Hydrol. Earth Syst. Sci. Discuss., 8, 11315–11355, 2011
www.hydrol-earth-syst-sci-discuss.net/8/11315/2011/
doi:10.5194/hessd-8-11315-2011

Hydrology and
Earth System
Sciences
Discussions

Measurement of spatial and temporal fine sediment dynamics in a small river

Y. Schindler Wildhaber[1], C. Michel[2], P. Burkhardt-Holm[2], D. Baenninger[1,*], and C. Alewell[1]

[1]Institute for Environmental Geosciences, Basel, Switzerland
[2]Man-Society-Environment MGU, Basel, Switzerland
[*]now at: Environment protection and energy agency, Liestal, Switzerland

Received: 23 November 2011 – Accepted: 11 December 2011
– Published: 20 December 2011

Correspondence to: Y. Schindler Wildhaber (yael.schindler@unibas.ch)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Empirical measurements on fine sediment dynamics, infiltration and accumulation have been conducted worldwide, but it is difficult to compare the results because the applied methods differ widely. We compared established methods to capture temporal and spatial dynamics of suspended sediment (SS), fine sediment infiltration and accumulation and tested them for their suitability in small, canalized rivers of the Swiss Plateau. Suitability was assessed by data comparison, relation to hydrological data and in the context of previously published data. SS were assessed by optical backscatter (OBS) sensors and SS samplers. The former exhibit a better temporal resolution but were associated with calibration problems. Due to the relatively low cost and easy mounting of SS samplers, they can provide a higher spatial distribution in the cross section. This results in a better correlation between sediment infiltration and SS assessed by SS samplers than with OBS sensors. Sediment infiltration baskets and bedload traps were able to resolve the temporal and spatial distribution of fine sediment infiltration. Data obtained by both methods were positively correlated with water level and SS. In contrast, accumulation baskets can not assess the temporal behavior of fine sediment but the accumulation over a certain time period. Results indicate that less fine sediment accumulated in upwelling zones and within areas of higher mean water level due to scouring of fine sediment. Even though there was an increase of SS and sediment assessed with the bedload traps from up- to downstream, less fine sediment accumulated downstream. This is probably also due to more scouring downstream.

1 Introduction

It is observed, that fine sediment (sediments < 2 mm) loads in rivers are generally increasing throughout the world in catchments that are impacted both directly and indirectly by human activities (Owens et al., 2005). Not only human activities can increase fine sediment loads in rivers but also other factors as climate change. Sediment supply

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀▮ | ▶▮
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

in the alpine Rhine basin is estimated to increase between 220 % and 284 % by the year 2100 due to climate and land use change (Asselman et al., 2003). These observed and anticipated changes in fine sediment dynamics in rivers can provide a serious threat to aquatic ecosystems including phytoplankton, aquatic invertebrates and salmonid fish (for a review see Bilotta and Brazier, 2008). Salmonid fish can be affected by suspended sediment (SS) in several ways. While SS can directly impact health and fitness of free swimming fish (Newcombe and Jensen, 1996), fine sediment deposition in the gravel bed can induce siltation of the riverbed resulting in a decrease in hydraulic conductivity (Schalchli, 1995), which affects the oxygen supply to the developing salmonid embryos in the redd negatively, and hence their survival (Greig et al., 2005). The consequences of climate and land use change on the transport of sediment into rivers, on sediment transport in the river and on clogging processes are poorly known. Studies for the Alps, Pre-Alps and the hilly regions of the Swiss Plateau are rare. This includes small rivers, which serve as recruitment sites of gravel spawning fish (Scheurer et al., 2009).

Several studies have shown a strong correlation between sediment deposition and the occurrence of fine sediment in the water column. Thus, higher fine sediment loads in rivers generally lead to increased infiltration into the riverbed (Greig et al., 2005; Zimmermann and Lapointe, 2005) while periods of low flow trigger low infiltration rates with finer grain sizes (Sear, 1993; Soulsby et al., 2001). Thus, direct measurement of SS loads may be a straight forward method to assess sediment deposition. The estimation of SS from turbidity measurements with optical backscatter (OBS) sensors depends on the content of fine particulate organic matter as well as grain size distribution of the SS and color and shape of the grains (Packman et al., 1999). Accordingly, OBS turbidity measurements require calibration at individual test sites.

Deposition of fine sediment is not only controlled by SS concentration, but also by flow hydraulics and inter-gravel flow. These specific hydraulic conditions, influenced by the topography and the permeability of the river bed, can have a large influence on sediment deposition (Brunke, 1999; Seydell et al., 2009). For example, Seydell et al. (2009) found significant higher infiltration rates in down welling zones than upwelling zones. Rivers of the hilly regions of the Swiss Plateau and in Europe in general are widely canalized and laterally stabilized by steps for land drainage and flood control. These steps lower the flow velocity resulting in an increase of fine sediment infiltration. Clogging of the riverbed is possible due to enhanced seepage flow (Bucher, 2002). Additionally, steps may impede desiltation, a term referring to all processes, which contribute to an increase of hydraulic conductivity due to higher bed-shear stress (Schalchli, 1995).

Numerous studies have been conducted on fine sediment dynamics, infiltration and accumulation in Canada (e.g. Levasseur et al., 2006; Zimmermann and Lapointe, 2005), USA (e.g. Lisle and Lewis, 1992) and the United Kindom (e.g. Greig et al., 2005; Heywood and Walling, 2007; Sear, 1993; Soulsby et al., 2001). But the results of empirical measurements of infiltration rates are difficult to generalize mostly due to different measurement methodologies (Sear et al., 2008). Hence, there is a strong need to compare methodologies as well as data on sediment input and river bed clogging to achieve a better comparability of results from different studies and to increase knowledge on the interaction between fine sediment dynamic, infiltration and accumulation (Scheurer et al., 2009). Accordingly, the aim of this study was to (I) compare results obtained by different methods used to capture temporal and spatial dynamics of suspended sediment and fine sediment infiltration and accumulation, (II) test their suitability for rivers in the Swiss Plateau and other European lowland rivers (III) compare the data with hydrological data and (IV) compare the assessed data with literature data. The tested methods have been used in the past to assess sediment dynamics for different research questions. Because these questions are crucial for gravel spawning salmonid embryos, the study was conducted in artificial redds.

2 Materials and methods

2.1 Study site and general setup

The river Enziwigger is a small canalized river located near Willisau (Canton Luzern, Switzerland) with a total watershed of about 31 km^2 (Fig. 1). The flow regime of the Enziwigger is not affected by hydro-power and no waste water treatment plant is located above Willisau. Like most rivers in the Swiss Plateau, its morphology is strongly modified. Classified with the Swiss modular stepwise procedure for ecomorphology (Hütte and Niederhauser, 1998), only 5 % is close to natural or natural, 21 % is little affected and 74 % is strongly affected or even artificial, including steps that have been inserted to prevent heavy bed scouring during flood events (EBP-WSB-Agrofutura, 2005). In spite of these strong modifications, its biological condition – classified with the *macrozoobenthos* module of the Swiss modular stepwise procedure (Stucki, 2010) – is considered good (EBP-WSB-Agrofutura, 2005). The only fish species in the Enziwigger is the brown trout, *Salmo trutta* (EBP-WSB-Agrofutura, 2005).

The bedrock of the watershed consists of upper fresh water molasse. The soil types are mainly (stagnic) Cambisol and Leptosol (classified according to WRB; IUSS, 2006). The mean annual temperature in Willisau is 8.5 °C with a mean annual rainfall of 1050 mm. Mean annual rainfall on the mountain Napf, were the river Enziwigger originates, is 1700 mm per year (1961–2007; Data from MeteoSwiss). Discharge was measured in Willisau from November 2007 until November 2008 by the Canton of Lucerne. Minimal discharge was 1.1 m^3 s^{-1}, maximal 10.1 m^3 s^{-1} and the mean 2.1 m^3 s^{-1}.

Measurements were set up in artificial redds located at three experimental sites along the river (A, B and C; from up- to downstream; Fig. 1) at an altitude of 757, 625 and 583 m above sea level, respectively (for site characteristics see Table 1). Each site was equipped with six artificial redds in places were natural brown trout redds had been mapped in November 2008. These locations are mostly consistent over years (Philip Amrein, fish warden of the canton Lucerne, personal communication, 2009). Data were assessed during two spawning seasons (Season 1: November 2009 to end of March 2010; Season 2: November 2010 to end of March 2011) in 18 artificial redds per year ($n_{\text{tot}} = 36$).

2.2 OBS sensors and time integrated samplers to measure suspended sediment (SS)

Turbidity was measured continuously during both field periods at each side with one optical back scatter (OBS) probe (Campbell Scientific, OBS-3+) every 15 s of which the median was logged every 10 min (median from 40 measurements). To calibrate the nephelometric turbidity unit (NTU) to suspended sediment concentration (SSC_{NTU}) in mg l^{-1}, water samples were taken every seven hour with an automatic water sampler (ISCO 6700, Isco Inc., USA). Because of freezing of the suction hose during the first field season, weekly water samples were taken manually during the second field season. The latter were complemented with samples collected by local habitants during storm events. Water samples were taken to the laboratory to asses the total SSC (see Sect. 2.7).

To determine the spatial variation of the SS, time-integrated samplers following Philips et al. (2000) were installed behind each redd and emptied at a weekly interval. They consisted of commercially available one meter 110 × 4.2 mm PE pipes (inner diameter (i.d.) = 101.6 mm), sealed with a plugged polyethylene funnel at the inlet and a cap at the outlet. An aluminum tube with 4 mm i.d. was passed through the funnel and the cap as inlet and outlet. The SS samplers were mounted parallel to the riverbed at two upright steel bars driven into the channel bed, with the inlet tube pointing directly into the direction of the flow. Within the samplers, the flow velocity is reduced by a factor of 600, relative to that of the ambient flow, due to the greater cross-sectional area of the main cylinder compared to that of the inlet tube. This reduction in flow velocity induces sedimentation of the SS particles as the water moves through the cylinder towards the outlet tube (Phillips et al., 2000). These SS samplers collect a statistically representative sample under field conditions (Phillips et al., 2000).

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

2.3 Sediment baskets to measure fine sediment infiltration and accumulation

Fine sediment (i.e. particles < 2 mm) infiltration and accumulation was determined with sediment baskets (cf. Acornley and Sear, 1999; Heywood and Walling, 2007; Greig et al., 2005). They consisted of two baskets made of 20 × 20 mm wire mesh with 2.5 mm wire and a solid bottom. The inner baskets had a diameter of 125 mm and were 160 mm deep. They were filled with riverbed sediment >4 mm to start with initial conditions without fine sediments. A second basket with a diameter of 150 mm was dug in the riverbed as a placeholder. To prevent loss of fine sediment during removal of the inner baskets, a polyethylene bag with two long handles was placed around the inner baskets and stuffed to the bottom between the two baskets.

Each redd was equipped with two sediment baskets. One of them was emptied at weekly intervals to investigate the weekly infiltration rates (=infiltration basket). The baskets' sediment was sieved with a 4 mm sieve and refilled with the same sediment during each sampling event. Sediment < 4 mm was taken to the laboratory for grain size analysis. The second set of sediment baskets was emptied only at the end of the spawning season to asses the total accumulation of fine sediment during the incubation period (=accumulation basket) (Sear et al., 2008). During Season 1 (2009/2010) 10 of the initial 18 accumulation baskets were washed away at high flow. Therefore we installed two accumulation baskets in each redd during Season 2 (2010/2011).

2.4 Bedload traps to measure sediment transported along the bed

The volume of the described infiltration baskets is small. Most of the space within the trap is taken up by coarse bed material. Thus, these baskets can fill very quickly in situations where sediment loads are high (Bond, 2002) resulting in an underestimation of the infiltration rate. To overcome this problem bedload traps similar to Bond (2002) were designed, consisting out of two nestable 180 × 145 × 115 mm dug boxes with a 25 × 25 mm wire lid, above which coarse bed material was placed to avoid resuspension of the settled material in the trap. To empty the box, it was covered by a lid and the inner box was removed. Due to turbulence caused by the coarse bed material above the trap, part of the settled fine sediment might not be material transported as bedload but also as suspension. Nevertheless we call the described trap “bedload sampler” to clearly distinct them from the infiltration baskets and to use the same nomenclature as Bond (2002). During the first field season, each redd was equipped with one bedload trap, which was emptied weekly.

2.5 Hydraulic conditions

The temporal dynamic of the water level at the three sites was measured every 15 s with pressure transmitter probes (STS, Sensor Technik Sirnach, Switzerland) during both seasons. Average values were logged at 10 min intervals. The water level above each redd was measured weekly to assess its heterogeneity within a site.

The vertical hydraulic gradient (VHG) in the redds was measured weekly within mini piezometers after Baxter et al. (2003) which were installed in the pit and tail of each redd. The piezometers had a length of 300 mm and consisted of 25 mm diameter polypropylene (PP) pipe with an i.d. of 21.4 mm. They were perforated with approximately 30 evenly spaced holes in the lower 16 cm and plugged at the bottom. The VHG is a unitless measure that is positive under upwelling conditions and negative under downwelling condition. It is calculated by the formula

$$\mathrm{VHG} = \Delta h / \Delta l \quad (1)$$

where Δh is the difference in head between the water level in the piezometer and the level of the stream surface and Δl is the depth from the streambed surface to the first opening in the piezometer sidewall (Baxter et al., 2003).

2.6 Freeze core samples

Freeze core samples were taken with a copped and plugged 400 mm diameter steel pipe. The pipe was pounded in the river sediment to a depth of approximately 350 mm and filled with liquid nitrogen. Freeze cores roughly 350 mm high and 150 mm in diameter were removed, divided vertically in 100 mm wide layers, dried and sieved.

2.7 Sample analysis

The grain size distribution of the sediment was determined by sieving the sediments with sieves of different mesh size with the standardized sieve techniques. Grains with a diameter < 32 µm were measured with a sedigraph (Micrometrics 100, Coulter Electronics, Germany). Grain size fractions were named according to the German soil taxonomy: sand: 63 µm–2 mm, silt: 2 µm–63 µm and clay: <63 µm (Sponagel et al., 2005). Water samples for suspended sediment concentration were filtered through pre-weighed Whatman-filters with an 11 µm pore diameter, dried at 40 °C and weighed. Organic carbon concentration was measured with a CHN-Analyzer (Leco, USA).

3 Results and discussion

3.1 Suspended sediment

3.1.1 Turbidity measured by optical backscatter sensors

The calibration of the nephelometric-turbidity-unit (NTU) values of the OBS sensors to suspended sediment concentration (SSC_{NTU}) was difficult and associated with a high variance (Fig. 2). Nevertheless some general statements were possible: SSC_{NTU} varied at all sites between 2 and 10 $mg\,l^{-1}$ during low flow conditions and increased, depending on the site, to around 150 $mg\,l^{-1}$ (site A) to 300 $mg\,l^{-1}$ (site C) at high flow (Fig. 3). Only small floods occurred during the second season resulting in significant (t.test, $p < 0.05$) smaller mean SSC_{NTU} at all sites with an overall mean of 17.0 $mg\,l^{-1}$ compared to an overall mean of 42.7 $mg\,l^{-1}$ during the first season (Table 2). There was a significant increase of SSC_{NTU} from upstream (site A) to the two downstream sites (B and C) during both seasons (Table 2). The high mean SSC_{NTU} at site B for the second season might be due to measurement artifacts since the OBS sensor at this site was often shielded by leaves. Even though we did exclude statistical outliers from the dataset, there were still many high value data points which we could not exclude with statistical certainty, but which might still be influenced by measurement artifacts.

An advantage of SSC_{NTU} measurement with OBS sensors is the temporal resolution. SSC_{NTU} increased rapidly with increasing water level at all sites and there is evidence of sediment exhaustion during the falling limb of flood events (Fig. 3). Although OBS sensors are widely used for turbidity measurements, their handling is an often underestimated problem (for a review see Downing, 2006). The most frequent problems with OBS sensors are their signal dependence on grain size distribution and on sediment composition (mineral shape of particles) as well as algae growing on the sensors (Downing, 2006; Minella et al., 2008; Packman et al., 1999). There is an infinite number of combinations of sediment characteristics, including size, shape, mineral compositions and surface texture. Each combination produces a unique signal and each meter has a unique emitter-detector geometry that samples the signal in a particular way (Downing, 2006). Thus, NTU is an arbitrary unit, incomparable to NTU measured at other times and places or with different turbidity meters (Downing, 2006). A calibration of NTU to SSC_{NTU} in $\mathrm{mg\,l^{-1}}$ is necessary for a comparison to other studies. However, measurement uncertainty is introduced into the SSC_{NTU} data when converting NTU to SSC_{NTU} (Downing, 2006; Navratil et al., 2011).

We observed several problems with the OBS sensors during the two field seasons. In the fall months drifting leaves were caught by the sensors, resulting in abnormally high NTU values. In this study, this was particularly the case at site B during Season 2. This shortcoming could be partly counterbalanced by more frequent checks at the field site, similar to the SS samplers (see below). Moreover freezing of the suction hose of the ISCO samplers during the winter stopped the collection of water samples. Regularly water samples are necessary for a good calibration. Finally the D_{50} (50th percentile grain size diameter; data assessed by SS samplers, see section below) of the SS fluctuated strongly during the field season with a minimum of 6.7 µm at low flow with low SSC_{NTU} and a maximum of 110.5 µm at high flow associated with high SSC_{NTU} (Fig. 4). The large effect of the change in grain size composition on the OBS signal has been documented in numerous studies (see Downing, 2006 for an overview). The organic carbon fraction of the suspended sediment was also highly variable with minimum values around 1.5 % at high flow and maximum values around 10.5 % at low flow. This change in organic carbon fractions also has an influence on the conversion of NTU to SSC_{NTU} values (Downing, 2006).

3.1.2 Suspended sediment samplers

Results from the SS samplers paralleled the observations with the OBS sensors, showing a significant higher SS input during the first season than the second season (t.test, $p < 0.05$) and a SS increase downstream (Table 2). The SS captured by the six SS samplers per site during one week varied highly with coefficient of variation (CV) between 12 and 100 %. This represents the well known variation in suspended sediment concentration through the cross-section (e.g. Minella et al., 2008). D_{50} of the SS varied highly across the channel and with time, again representing the variation of SS within a river both with low and high mean SS concentrations in the water column (Fig. 4).

A major advantage of the SS samplers is that the deposited sediments can be retained for further analyses of their composition. In addition, the SS samplers can be installed in a relatively dense sampling network because they are reasonably inexpensive and easily fabricated. Furthermore, they can also be installed at specific test sites close to the sediment baskets, for example behind individual artificial redds. Thus, they can provide information about spatial differences of SS across the channel and about SS load at a specific test location. Problems of this method include clogging of the inlet with leaves and the difficulty of placing the samplers horizontally with the inlet tube directly pointing into the flow. Therefore, we suggest that close monitoring of the samplers should be conducted to ensure their proper performance, especially during fall when a large number of leaves drift in a river.

3.2 Sediment infiltration

We found a strong temporal variation of fine sediment infiltration, with values ranging between $0.01\,\mathrm{kg\,m^{-2}\,d^{-1}}$ during low flow conditions and $10.36\,\mathrm{kg\,m^{-2}\,d^{-1}}$ during peak discharge (Table 3). At all sites we found an exponential increase in sediment infiltration with increasing water level with very small infiltration rates until a certain threshold (Fig. 5). At site B and C, sediment infiltration reached a maximum at a certain water level. This indicates a saturation or equilibrium of input and scouring above this water level. At site A this level was never reached most likely due to an overall lower water level (Fig. 5). Our results confirm the conclusions of previous field studies that infiltration of fine sediment is maximum during peak discharge when sediment transport is high (Soulsby et al., 2001; Zimmermann and Lapointe, 2005; Acornley and Sear, 1999; Greig et al., 2005).

Since the sediment infiltration baskets were not filled with homogenous gravel but with river bed gravel collected during redd construction, the D_{50} (27.1 ± 2.1 mm; note here and in the following all values are given as mean ± sd) as well as the sorting coefficient ($\mathrm{SO} = (D_{75}/D_{25})^{0.5}$; 1.6 ± 0.1) among the cleaned sediment baskets differed. Spearmen rank correlation tests showed that these differences had no influence on the amount of sediment infiltration though ($p = 0.5$ and 0.2 respectively).

Due to numerous high flows during the first field season, we got significant higher sediment infiltration rates at all sites during the first season with a mean of $1.54 \pm 0.24\,\mathrm{kg\,m^{2}\,day^{-1}}$ compared to the second season with a mean of $0.74 \pm 0.21\,\mathrm{kg\,m^{2}\,day^{-1}}$ (t.test, $p < 0.05$). For both seasons, we found the lowest fine sediment infiltration rates of the three sites for site B (ANOVA, $p < 0.05$; Table 4). This can be explained by the high fine sediment input from the upper watershed for site A. At site C, a high amount of fine sediment comes from the relatively large western tributary river (Fig. 1; Philip Amrein, local fishery supervisor, personal communication, 2009). There was a high variation among the sediment infiltration baskets at all sites with CV up to 100 % (Table 4). The most possible explanation for this is the cross-channel variation due to difference flow velocity caused by bank roughness effects (Acornley and Sear, 1999) (see also Sect. 3.4).

Overall, the observed infiltration rates are relatively high compared to other infiltration studies conducted with sediment baskets (Table 3). These high infiltration rates could partly be explained by the high input of fine sediment from the molasse bedrock in the catchment area. Furthermore, we sampled with a higher frequency (Table 3). The efficiency of newly cleaned gravel in trapping fine sediment is at its maximum with initial conditions and decreases with time (Heywood and Walling, 2007). Hence, weekly sampled sediment baskets will yield higher daily mean values compared to monthly sampled baskets. We also assume that part of deposited sediments might be washed out again. The difference between unequal sampling intervals can also be seen in the large discrepancy between the infiltration rates calculated from the weekly obtained sediment infiltration data and those calculated from the accumulation baskets, which were only sampled at the end of the seasons after four months (Table 3). As such, comparisons of sediment infiltration rates from studies with different sampling intervals have to be done with caution, especially if the results are related to each other quantitatively.

Grain size analysis showed an increase of silt and clay with increasing fine sediment infiltration in absolute values (Fig. 6, left), but a decrease in relative values (i.e. fraction of silt and clay of the total fine sediment deposition) (Fig. 6, right). With small infiltration rates, up to 94 % of the sediment consisted of sediment <0.25 mm, thus, sediments of a size most likely to be transported in suspension. This agrees with Acornley and Sear (1999) and Sear (1993), who found that during low flow infiltration is mainly composed of sediments transported in suspension (<0.25 mm) while during high flow a greater proportion of sediment has a diameter between 0.25 and 4 mm. This fraction is large enough to be in intermittent contact with the bed yet small enough to pass through small interstices of the weekly cleaned infiltration baskets (Lisle, 1989).

3.3 Sediment accumulation

The highest values for fine sediment accumulation over the two seasons were observed at site A, the furthest upstream site (ANOVA, $p < 0.05$). At the end of the two seasons, 20.1 % of the sediment basket consisted of particles <2 mm at site A, 18.7 % at site B and 13.9 % at site C (Table 5). The decrease of fine sediment accumulation from up- to downstream could be due to higher scouring of the fine sediment down the stream due to higher water level. Despite the significant higher fine sediment infiltration during the first field season at all sites, there was no significant difference in sediment accumulation between the two seasons at site B and C (t.test, $p = 0.3$ and 0.5 respectively). Only at site A we obtained significant higher fine sediment accumulation during the first season (t.test, $p < 0.05$, Table 5). Thus, the down stream scouring of fine sediment seems to play a more important role on the total sediment accumulation than the sediment infiltration.

The sediment accumulation baskets were not filled with standardized gravel but with river bed gravel to represent natural conditions. Spearmen rank correlation tests showed that the differences in D_{50} as well as in sorting coefficient (SO) of the accumulation baskets had no influence on the amount of sediment accumulation.

Comparison with other studies reveals similar rates of sediment accumulation to those reported in this study (Table 6). 90 ± 2.6 % of the accumulated fine sediment was sand and 67 ± 5.6 % had a diameter >0.25 mm. Thus, the size most likely carried in suspension (<0.25 mm) accounted for only 33 % of the sediment accumulated in the sediment basket. This is in the same range as found by Lisle (1989). During high flow the main component of the infiltrated sediment is in the bedload fraction (see Sect. 3.2). This fraction deposits and accumulates at all depths down to the bottom of the basket as long as size distributions of transported sediment and the riverbed particles do not overlap (Lisle, 1989).

The fine sediment fraction (<2 mm) in the accumulation baskets was higher than in the river bed sediment obtained by freeze core samples (Table 5). The differences were only significant at site A due to the high variation among the accumulation baskets and among the freeze core samples (t.test, $p < 0.05$). Zimmermann and Lapointe (2005) noted that this difference could reflect the influence of the effective size of the pore spaces available in the substrate on sediment infiltration. The overestimation of fine sediment in the baskets in this study could also be due to the small gap of about 4 mm between the inner and the outer sediment basket, in which the fine sediment (mainly in the bedload fraction) was able to infiltrate. This gap accounts for about 13 % of the volume of the inner baskets and was entirely filled with fine sediment at the end of the spawning season. The differences could also reflect an overestimation of the coarse fraction by freeze cores since individual pieces of coarse gravel and cobbles protruding out of the freeze cores can result in a smaller percentage of fine sediment of the sample (Zimmermann et al., 2005; Young et al., 1991).

Comparisons with the freeze core samples showed also significant (t.test, $p < 0.05$) higher fraction of silt and clay of the total fine sediment in the accumulation baskets with 7.8 to 10.5 % compared to 4.8 to 5.1 % in the freeze core samples (Table 5). We assume that this high fraction in the accumulation baskets is due to silt and clay particles which would have infiltrated to deeper layers in a natural environment. At the beginning of the measurement campaign, the sediment in the sediment basket is comparable to a freshly cut redd. This cleaned gravel is vulnerable to deep infiltration by fines before a seal is formed during entrainment of the armor layer (Lisle, 1989). In the sediment baskets, sediment can only infiltrate until the bottom of the baskets. Freeze core data support this assumption indicating a significant higher silt and clay fraction at a depth of 10–20 cm and 20–30 cm with silt and clay content of 6.0 ± 2.0 % and 6.3 ± 2.5 % respectively compared to the upper layer (0–10 cm) with a silt and clay content of 3.6 ± 2.4 %. In general, there was a big variation between the fraction of particles <63 µm of the accumulated sediment within a site and between the two seasons (Table 5). Thus, no general conclusions about the differences between the three sites and the two seasons can be drawn. The hydraulic differences within a site and the forming of a surface seal of sand (Lisle, 1989) has probably a larger influence on the deposition and accumulation of silt and clay particles than their abundance in the water column. The silt and clay fraction assessed in other studies was also highly variable, making a comparison difficult (Table 6).

3.4 Fine sediment transported along the bed

Mean sediment caught by the bedload samplers increased along the river from 1.93 $\mathrm{kg\,m^2\,d^{-1}}$ at site A to 2.24 $\mathrm{kg\,m^2\,d^{-1}}$ at site C (Table 7). This pattern parallels the data from the SS samplers and OBS sensors and could be related to an increasing shear stress due to higher water levels down the stream or/and to a higher input of fine sediment from the arable corn fields in the lower part of the catchment.

At all sites bedload rates were very small until a certain water level (data not shown). Above this level, bedload increased exponential with increasing water level. This matches the pattern we found with the infiltration baskets (Fig. 5).

The percentage of fines in the total captured bedload was highest at site A. This again is probably due to the low water level compared to the other two sites and the relative small slope due to the frequent artificial steps. The percentage of the bedload smaller <2 mm of the total bedload decreased with higher water level and total bedload (highly significant spearman rank correlation, Table 8).

There was a very high variation within the bedload rates as well as within the percentages of fines of the total bedload caught by the six bedload samplers per site (Table 7). We assume that this variation can be partly accounted for by cross-channel differences also observed in the SS, infiltration and accumulation data. The higher CV of the bedload data compared to the other data is likely explained by (I) the variation of precision in placing the traps flush with the sediment surface. If the boarder of the trap is not flush with the bed, fine sediment transported along the bed could not get trapped and (II) the turbulence caused by the coarse bed material above the trap differs between traps and triggers different trapping efficiencies.

In total 26 bedload traps were lost at the 18 research plots during the first field season, thus, on average at every sampling spot traps were lost 1.5 times. Hence we found that a major disadvantage of the bedload samplers is their big contact surface, making them more susceptible to scouring at high discharge. For those reasons, no bedload traps were installed the second field season.

3.5 Comparison of the different methods

3.5.1 SS samplers and OBS turbidity sensors

Our results clearly suggest that both the SS samplers and the OBS turbidity sensors are suitable to resolve large scale spatial and temporal differences in suspended sediment (Table 2). Both methods revealed a significant increase in suspended sediment along the river and a significant higher suspended sediment load in the season 2009/1010 than the season 2010/2011. Similarly, both methods show a significant positive Spearman correlation between SS and water level (Table 2). We suspect that the weak correlation between SSC_{NTU} and water level at site B is related to measurement problems with the OBS sensor due to leaves caught by the sensor (see Sect. 3.1.1). Even though the methods differ in their quantitative results, correlation analysis showed a highly significant correlation between SS caught by the sampler during one week and the average SSC_{NTU} per week (Table 8).

The advantage of the SS samplers is their relatively low cost and their easy mounting making a high spatial distribution across the channel possible. Therefore the correlation between SS obtained with the samplers and the infiltration rate was better than the correlation between SSC_{NTU} assessed by OBS sensors and the infiltration rates (Table 8). SS sampler data is positively correlated to fine sediment infiltration (Fig. 7). At a deposition of about 40 kg m^{-2}, saturation or equilibrium of input and scouring is reached at site B and C. At site A, deposition increased until about 65 kg m^{-2}. This can be explained by less scouring at site A due to lower water levels. OBS data is only weakly correlated with sediment infiltration (Table 8) probably due to the discussed negligence of the cross channel differences in SS with just one point measurement of SSC_{NTU} per site. Certainly, a higher cross channel resolution could also be obtained by OBS sensors by mounting multiple sensors across the channel. But the fixation of the sensors across the channel can be quit difficult and is also connected with high costs.

3.5.2 Sediment infiltration baskets and bedload traps

There was a highly significant correlation between the fine sediment infiltration rate measured with sediment baskets and sediment transported as bedload measured with bedload traps (Table 9). A non linear regression (saturation curve) describes the observed relationship best (Fig. 8, left). Above an infiltration rate of 2 $\text{kg m}^{-2}\,\text{d}^{-1}$ values might be highly variable due to higher scouring. While the infiltration baskets reach a saturation around 10 $\text{kg m}^{-2}\,\text{d}^{-1}$, bedload traps can capture sediment until about 15 $\text{kg m}^{-2}\,\text{d}^{-1}$ due to their large volume (Fig. 8, left). Thus, with high water level, infiltration baskets are filled very quickly if not emptied in short enough intervals.

Results suggest a linear relationship of the data with smaller infiltration rates (0 to 2 $\text{kg m}^{-2}\,\text{d}^{-1}$; Fig. 8, right). According to Bond (2002), sediment infiltration is governed primarily by sediment supply or transport rates up until the point when interstitial spaces become clogged with fine sediments. The presented data support this statement qualitatively (see Sect. 3.2 and the highly significant correlation between both water level and SS with infiltration rate as well as with bedload rate, Table 8), but from a quantitative perspective, the infiltration rate is almost twice of the bedload (Fig. 8, right) until the mentioned level. This can be explained by the high silt and fine sand (<0.25 mm) fraction during low infiltration rates (Fig. 6). According to Bond (2002), trapping efficiency of the bedload trap is lower for these fractions (only 20–40 % at some sites). In contrasts to the sediment baskets, where infiltrated sediments get caught in a matrix of coarse sediment, fines can be easier washed out of bedload traps.

Sediment caught by bedload traps is mainly dependent on the water level and SS load. Due to the solid wall of the traps, vertical hydraulic gradient (VHG) has no influence on this process (Table 8). In contrast, we expected less fine sediment infiltration with a positive VHG (=upwelling) in the infiltration baskets. This has been shown in previous infiltration research (Brunke, 1999; Seydell et al., 2009). However, we were not able to show this relationship: at sites A and B fine sediment infiltration was slightly higher in upwelling zones compared to down welling zones (Table 8). This is likely due to high variability of hydrological exchange processes (e.g. Brunke and Gonser, 1997). The VHG measurements represent only the specific hydraulic conditions at a certain time while infiltration was measured over a week with possible changing VHG. In addition, the installation of the mini piezometers might create a macro pore where river water can infiltrate. This would falsify the VHG measurements.

Multiple regression analysis for sediment infiltration with SS (measured by SS sampler), $\mathrm{SSC_{NTU}}$, bedload, water level and VHG as dependent variable were conducted. At site A, a general linear model with gamma errors with SS as single dependent variable was the best predictor for sediment infiltration (Fig. 7). Due to the equilibration or saturation of sediment infiltration at site B and C, the infiltration rate at those sites is best described by a non linear regression model (Fig. 7):

$$\text{site A} : \text{Infiltration} = 0.14 + 0.9 \times \text{SS} \tag{2}$$

$$\text{site B} : \text{Infiltration} = 36.5\,(1 - e^{-0.03\,\text{SS}}) \tag{3}$$

$$\text{site C} : \text{Infiltration} = 38.9\,(1 - e^{-0.05\,\text{SS}}) \tag{4}$$

3.5.3 Sediment accumulation baskets

Only a small number of accumulation baskets resisted the flood, thus there is only a small data set across the two field seasons (site A: $n = 14$, site B: $n = 6$, site C: $n = 6$), making statistical analysis difficult. Only general conclusions about the total amount of fine sediment accumulation are possible (see Sect. 3.3). Fine sediment accumulation decreased from upstream to downstream, i.e. from site A to site C. In contrast, highest fine sediment infiltration was assessed at site A as well as site C. This might suggest a high sediment supply and infiltration at sites A and C, but also higher resuspension and scouring of fines due to higher water level at site C than site A.

Correlation analyses with other methods are only possible within site A the one with the largest data set. These analyses indicate a highly significant positive correlation between accumulated fine sediment and mean SS as well as infiltration of fines (Table 8). Both relationships are linear:

$$\text{Accumulation} = 384 + 361 \times \text{infiltration},\ R^2 = 0.7,\ p < 0.05 \tag{5}$$

$$\text{Accumulation} = 403 + 36 \times \text{SS},\ R^2 = 0.5,\ p < 0.05 \tag{6}$$

Higher mean water levels above the accumulation baskets lead to resuspension of fine sediment, resulting in a negative correlation between water level and sediment accumulation (Table 8). Again, this correlation can be described by a linear regression:

$$\text{Accumulation} = 1175 - 40 \times \text{water level},\ R^2 = 0.3,\ p < 0.05 \tag{7}$$

The smaller amount of fine sediment accumulation in plots with higher water level and flow velocity compared to plots with lower water level was reported previously (e.g. Acornley and Sear, 1999; Levasseur et al., 2006). Finally, multiple regression analyses indicate less sediment accumulation in upwelling zones than in downwelling zones:

$$\text{Accumulation} = 14.2 + 0.6 \times \text{SS} - 21.5 \times \text{VHG},\ R^2 = 0.7,\ p < 0.05 \tag{8}$$

The results of Seydell et al. (2009) support these findings. They even noted that subsurface flow patterns have a larger influence on sediment deposition than the suspended sediment concentration in the river.

Due to cross correlations between the mentioned dependent variables (Table 8), other multiple regressions are not possible.

4 Conclusions

We compared different methods to capture the temporal and spatial dynamic of suspended sediment (SS), fine sediment infiltration and accumulation. These methods were correlated and tested for their suitability for rivers in the Swiss Plateau. The assessed data were comparable to literature data, indicating a general reliability of the methods.

Methods to capture SS (OBS sensors and SS samplers) indicate big spatial and temporal differences. OBS data have a higher temporal resolution. SS samplers can provide important information on the composition of SS. Due to the relatively low construction cost of the SS samplers a better spatial distribution can be achieved. A dense sampling network installed with SS samplers can therefore result in a better correlation between sediment infiltration and SS as with a single OBS sensor per site.

Sediment infiltration baskets and bedload traps demonstrate the temporal and spatial distribution of fine sediment infiltration. This process is mainly governed by water level and SS. A major hydrological event can result in a total siltation of the sediment infiltration baskets. Bedload traps have a larger volume, but they are associated with other problems as it is difficult to dig them flush into the riverbed. Further, they are susceptible to scouring at high flows due to their large contact surface. We conclude that sediment infiltration baskets are better suited for highly dynamic canalized rivers of the Swiss Plateau.

In contrast to the sediment infiltration baskets, accumulation baskets do not assess the temporal behavior of fine sediment infiltration but the accumulation over a certain time period. Their loss at high flow generated the biggest problem associated with the accumulation baskets. They can not be renewed as their purpose is the assessment of accumulation during the entire field period. Additionally, they seem to overestimate fine sediment. Differences in the effective size of the pore spaces, the gap between the inner and the outer sediment baskets or the solid bottom of the baskets are possible reasons for this overestimation. Less fine sediment accumulates in upwelling zones and with a higher mean water level due to scouring. Even though there was an increase in SS and sediment assessed with the bedload traps from up- to downstream, less fine sediment accumulated downstream probably due to more scouring.

Acknowledgements. This study was funded by the Swiss national foundation (SNFK-32K1-32K1-120486/1). We would like to thank Annina Gysel, Sandra Rudolf and Bastian Brun for their help in the field, Philipp Amrein and Sepp Lustenberger for support during the field work, Marianne Caroni and Ruth Strunk for laboratory assistance and Claude Schneider for technical support.

References

Acornley, R. M. and Sear, D. A.: Sediment transport and siltation of brown trout (*Salmo trutta* L.) spawning gravels in chalk streams, Hydrol. Process., 13, 447–458, 1999.

Asselman, N. E. M., Middelkoop, H., and van Dijk, P. M.: The impact of changes in climate and land use on soil erosion, transport and deposition of suspended sediment in the River Rhine, Hydrol. Process., 17, 3225–3244, doi:10.1002/hyp.1384, 2003.

Baxter, C., Hauer, F. R., and Woessner, W. W.: Measuring groundwater-stream water exchange: New techniques for installing minipiezometers and estimating hydraulic conductivity, T. Am. Fish. Soc., 132, 493–502, 2003.

Bilotta, G. S. and Brazier, R. E.: Understanding the influence of suspended solids on water quality and aquatic biota, Water Res., 42, 2849–2861, doi:10.1016/j.watres.2008.03.018, 2008.

Bond, N. R.: A simple device for estimating rates of fine sediment transport along the bed of shallow streams, Hydrobiologia, 468, 155–161, 2002.

Brunke, M.: Colmation and depth filtration within streambeds: Retention of particles in hyporheic interstices, Int. Rev. Hydrobiol., 84, 99–117, 1999.

Brunke, M. and Gonser, T.: The ecological significance of exchange processes between rivers and groundwater, Freshwater Biol., 37, 1–33, 1997.

Bucher, R.: Feinsedimente in schweizerischen Fliessgewässern, Fischnetz-Publikation. Projekt “Netzwerk Fischrückgang Schweiz”, Teilprojekt 01/07, EAWAG, Dübendorf, 2002.

Downing, J.: Twenty-five years with OBS sensors: The good, the bad, and the ugly, Cont. Shelf Res., 26, 2299–2318, doi:10.1016/j.csr.2006.07.018, 2006.

EBP-WSB-Agrofutura: Ganzheitliche Gewässerplanung im Einzugsgebiet Wiggertal, Bau- und Umwelt und Wirtschaftsdepartement des Kantons Luzern und Baudepartement des Kantons Aargau, 2005.

Fehr, R.: Einfache Bestimmung der Korngrössenverteilung von Geschiebematerial mit Hilfe der Linienzahlanalyse Schweizer Ingenieur und Architekt, 38, 1104–1109, 1987.

Gail, M., Krickeberg, K., Samet, J. M., Tsiatis, A., and Wong, W.: Mixed effects models and extensions in ecology with *R*, Springer Science + Business Media, New York, 2009.

Greig, S. M., Sear, D. A., and Carling, P. A.: The impact of fine sediment accumulation on the survival of incubating salmon progeny: Implications for sediment management, Sci. Total Environ., 344, 241–258, doi:10.1016/j.scitotenv.2005.02.010, 2005.

Heywood, M. J. T. and Walling, D. E.: The sedimentation of salmonid spawning gravels in the Hampshire Avon catchment, UK: implications for the dissolved oxygen content of intragravel water and embryo survival, Hydrol. Process., 21, 770–788, doi:10.1002/hyp.6266, 2007.

Hütte, M. and Niederhauser, P.: Ökomorphologie Stufe F. Methoden zur Untersuchung und Beurteilung der Fliessgwässer in der Schweiz, Bundesamt für Umwelt, Wald und Landschaft, Mitteilungen zum Gewässerschutz, 27, 1998.

IUSS: World reference base for soil resources, FAO, Rome, 2006.

Julien, H. P. and Bergeron, N. E.: Effect of fine sediment infiltration during the incubation period on Atlantic salmon (*Salmo salar*) embryo survival, Hydrobiologia, 563, 61–71, 2006.

Levasseur, M., Bergeron, N., Lapointe, M., and Bérubé, F.: Effects of silt and very fine sand dynamics in Atlantic salmon (*Salmo salar*) redds on embryo hatching success, Can. J. Fish. Aquat. Sci., 63, 1450–1459, 2006.

Lisle, T. E.: Sediment transport and resulting deposition in spawning gravels, North Coastal California, Water Resour. Res., 25, 1303–1319, 1989.

Lisle, T. E. and Lewis, J.: Effects of sediment transport on survival of salmonid embryos in a natural stream – a simulation approach, Can. J. Fish. Aquat. Sci., 49, 2337–2344, 1992.

Minella, J. P. G., Merten, G. H., Reichert, J. M., and Clarke, R. T.: Estimating suspended sediment concentrations from turbidity measurements and the calibration problem, Hydrol. Process., 22, 1819–1830, doi:10.1002/hyp.6763, 2008.

Navratil, O., Esteves, M., Legout, C., Gratiot, N., Nemery, J., Willmore, S., and Grangeon, T.: Global uncertainty analysis of suspended sediment monitoring using turbidimeter in a small mountainous river catchment, J. Hydrol., 398, 246–259, doi:10.1016/j.jhydrol.2010.12.025, 2011.

Newcombe, C. P. and Jensen, J. O. T.: Channel suspended sediment and fisheries: A synthesis for quantitative assessment of risk and impact, N. Am. J. Fish. Manage., 16, 693–727, 1996.

Owens, P. N., Batalla, R. J., Collins, A. J., Gomez, B., Hicks, D. M., Horowitz, A. J., Kondolf, G. M., Marden, M., Page, M. J., Peacock, D. H., Petticrew, E. L., Salomons, W., and Trustrum, N. A.: Fine-grained sediment in river systems: Environmental significance and management issues, River Res. Appl., 21, 693–717, 2005.

Packman, J. J., Comings, K. J., and Booth, D. B.: Using turbidity to determine total suspended solids in urbanizing streams in the puget lowlands, Managing change in water resources and the environment, Can. Wat. Resour. Association annual meeting, Vancouver, 158–165, 1999.

Phillips, J. M., Russell, M. A., and Walling, D. E.: Time-integrated sampling of fluvial suspended sediment: a simple methodology for small catchments, Hydrol. Process., 14, 2589–2602, 2000.

Schalchli, U.: Basic equations for siltation of riverbeds, J. Hydraul. Eng.-Asce., 121, 274–287, 1995.

Scheurer, K., Alewell, C., Banninger, D., and Burkhardt-Holm, P.: Climate and land-use changes affecting river sediment and brown trout in alpine countries – a review, Environ. Sci. Pollut. R., 16, 232–242, doi:10.1007/s11356-008-0075-3, 2009.

Sear, D. A.: Fine sediment infiltration into gravel spawning beds within a regulated river experiencing floods – ecological implications for salmonids, Regul. River., 8, 373–390, 1993.

Sear, D. A., Frostick, L. B., Rollinson, G., and Lisle, T. E.: The significance and mechanics of fine-sediment infiltration and accumulation in gravel spawning beds, Am. Fish. S. S., 65, 149–173, 2008.

Seydell, I., Ibisch, R. B., and Zanke, U. C. E.: Intrusion of suspended sediments into gravel riverbeds: influence of bed topography studied by means of field and laboratory experiments, Adv. Limnol., 61, 67–85, 2009.

Soulsby, C., Youngson, A. G., Moir, H. J., and Malcolm, I. A.: Fine sediment influence on salmonid spawning habitat in a lowland agricultural stream: a preliminary assessment, Sci. Total Environ., 265, 295–307, 2001.

Sponagel, H., Grottenthaler, W., Hartmann, K.-J., Hartwich, R., Janetzko, P., Joisten, H., Kühn, D., Sabel, K.-J., and Traidl, R.: Bodenkundliche Kartieranleitung, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, 2005.

Stucki, P.: Methoden zur Untersuchung und Beurteilung der Fliessgwässer. Makrozoobenthos

Stufe F, Bundesamt für Umwelt, Bern, Umwelt-Vollzug 1027, 2010.

Young, M. K., Hubert, W. A., and Wesche, T. A.: Biases associated with four stream substrate samplers, Can. J. Fish. Aquat. Sci., 48, 1882–1886, 1991.

Zimmermann, A. E. and Lapointe, M.: Sediments infiltration traps: their use to monitor salmonid spawning habitat in headwater tributaries of the Cascapedia River, Quebec, Hydrol. Process., 19, 4161–4177, doi:10.1002/hyp.5879, 2005.

Zimmermann, A., Coulombe-Pontbriand, M., and Lapointe, M.: Biases of submerged bulk and freeze-core samples, Earth Surf. Proc. Land., 30, 1405–1417, doi:10.1002/esp.1202, 2005.

Table 1. Site characteristics: D_{50} of the riverbed sediment was defined by freeze core samples and with the line-number-analysis (Fehr, 1987). Data are given as mean ± standard deviation.

Site	A	B	C
Altitude (m a.s.l.)	757	625	583
Watershed area (km^2)	28.9	22.6	5.5
Mean watershed slope (°)[a]	26.0	20.3	19.5
River slope at the site (°)[b]	5.0	1.5	1.4
River slope of riffle between 2 steps (°)	0.27	0.24	0.23
D_{50} (freeze core) (mm)	20 ± 4	19 ± 6	16 ± 1
D_{50} (line-nr-analysis) (mm)	25 ± 8	25 ± 4	16 ± 4
Channel width (m)	3–3.5	4–4.5	4.5–5
Water depth above redds (cm)	10.9 ± 3.9	23.2 ± 6.0	20.9 ± 7.9
Step length (m)	11–15	9–12	7–10
Mean bed shear stress above redds (Pa)[c]	5.0	9.5	8.2

[a] Calculation based on the slope value for each pixel from a digital elevation model of the watershed.

[b] Based on the slope value from a digital elevation model.

[c] Calculated by the reach-average bed shear stress formula: $\tau_0 = \rho g R S$, where τ_0 is bed shear stress, ρ is water density, g is acceleration due to gravity, R is hydraulic radius and S is the slope.

Table 2. Mean and standard deviation of suspended sediment concentration (SSC_{NTU}) measured with the OBS sensors and suspended sediment (SS) caught by suspended sediment samplers at the three sites during the two field seasons.

	Field season 1 (2009/2010)		Field season 2 (2010/2011)	
Site	SSC_{NTU} (mg l^{-1})	SS (g week^{-1})	SSC_{NTU} (mg l^{-1})	SS (g week^{-1})
A	28.0 ± 37.8	14.4 ± 3.5	12.9 ± 7.6	7.0 ± 1.7
B	49.1 ± 56.5	16.8 ± 3.3	21.4 ± 12.8	11.5 ± 0.4
C	54.9 ± 62.8	20.3 ± 2.5	16.2 ± 23.3	11.2 ± 0.5
mean	42.7 ± 53.3	17.2 ± 3.9	17.0 ± 16.5	9.9 ± 2.3

Table 3. Range or mean ± sd of infiltration rate (IR) of sediment < 2 mm in permeable sediment baskets.

Reference	Study site	IR ($\text{kg m}^{-2}\text{ d}^{-1}$)	Sampling interval
This study	River Enziwigger, Lucerne, Switzerland	0.01–10.36	weekly
This study	River Enziwigger, Lucerne, Switzerland	0.21–0.70	4 month
Acornley and Sear (1999)	River Test, Hampshire	0.02–1.00	monthly
Acornley and Sear (1999)	Wallop Brook	0.04–0.40	monthly
Sear (1993)	North Tyne, Northumberland, UK	0.005–1.60	monthly
Seydell et al. (2009)	River Lahn, near Marburg, Germany	0.16 ± 0.07	two weeks interval
Zimmermann and Lapointe (2005)	Cascapédia River watershed, upper reaches; Québec	0.006–6.80	after suspension event

Table 4. Mean and range of daily sediment < 2 mm infiltration rate (IR) during the two seasons at the three sites and the mean and range of the coefficient of variation (CV) of the weekly values within the six samplers per site.

	Field season 1 (2009/2010)		Field season 2 (2010/2011)	
Site	IR (kg m^2 day^{-1})	CV (%)	IR (kg m^2 day^{-1})	CV (%)
A	1.67 (0.02–10.36)	32.9 (7.6–58.4)	0.68 (0.02–7.57)	31.1 (10.5–67.3)
B	1.29 (0.01–8.22)	40.6 (17.2–75.1)	0.62 (0.03–5.31)	27.5 (14.7–50.0)
C	1.55 (0.06–7.46)	38.3 (0–86.4)	0.66 (0.05–7.38)	48.7 (15.5–106.1)

Table 5. Mean ± sd of fine sediment (< 2 mm) fraction of the accumulation baskets and sediment < 63 µm fraction of the fine sediment accumulated during the two spawning seasons S1 (2009/2010) and S2 (2010/2911) and in freeze cores (FC) taken in winter 2008/2009.

Site	% < 2 mm S1	% < 2 mm S2	% < 2 mm mean	% < 2 mm in FC	% < 63 µm S1	% < 63 µm S2	% < 63 µm mean	% < 63 µm in FC
A	25.5 ± 1.4 (*n* = 4)	18.0 ± 3.3 (*n* = 10)	20.1 ± 4.5 (*n* = 14)	13.6 ± 4.1 (*n* = 6)	8.2 ± 1.3 (*n* = 4)	11.3 ± 2.1 (*n* = 10)	10.4 ± 2.4 (*n* = 14)	5.1 ± 1.7 (*n* = 6)
B	16.0 ± 4.3 (*n* = 2)	20.1 ± 4.4 (*n* = 4)	18.7 ± 4.5 (*n* = 6)	13.3 ± 4.5 (*n* = 6)	9.3 ± 2.4 (*n* = 2)	7.0 ± 1.0 (*n* = 4)	7.8 ± 1.8 (*n* = 6)	4.8 ± 1.1 (*n* = 6)
C	15.4 ± 3.3 (*n* = 2)	13.1 ± 2.6 (*n* = 4)	13.9 ± 2.8 (*n* = 6)	12.5 ± 4.1 (*n* = 6)	13.8 ± 4.1 (*n* = 2)	8.9 ± 0.6 (*n* = 4)	10.5 ± 3.1 (*n* = 6)	5.0 ± 2.5 (*n* = 6)

Table 6. Fine sediment (<2 mm) and silt and clay (<63 µm) accumulation in the accumulation baskets as % of the whole baskets and the silt and clay fraction of the sediment < 2 mm. Range (mean) or mean ± sd.

Reference	Study site	<2 mm (%)	<63 µm (%)	<63 µm of <2 mm (%)
This study	River Enziwigger, Lucerne	9.6–26.7 (18.3)	0.9–2.4 (1.7)	6.1–16.7 (9.8)
Greig et al. (2005)	River Test and Blackwater, Hampshire	10.0, 12.2		
Greig et al. (2005)	River Ithon and Aran, Wales	28.9, 15.7		
Heywood and Walling (2007)	Avon catchment, Hampshire	1.3–17.2		31 ± 14
Levasseur et al. (2006)	Sainte Margerite River, Quebec	0.4–27 (13.2)	0.04–0.72 (0.16)	
Lisle (1989)	Coast Range of northern California			4.8–5.9
Julien and Bergeron (2006)	Sainte Margerite River, Quebec	3.3–29.2*	0.03 ± 0.02–0.41 ± 0.2	
Zimmermann and Lapointe (2005)	Cascapédia River watershed, upper reaches; Québec	3.5–10		4–9

* sediment <1 mm.

Table 7. Mean and range of daily bedload (BL) <2 mm, of the percentage of BL < 2 mm of the total BL and of the coefficient of variation (CV) of the weekly values within the six samplers at the three sites.

Site	BL < 2 mm (kg m^2 d^{-1})	CV (%)	% < 2 mm of BL	CV % < 2 mm of BL (%)
A	1.93 (0.02–14.26)	72.0 (10.7–193.4)	73.8 (32.2–98.3)	45.0 (0–86.6)
B	2.01 (0.01–10.80)	79.8 (0–183.2)	30.3 (4.0–60.6)	64.2 (24.3–96.3)
C	2.24 (0.02–8.5)	61.9 (0–178.2)	58.7 (23.7–92.5)	27.5 (0–62.8)

Table 8. Spearman rank correlation between the measured parameters of both seasons for the three sites with mean weekly $\mathrm{SSC_{NTU}}$ measured with OBS sensors, total weekly SS measured by SS samplers, daily fine sediment infiltration rate, fine sediment accumulation, daily bedload of fine sediment, the percentage of fine sediment of the total bedload, maximal weekly water level and vertical hydraulic gradient (VHG). The accumulation baskets were correlated with the mean values of the parameters during the whole field seasons. The record number is given in parentheses.

	SS	Infiltration	Accu.	Bedload	Bedload (%)	Water	VHG
$\mathrm{SSC_{NTU}}$ ($\mathrm{mg\,l^{-1}}$)	0.8 (212)**	0.8 (218)**	0.8 (14)**	0.7 (104)**	−0.4 (104)**	0.7 (196)**	0.2 (131)*
	0.2 (204)*	0.2 (204)**	0.2 (6)	−0.4 (96)*	0.1 (96)	0.2 (204)**	0.1 (121)
	0.7 (204)**	0.5 (204)**	0.6 (6)	0.8 (90)**	−0.5 (90)**	0.9 (180)**	0.2 (90)
SS ($\mathrm{g\,week^{-1}}$)		0.9 (212)**	0.8 (14)**	0.8 (104)**	−0.4 (104)**	0.6 (212)**	0.3 (131)**
		0.9 (204)**	−0.4 (6)	0.8 (96)**	−0.4 (96)**	0.8 (204)**	0.4 (121)**
		0.8 (204)**	0.8 (6)	0.8 (90)**	−0.5 (90)**	0.8 (204)**	0.2 (90)
Infiltration ($\mathrm{kg\,m^2\,d^{-1}}$)			0.6 (14)*	0.9 (104)**	−0.4 (104)**	0.7 (218)**	0.3 (131)**
			0.0 (6)	0.8 (96)**	−0.5 (96)**	0.8 (204)**	0.4 (121)**
			0.3 (6)	0.9 (90)**	−0.6 (90)**	0.6 (204)**	0.0 (90)
Accu. (% <2 mm)				– (4)	– (4)	−40.6 (14)*	−40.3 (14)
				– (2)	– (2)	0.1 (6)	−0.6 (6)
				– (2)	– (2)	−0.2 (6)	−0.1 (6)
Bedload ($\mathrm{kg\,m^2\,d^{-1}}$)					−0.4 (104)**	0.9 (104)**	0.2 (57)
					−0.4 (96)**	0.7 (96)**	0.2 (39)
					−0.6 (90)**	0.8 (90)**	0.0 (35)
Bedload (% < 2mm)						−0.5 (104)**	0.1 (57)
						−0.2 (96)*	0.1 (39)
						−0.6 (90)**	−0.2 (35)
Water level (cm)							0.1 (131)
							0.4 (121)**
							0.2 (90)

* = $p < 0.05$.
** = $p < 0.01$.

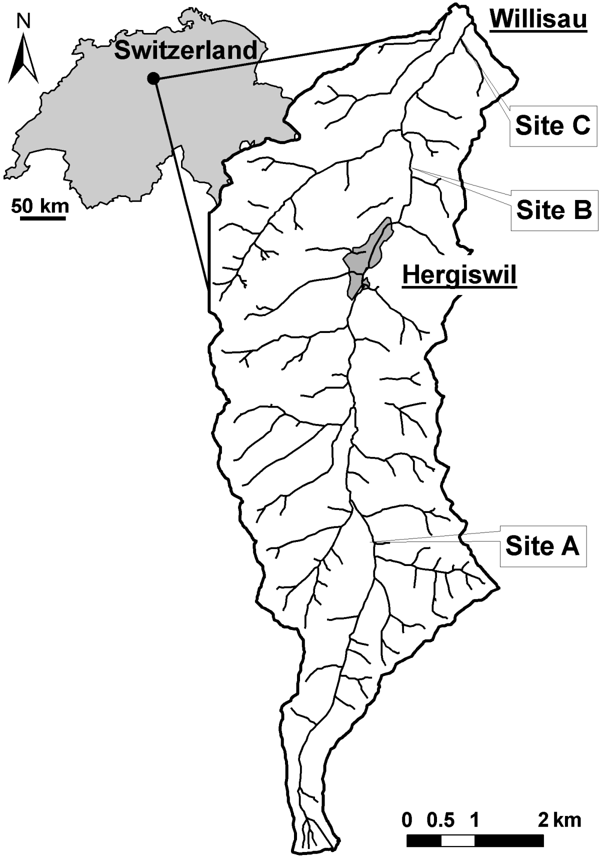

Fig. 1. Watershed of the river Enziwigger with the three field sites A, B and C and the towns Willisau and Hergiswil (Canton of Lucerne, Switzerland).

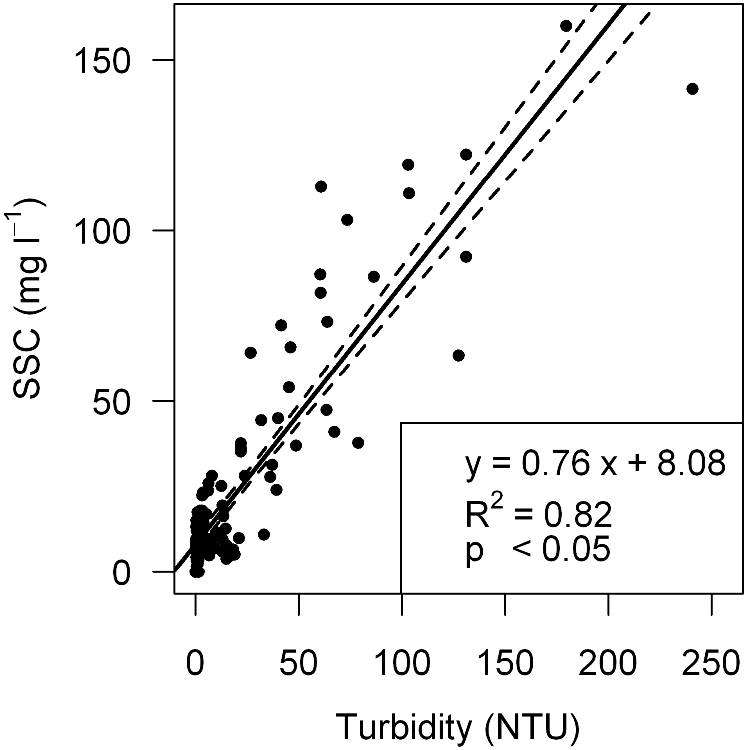

Fig. 2. Correlation between NTU and suspended sediment concentration (SSC). Dashed lines are the 95 % confidence intervals.

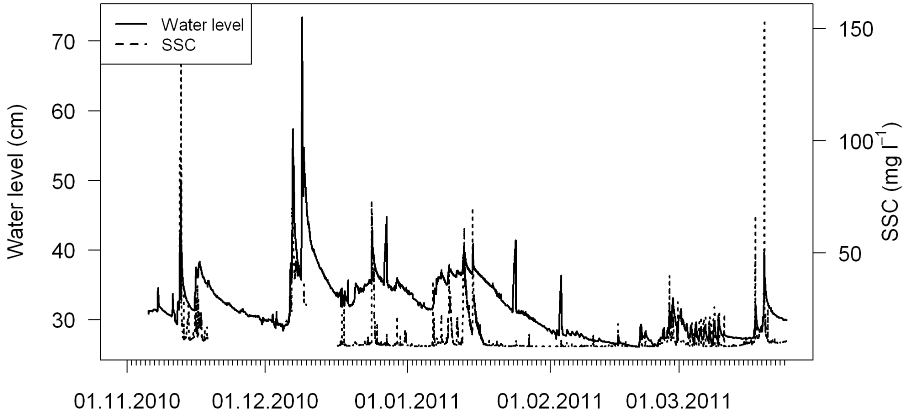

Fig. 3. Temporal variation of the suspended sediment concentration (SSC) and water level at site A for the Season 1.

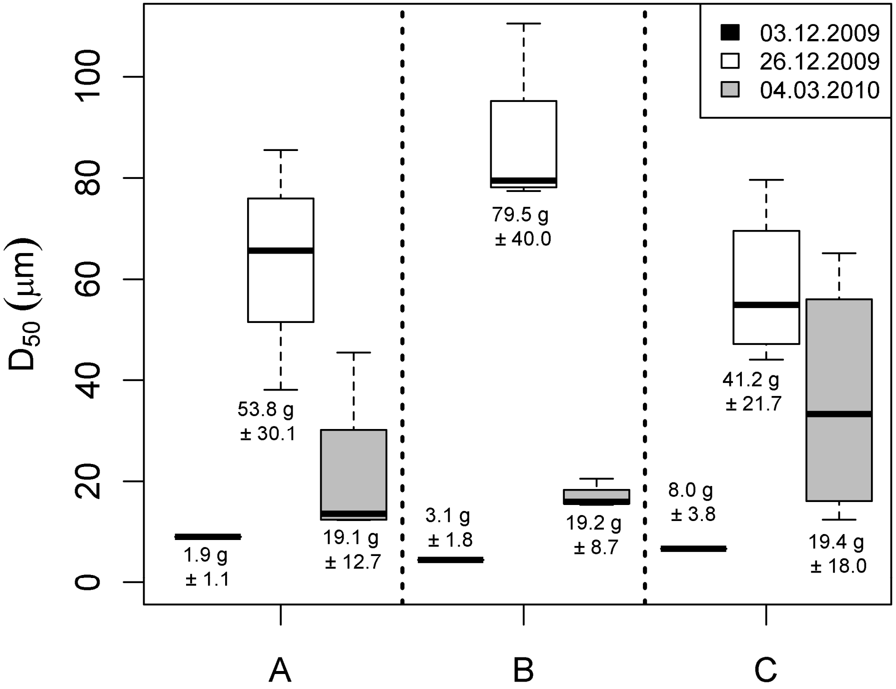

Fig. 4. D_{50} of the suspended sediment (SS) caught by the SS samplers ($n = 6$/site) during one week at the three sites A, B and C. Total amount of SS is given as number below/above the boxes. The 6 samples of the 3 December 2009 had to be merged for grain size analysis due to the small quantity of SS.

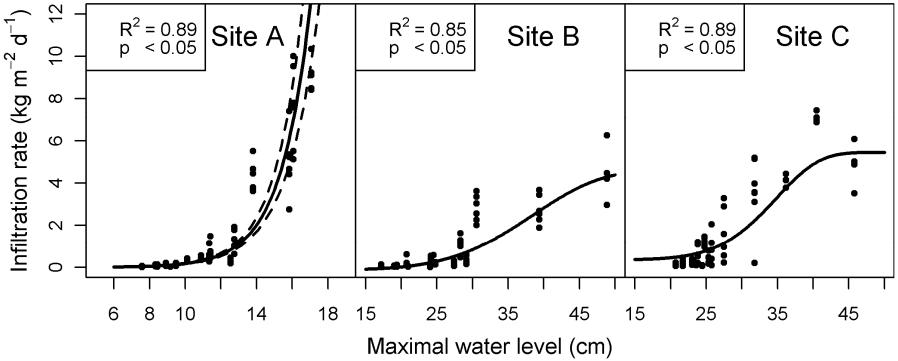

Fig. 5. Infiltration rate in relation to the maximal weekly water level at the site. Dashed lines at site A are the 95 % confidence intervals of the exponential model, the relationship at site B and C is described by a Weibull growth function.

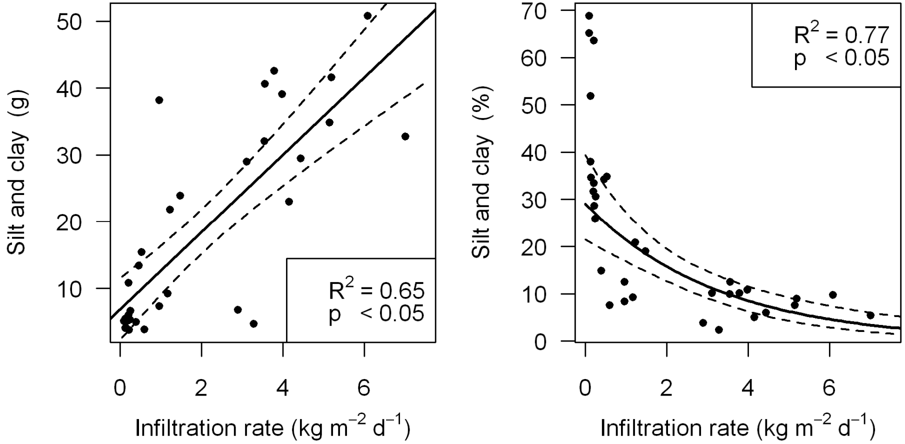

Fig. 6. Weekly silt and clay infiltration at site C in absolute values (left) and relative values (i.e. fraction of silt and clay of the total fine sediment deposition; right) in relationship with the daily infiltration rate of sediment < 2 mm. Dashed lines are the 95 % confidence intervals.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

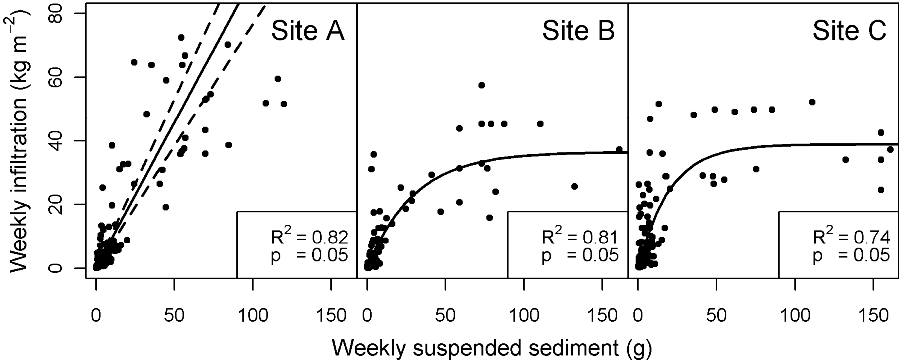

Fig. 7. Weekly infiltration in relation to the total weekly SS assessed with SS samplers at the three sites. Site A: general linear model with gamma error, dashed lines are the 95 % confidence intervals, site B and C: non linear regression. R^2 and p were calculated after Gail et al. (2009).

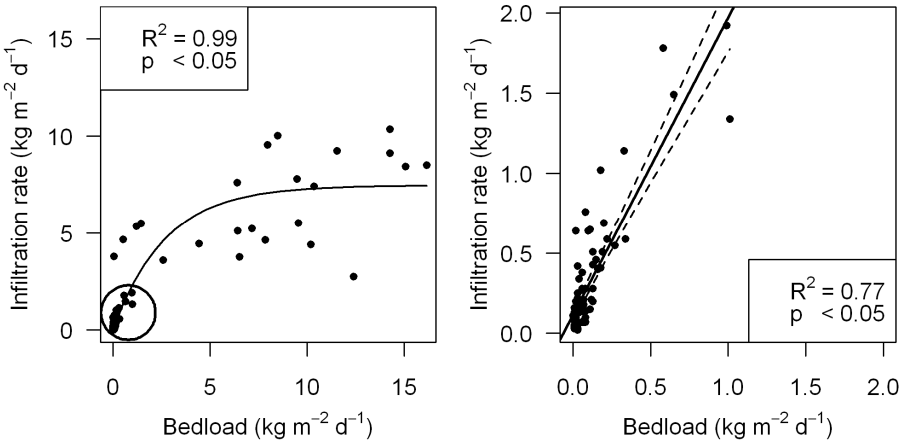

Fig. 8. Relationship between infiltration rate (IR) of fine sediment measured with sediment baskets and bedload measured with bedload traps at site A. Left: all data with a non linear regression line, R^2 and p were calculated after Gail et al. (2009), the circle indicates IR smaller 2 kg m^{-2} d^{-1}; right: data with IR smaller 2 kg m^{-2} d^{-1}. Dashed lines are the 95 % confidence intervals.