluating short-term morphological changes in a gravel-bed braided river using Terrestrial Laser Scanner. Geomorphology 201, 323-334. doi.10.1016/j.geomorph.2013.07.007.

Picco, L., Mao, L., Rainato, R. and Lenzi, M.A., 2014. Medium-term fluvial island evolution in a disturbed gravelbed river (Piave River, Northeastern Italian Alps). Geografiska Annaler: Series A, Physical Geography, 96, 83-97. doi:10.1111/geoa.12034.

Piégay, H., 2003. Dynamics of wood in large rivers. In: Gregory, S.V., Boyer, K.L., Gurnell, A.M. (Eds.), The Ecology and Management of Wood in World Rivers. American Fisheries Society, Bethesda, Maryland, pp. 109–133.

Piégay, H., Thévenet, A., Citterio, A., 1999. Input storage and distribution of large woody debris along a mountain river continuum, the Drôme River, France. Catena 35, 13–39.

Ravazzolo, D., Picco L., Mao, L., Lenzi M.A. Instantaneous movements of logs during floods in the Piave River, in preparation.

Rigon, E., Comiti, F., Lenzi, M.A., 2012. Large wood storage in streams of the Eastern Italian Alps and the relevance of hillslope processes. Water Resources Research. 48, W01518.

Schenk, E.R., Moulin, B., Hupp, C.R., Richter, J.M., 2013. Large wood budget and transport dynamics on a large river using radio telemetry. Earth Surface Processes and Landforms 39, 487-498, DOI: 10.1002/esp.3463.

Sedell, J.R., Froggatt, J.L. 1984. Importance of streamside forests to large rivers: the isolation of the Willamette River, Oregon, U.S.A., from its floodplain by snagging and streamside forest removal. Association of Theoretical and Applied Limnology 22, 1928-1834.

Seo, J.I., Nakamura, F., 2009. Scale-dependent controls upon the fluvial export of large wood from river catchments. Earth Surface Processes and Landforms 34(6), 786–800.

Stockdale, R.J., McLelland, S.J., Middleton, R., Coulthard, T.J., 2007. Measuring river velocity using GPS River Flow Tracers (GRiFTers). Earth Surface Processes and Landforms 33(8), 1315-1322.

Tockner, K., Ward, J. V. & Arscott, D. B., 2003. The Tagliamento River: a model ecosystem of European importance. Aquatic Sciences 65, 239–53.

Van der Nat, D., Tockner, K., Edwards, P.J., Ward, J.V., Gurnell, A.M., 2003. Habitat change in braided flood plains (Tagliamento, NE-Italy). Freshwater Biology 48(10), 1799-1812.

Wallerstein, N.P., Alonso, C.V., Bennett, S.J., Thorne, C.R., 2001. Distorted Froude-scaled flume analysis of large woody debris. Earth Surface Processes and Landforms 26, 1265-1283.

Ward, J.V., Tockner, K., Edwards, P.J., Kollmann, J., Bretschko, G., Gurnell, A.M., Petts, G.E., Rossaro, B., 1999. A reference system for the Alps: the 'Fiume Tagliamento'. Regulated Rivers 15, 63–75.

Warren, D.R., Kraft, C.E., 2008. Dynamics of large wood in an eastern U.S. mountain stream. Forest Ecology and Management 256, 808-814.

Welber, M., Bertoldi, W., Tubino, M., 2012. The response of braided planform configuration to flow variations, bed reworking and vegetation: The case of the Tagliamento River, Italy. Earth Surface Processes and Landforms 37(5), 572-582.

Welber, M., Bertoldi, W., Tubino, M., 2013. Wood dispersal in braided streams: results from physical modeling. Water Resources Research 49, 7388–7400.

Wilcock, P.R., 1997. Entrainment, displacement, and transport of tracer gravels. Earth Surface Processes and Landforms 22, 1125-1138.

Wohl, E., Goode, J.R., 2008. Wood dynamics in headwater streams of the Colorado Rocky Mountains. Water Resources Research 44, doi:10.1029/2007WR006522, W09429.

Table 1

Number of installed, immobile, transported, and lost RFID tags and GPS tracker devices on the three main periods of searching after major floods

| Period | $h_{max}$ | Device | Installed tags | Immobile tags | Transported tags | Lost tags | Avilable tags for next period | % Recovered |
|---|---|---|---|---|---|---|---|---|
| 06/07/2010 - 21/10/2010 | 1.91 | RFID | 63 | 19 | 2 | 42 | 21 | 33.3 |
| | | GPS | 21 | 15 | 2 | 4 | 17 | 81.0 |
| 21/10/2010 - 01/06/2011 | 2.90 | RFID | 106 | 1 | 10 | 10 | 54 | 52.4 |
| | | GPS | 42 | 3 | 1 | 13 | 25 | 23.5 |
| 01/06/2011 - 04/10/2011 | 2.11 | RFID | 113 | 16 | 8 | 30 | 31 | 44.4 |
| | | GPS | 42 | 3 | 2 | 20 | 5 | 20.0 |

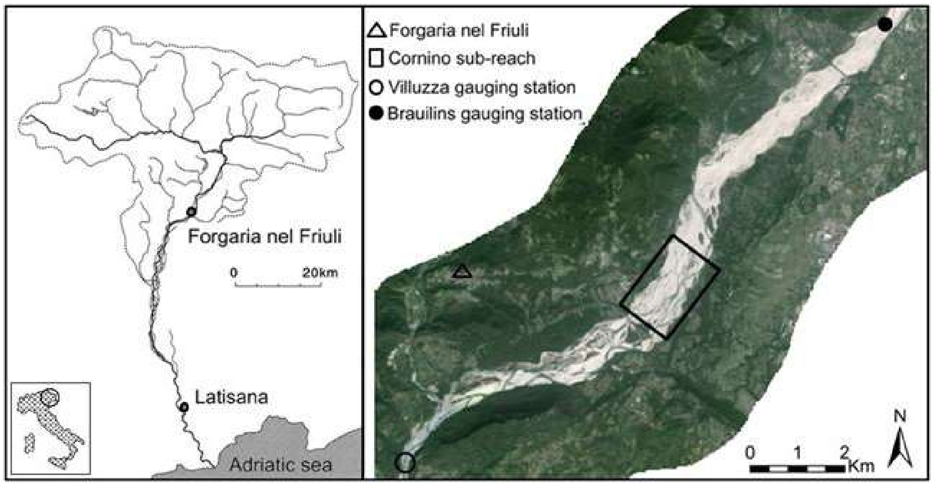

**Fig. 1.** Location of the Tagliamento basin and aerial photo of the study reach.

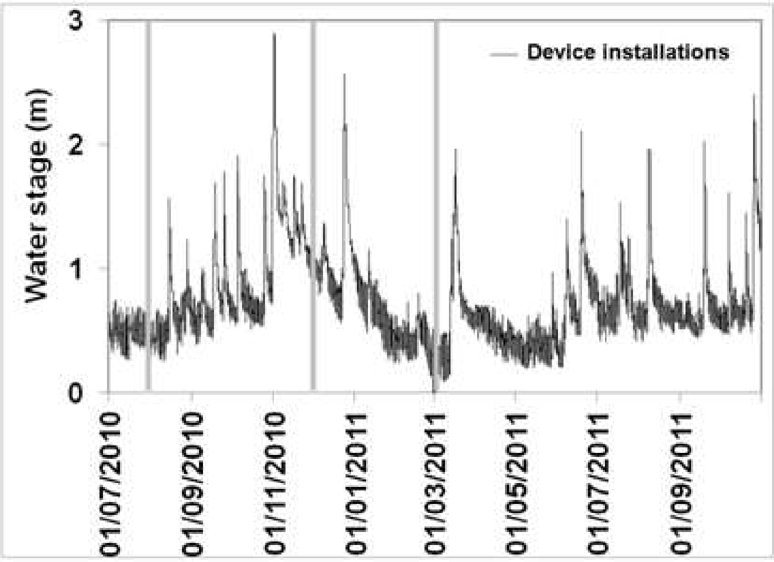

**Fig. 2.** Flood events occurred during the study period along the Tagliamento River. The grey lines indicate the date of device installations.

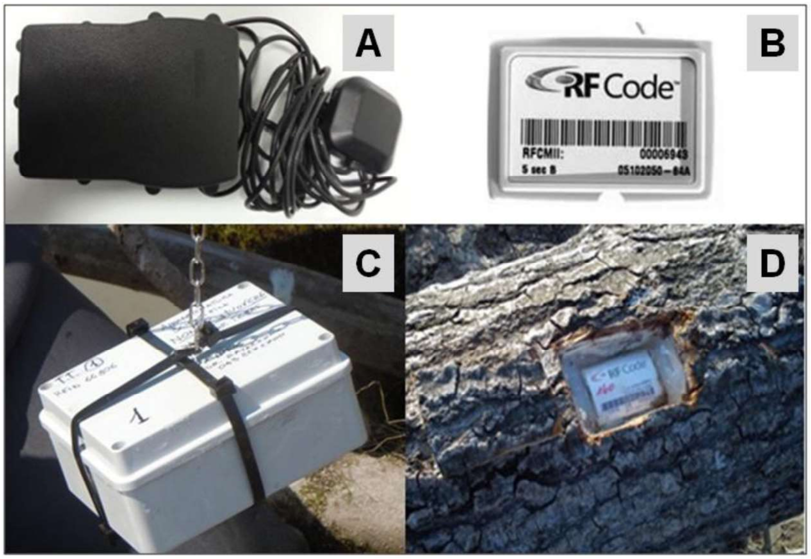

**Fig. 3.** RFID tag (B and D) and GPS tracker (A and C) devices as installed in logs in the Tagliamento River.

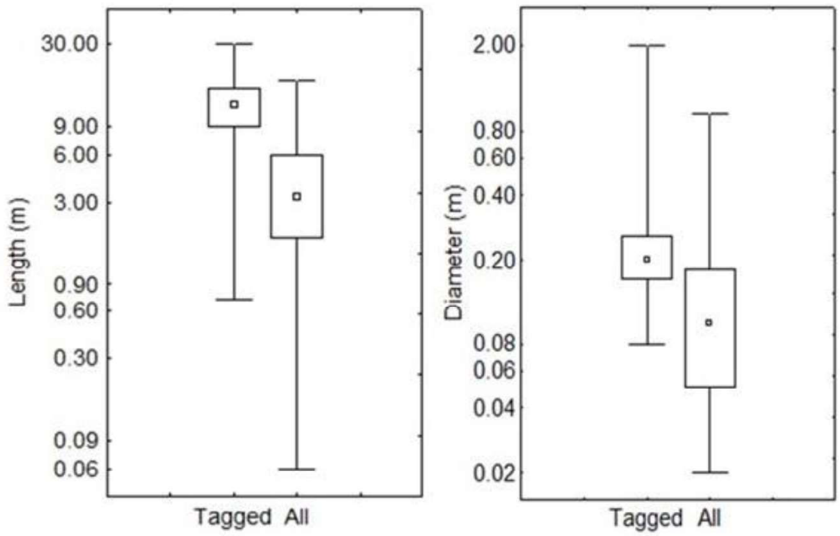

**Fig. 4.** Length (on the left) and diameter (on the right) of tagged logs and all logs surveyed in the study reach.

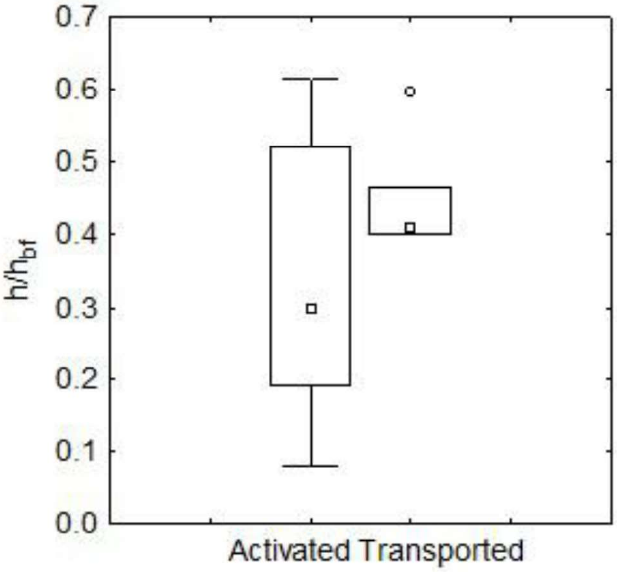

**Fig. 5.** Water stage relative to bankfull level needed to activate and to actually entrain and transport GPS tracker devices attached to logs stranded on low bars of the Tagliamento River. The whiskers represent the 10th and 90th percentiles, the box limits indicate the 25th and 75th percentiles and the square icon within the box marks the median.

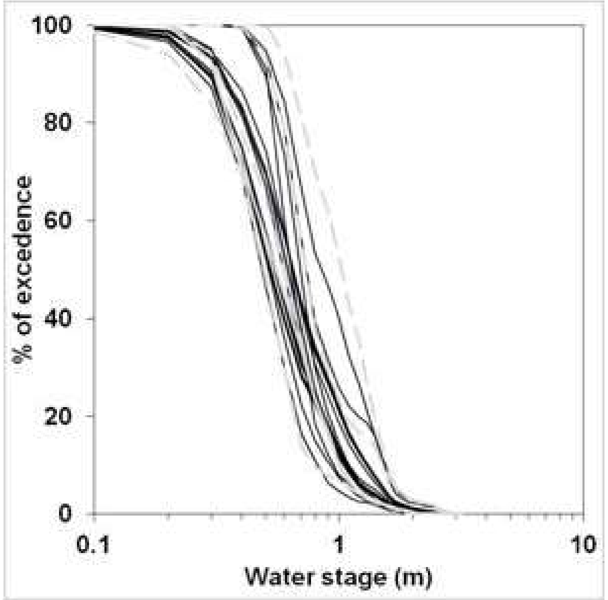

**Fig. 6.** Flow duration curves of the RFID tags (black lines) and GPS tracker devices (grey dashed lines).

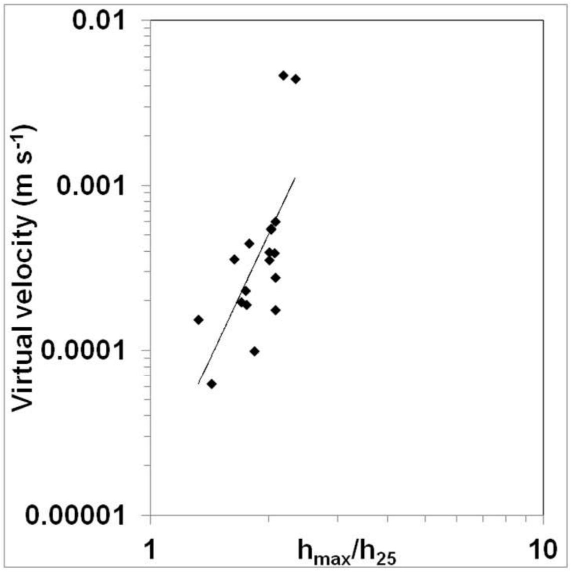

**Fig. 7.** Relationship between the ratio of maximum peak flow and the water stage exceeded for 25% of the time in the flow duration curve ($h_{25}$), and the virtual velocity of logs (which includes long periods of rest during low flows).

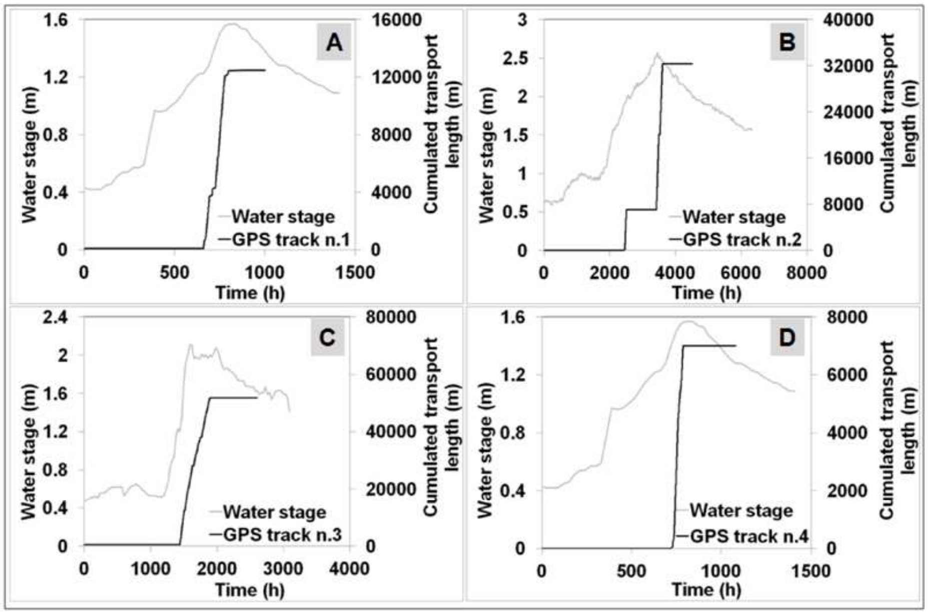

**Fig. 8.** Water stage and cumulated transport distance of logs tagged with GPS tracker devices. Times were set at zero for GPS tracker 1 at 00:00:00 of the 15/08/2010 event (A), at 17:00:00 of the 22/12/2010 event for GPS tracker 2 (B), at 00:00:00 of the 19/06/2011 event for GPS tracker 3 (C), and at 12:00:00 of the 15/08/2010 event for GPS tracker 4 (D).

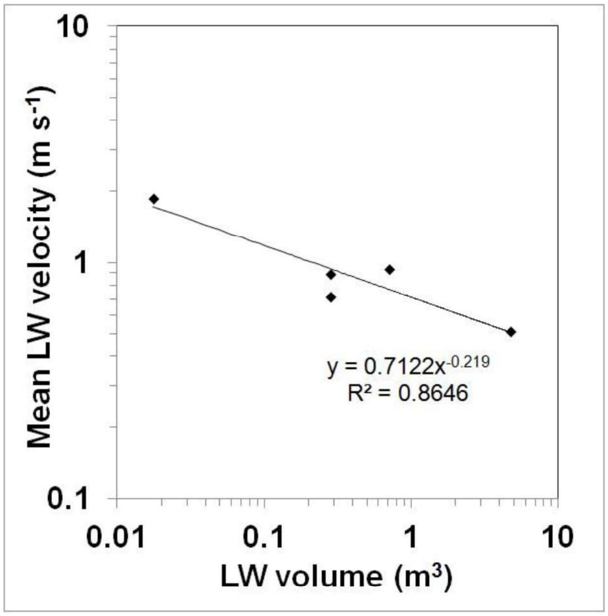

**Fig. 9.** Correlation between volume and mean velocity of transported logs.

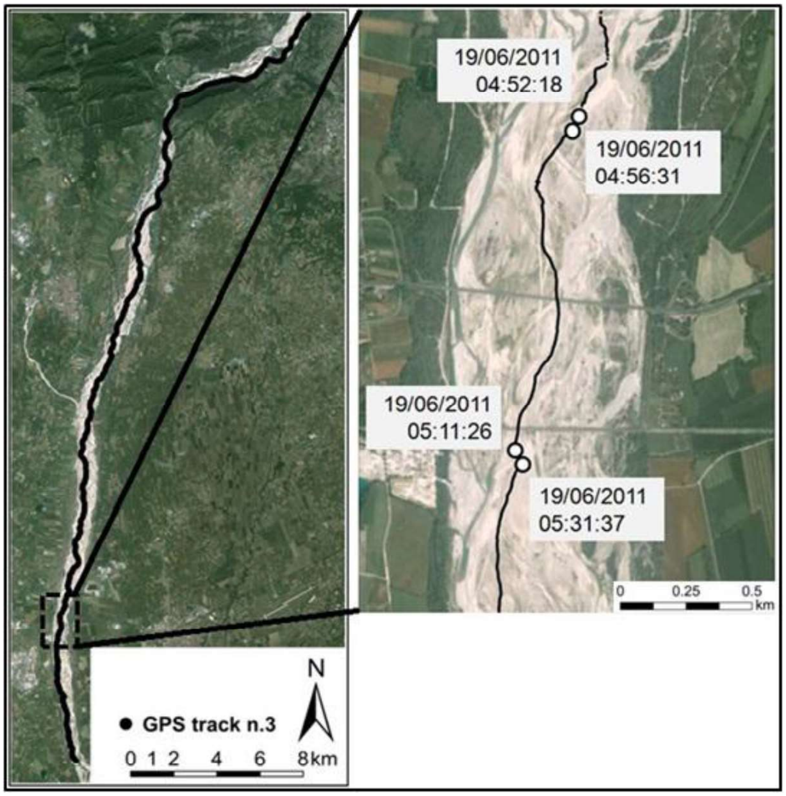

**Fig. 10.** Example of a travelled path followed by a log equipped with a GPS tracker device.