Environmentally preferable two-stage drainage channels: considerations for cohesive sediments and conveyance

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Abstract:
Design of environmentally preferable agricultural drainage channels calls for an improved understanding of cohesive sediment processes. Flow and cohesive sediments were investigated in a new demonstration and test channel where a floodplain was excavated on one side of the existing channel to improve flood conveyance. In this approach, the existing, naturally recovered channel was mostly left intact to reduce environmental impacts. Continuous monitoring of discharge and suspended sediment concentration (SSC) during one year revealed that the construction work of the two-stage channel caused 2% of the annual suspended sediment (SS) load. Agricultural areas covering 13% of the catchment were estimated to contribute over half of the annual SS, predominantly during the rising stages. Seasonal positive hysteresis was found in SSC which was explained by the different drainage efficiencies of two distinct sediment sources. The temporally varying shares of the two sources caused scatter in the rating curves between discharge and SSC or SS load. Out-of-channel processes were shown to govern the amount and timing of suspended sediment input into the channel, indicating that environmentally preferable agricultural channel design should consider the cohesive sediment processes and sources at the catchment scale.

Keywords: drainage channels, cohesive sediment, suspended sediment, hysteresis, flood conveyance

Introduction
Agricultural drainage systems are necessary to improve crop yields, but they cause adverse environmental impacts and disturb the natural sediment processes both in channels and catchment areas. Drainage of fields is based on either surface or sub-surface drains which often discharge into adjacent small streams. These streams have usually been channelized to increase conveyance, which has significantly decreased habitat quality and variability in e.g. Finnish streams [1]. Channelization has included widening, deepening and straightening streams to a constant bottom slope and cross-section, and clearing vegetation and other obstructions. In this paper, these originally natural but heavily modified streams are referred to as agricultural brooks or channels.
Channelization and sub-surface drainage alter the catchment hydrology by creating a more rapid response to rainfall and by increasing the peak discharges compared to non-drained areas [2]. This along with the increased bottom slopes explain the excessive erosion encountered in some channelized reaches. On the other hand, field drainage is assumed to augment the input of fine sediment into the channel network [3]. Sediment is an important factor to be controlled in agricultural drainage since it degrades water quality [4], and causes siltation by depositing in reaches with low flow velocity. For instance, one third of the formerly channelized agricultural brooks in Finland are currently in need of maintenance since they do not provide the required drainage depth [5]. The conventional drainage practices based on channelization and trapezoidal cross-sections are thus not only environmentally harmful but also require costly re-dredging at certain intervals.

Environmentally preferable drainage practices have been presented as an alternative to conventional channelization [e.g. 1]. They aim at ensuring the long-term functionality of agricultural drainage while mitigating the adverse environmental impacts by adopting some of the features and functions of natural streams. The long-term functionality of the drainage requires that the channel does not undergo changes that hinder it from providing the required drainage depth or conveying the design discharges. Such changes include siltation and excessive in-channel vegetation slowing down the flow. The features and functions implemented in environmentally preferable channels are similar to those used in stream restoration, such as enhancing the channel’s morphological variability and dynamics as well as utilizing bank vegetation for erosion control. However, the boundary conditions imposed on the channel design by the surrounding intensive land use require careful selection and possibly maintenance of the implemented features. For instance, bank vegetation may need regular thinning since it typically reduces conveyance, and the variability in channel geometry recommended for restored streams [6] can be accepted in drainage channels only to the degree at which it does not impair drainage. Both the drainage and environmental objectives can be best achieved by steering the channel towards dynamic equilibrium. Such channels maintain their long-term temporal average properties, including width, depth and sediment input and output, but may experience morphological processes such as meander development and seasonal or annual cycles of erosion and sedimentation.

One of the novel solutions recommended by the environmental authorities for small agricultural brooks is a two-stage cross-section with natural-like features [1]. Two-stage drainage channels are expected to provide environmental benefits while being more self-sustaining and needing less management than simple trapezoidal channels. For instance, two-stage channels constructed in the US Midwest have cost more than trapezoidal channel maintenance, but they have been found morphologically stable [7]. Two-stage channels are formed of a narrow main channel and a wider floodplain above the mean water level. During low stage, the main channel sustains enough flow velocity to prevent excessive
sedimentation. The floodplain provides additional flow area during high flows while maintaining the boundary shear stress and the associated channel erosion at acceptable levels. A two-stage cross-section also provides limited main channel–floodplain connectivity during high flows. In Finland, agricultural two-stage channels have been realized by either excavating a floodplain on the side of an existing channel [8] or by digging a narrow channel in the bed of a widened reach. Constrained natural meandering can be allowed in these channels as long as the desired conveyance and drainage depth are maintained. The meanders reduce the bottom slope of the channel and thus the potential for channel degradation. To promote the natural morphological development, small meanders have been excavated in previously straightened channels [1].

The strict boundary conditions and disturbed sediment regimes require addressing the fine sediments in environmentally preferable channel design. The transport of fine, cohesive clays or silts is often considered as non-capacity load [e.g. 9]. However, the widely occurring siltation indicates that the processes of these sediments are not fully understood in lowland agricultural channels. The purpose of this paper is to provide a physically-based description of the catchment-scale cohesive sediment sources and processes that are relevant for the design and management of small agricultural channels. The paper reports the design and construction of an environmentally preferable two-stage drainage channel, investigates the seasonal flow and sediment dynamics, and examines the sediment load during the construction as well as the functioning of the channel during the first year.

Two-stage demonstration channel: construction and study methods

The Ritobäcken Brook in Sipoo, Southern Finland, serves as a drainage channel for the surrounding agricultural fields. The brook has been channelized in the past using conventional methods but has naturally recovered. Significant bank and bed erosion has occurred in some of the upstream reaches while siltation has reduced the conveyance in the downstream reaches. The landowners wanted to improve the drainage conditions as the adjacent fields have been inundated during high flows. To demonstrate an environmentally preferable two-stage drainage channel approach, the local water and environmental authority designed and established a field site, which we adopted for our study (Figure 1). The study reach is 1 km long and has an average bottom slope of 0.002. The banks grow both grassy and woody vegetation. Before the construction, the bottom and bankfull widths of the channel were 0.5–2 m and 3–7 m, respectively (Figure 2).

Surface or sub-surface drained agricultural fields constitute 13% of the 10-km² catchment area. The remaining non-agricultural catchment is mainly comprised of forests and mires that are partly drained by open ditches. Sub-surface flow is the dominant runoff type due to the low rain intensities and permeable soils, and only small amounts of surface runoff have been observed. The region’s mean
rainfall is approximately 700 mm/a and annual mean temperature +5 °C. The nation-wide specific discharge generally varies between 8 and 12 l s\(^{-1}\) km\(^{-2}\) [5]. A hydrometer test showed that over 90% of the bank soil was formed of clay and silt fractions, the clay fraction constituting 30–40%. The cohesive channel bed was partly covered by fluffy sediment with a water content of 40–50% and an organic content of 2–10%. The mineral soil in the catchment is clayey.

![Figure 1. Ritobäcken Brook after the excavation of the two-stage profile. Space was created for flood conveyance by forming a floodplain above the mean water level (left, high flow after the first spring’s snowmelt) while the existing low flow channel was left intact (right, mean flow during the late spring).](image)

**Design and construction of the two-stage channel**

The local water and environmental authority commissioned an engineering consultancy to design the two-stage channel. The objective of the hydraulic design was to decrease water levels, and thus field flooding, caused by 10-year or more frequent flow events. The authority also expected that the two-stage cross-section would control the in-channel erosion during high flows and siltation during low flows, and thus improve the design life of the channel. Because discharges or water levels had not been previously monitored in the brook, the consultancy determined the flow frequencies from a region-specific empirical nomogram based on the size and shape of the catchment area, and the field and lake percentages. The catchment area measured 8 km\(^2\) according to the contour map prepared by the environmental authority, and the corresponding mean and minimum discharges were estimated at 80 l/s and 4 l/s, respectively. The discharge caused by the snowmelt was assumed moderate, and the annual maximum discharge was presumed to take place during the late spring or summer with an estimated average value of 1600 l/s. It was detected only after the construction that earlier drainage works had increased the catchment area to 10 km\(^2\).
The consultancy designed the channel with the HEC-RAS 4.0 model based on conveyance criteria but did not simulate the sediment processes, as the water authority did not require that. Due to the lack of field data, professional judgment was used in estimating the values of the Manning coefficient. The design of the two-stage cross-section was based on excavating a floodplain on one side of the channel and leaving the opposite side and bottom intact, i.e. the width and depth of the main channel did not change. The level of the floodplain was determined so that the flow would inundate it when discharge is above the mean flow. Floodplain was planned for an 850-m long reach that suffered from frequent flooding. The designed depth and width of the floodplain were 0.6–0.8 m and 4–6 m, respectively, and the floodplain bank was set to the slope of 1:2 (Figure 2). The downstream impacts were expected to be insignificant as the immediate downstream reach is not cultivated.

Figure 2. An example cross-section before (left) and after (right) the floodplain construction. Simulated water levels for MQ, MHQ and HQ 1_10 refer to the mean discharge, and 1-year and 10-year flow events, respectively.

The floodplain was constructed in the winter when the ground frost supports heavy machines. The winter allowed working during low flow, and the water level was expected to remain below the excavation level. However, water level was 5–10 cm above the floodplain during the excavation. The floodplain was constructed on the inner sides of the existing meanders, but no side changes were made in the straight reaches. The opposing bank was left mostly intact, but large bushes were removed. The work took 11 days, eight of which involved excavation. After the excavation the surface of the floodplain was smooth and bare except for some exposed roots of willows. As the authority did not require any erosion protection measures, the floodplain was left to bare soil. After the first spring flood, four differently vegetated, 20-m-long test reaches were established for future investigation on the response of cohesive sediment processes and conveyance to bare, naturally developing, grassy, and woody floodplain conditions over a 3-y period. Natural vegetation development began in most other
reaches during the summer. Excessive woody debris was removed from the channel in the spring to reduce the flow resistance.

**Sampling and analyses**

The brook has been sampled and monitored since the summer before the floodplain construction. In addition, regular field observations were performed, as the site was visited once or twice a week except during the winter. Bank soil was sampled above the mean water level, and sediment samples were collected from the bottom of the brook with sediment tubes (diameter 45 mm). Grain size distribution of the soil was determined in a hydrometer test. Water content and organic content were analyzed according to the Finnish standard SFS 3008.

A continuous monitoring station was set up in the autumn 30 m downstream from the reach to be excavated. Turbidity and water level were monitored by a turbidity sensor and a pressure transducer, respectively. The vertical position of the turbidity sensor was manually changed according to the water level in order to ensure its representative location in the cross-section. A weather station was instrumented with sensors measuring rainfall and air temperature. Sensor values were recorded with a data logger at time steps of 5–15 min, and the recorded turbidity values were the average of 20 consecutive measurements in 10 seconds. The monitoring covered 344 days but was interrupted for one month in the winter to prevent potential damage to the sensors during the construction. However, the impacts of the construction were intensively monitored during one workday at time steps of 30 s and in the following night at 15-min intervals. During the year, there were some problems with the modem, and the continuous data had three gaps with durations of 1–3 days. In addition, although sensors were cleaned about weekly, suspended matter depositing on them caused some short periods with unreliable turbidity values which were easily identifiable from the data. Both the gaps in the data and the unreliable turbidity values occurred outside of major discharge events. The gaps in the water level data were filled by linearly interpolating between the last value before the gap and the first value after it. The gaps and unreliable values in the turbidity data were replaced by using the preceding reliable data.

Discharge was determined from flow velocities measured with a propeller-type current meter in a minimum of 39 points in a culvert just upstream of the pressure transducer. The discharge measurements included both rising and falling stages, and all discharges fell on a second-order rating curve. This curve type was selected since the highest discharges had to be extrapolated, and other alternatives would have provided unrealistically high discharges when the culvert was full. The rating curve was extrapolated only during the snowmelt by a maximum of 32 cm since measurements could not be conducted during that period. Because small flow velocities prevented measuring the lowest
discharges, a linear rating curve was constructed between the estimated minimum discharge and the lowest measured discharge. The relative errors were likely greater for the smaller discharges, but overall the errors were expected to be small since the culvert was regular-shaped.

A stage–discharge graph representing a typical two-stage cross-section was formed for a point just upstream of the vegetated test reaches where the water level was continuously monitored with a second pressure transducer. As this point was situated approximately 200 m upstream from the downstream monitoring station in a reach without tributaries, the discharge was assumed to be equal between the two stations. The stage–discharge relationship was formed by plotting all individual 15-min average values during a 4-month period starting from the snowmelt. The graph clearly showed the cross-sectional shape change, i.e. the level of the floodplain (Figure 3). No significant differences between the rising and falling stages were detected, likely due to the only partially established vegetation cover, and the steeper bottom slope in the reaches downstream of the culvert. The observed variation in the water level corresponding to a certain discharge was generally 0–2 cm and at the maximum 4 cm.

Figure 3. Measured stage–discharge relationship for a typical two-stage cross-section.

Water samples were collected at different turbidity levels both manually and with an automatic sampler. They were analyzed for suspended sediment concentration (SSC) according to the standardized method EN 872:2005 using two filter types: GF-52 glass microfibre filters (nominal pore size 1.2 µm), hereafter referred to as GF, and the Nuclepore track-etched polycarbonate membranes (pore size 0.4 µm), referred to as Np. The Np filters have a smaller pore size and a more regular pore pattern than the glass microfibre filters, and they were chosen because previous studies have found them suitable for waters with very fine, clayey suspended sediment [10]. Organic content of the suspended sediment was determined with the GF filters by incinerating the samples at 550 °C and measuring the weight loss according to the Finnish standard SFS 3008. Parallel analyses were made from each water sample, and the deviation from each sample’s mean value was on average 3% for all
the three analyzed variables. However, this deviation had a higher coefficient of variation (determined as the standard deviation divided by the mean) with the Np filters, likely due to their gradual blocking.

Sensor turbidity (T) was regressed to SSC analyzed with both GF and Np filters to obtain site-specific rating curves. A linear regression equation \( \text{Np} = 0.63T + 12 \) was fitted for Np with a squared correlation coefficient, \( R^2 \), of 0.93 (Figure 4). The relation between turbidity and SSC obtained with the GF filters separated at around 50 NTU. This value corresponded to the highest background turbidity measured in the brook between the autumn and spring and was associated with a change in the source of sediment (discussed in detail below). Separate linear regression equations were thus fitted for the GF below \( \text{GF} = 0.21T + 4 \), \( R^2=0.45 \) and above \( \text{GF} = 0.67T - 24 \), \( R^2=0.92 \) 50 NTU. These equations intersected at about 60 NTU (Figure 4), which corresponded to the highest background turbidity during the summer. The equations had to be extrapolated up to 860 NTU during four events. This was considered justified as the properties of the suspended matter were not expected to vary according to discharge, for which case the turbidity–SSC regression has been found linear [11].

![Figure 4. Linear regression between sensor turbidity and SSC for the GF and Np filters.](image-url)

Continuous water level and turbidity data were transformed into discharge (Q) and SSC with the obtained rating curves. Suspended sediment load (\( Q_S \)) was computed at time steps of 5–15 minutes by multiplying the discharge and respective SSC. To compute seasonal average values, the year was divided into five hydrological seasons: autumn, winter (excluding the additional load due to the construction), snowmelt, spring, and summer. The autumn covered the period when rain events caused notable increase in discharge while winter was defined as the period when rainfall came in the form of snow. Snowmelt began as discharge increased from the winter baseflow value and lasted until discharge declined below the annual average. The season referred to as spring began after the snowmelt and lasted until discharge had decreased to the summer baseflow value. The spring was followed by the summer that lasted until the following autumn. To obtain the annual values, the 344-
day-long data series was complemented into a full year by utilizing the daily average autumn values for 10 of the 21 missing days and the daily average summer values for the remaining 11 days. The seasonal and annual average values are presented in Table 1 according to both the Np and GF rating curves to allow comparison with other studies. All the other results were computed using solely the GF rating curve as it was considered more reliable with the present data due to its lower coefficient of variation in the SSC analyses.

Sediment rating curves [12] were constructed for the autumn, snowmelt and spring by fitting power-type regression equations between Q and SSC or Qₜ. 3-hour average values were used since they were found to adequately describe the dynamics of the flashy channel while balancing out the short-term fluctuations in SSC. To obtain more insight into the suspended sediment (SS) dynamics, regression equations were additionally fitted between the 3-h changes in Q and Qₜ. The rising and falling stages of discharge events were treated separately (herein a discharge event refers to each period between two local minima in discharge). For the spring, the regressions were formed by both including and excluding the first rain event on bare soil after the snowmelt since this greatly affected the correlation coefficients.

Results and discussion

Seasonal flow patterns and suspended sediment loads

The brook’s discharge was highly variable, exhibiting large daily as well as seasonal changes (Figure 5). The five hydrological seasons differed regarding to the magnitude of the discharge peaks and the behavior of SSC during the events. The differences were related to the seasonal air temperature, which governed the timing and amount of runoff entering the channel. In the autumn, spring and summer the air temperature was above 0 °C, and the seasons were characterized by discharge events peaking 2–8 hours after the end of a rain. The highest discharges occurred when the soil was the most saturated and a larger proportion of the rainfall was conducted to the channel. By contrast, the summer was characterized by very small discharge events due to the unsaturated soil. In the winter, discharge and SSC remained steadily at the winter baseflow values since the snow did not notably melt during the season (Figure 5a). Discharge and SSC sharply rose as the snowmelt began, fluctuating according to daytime snowmelt (Figure 5b). The snowmelt created lower SSC peaks than the rain events in the autumn or spring. Some SSC peaks occurred just before the snowmelt although the discharge remained constant, which was likely explained by the ice cover inducing error in the water levels obtained from the pressure transducer. All discharge events were accompanied with a peak in SSC. After each peak, discharge slowly returned towards the season-specific baseflow value. During the periods when discharge remained steady, the SSC was 7–12 mg/l with an organic content of over 30% (Figure 6).
This background SSC fell within the low-flow concentrations of 4–15 mg/l measured in a drained peatland forest [13] and can be assumed to represent the suspended matter that is associated with the baseflow from the partly surface-drained forests and mires.

Figure 5. Discharge and SSC patterns during the autumn and early winter (a), and during the snowmelt and spring (b).
Figure 6. Organic content of the suspended sediment as a function of SSC.

The Np rating curves produced higher average SS concentrations and loads than the GF curves (Table 1). The differences between the filters were pronounced because for the most of the time SSC was low, and the relative difference between Np and GF was at its greatest at small concentrations (Figure 4). The average SSC did not vary much with the seasons, and most of the differences in average seasonal loads were caused by the seasonally varying average discharge (Table 1). Approximately half of the annual SS load was contributed by the short snowmelt period (50% and 53% determined with the GF and Np filters, respectively). The summer caused only 3% (with both GF and Np) and the winter from 5% (GF) to 7% (Np) of the annual load. Between 90% (Np) and 92% (GF) of SS was transported during the snowmelt, spring and autumn high flow periods, which corresponded closely to the shares reported from automatic monitoring for a larger, agriculture-dominated clayey catchment with a similar climate [10]. Annual specific loads were 10.4 t/km² and 20.9 t/km² according to the GF and Np filters, respectively. Although both filters produced similar seasonal shares of SS load, the annual loads indicated that approximately half of the fine suspended matter passed the GF filter.

Table 1. Average discharge and suspended sediment parameters in the hydrological seasons.

<table>
<thead>
<tr>
<th>Season</th>
<th>Duration (d)</th>
<th>Average discharge (l/s)</th>
<th>Average SSC by GF (mg/l)</th>
<th>Average SSC by Np (mg/l)</th>
<th>Average Qₘ (by GF) (t/d)</th>
<th>Average Qₘ (by Np) (t/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autumn</td>
<td>63</td>
<td>159</td>
<td>25</td>
<td>50</td>
<td>0.50</td>
<td>0.87</td>
</tr>
<tr>
<td>Winter</td>
<td>103</td>
<td>44</td>
<td>14</td>
<td>39</td>
<td>0.05</td>
<td>0.14</td>
</tr>
<tr>
<td>Snowmelt</td>
<td>35</td>
<td>643</td>
<td>24</td>
<td>54</td>
<td>1.48</td>
<td>3.19</td>
</tr>
<tr>
<td>Spring</td>
<td>41</td>
<td>87</td>
<td>24</td>
<td>53</td>
<td>0.32</td>
<td>0.54</td>
</tr>
<tr>
<td>Summer</td>
<td>123</td>
<td>11</td>
<td>21</td>
<td>48</td>
<td>0.03</td>
<td>0.06</td>
</tr>
</tbody>
</table>

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Sources and processes of cohesive sediment

In the autumn and spring, SSC was characterized by positive hysteresis as it reached its peak value 0–6 hours before discharge and decreased more rapidly than discharge during the falling stages (Figure 5). Positive hysteresis is often associated with deposited matter being re-suspended from the channel bed rapidly after the discharge increases [14] or with depletion in the sediment available for transport [15]. Examination of consecutive discharge events showed, however, that neither of these explanations was the major cause for positive hysteresis at the Ritobäcken Brook. Figure 7 presents an example of three consecutive events during a period of six days. As all the rising stages of these events had a greater SSC than the preceding falling stages, sediment depletion was ruled out. The transport capacity of a certain discharge was assumed similar during the rising and falling stages as the rating curve did not notably differ between the stages. Re-suspension could not explain positive hysteresis either, as there was no time for additional deposition before the rising stages of the consecutive events. However, re-suspension possibly contributed to the hysteresis during events that took place after low flow periods.

![Figure 7. Positive hysteresis in SSC during three consecutive discharge events within six days.](image)

The Q–Qₙ rating curves had higher correlations than the Q–SSC curves for both the rising and falling stages (Table 2). However, the predictive capacity of the curves was only satisfactory as higher discharges were sometimes associated with a low SSC or Qₙ. During the falling stages, SSC declined near to the background value more rapidly than the discharge, indicating that at a certain time after the peak discharge, most of the discharge and SS originated from the non-agricultural areas. The background SSC did not change according to the discharge, suggesting that the SSC peaks were caused by the runoff from the agricultural areas. If agricultural areas produced most of the SS load during the rising stage, a certain change in discharge would explain the change in SS load irrespective of the absolute value of the discharge. Indeed, high correlations were found between the 3-hour changes in Q and Qₙ for the rising stages (R² = 0.88 and 0.96, respectively). This implied that the
change in Q₀ was the same if the discharge increased from e.g. 100 l/s to 200 l/s or from 500 l/s to 600 l/s. Including the first rain event on bare soil into the analysis further decreased the correlations for the Q–Q₀ and Q–SSC regressions whereas the explanatory capacity remained high between the rate-of-change parameters (Table 2). However, the rate-of-change parameters had notably lower correlation coefficients during the falling stages. The differences in the regression equations between the autumn and spring may be related to seasonal differences in the turbidity–SSC relation which were not analyzed within this study.

Table 2. Squared correlation coefficients (R²) for the sediment rating curves derived with 3-h average values.

<table>
<thead>
<tr>
<th>Season</th>
<th>Rising stage</th>
<th></th>
<th>Falling stage</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q–SSC Q–Q₀</td>
<td>Change in Q–Q₀</td>
<td>Q–SSC Q–Q₀</td>
<td>Change in Q–Q₀</td>
</tr>
<tr>
<td>Autumn</td>
<td>0.55 0.85</td>
<td>0.88</td>
<td>0.19 0.66</td>
<td>0.04</td>
</tr>
<tr>
<td>Spring, without first rain</td>
<td>0.28 0.66</td>
<td>0.96</td>
<td>0.28 0.81</td>
<td>0.68</td>
</tr>
<tr>
<td>Spring, with first rain</td>
<td>0.02 0.56</td>
<td>0.97</td>
<td>0.26 0.83</td>
<td>0.58</td>
</tr>
</tbody>
</table>

The encountered positive hysteresis in the Ritobäcken Brook was mainly explained by the runoff originating from two distinct SS sources with a differing response to rainfall. During the rain events, the agricultural areas started to produce runoff more rapidly than the non-agricultural parts of the catchment due to the more effective drainage of the fields. Agricultural runoff was the major source of SS during the rising stages. The contribution from the non-agricultural areas slowly grew after the discharge peaks, and the falling stages were dominated by the mixing of runoff from the two sources that had distinctly different specific SSC. These temporally differing contributions of agricultural and non-agricultural catchment to the Q₀ caused scatter in the rating curves. The mixing of sediment from different sources was observed in the decreasing organic content of the SS at higher concentrations (Figure 6). By contrast, there was no notable hysteresis in SSC during the snowmelt. Thus, a rating curve covering both the rising and falling stages had high correlations for both the Q–Q₀ (R²=0.85) and the Q–SSC (R²=0.72) regression. The snowmelt period was an example of the case when the agricultural and non-agricultural areas produced runoff simultaneously, allowing the concentration differences between the two sources to balance out before the monitoring station. Attributing the positive hysteresis to the spatial differences in the drainage efficiency corresponds to some previous explanations that have related it to other spatial factors, such as to an early SS load from a downstream tributary [9] or to rainfall near the catchment outlet [16].
Comparing the background SSC of 7–12 mg/l to the measured annual SS load indicated that over half of the SS originated from the agricultural areas that covered only 13% of the catchment. The agricultural areas thus appeared to have an approximately six times higher specific load than the remaining catchment. Field erosion has been found to contribute up to 88–95% of the SS transported in clayey lowland agricultural channels [12, 17]. As the share of surface runoff was supposed to be small in the Ritobäcken catchment, sub-surface drainage was assumed to transport most of the agricultural SS into the channel. Sub-surface drainage associated with a good macropore structure in the soil has been shown to convey 30–60% of the sediment load in similar catchments [12]. The mean SSC values reported for sub-surface drainage runoff range from 110 mg/l [18] to over 1000 mg/l [19], likely reflecting the differences in soil, the level of soil saturation and the vegetation cover between the sites. Determining the required transport capacity of a drainage channel necessitates an estimate of the SS load, but the load from an unmonitored catchment may not be reliably estimated by using reference values from other catchments.

The field investigations provided some new insights into the important mechanisms controlling transport of cohesive sediments in agricultural catchments. Firstly, splash erosion by raindrops was found to be a significant detachment mechanism when the soil was not protected by a snow cover. This finding was supported by the fact that the SS loads during the snowmelt were notably lower than the loads in the autumn and spring at comparable discharges. In addition, rain events created ponds of turbid water on the bare floodplain, and this water was released into the channel as water level rose above the floodplain. Another potentially important, but little researched entrainment mechanism for wet clayey soils is the dispersion of clay particles into the soil pore water via Brownian movement [20]. Secondly, the low SSC values at high discharges during the falling stages indicated that the contribution of channel erosion to the SS load was generally small. However, the high correlation between discharge and SS load during the snowmelt was partly explained by channel erosion as splash erosion and surface runoff were low during the season. Thirdly, significant deposition was noticed in the channel. During the summer low flows, notable amounts of cohesive sediment settled on the sensors. The deposition of fine cohesive particles in turbulent flows is explained by their aggregation into larger flocs which enhances their settling velocity [21]. It is notable that settling occurred although the SSC was low. When excessive woody debris was removed from the channel in the spring, large amounts of crop residue and willow stems were found on the channel bed, partly covered by deposited sediment. Although woody debris can be used in environmental drainage channels to slow down flow and to initiate the creation of depth variation [22], it is not suitable for all locations since it may dam the flow and cause unacceptable morphological changes. Crop residue and felled bushes should therefore be taken away from the channel banks if the channel is prone to siltation. Overall, the design of morphologically stable channels requires understanding of the processes of mobilized cohesive SS
in the channel network, and subsequently our further research will focus on the in-channel sediment processes in the differently vegetated reaches.

*Sediment load during the excavation, and post-construction functioning of the two-stage channel*

The observed changes in SSC during the day of intensive monitoring were associated with the excavation as discharge remained low and steady (Figure 8). SSC varied greatly depending on the phase of the work, peaking during the excavation. SSC rapidly decreased during other phases of work, such as removal of snow and marking of the excavation area. After the workday ended at 16:00, SSC quickly declined and remained at a lower level than during the workday. A high SSC peak occurred during the evening, likely due to a single rapid erosion event. The peak was followed by slightly elevated SSC values, but the average concentration during the night almost equaled to the average winter background value. SSC rapidly grew as the work was started at 7:30 the next morning. The SSC peaks during the construction exceeded the majority of the peaks caused by the discharge events. Comparing the SS load during the construction to the daily average SS load of the winter revealed that the additional load during the 21.5 hours of monitoring amounted to 0.20 t. Assuming that the working pattern was similar on all the workdays, the estimated additional load during the eight days involving excavation was 1.8 t. This load was of minor significance as it corresponded to 2% of the total annual load. The SS load was likely augmented by the shallow layer of water on the floodplain during the excavation. For comparison, restoration of a clayey channel in the same region did not cause additional turbidity during the work [23]. The restoration caused less SS load since it included e.g. placing boulders and gravel on the channel bed as opposed to the excavation and handling of the sediment during the floodplain construction.
Figure 8. Suspended sediment concentration during the construction phase on the day of intensive monitoring.

The first spring flood inundated the floodplain but was contained within the two-stage channel. After the flood, small rills were observed on the floodplain bank and minor hydraulic erosion on the toe, likely because vegetation had not yet developed to protect the excavated surface. On the other hand, some deposition had occurred on the floodplain. Studies in a similar-sized, engineered channel demonstrate that up to tens of centimeters of sediment may deposit on the floodplain within 2 to 10 years [24, 25]. Further, heavy floodplain sedimentation associated with vegetation development has been shown to notably reduce the conveyance of flood flows within a decade [26]. These observations stress the importance of using reliable hydraulic approaches in the design and management of two-stage channels. Approaches taking into account the complex flow patterns of such channels have recently been developed, and they are capable of estimating the conveyance and the lateral distribution of depth-averaged velocities [27, 28].

The water level did not rise above the floodplain during the summer, since even high-intensity summer rain events do not typically cause significant runoff increase in the region’s dry, permeable soils. If main channel–floodplain connectivity is sought after, excavating the floodplains lower than the mean water level would allow for their inundation during the summer. However, this may increase floodplain sedimentation and the need for maintenance. Furthermore, the flow velocity in the main channel was small below the mean flow, and water was almost stagnant during the lowest flows. The width of the main channel should thus be carefully determined if it is a critical design variable. Overall, the designed cross-section was easy to excavate and enables maintenance work with machines. However, in these lowland areas, cohesive streams have naturally steep, often undercut banks and wide
floodplains [22], and therefore it remains to be investigated whether the designed mild bank slopes and the constrained floodplain are suitable to these sediment and climatic conditions in the long term.

**Conclusions**

The constructed environmentally preferable two-stage agricultural channel was found to perform as expected in terms of conveyance. Morphological changes were small during the first year, but some sediment deposited on the floodplain after high flows and in the main channel during low flows. The SS load during the floodplain excavation was minor as it corresponded to 2% of the catchment’s specific annual load of 10 t km\(^{-2}\) a\(^{-1}\). The majority of the SS was inferred to originate outside of the channel, and the agricultural areas were estimated to have an approximately six times higher specific load than the rest of the catchment. Ensuring the desired transport capacity of lowland agricultural channels thus requires that the channel design takes into account the shares of different catchment land uses and the associated sediment loads. The differences in the drainage efficiency between the intensively drained agricultural and the mostly non-drained forest areas were shown to cause strong positive hysteresis in SSC. This explanation for positive hysteresis may apply to other small, partly effectively drained catchments. The derived rating curves between the discharge and SSC or SS load had only a satisfactory predictive capability due to the temporally varying shares of the two sediment sources. The findings highlighted the significance of the out-of-channel processes in governing the amount and timing of suspended sediment input into the channel. In consequence, cohesive sediment processes and sources should be considered at the catchment scale in order to ensure the long-term functioning of agricultural channels.

**List of symbols and abbreviations**

- GF: glass microfiber filters
- HQ 1_10: discharge corresponding to a 10-year flow event (l/s)
- Np: track-etched polycarbonate membrane filters
- MHQ: discharge corresponding to a 1-year flow event (l/s)
- MQ: mean discharge (l/s)
- Q: discharge (l/s)
- Q\(_S\): suspended sediment load (kg/s)
- SS: suspended sediment
- SSC: suspended sediment concentration (mg/l)
T sensor turbidity (NTU)

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References


Figure 1. Ritobäcken Brook after the excavation of the two-stage profile. Space was created for flood conveyance by forming a floodplain above the mean water level (left, high flow after the first spring’s snowmelt) while the existing low flow channel was left intact (right, mean flow during the late spring).

536x183mm (180 x 180 DPI)
Figure 2. An example cross-section before (left) and after (right) the floodplain construction. Simulated water levels for MQ, MHQ and HQ 1_10 refer to the mean discharge, and 1-year and 10-year flow events, respectively. 171x55mm (600 x 600 DPI)
Figure 3. Measured stage-discharge relationship for a typical two-stage cross-section.

80x63mm (600 x 600 DPI)
Figure 4. Linear regression between sensor turbidity and SSC for the GF and Np filters.

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Figure 5. Discharge and SSC patterns during the autumn and early winter (a), and during the snowmelt and spring (b).

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Figure 6. Organic content of the suspended sediment as a function of SSC.
85x65mm (600 x 600 DPI)
Figure 7. Positive hysteresis in SSC during three consecutive discharge events within six days.
85x65mm (600 x 600 DPI)
Figure 8. Suspended sediment concentration during the construction phase on the day of intensive monitoring.

170x74mm (600 x 600 DPI)