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Studying sediment transport in mountain rivers by mobile and stationary RFID antennas

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ABSTRACT: Sediment transport is an important factor in the assessment of natural hazards, but due to the complexity of the systems the predictability is very restricted, especially in mountain rivers. Thus, accurate data from natural streams are essential to assess and develop current approaches. Tracing techniques are widely used to study the processes in sediment transport. Recently, the Radio Frequency Identification (RFID) method was successfully employed in various streams using mobile antennas to determine the displacement of single transponders-tagged particles. We have developed an antenna system that can be permanently installed in the channel bed to continuously record the tagged pebbles passing over it. In this study, we discuss the advantages and limitations of using such tracer systems for monitoring bedload transport in steep channels. We illustrate the application of the mobile antenna system using data from the mountain stream Erlenbach and the stationary antenna system using data from field and laboratory experiments. Both methods complement other methods used to investigate the mechanics of sediment transport in steep mountain rivers.

Keywords: Sediment transport, Bedload transport, Tracer, Radio frequency identification, RFID, Mountain streams

1 INTRODUCTION

Sediment transport can cause considerable damage to infrastructure and human lives during large flood events. With a better understanding and assessment of these natural hazards the risks and potential consequences can be reduced significantly. Steep mountain streams differ from lower-gradient rivers in several ways. They are characterized by a wide range of sediment sizes and temporally and spatially variable sediment sources. In addition, the channel bed morphology is influenced by large boulders, woody debris and bedrock constrictions (e.g. Church & Zimmermann, 2007; Montgomery & Buffington, 1997). The complex and heterogeneous conditions result in large variations in channel geometry, roughness and stream flow velocity, and thus in highly fluctuating bedload transport rates (Hassan et al., 2005). Field measurements of bedload transport rates are rare, especially for alpine regions, and the controlling processes are poorly understood. These circumstances make the prediction of sediment transport rates difficult. Conventional bedload transport equations may over-estimate sediment fluxes by several orders of magnitudes when applied to steep streams (Recking et al., 2008; Rickenmann, 2001; Yager et al., 2007).

Tracer methods have successfully been applied in sediment transport research and can provide field data of sufficiently high quality for model development and validation (Sear et al., 2000). Tracer studies can yield information about the fluvial transport rates of sediment, transport distances and pathways, the thresholds of particle entrainment, sediment sorting by particle size or shape, the depth of the active layer, and sediment sources and deposition areas (e.g. Hassan & Ergenzinger, 2005; Lamarre et al., 2005; Sear et al., 2000). The RFID tracer method in bedload transport monitoring with mobile antenna systems has been successfully applied by several research groups with particle recovery rates of 60 % to 100 % (Lamarre et al., 2005; Lamarre & Roy, 2008; Liébault et al., 2009; Nichols, 2004). Stationary RFID antenna systems installed in river beds have previously been used for tracking the movements of fish populations (Armstrong et al., 1996; Johnston et al., 2009). An advantage of the RFID system is its ability to uniquely identify individual objects without having to physically inspect them. Thus, buried particles can be identified without disturbing the channel bed surface. In addition, the markers are independent of an internal power supply, which makes long-term studies possible.

The objective of this paper is to discuss the advantages and limitations of the RFID tracer technique for bedload transport. Recovery rates with mobile and stationary antennas in two mountain streams have so far been low in the field. We describe the systematic development and performance testing of stationary antennas in the laboratory, as well as the preliminary results of a mobile particle tracking survey in a mountain stream.

2 METHODS & FIELD SITES

2.1 *The Radio Frequency Identification System (RFID)*

The radio frequency identification system was developed as a wireless automatic identification system and has already been employed in a broad range of industrial and consumer applications (Shepard, 2004). The operating frequency of the system used in this study is 134.2 kHz, which is the Low-Frequency (LF) category. Compared to High-Frequency or Ultra-High-Frequency systems, the LF signal can pass through most non-metallic materials, including water, rock, concrete, wood and mud.

The RFID system consists of three main components (Figure 1): (i) the reader and control unit for reading out information, (ii) the antenna and (iii) the transponder (tag) used for tagging the object of interest. Typical reading distances are of the order of 50 cm, but can vary strongly depending on the technical configuration of the system and the specifics of the operating site.

The reader components used in this study were manufactured by Texas Instruments (TI-RFID, 2002) and consist of a reader (RI-RFM-008B), a control module (RI-CTL-MB2B), and a tuning board (RI-ACC-008B). In half duplex type (HDX), the RFID reader generates short magnetic impulses at the antenna and waits for the response of the transponder. Such a system has a larger reading distance than a full duplex type, which can send and receive simultaneously. In HDX, each reading cycle includes a charge-up and a listening time of 50 ms each in default settings, resulting in a scan rate of 10 scans per second. Enlarging the charge-up/listening time results in lower detection ranges, while lowering the scan rate may enlarge the reading distance and may be helpful where transport velocities are low.

The antenna is made either from twisted fine wire or a few turns of stranded wire, which is suitable for large antennas. In this study, a 2 x 2.5 mm^2 double winding cable of stranded wire was used for antenna design. To enlarge the reading field, several synchronized antennas in close succession can be used.

The transponders available may be active or passive. Passive transponders are cheaper and

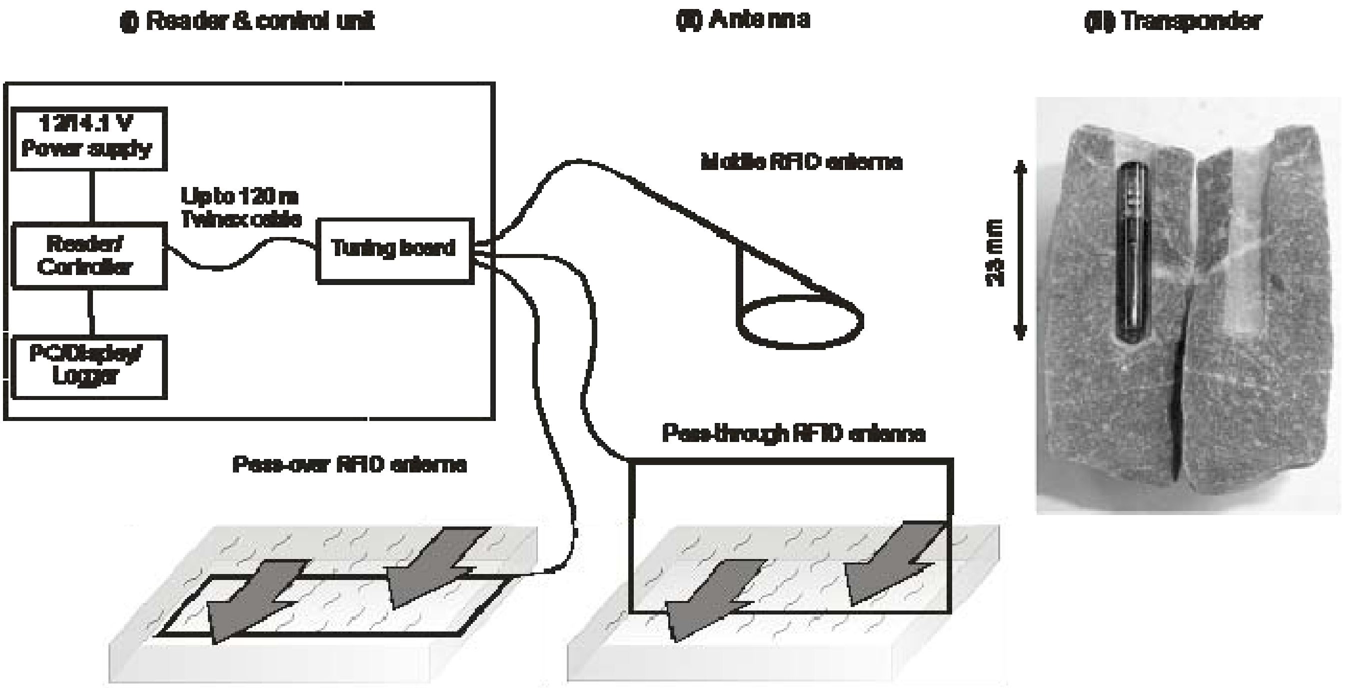

Figure 1: RFID System: (i) Reader & control unit, (ii) Mobile, 'pass-over' and 'pass-through' RFID antenna, and (iii) 23 mm transponder in pebble

have a longer lifetime because they are independent of an internal power supply. Their main disadvantage is the shorter reading distance. Inside the transponder is a resonant circuit which is energized by the electromagnetic field of the antenna and thus charges a capacitor. The capacitor delivers the energy to the transmitter that sends the return signal. The transponders used in this study are 23.1 or 31.2 mm long and 3.85 mm in diameter (Tiris, 2000, RI-TRP-WR3P/RI-TRP-WR2B). The size and shape of the 23/32 mm transponder allow them to be inserted into natural clasts with a minimum b-axis of ≈30/50 mm and a weight of ≈50/200 g.

The maximum reading distance, i.e. the maximum distance from the transponder to the antenna where detection is still possible, depends on the antenna type as well as the transponder size and its orientation and location relative to the antenna. In cases with two or more transponders in the antenna field, interferences may preclude the registration of some or all of the transponders.

The mobile RFID system used is the commercially available Léoni system (Aquartis, 2010). It consists of a reader unit, power supply, display, a long range (0.84 m diameter) and a short range (0.53 m diameter) antenna. The maximum reading distance of the mobile system was investigated in a series of laboratory experiments (Table 1). The reading distance refers to a perpendicular transponder orientation to the antenna in the centre of the antenna circuit. Antenna performance was tested with air, dry and wet sediment and water filling the space between the antenna and the transponder.

Table 1: Reading distance with 0.53/0.84 m loop antenna and two transponder types (23/32 mm)

Antenna Type:	0.53 Antenna		0.84 Antenna	
Transponder Type:	23 mm	32 mm	23 mm	32 mm
Reading distance:	Dist[m]	Dist[m]	Dist[m]	Dist[m]
Air	0.33	0.41	0.49	0.61
Buried dry (0.2 m)	0.30	0.40	0.46	0.60
Buried dry (0.3 m)	0.30	0.41	0.45	0.60
Buried wet (0.3 m)	0.31	0.41	0.46	0.61
Submerged (0.5m)	0.31*	0.38*	0.49*	0.61
Buried (0.4 m)/ Water table (0.5m)	-	0.40*	0.49*	0.61

* Antenna below the water table

2.2 *Field experiences: Erlenbach*

The mobile particle tracking system was used in the Erlenbach stream (Alptal, Canton Schwyz, Switzerland) in summer 2009 (Figure 2a). The Erlenbach drains a catchment area of ≈0.74 km^2 and its mean annual runoff is around 43 l/s. The channel bed has a mean slope of ≈17 % and the runoff regime is dominated by snowmelt in spring and convective storms in summer, with the storms having more impact on sediment transport (Rickenmann & McArdell, 2007). In June 2009, 298 tagged and painted natural pebbles in six equal weight classes from 50 to 1600 g were inserted into the Erlenbach, followed by an additional 127 pebbles after the first flood event. Particles were relocated after each of the eight flood events from 15.06.2009 to 10.08.2009.

Figure 2: a) Erlenbach, Slope: 0.17, D_{50}: 8 cm; b) Riedbach, Slope: 0.4, D_{50}: 21 cm

The recovery rate of the mobile particle tracking in the Erlenbach was ≈30 % which is not as high as that found in comparable studies (Lamarre et al., 2005; Lamarre & Roy, 2008; Liébault et al, 2009; Nichols, 2004). The reasons for this low recovery rate might be that (i) coarse boulder, large woody debris, channel steps and a generally rough surface prevented easy antenna access to all bed locations, (ii) the tagged pebbles were often buried at a depth greater than the detection range of the antenna, (iii) the pebbles were deposited too close together so that individual detection of each pebble was not possible, and (iv) some of the tagged pebbles were probably flushed out of the study reach during two high discharge events at the beginning of the field campaign.

Preliminary results

Despite the low recovery rates, some preliminary results can still be reported, in particular with respect to particle entrainment and transport distances. The critical Shields stress (Shields, 1936) is commonly used to describe the initiation of motion for uniform bed material. The entrainment of fluvially deposited pebbles during flood events follows an increasing function of the critical Shields stress (Figure 3a). This suggests that smaller pebbles are more easily entrained than larger particles. Nearly all of the pebbles that were

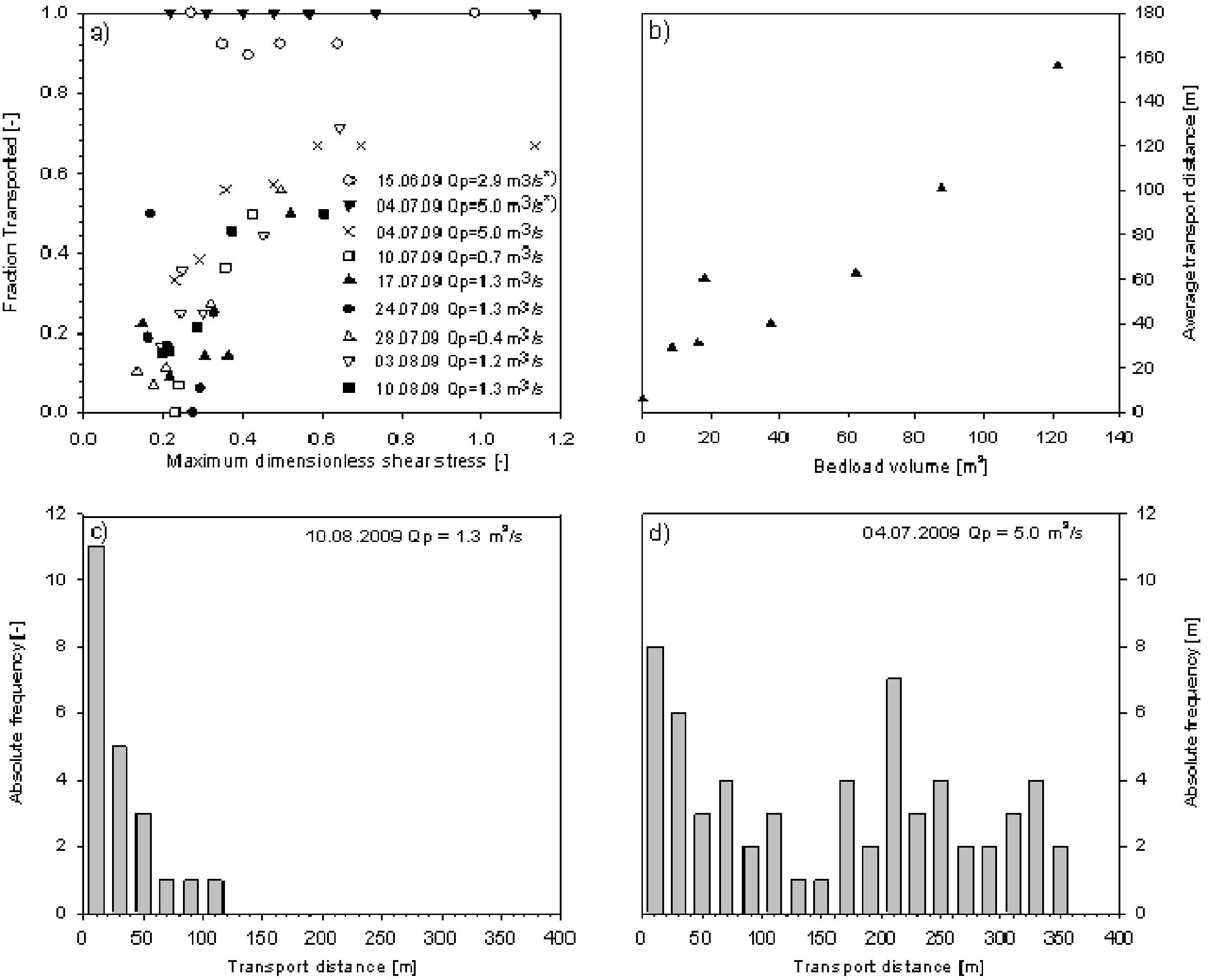

Figure 3: Results from the Erlenbach stream observations. a) Fraction of transported pebbles (displaced pebbles divided by total recovered pebbles as a function of maximum dimensionless shear stress for different flood events, *) transported fraction of arbitrary deposited pebbles; b) Transport distance as a function of bedload volume for different flood events; c) & d) Frequency distribution of transport distance for the flood event of (c) 10th August 2009 with a peak discharge (Q_p) of 1.2 m^3/s and (d) 4th July 2009 with Q_p of 5.0 m^3/s. Absolute Frequency = number of particles.

manually placed on the stream bed, however, were entrained during the subsequent flood regardless of peak discharge and particle diameter (Figure 3a), probably due to higher particle exposure.

The transport distances of particles during flood events are correlated with the total transported bedload volume (Figure 3b), and are dependent on the maximum peak discharge (Figure 3c & 3d). Furthermore, the distribution of travel distances for the event of 4th July with a peak discharge of ≈ 5 m^3/s (Figure 3d) suggests that during this flood an unknown number of tagged grains were flushed out of the 350 m study reach into the sediment retention basin.

2.3 *Field experiences: Riedbach*

In the Riedbach stream in Switzerland (Matterhorn Valley, Canton Valais) the first experiments were carried out with a stationary horizontal 'pass over' RFID antenna in the summer of 2009 (Figure 2b). The Riedbach catchment area is around 18 km^2. The study reach has a mean slope of ≈40%, and the glacially dominated runoff regime shows typical peak flows in the late afternoon with up to ≈3 m^3/s in July and August. The stationary antenna was rectangular with a streamwise length of 0.6 m and a width of 3.4 m. It was installed downstream of a tyrolean weir with a grid spacing of 25 mm. Due to the steep gradient of the channel and the local geometry of the weir, the sediment reaches high velocities and is sometimes far from the antenna when passing over it.

The RFID application in the Riedbach differs from the Erlenbach site because mobile particle tracking is not possible due to the steep channel gradient, difficult terrain, and high flow rates. Thus, a total of 270 tagged pebbles were inserted

≈40 m upstream of the antenna to obtain observations on short transport distances and frequent registrations. In the one month test phase at least 58 of the 278 inserted pebbles were found below the water intake, only 23 of which were registered by the antenna. The small number of data points does not currently allow further analysis.

The low registration rate in the Riedbach might be due to a combination of: (i) Very high velocities of transported pebbles, (ii) the transported pebbles out of the detection range of the antenna when flying through the air, and (iii) unfavorable transponder orientations while passing through the antenna field.

3 TESTING STATIONARY RFID ANTENNAS

To be able to optimize the configuration of the stationary antenna for different field applications, laboratory tests were carried out. First, several antenna geometries were investigated for installation in the cross-sections of the Erlenbach and the Riedbach, with the aim to maximize the reading field and reading distance. Second, registration rates of the antenna were evaluated in free fall tests and flume experiments, investigating the effect of (i) transport velocities, (ii) transport distances from the antenna, (iii) transponder types used, (iv) transponder orientation to the antenna field, and (v) the rock material enveloping the transponder when using tagged pebbles.

In general, the following antenna configurations are possible: (i) horizontal: the particles ‘pass over’ the antenna; and (ii) vertical: the particles ‘pass through’ the antenna (Figure 1). To enlarge the reading field, a ‘double pass through’ configuration with two synchronized antennas 0.6 m apart from each other was tested as well.

3.1 *Antenna geometry*

The width of the antenna was selected according to the width of the cross-sections at the field sites (3.5 m for Riedbach and 4.0 m for Erlenbach). Within the laboratory experiments the streamwise antenna length (respectively the height in the ‘pass through’ configuration) of the antenna circuit was varied from 1.0 to 2.0 m. The reading distance shown in Table 2 refers to the maximum reading distance of a transponder placed perpendicularly to the antenna on a perpendicular axis at half the streamwise antenna length (see arrow in Figure 4). The difference in the width of the antenna did not have a noticeable effect on detection range and efficiency, but the reading distance of a rectangular RFID antenna in a streamwise direction depends on the transponder orientation and its location relative to the antenna (Figure 4).

The detection of the smaller 23 mm transponders is less efficient than the detection of the 32 mm transponders. In general, when enlarging the streamwise length of the antenna circuit, the detection efficiency of a 23 mm tag declines towards the middle of the antenna, or even goes to zero.

Table 2: Averaged reading distance (Dist.) with rectangle RFID antennas of perpendicular-oriented transponders (23/32 mm) on half streamwise antenna length.

Length [m] Width 3.5m	Dist. 23mm	Dist. 32mm	Length [m] Width 4m	Dist 23mm	Dist. 32mm
1.00	0.34	0.66	1.00	0.34	0.61
1.25	0.20	0.54	1.20	0.21	0.54
1.40	0.28	0.54	1.40	0.31	0.65
1.50	0.25	0.67	1.60	0.25	0.68
1.75	0.16	0.61	1.80	-	0.42
2.00	0.10	0.61	2.00	-	0.52

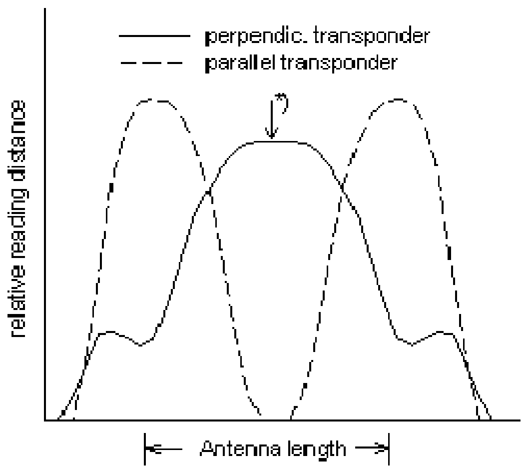

Figure 4: Reading distance profile (relative) of a rectangle RFID antenna in “pass over” configuration (antenna length in streamwise direction for parallel- and perpendicular-oriented transponders. *) refers to the reading distance listed in Table 2.

Finally, the reading distance depends on the environment of the antenna, since nearby metallic objects or other electromagnetic fields can influence the antenna field. In this study, such potential disturbances could not be quantified systematically, but they were avoided as far as possible.

3.2 *Identification of moving particles*

To identify the registration rate with moving particles, free fall tests with an antenna geometry of 3.5 x 1.5 m in ‘pass over’, ‘pass through’ (Figure 5) and ‘double pass through’ configurations were performed. In the latter case, the distance between the two synchronized antennas was 0.6 m. The 23 and 32 mm transponders in perpendicular (T_{PE}) and parallel (T_{PA}) orientation to the antenna as

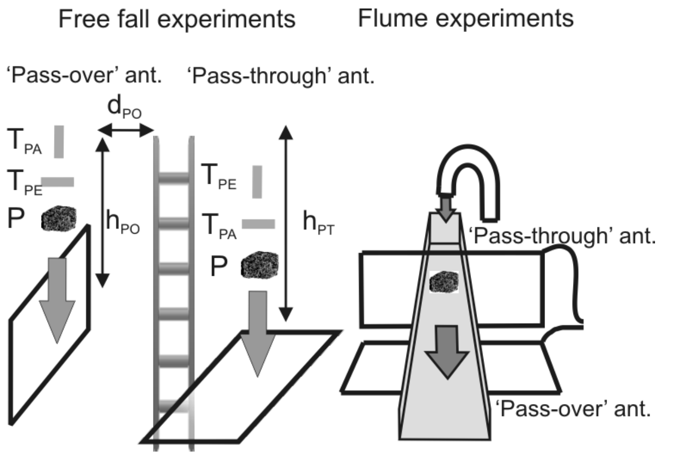

Figure 5: Antenna setup of free fall and flume experiments. h_{PO} = drop height 'pass over' antenna; h_{PT} = drop height 'pass through' antenna; d_{PO} = distance from 'pass over' antenna; T_{PA} = parallel oriented transponder; T_{PE} = perpendicular oriented transponder; P = tagged pebble with random orientation of the inserted transponder.

well as tagged pebbles (P) in random orientation were dropped from changing heights (h_{PO}/h_{PT}) and distances (d_{PO}) to the stationary antenna. In 'pass-through' configuration, no significant differences in the registration rates could be observed regardless whether the transponders passed in the center of the antenna circuit or near the edges. Therefore, the transponders were always dropped in the center of the 'pass through' antenna circuit. The transponder velocity of the free fall tests was calculated as the mean velocity inside the detection range, not taking aerodynamic resistance into account.

In addition, the 3.5 x 1.5 m rectangular antenna was tested in 'pass over', 'pass through' and 'double pass through' configurations in a laboratory flume, to better simulate natural transport conditions. The flume had a length of 5.0 m, a cross-sectional area of 0.3 x 0.3 m and a gradient

Table 3: Registration rates by one/two 3.5 x 1.5 m RFID antennas in the free fall and flume experiments with tags in perpendicular and parallel orientation to the antenna as well as with tagged pebbles with a random orientation of the inserted tags.

		Tag	Drop height [m]	Velocity* [m/s]	Time Tag in detect. Range [s]	Dist. to Antenna [m]	Tag orient. perpend. n	Tag orient. perpend. % reg.	Tag orient. parallel n	Tag orient. parallel % reg.	Tagged Pebble n	Tagged Pebble % reg.
'Pass over' Antenna	Free Fall	23	0.8	3.8	0.46	0.25	20	85	0	-	24	42
		23	1.5	5.4	0.28	0.15	20	55	20	60	24	63
		23	1.5	5.4	0.28	0.25	21	62	29	60	8	13
		23	1.5	5.4	0.28	0.40	10	0	10	0	8	0
		23	3	7.7	0.19	0.15	20	50	20	55	24	46
		23	3	7.7	0.19	0.25	10	20	10	10	24	17
		32	1.5	5.4	0.28	0.15	10	100	20	80	44	77.5
		32	1.5	5.4	0.28	0.40	10	100	20	85	20	65
		32	1.5	5.4	0.28	0.60	5	0	7	14	20	20
		32	3	7.7	0.19	0.15	20	95	20	85	30	82.5
		32	3	7.7	0.19	0.25	24	96	27	93	32	77.5
		32	3	7.7	0.19	0.40	26	69	26	73	45	52
	Flume	23	-	2.2	0.68	0.15	-	-	-	-	88	26
		23	-	2.2	0.68	0.25	-	-	-	-	98	12
		32	-	2.0	0.75	0.15	-	-	-	-	99	92
		32	-	2.0	0.75	0.25	-	-	-	-	111	85
		32	-	2.0	0.75	0.40	-	-	-	-	55	89
		32	-	2.0	0.75	0.60	-	-	-	-	54	74
'Pass through' Antenna	Free Fall	23	0.5	3	0.28	centre	20	45	-	-	22	45
		23	1	4.3	0.18	centre	10	0	-	-	-	-
		32	1	4.3	0.28	centre	20	95	20	40	32	83
		32	2	6.2	0.19	centre	20	100	20	60	50	56
		32	3	7.7	0.15	centre	20	100	20	65	40	53
	Flume	23	-	2.2	0.54	centre	-	-	-	-	160	45
		32	-	2.0	0.60	centre	-	-	-	-	200	72
'Double pass' through Antenna	Free Fall	23	2	6.2	0.29	centre	10	0	-	-	-	-
		32	2	6.2	0.29	centre	10	100	10	90	30	75
		32	3	7.6	0.23	centre	10	100	10	90	30	67
		32	5	9.8	0.18	centre	10	100	10	80	30	46
	Flume	23	-	2.2	0.81	centre	-	-	-	-	24	0
		32	-	2.0	0.90	centre	-	-	-	-	103	90

*Free Fall: Calculated velocity without taking aerodynamic resistances into account; Flume: Velocity determined by a high-speed camera.

of 50 %. The flume floor was rough to ensure that particles were rolling. The velocity of the flume-tests is a mean velocity of the transported particles derived from high-speed camera images.

From the free fall and flume experiments, it was apparent that the registration rate is influenced by the transponder type used, the transponder orientation and distance to the antenna, but also by the particle velocity, the antenna configuration and whether the transponder is inside a pebble or not (Table 3).

Compared to the 32 mm transponder, the smaller 23 mm tag is less detectable in all configurations. In 'pass over' configuration (flume) 0.15 m away only a rate of 26 % could be observed, unlike the 92 % with the 32 mm tag (Table 3). In addition, the registration rate depends on the transponder orientation with respect to the antenna field and whether the transponder is encased by rock material or not. For example, the registration rate of the perpendicularly dropped 32 mm transponders is 100 %, of the parallel transponders 80 % and of the tagged pebbles 77.5 % from a 1.5 m drop down height (Table 3).

Comparing the 'pass over' with the 'pass through' antenna, the results of both the free fall and the flume tests show that the 'pass over' antenna yields better registration rates when the pebbles pass close to the antenna. Increasing distances result in rapidly declining registration rates (Table 3). With the 'pass through' antenna the registration rates over the whole antenna height were relatively homogenous, although they were somewhat lower than for the 'pass over' antenna.

The tag/particle velocity also affects the registration, but to a lesser extent than the distance from the antenna. The higher the fall velocity, the lower the registration rate (Table 3). During natural transport conditions in the Erlenbach, maximum particle velocities of around 3 m/s can be expected. Therefore the setting should be sufficient for several reading cycles. In general however, the larger the number of scans, the greater the probability of receiving a signal back.

4 CONCLUSIONS

Particle tracking by RFID systems can be a useful tool for monitoring sediment transport in mountain streams. Our experiences in field in summer 2009 highlight the limitations of the mobile antenna system in boulder bed channels, as well as in steep streams with high discharges. A permanently installed antenna adapted to the stream and transport characteristics of the investigation reach can be used to complement the mobile particle tracking and improve the recovery rate. In addition, the temporal resolution for monitoring transported pebbles increases with permanent antennas.

The laboratory experiments indicate that the registration rate depends mainly on the signal strength received back from the transponder, which is strongly correlated with the distance of the transponder from the antenna. What also influences the registration rate is the stone material enveloping the transponder. The particle velocity of naturally transported sediment plays a minor role, but in general, the larger the number of reading cycles, the larger the registration rate. Therefore, with a suitable configuration of the stationary antennas, high detection efficiency should be feasible. In the Erlenbach, in which sediment is transported naturally in water close to the bed surface, a 'pass over' antenna should give the best results because the reading field in the flow direction is longer. To cover the vertical extension as well, an additional synchronized 'pass through' antenna would be useful. Because of the geometry of the water intake in the Riedbach, the sediment moves at high velocities and is sometimes far from the antenna when passing over it (i.e., mostly flying through the air). Here, a 'pass through' configuration with two synchronized antennas would be favorable. However, the installation of a 'pass through' antenna is more vulnerable as it is much more difficult to protect the upper cable from flowing water, transported sediment and floating wood.

The laboratory experiments have shown the RFID antennas are very sensitive to the environment and disturbances. Extensive antenna tests in the field would help to choose the optimum antenna configuration.

In future, additional RFID tagged particles will be inserted in the streams and both 'pass over' and 'pass through' RFID antennas will be installed in the Erlenbach and the Riedbach. Future data analysis will focus on the initiation of motion, transport velocities and distances, and particle pathways as a function of hydraulic and morphologic conditions. The findings of this research are complementary to other sediment transport surveys that are currently being carried out in the Riedbach and Erlenbach.

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