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Cohesive sediment processes in vegetated flows: preliminary field study results

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ABSTRACT: Understanding cohesive sediment processes in complex vegetated flows is fundamentally important in ecohydraulics. Therefore, a multi-year field study has been designed to improve the knowledge of flow–vegetation–sediment interaction in environmentally preferable channels. This paper reports the instrumentation and preliminary results of the study. The field site is a vegetated brook that serves as a drainage channel for the surrounding agricultural fields. The brook's water level and turbidity were continuously monitored during the autumn high flow season. The monitoring was accompanied by high-resolution cross-sectional surveys and sampling of water, sediment and soil. Vegetation patches on the brook's bottom and debris accumulations affected the local geomorphological development, and woody vegetation was associated with greater bank erosion than grassy vegetation. The suspended sediment concentration exhibited a strong correlation with the rate of discharge increase, highlighting the significance of flow unsteadiness. The positive hysteresis in suspended sediment concentration and the changes in the hysteresis pattern during the high flow season suggested that the easily erodible sediment was slowly depleted during the season. Particle size distribution of the suspended sediment changed according to discharge, indicating that cohesive sediments underwent selective erosion.

Keywords: cohesive soil, river bank erosion, vegetation, suspended sediment

1 INTRODUCTION

A good understanding of the cohesive sediment processes in vegetated channels of complex geometry is essential for promoting environmentally sound hydraulic engineering. Cohesive sediment processes are directly linked with issues such as channel degradation or aggradation, design of treatment wetlands or habitat restoration projects, and modelling of the transport of sediment-bound substances. Vegetation particularly influences the sediment processes and geomorphological development in environmentally preferable channels and restored streams. Models developed for predicting the impacts of vegetation on the 3-dimensional flow structure can satisfactorily simulate sediment transport within artificial vegetation (Liu & Shen 2008). However, to advance environmentally sound hydraulic engineering practices, the models and the findings of the research need to be applicable to natural conditions. Characteristics of natural vegetation, such as flexibility, differ from those of artificial vegetation. Further, vegetation influences the sediment processes not only by altering the flow structure, but also by modifying the erosion properties of the soil (Wynn & Mostaghimi 2006). Most models do not take into account certain important cohesive sediment processes occurring in natural flows, including the aggregation of suspended sediment particles (McAnally & Mehta 2002) and the consolidation of the deposited sediment (Parchure & Mehta 1985).

Sediment processes are governed by both the flow hydraulics, most notably turbulence characteristics, and the sediment properties. For instance, the vertical movement of cohesive suspended sediment is determined by the balance between the vertical turbulent mixing, diffusing the sediment upward, and the gravitation-induced fall velocity that depends on the density and form of the particles. The existence of sedimentation threshold has been debated, but findings of Maa et al. (2008) suggest that although fine sediments may settle even at high boundary shear stresses, sedimentation occurs only when local boundary shear stress is below a critical value. Another critical value, the critical shear stress for erosion, is the main factor governing the onset of entrainment. Non-cohesive sediments have a critical shear stress determined by the size of the particles and are thus characterized by selective erosion. By contrast, erodibility of cohesive sediments depends on such sediment characteristics as dry bulk density, moist bulk density, water content, organic content and sand content (Aberle et al. 2004; Mostafa et al. 2008; Thoman & Niezgoda 2008). There may be significant differences in the erosion parameters between the upper and lower layers of cohesive sediments (Marttila & Kløve 2008), which is one explanation for the hysteresis pattern widely observed in natural flows (e.g. Asselman 1999). Aberle et al. (2006) addressed this issue by developing a technique for estimating the parameters of the depth-limited erosion equation.

Field studies are crucial in the research on cohesive sediment properties and processes. Firstly, erosion parameters should be determined from undisturbed sediments. Secondly, cohesive sediment processes may be strongly affected by seasonal natural phenomena, including freeze–thaw and soil desiccation (Wynn et al. 2008), which are difficult to simulate in the laboratory. Thirdly, field investigations reveal the important issues that should be studied more closely in the laboratory or in-situ. Examples of these include the effects of unsteady flows on sediment processes and the long-term dynamic equilibrium between erosion and sedimentation. This paper presents preliminary results of a multi-year field study designed to increase the understanding on the interaction between vegetation, flow and cohesive sediments. The objectives of this paper are to analyse the cohesive sediment processes occurring in a small vegetated brook, and to assess the accuracy and suitability of selected measurement and analysis methods for studying cohesive sediments. The paper describes the geomorphological processes and examines the characteristics, dynamics and sources of the sediment.

2 STUDY SITE AND METHODS

A field study site for investigating cohesive sediment processes was established in the Ritobäcken Brook in Sipoo, Southern Finland. The brook serves as a drainage channel for the surrounding agricultural fields and has been dredged in the past. The study reach is 1 km long and has an average bottom slope of 0.002. The catchment area measures 9 km^2 and the estimated average discharge is 80 l/s. The annual minimum discharge occurs in the summer with an estimated average value of 4 l/s. The annual maximum discharge takes place during the snowmelt with an estimated average value of 1600 l/s. The bottom width of the brook is 0.5–2 m and the bankful width 3–7 m. The brook has both flexible and woody bank vegetation (Figure 1). Bed and bank material is cohesive clay. Dredging works have modified the natural hydraulics and geometry of the brook, whereas alterations in land use and catchment hydrology, including the implementation of sub-surface drainage, have likely caused changes in the patterns of runoff and the amount of sediment input into the brook. These factors have disturbed the balance of the natural sediment processes, and the brook's water is turbid with fine suspended sediment. Excessive sedimentation has reduced the conveyance in some parts of the brook, and the adjacent fields are inundated during high flows. On the other hand, there are signs of significant bank erosion along the brook.

A measurement and monitoring campaign was organized in the Ritobäcken Brook during the autumn high flow season. High-resolution cross-sectional surveys were carried out before and after the high flow season in three cross-sections with different geometry. The cross-sections had essentially the same discharge as they were located at a 135 m long reach with no tributaries. The survey conducted after the high flow season could only measure the bottom topography due to the heavy snow on the channel banks. The cross-sections were marked with steel poles hammered approximately 1.5 m into the ground to ensure that the vertical reference level did not change between the surveys. The cross- sections were surveyed with a custom-built system (Figure 1). It was formed of a rigid horizontal framework that was spanned over the cross-section and attached to the steel poles at both ends. The depth at each vertical was measured by a vertical point gauge that could be moved horizontally across the framework. The system allowed surveying the cross-sectional geometry rapidly and at a high accuracy (approximately 6 mm).

Eight water samples were collected at different discharges. Soil and sediment samples were collected before the high flow season. Bank soil was

Figure 1. The surveying system and the Ritobäcken Brook during low water level.

sampled above the average water level, and the sediment samples were collected from the bottom of the brook with sediment tubes (diameter 45 mm). The soil and sediment samples were analysed for water content (WC) and organic content (OC) according to the Finnish standard SFS 3008. The grain size distribution of the soil was determined in a hydrometer test. The water samples were analysed for turbidity, suspended solids concentration (SSC), volatile solids concentration (VSC), total solids concentration (TSC), total volatile solids concentration (TVSC) and settling velocity. SSC represents the solid matter that does not pass the selected filter and was analyzed according to the standardized method EN 872:2005 as the average value of two parallel samples. Two filter types were used: GF-52 glass fibre filters (pore size 1.2 µm), hereafter referred to as GF, and the Nuclepore polycarbonate filters (pore size 0.4 µm), hereafter referred to as Np. The Np filters have a smaller pore size and a more regular pore pattern than the glass fibre filters, and they were chosen because previous studies have found them suitable for waters with very fine, clayey suspended solids (e.g. Valkama et al. 2007). VSC, TSC and TVSC were determined according to the standard SFS 3008 as the average value of two parallel samples. TSC represents the total amount of particle and dissolved substances present in the sample and was determined by evaporating the unfiltered sample and weighting the residue. The concentration of organic matter was determined for both the matter remaining in the filter (VSC) and the unfiltered sample (TVSC) by heating the samples at 550 °C and measuring the weight loss. The ratios between TVSC and TSC, and between VSC and SSC, express the total and particle-form organic content (OC, in %) of the sample. Turbidity was analysed from both mixed and settled (2–3 hours) samples following the standard ISO 7027:2000. Approximate settling velocity was measured for four samples with different SSC by letting a mixed water sample settle in a decanter. Maximum settling velocity was obtained when the first particles hit the bottom.

A continuous monitoring station was set up at the Ritobäcken Brook. A turbidity sensor and a pressure transducer to determine water level were installed in a culvert. A weather station was instrumented with sensors measuring solar radiation, rainfall, air temperature and relative humidity. Sensor values were recorded every 15 minutes with a data logger, and the monitoring period lasted 48 days. The recorded turbidity values were the average over 20 consecutive measurements in 10 seconds. The monitoring station functioned reliably, and the sensors produced smooth, continuous datasets. Approximately 1% of the turbidity data points were significantly above the otherwise smooth turbidity curve; however, these outliers occurred temporally close to each other and might thus represent single greater erosion events. The turbidity data were somewhat scattered at low turbidity levels (20–40 NTU) when the water temperature was -0.2–0 °C, but it is not known whether this represented the real behaviour of the system or was noise. The data of the turbidity sensor was validated by comparing them against turbidity analysed from the water samples. Squared correlation coefficient was slightly better with the settled sample (R^2=0.99) than with the mixed sample (R^2=0.98). Sensor turbidity correlated well with the SSC analysed from the water samples (R^2=0.98), so the turbidity data were transformed to SSC with a linear regression equation. Discharge was obtained at five water levels by integrating the point flow velocities measured with a propeller-type current meter. A polynomial rating curve was developed between the water levels obtained from the pressure transducer and the measured discharges (R^2=1.00).

3 RESULTS AND ANALYSIS

3.1 *Geomorphological processes*

Visible erosion and sedimentation was observed in many locations along the Ritobäcken Brook. Unvegetated banks showed more erosion than banks covered by dense grassy vegetation. On the other hand, locations with woody in-stream and bank vegetation demonstrated bank erosion and local broadening. In these locations, the ground was bare and almost devoid of grassy vegetation, making the top layer of the soil susceptible to erosion. On the bed of the brook, vegetation patches tens of centimetres higher than the surrounding channel bottom were observed. There were visible sediment deposits on the vegetated floodplains, and almost stagnant water was observed there during the high discharges. Several small debris accumulations were found in the brook, and small meanders were observed downstream from the debris accumulations.

Two of the monitored cross-sections showed statistically significant bottom erosion during the high flow season (Figure 2b, 2c). Their erosion depths averaged over the bottom were 6.8±0.8 cm and 1.5±0.6 cm (at 95% confidence level). In the third cross-section, the measuring error (0.5 cm) was larger than the average bottom erosion (0.4 cm) (Figure 2a). Geomorphological development was uneven across the cross-sections as some verticals exhibited significantly higher erosion than others. Erosion depth strongly correlated with the hydraulic radius, and thus the average boundary shear stress, of the cross-section (R^2=0.89). The differences in measuring error between the cross-sections were mainly caused by the bottom characteristics: the fluffier the bottom, the higher the measuring error. Other factors causing error were the bank vegetation and woody debris below the surface. Excluding the significant outliers, the overall measuring error of the equipment was 0.6 cm at 95% confidence level.

3.2 *Sediment characteristics*

The hydrometer tests showed that over 90% of the soil was formed of clay and silt fractions, the clay fraction constituting 30–40%. The soil and sediment had similar water and organic contents (Table 1). The top layer of the sediment had a higher organic content than the deeper layers. The organic content of the sediment was also higher where the bottom was fluffier and the local topographical gradient smaller.

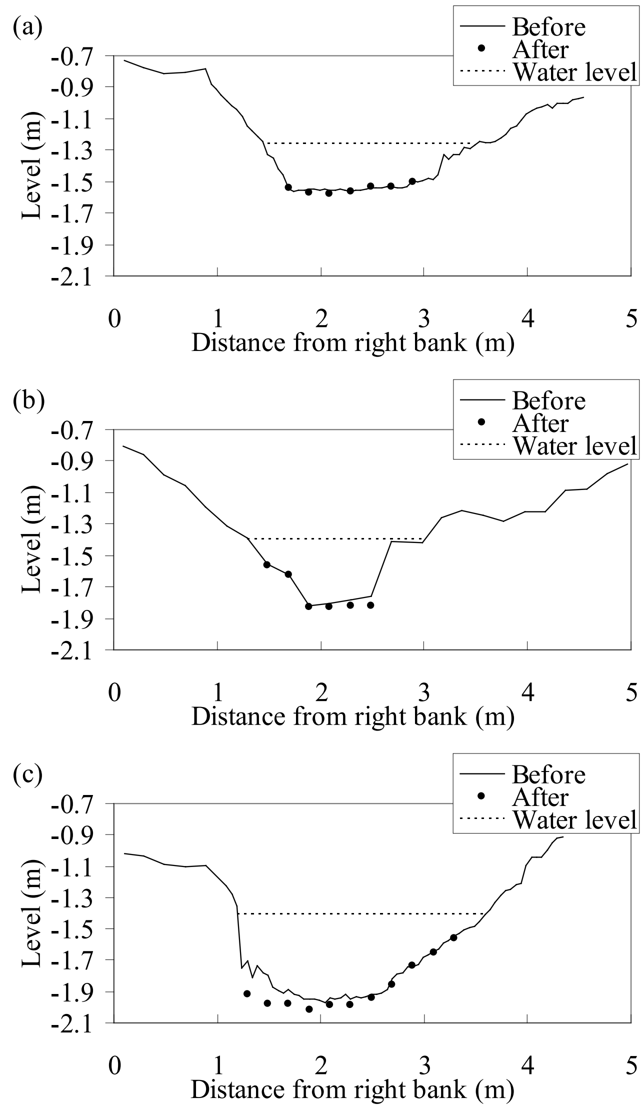

Figure 2. Cross-sectional geometry of the three cross-sections before and after the high flow season, and water level during the “before” survey.

Table 1. Ranges and average values (in parentheses) of concentration in water (C), water content (WC) and organic content (OC) for different solid fractions.

	C (mg/l)	WC (%)	OC (%)
Soil		48	3
Sediment		38–49 (43)	2–10 (5)
SSC (GF)	9–39 (18)		20–43 (30)
SSC (Np)	22–86 (48)		
TSC	90–165 (132)		41–65 (56)

SSC varied notably during the autumn high flow season (Table 1), and the higher concentrations occurred during greater discharges. The SSC obtained with Np filters was on average 160% greater than with GF filters. A second-order polynomial regression equation could best represent the correlation between SSC obtained with GF and Np filters (R^2=0.93). TSC represents the amount of all the suspended and dissolved matter and was on average 630% higher than the SSC obtained with GF filters (Table 1). The analysed concentration distributions can be compared by calculating their coefficient of variation, c_v, which is defined as the ratio between standard deviation and mean. The coefficient of variation was significantly higher for the distributions of SSC (c_v=0.57 for GF and c_v=0.49 for Np filters) than of TSC (c_v=0.18), indicating that SSC reacts more strongly to flow variations than TSC. TSC had a higher organic content than SSC, but the correlation between the concentration and organic content was negative for both SSC (R^2=0.71) and TSC (R^2=0.46). Suspended sediment particles had a wide range of settling velocities. The highest settling velocities were 1–4 mm/s, the greater values associated with higher SSC. However, the settling velocities were 1–2 orders of magnitude smaller for a significant portion of the suspended matter.

Linear regression equations were determined between sensor turbidity and different variables describing the amount of solid and dissolved matter present in the water samples (Figure 3). The highest correlation coefficient was obtained for SSC (GF) and the lowest for TSC. This indicates that

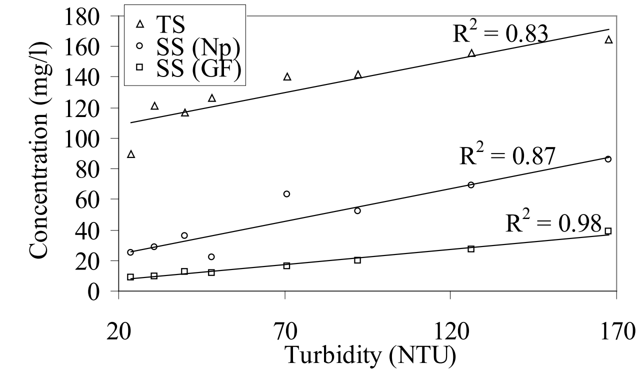

Figure 3. Linear regression between sensor turbidity and TSC, SSC (Np) and SSC (GF).

Table 2. Mean and coefficient of variation, c_v, of relative differences between parallel samples.

	Mean (%)	c_v
SSC (GF)	8.3	0.79
VSC (GF)	13	0.61
SSC (Np)	9.3	0.55
TSC	15	0.75
TVSC	25	0.89

turbidity was a good surrogate for the concentration of coarser suspended matter but was not as reliable a surrogate for the concentration of very fine suspended or dissolved matter.

The accuracy of the laboratory analyses was assessed based on the difference between parallel samples relative to their average value. Table 2 compares the parameters by showing the mean value (in %) and the coefficient of variation for the distributions of the relative differences. A low mean relative difference signifies that the analysis method generally produces accurate results while a low coefficient of variation is an expression of the overall reliability. For example, SSC (GF) had the lowest mean but a rather high c_v, indicating that the method had a high accuracy for the majority of samples but a low accuracy for some samples. The overall reliability of SSC (GF) was thus lower than that of SSC (Np).

3.3 *Flow and sediment dynamics*

The continuous monitoring data included 17 rainfall-induced discharge events. A discharge event is here defined as the period between two consecutive local minima in discharge. The average discharge during the monitoring period was 168 l/s and the average SSC amounted to 17 mg/l. The Ritobäcken Brook's response to rainfall was rapid: the discharge began to grow 1–4 hours after the beginning of a rain and achieved its highest value 2–5 hours after the end of a rain. The SSC curve followed the pattern of the discharge curve on the rising stage, and SSC reached its maximum value 0–6 hours before the discharge. The monitoring period's peak SSC (1-h average) was 67 mg/l and the peak discharge 567 l/s. In most discharge events, SSC decreased more rapidly than discharge on the falling stage. After the discharge peaks, SSC decreased to a background level of 7–11 mg/l in approximately 2 days independently of discharge or the peak SSC. During the monitoring period, the Ritobäcken Brook carried approximately 13 tons of suspended sediment.

A power-type sediment rating curve fitted best to the monitoring data, but the correlation was weak (R^2=0.36) and there was much scatter in the discharge–SSC plot. Even though SSC was generally higher for the greater discharges, relatively high discharge values were sometimes associated with low SSC. SSC was mostly higher on the rising stage than the falling stage at each discharge value. Correlations between discharge and SSC were somewhat better if rising and falling stages were considered separately (Table 3). Higher correlations were found for the rising stage if the rate of discharge increase (m^3/s^2) was considered instead of the absolute discharge (m^3/s). The best correlations were obtained between the 3-h average increase in discharge and the 3-h average increase in SSC for the rising stage. The correlation was the highest if a 15-min or 30-min shift was introduced between the discharge increase and the SSC change. Correlations between the rate of discharge decrease and the SSC decrease were very weak for the falling stage and were not improved by introducing any time-shift. Absolute discharge and the SSC change correlated very weakly. The peak SSC (1-h average) of each discharge event was only slightly correlated with the peak discharge of the event but was more strongly correlated with the average rate of discharge change (m^3/s^2) during the rising stage.

Different patterns of SSC–discharge curves for single discharge events have been described by e.g. Williams (1989). In the Ritobäcken Brook, the clock-wise, or positive, hysteresis in SSC was very clear for most discharge events. However, as the high flow season progressed, discharge events of similar peak discharge showed less hysteresis, and the discharge required to achieve a certain SSC level increased (Figure 4). In addition, greater rates of discharge increase were required to create a certain peak SSC. The linear regression equation between the average rate of discharge increase (m^3/s^2) and the peak SSC (1-h average) tended to under-estimate the peak SSC in the beginning of the season and over-estimate it in the end of the season, and there was an increasing trend in the error between the observed and modelled peak SSC as the high flow season progressed (R^2=0.32).

Table 3. Squared correlation coefficients between discharge and SSC for both absolute values and rates of changes.

	Discharge		Discharge change	
	Rising	Falling	Rising	Falling
SSC	0.49	0.36	0.56	0.16
Peak SSC	0.29		0.63	
SSC change	0.08	0.02	0.69	0.04
SSC change +15min			0.70	0.04
SSC change +30min			0.70	0.04
SSC change +45min			0.67	0.04

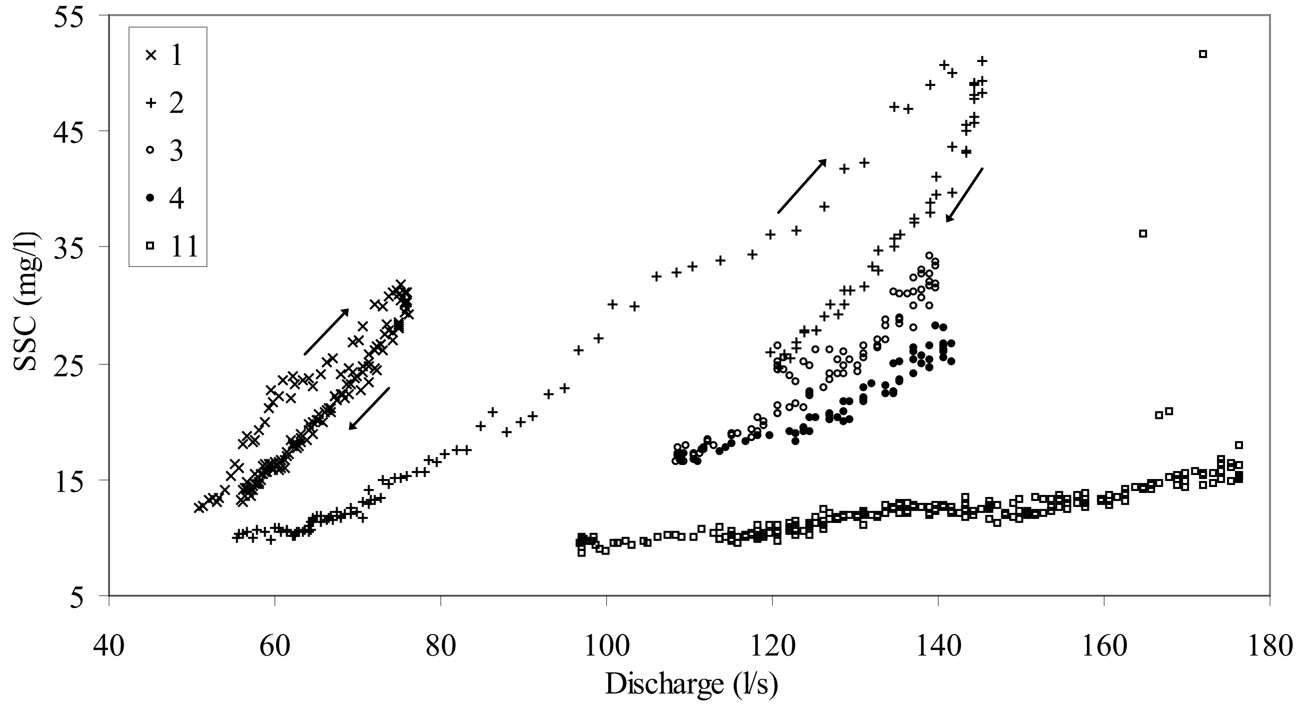

Figure 4. Hysteresis curves for discharge events of similar peak discharge (numbering represents the consecutive order of all the discharge events during the monitoring period).

4 DISCUSSION

The role of dense, flexible vegetation in decreasing erosion and increasing sedimentation has been confirmed in other studies (e.g. Samani & Kouwen 2002; Cotton et al. 2006). Two mechanisms contribute to this finding: firstly, flow resistance of vegetation decreases the boundary shear stresses (e.g. Baptist 2005). Secondly, roots of vegetation reinforce the soil, and particularly woody vegetation characterized by large roots and high root density decreases the erodibility of cohesive soil (Wynn & Mostaghimi 2006). In addition, herbaceous vegetation regulates the local micro-climate, decreasing the amount of freeze–thaw events and thus the erodibility of soil (Wynn & Mostaghimi 2006). This regulating effect may be particularly important in the Ritobäcken Brook since woody vegetation was associated with more erosion than grassy vegetation, and since the air temperatures were changing between freeze and thaw during the autumn high flow season.

Another reason for erosion observed in conjunction with patchy woody vegetation could be the increased near-boundary turbulence caused by sparse vegetation (Baptist 2005; Luhar et al. 2008). Single trees decrease the near-surface velocities and increase the near-bottom velocities in their wakes which may increase erosion (Yagci & Kabdasli 2008). Geomorphological development associated with vegetation patches on the channel bed as well as debris accumulations may be attributed to their non-uniform location in the cross-section, leading to modified flow patterns on their sides. For instance, woody floodplain vegetation decreases the near-bed turbulence and boundary shear stress on the floodplain but increases them in the main channel and the main channel–floodplain interface (McBride et al. 2007). In addition to the sideward development, the vegetation patches likely develop by downward extension due to fine sediment deposition inside and downstream of the vegetated area (Tsujimoto 1999).

The correlation between both SSC and discharge, and peak SSC and peak discharge, was poor even though the data were obtained during one high flow season and the rising and falling stages were considered separately. Physically based models would probably tackle the cohesive sediment processes better than statistical methods due to the physical phenomena involved, including the hysteresis and depth-limited erosion. The highest correlations were found between the rate of discharge increase and the rate of SSC increase or the peak SSC. These results agree with the findings of De Sutter et al. (2001), who discovered that the unsteadiness of the discharge increases the erosion of cohesive sediments for the same maximum discharge. The positive hysteresis in SSC is often attributed to either sediment depletion, or depth-limited erosion, or early sediment supply from a major downstream tributary (e.g. Williams 1989; Asselman 1999). Rising stage may also experience greater erosive forces since laboratory studies have shown that it is associated with higher turbulence and bed shear stress than the falling stage (Nezu et al. 1997). In the Ritobäcken Brook, positive hysteresis indicates that sediment entrained from the channel formed a significant source of suspended sediment during discharge events. The decreasing trend between the rate of discharge increase and the peak SSC as well as the changes in the SSC hysteresis pattern indicate that the easily erodible sediment was slowly depleted during the high flow season.

Higher discharges were able to erode coarser particles since they were associated with a higher ratio between SSC (GF) and SSC (Np). The same result has been found by Valkama et al. (2006). Selective erosion, well known for non-cohesive sediments, was thus occurring with cohesive sediments. Results of the settling test confirmed that higher suspended sediment concentrations were associated with coarser matter since they had higher settling velocities. However, the higher settling velocities may also be partly due to the more effective aggregation that increases the deposition of fine cohesive sediments (e.g. McAnally & Mehta 2002). The Ritobäcken Brook had a 160% difference in SSC between GF and Np filters while other studies have reported differences of 10–90% for similar streams (Hirvikallio et al. 1979; Valkama et al. 2006). There is thus much fine suspended matter in the Ritobäcken Brook that passes through the GF filter.

Catchment processes are important for cohesive sediments. The rather steady SSC between the discharge peaks likely represented the background concentration originating from catchment runoff. Suspended sediment had a markedly higher organic content than the bottom sediments and bank soil, suggesting that a significant amount of the suspended matter originated from sources other than the brook material, such as sub-surface runoff from the agricultural fields and the decaying bank vegetation. The organic content of suspended sediment decreased with increasing discharge, which is an indication of the increasing role of channel erosion at high discharges. The differences in the organic content of the bottom sediment were great, and a high organic content was likely associated with recent sedimentation.

5 CONCLUSIONS

The field study conducted under natural vegetated conditions revealed that woody in-stream and bank vegetation was associated with greater bank erosion than grassy vegetation. The unsteady flow was found to influence the sediment processes significantly since the rate of discharge increase explained the suspended sediment concentration better than the absolute discharge. The positive hysteresis in suspended sediment concentration and the changes in the hysteresis pattern during the high flow season suggested that the easily erodible sediment was slowly depleted during the season. Cohesive sediment processes were found to be selective since higher discharges were characterized by coarser particles. To improve the understanding related to natural vegetation and to promote environmentally sound hydraulic engineering practices, the next step in the field study is to physically model the interaction between flow, different types of floodplain vegetation and cohesive sediment as well as determine the seasonal changes in the processes.

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