Spatial variation in sediment transport across the Studibach catchment

GEO 511 Master's Thesis

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Abstract

Mountainous catchments tend to differ greatly in both streamflow and sedimentary behaviour. In addition, they usually exhibit a vast range of streamflow and suspended sediment concentration. This high variability, even within a single catchment, is the reason why it is almost impossible to transfer knowledge gained from other catchments without massive uncertainty. Hence, it is imperative each catchment be investigated on its own to hopefully better understand the underlying processes. If this goal were achieved, it might become possible to infer catchment characteristics even for other, similarly mountainous streams. In this study, the Studibach catchment located in the Swiss Prealps was surveyed in terms of suspended sediment transport. For this reason, water level and turbidity were measured at five locations and then transformed to streamflow and suspended sediment concentration using samples and manual measurements. From these two datasets, sediment yield was calculated. Results showed the already expected high variability as well as a lack of relation between streamflow and suspended sediment. It would appear that other factors drive sediment erosion and thus transport much more than streamflow does. Such factors might encompass sediment availability, erodibility and catchment steepness. Sediment availability was found to influence the results strongly since the sensor closest to a still open landslide recorded the highest suspended sediment concentrations. Furthermore, steepness seems to have influenced the results as well, considering that the locations further downstream contained less sediment than the one close to the landslide, likely due to intermittent deposition in flatter parts between the sensors. Lastly, the erodibility of sediment in the landslide area increased sediment concentrations strongly.

1 Introduction

Sediment transport has long been recognised as an important factor to measure when investigating river catchments, especially in mountainous regions such as the Alps (Rickenmann, 1997), as it controls the dynamic nature of streambeds. Since human life tends to concentrate around waterways, understanding how and why they change is of utmost importance (Coleman & Smart, 2011). For instance, the flood events in August 2005 in Switzerland display why it is crucial to comprehend how rivers and their sediment transport work (Rickenmann et al., 2008). Mountainous streams pose an exceptionally hard challenge for researchers as they exhibit extreme variability even over small distances or short time periods (Rickenmann, 2016; Whitaker & Potts, 2007). This highly variable nature renders

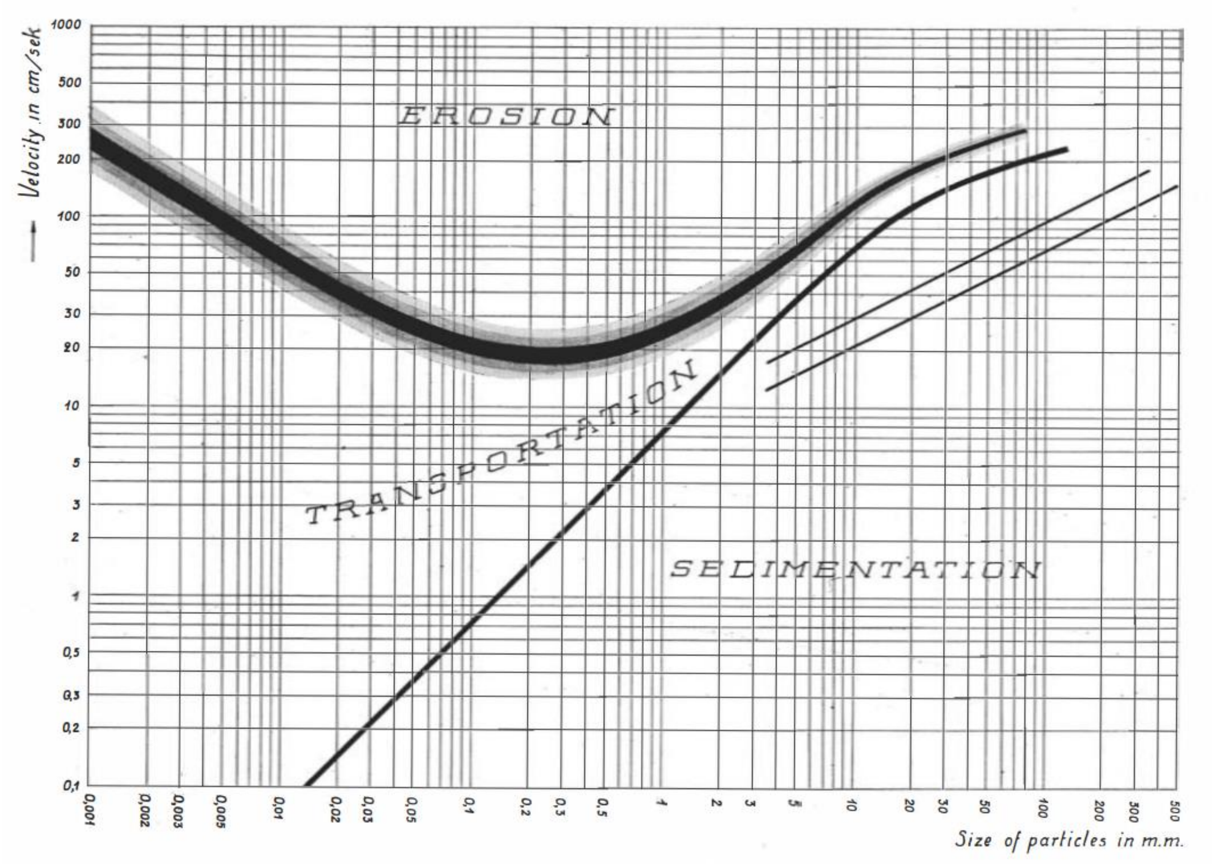

Fig. 1: Relation between particle size and water velocity which decides on whether material is eroded, transported or sedimented (Hjulström, 1935, 298).

any attempt at modelling the sediment transport in such streams difficult. Although a little dated, Gomez & Church (1989) found that not one of their twelve formulae performed well over the entirety of their data, further underlining how difficult modelling of such streams is. The main reason for this variability is that the environments in which mountain streams can be found are equally variable. There are numerous factors influencing a stream's behaviour – some examples are sediment supply, channel geometry and runoff. Thus, a consistent investigation of a river's behaviour must include geological and morphological aspects (Rickenmann, 2016).

1.1 Sediment transport

Another important factor to consider is the transport of sediment. The general rule is that the larger a grain is the more force is required to get it moving. Fig. 1 illustrates this nicely. However, this rule is not as straightforward as one might expect. Hjulström (1935) based his work on multiple authors before him and noted that the first issue was defining what velocity to use for the creation of such a relationship. In the end, he decided on using a bottom velocity – which is the one responsible for moving bed sediment – that he derived from either surface or average velocity. This mathematical derivation was necessary since information on bed velocity is often unavailable. He thus calculated the bottom velocity by reducing the average velocity by 40 %. If only the surface velocity was known, he first obtained the average velocity by lowering the surface one by 20 %. One of the most interesting aspects the diagram created by Hjulström demonstrates is the non-linear relationship between erosion and transportation. Hjulström (1935) explained this with the power of adhesion and cohesion. These two forces are present in all particles, but only with a high enough number of particles touching each other do they become visible in the diagram. Thus, only the very fine particles are influenced significantly by these forces. Although fig. 1 suggests a rather easily understandable relationship, the reality looks much more complicated. While the graph has been created for assumed uniform material lying on a bed of same-sized material, in a natural stream, particle sizes are much more diverse. As such, erosion velocities can differ depending on the composition of the material. Hjulström (1935) stated that coarse material requires more force to start moving, but once it started, it moves rather fast and takes a lot force to stop. Finer material, on the other hand, needs much less force to start moving, but it takes more to stop. For instance, it can be stopped by coming into contact with other particles again. Furthermore, its presence can increase the resistance of larger particles to erosion through adhesion to said finer material. Several studies quoted by Hjulström (1935) came to this conclusion. In addition, the movement of other sediment particles may increase erosion by disturbing the sediment resting on the riverbed. However, this effect is only noticeable for coarse materials (Hjulström, 1935).

Sediment can be classified in several ways, although the most intuitive one is characterisation by particle size. Others use size indirectly by classifying sediment according to how it moves. While Hassan et al. (2005) distinguish between suspended and bed load – the former meaning particles being carried entirely in the water while the latter are dragged over the bed –, others include an even finer, third category termed “wash load” (Coleman & Smart, 2011). Wash load is so fine that it is usually not deposited in rivers and hence moves directly through them. Only suspended and bed load contribute significantly to bed sediment. The most important sources for sediment in mountainous rivers tend to be landslides and debris flows (Cui et al., 2003).

A prime example for such a mountainous catchment is the Studibach. Several weirs and other measurement stations have been installed in the Studibach catchment. Five

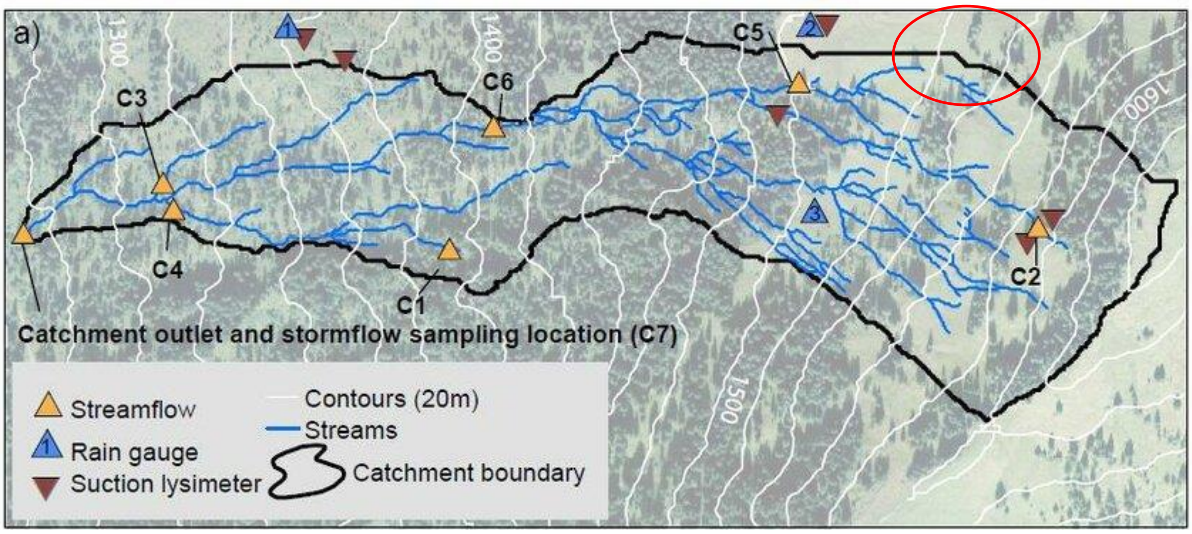

Fig. 2: map of the Studibach catchment including the locations to be investigated (C3, C4, C5, C6, C7). The approximate location of the landslide that happened after this picture was taken is marked by the red circle (Kiewiet, van Meerveld, Stähli, and Seibert, 2020, 3384; the map originated from the preprint; thus, it looks slightly differently from the published version).

of those (cf. fig. 2) are to be investigated in this study to answer the following research questions:

How fast do suspended sediment concentrations (SSC) respond to rainfall events and how do these responses differ across the Studibach catchment, and with increasing catchment size?

How does sediment transport vary spatially across the Studibach catchment, and can these differences be related to recent landslide activity or topographic characteristics?

I hypothesise that SSC reacts almost immediately, since the catchment is small and steep, thus probably does not delay the water input from precipitation that much. Furthermore, this response is bound to become more diluted, i.e. less extreme, but remain visible over a longer period the larger the catchment area becomes.

Additionally, I believe that spatial variation in sediment transport can be attributed to landslide activity or topographic characteristics, mainly steepness. This means that locations close to landslides or steep terrain should comparatively transport more sediment than their counterparts in flatter and more stable terrain.

2 Study site

A part of the much larger Alptal catchment (46.4 km^2) (Stähli et al., 2021), the Studibach catchment is located in the canton of Schwyz. It has a size of approximately 20 ha and ranges in elevation from 1270 m to 1650 m above sea level (Kiewiet, van Meerveld, & Seibert, 2020; Kiewiet, van Meerveld, Stähli, and Seibert, 2020) (fig. 2). It lies next to the 740 ha Erlenbach catchment, which is well known for sediment transport studies (Rickenmann, 1997, 2020; Rickenmann & McArdell, 2007). The Studibach

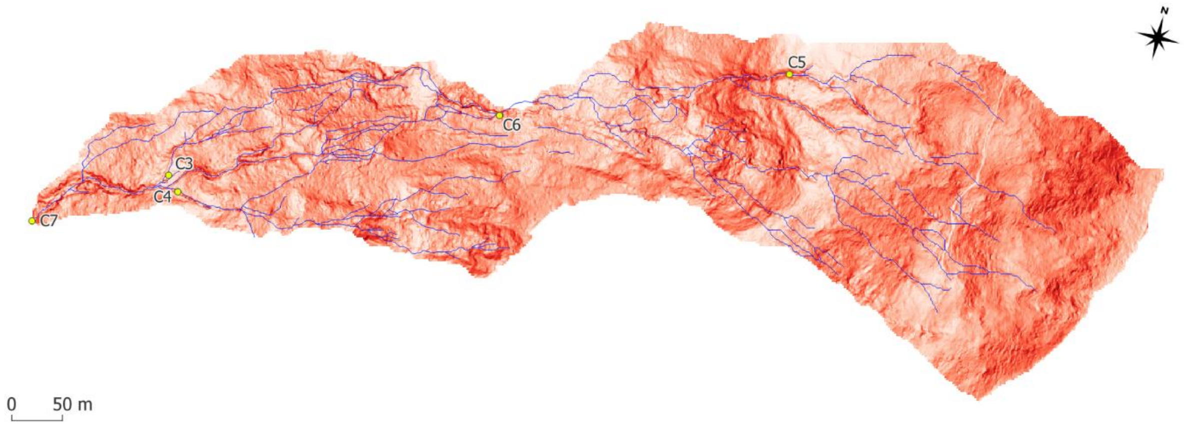

Fig. 3: Slope of the Studibach catchment. The darker the shade of red, the steeper the slope. One can easily see the variability of the catchment's slope (darker means steeper) (image created in QGIS using data provided by my supervisor and swisstopo).

catchment's topography is characterised by varying slopes, ranging from almost flat (< 1°) to quite steep (maximum slope of 64°) (Kiewiet, van Meerveld, Stähli, and Seibert, 2020) (fig. 3). The steepest parts of the catchment can be found in the uppermost regions as well as in a narrow swath from north to south in the catchment's upper half. Also, the channels themselves are often incised rather deeply into the landscape, meaning that they exhibit steep slopes. Another feature in fig. 3 is the path visible as an almost flat string moving in north-south direction through the upper part of the Studibach catchment. Looking at the mean of 22° (calculated using QGIS) or 35° (Kiewiet, van Meerveld, Stähli, and Seibert, 2020), however, the catchment seems to be moderately steep in general. Due to those partially steep slopes caused by soil creep, landslides occur relatively frequently in the area (Kiewiet, van Meerveld, & Seibert, 2020; Kiewiet, van Meerveld, Stähli, and Seibert, 2020). The location of one of those landslides is highlighted in fig. 2. The channels have a step-pool morphology with streambeds mainly consisting of course sand and gravel with some boulders mixed in, meaning that there is a wide variety of sediment grain sizes.

The small extent of this catchment sets it apart from the catchments that are investigated in most other sediment transport studies, which tend to focus on much larger rivers. The Studibach is a prime example for this situation, seeing as its large neighbour, the Erlenbach catchment, is one of the best studied in Switzerland, if not the world (one only needs to look at the vast number of publications on the website of the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) about the Erlenbach), whereas the Studibach's characteristics have not yet been investigated that thoroughly.

Half of the catchment is covered by coniferous forest, while the rest is mainly dominated by wetland and Alpine meadows

(Kiewiet, van Meerveld, Stähli, and Seibert, 2020). The 2300 mm of annual precipitation are generally evenly distributed over the entire year (Feyen et al., 1999). Circa one third falls as snow during winter (Stähli & Gustafsson, 2006), although that might already have changed in the almost 20 years since Stähli & Gustafsson's study due to climate change. Streamflow and groundwater respond rather quickly to rainfall events (Fischer et al., 2015; Rinderer et al., 2015), which can be attributed to the catchment's small size and steep slopes. In addition, the soil is quite wet in large parts of the catchment – beside the literature pointing that out, I also had several rather unpleasant encounters with that – which indicates that the soil storage, however large or small it may be, is most often filled. Using the easily applicable wetness classification of Rinderer et al. (2012), I would assume that the largest portions of the Studibach catchment would fall into categories 4–6, where the steeper parts are generally a little drier than the flatter ones.

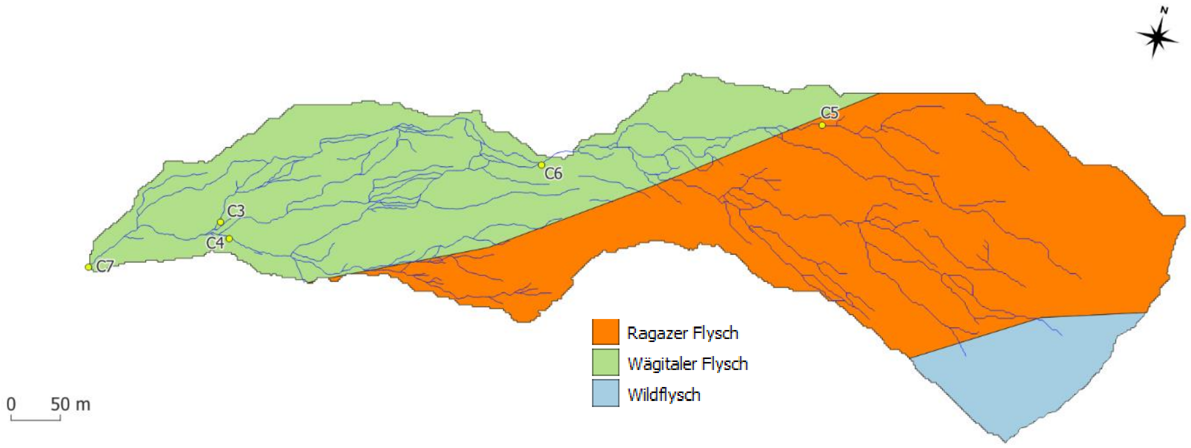

Fig. 4: Geology of the Studibach catchment (image created in QGIS using data provided by my supervisor and swisstopo).

As for the geology of the catchment (fig. 4), it consists of two separate units that cut through the catchment: while the northwestern and the outermost parts in the south-southeast lie on marl slate and phyllite, a large swath of limestone with marl layers is located in the catchment's centre. In short, this means that the entire catchment geology is defined by sedimentary (limestone) or partially metamorphosed (marl slate) rock rich in carbonate.

3 Methods

3.1 Suspended Sediment Concentrations (SSC)

To answer my research questions, data about sediment transport and discharge are crucial. Thus, the first priority was to install turbidity sensors at the chosen locations. I used Cyclops-7 loggers, which report turbidity in Nephelometric Turbidity Units (NTU). They were set to take a measurement every five minutes. To increase temporal comparability, the loggers were all set at times that matched those five-minute steps so that, ideally, every logger would take a measurement at exactly the same time. These intervals were kept when resetting the loggers after having deactivated them for reading the data. Sadly, it did not yield the intended synchronous measurements due to the internal clocks of the sensors changing slightly over the course of the measurement period.

Since the turbidity sensors do not provide information on the SSC, NTU values need to be related to the suspended sediment concentrations. For this, water samples were collected during two rainfall events (in October and early November 2023) using an ISCO 6712 Portable Sampler. This sampler took 24 500 ml samples over the course of 24 hours during the rainfall events. Only the murkiest samples and a few without sediment were taken back to campus. In order to determine the amount of sediment in the sample, they were filtered. The filters (including their envelope) were weighed before and after filtering and oven-drying. The difference between those weights represents, in theory, the weight of the sediment. Since the volume of the samples was known, this weight could then be transformed to SSC at the time of the sample collection. These concentrations were then related to the NTU values measured at the same location and time to obtain a curve by which all other NTU values could be converted into SSC.

3.2 Streamflow

In order to compare SSC to streamflow, I needed data on the latter. For this, several streamflow measurements at each of the five locations were conducted under different flow conditions. Depending on the amount of water and the location, either salt dilution measurements or the simpler bucket approach were chosen. At the locations with weirs the flow was usually low enough that bucket measurements worked fine. Only once did I use salt dilution for a location with a weir, namely C5, because I had moved the turbidity sensor to about 20 m below of the weir because of grazing buffalo further upstream. The next time I returned to bucket measurements because there was no influx of water from other sources between the weir and the sensor’s new location, meaning that bucket measurements at the weir should yield the same results as at the sensor. Of course, such measurements are not suitable to create any relationship with SSC on their own. To receive continuous streamflow values, water level measurements that were taken continuously in the catchment were used. The three locations with weirs (C3, C4, C5) are equipped with Odyssey capacitance water level loggers which directly output water level measurements in millimetres. In C6 and C7, in contrast, Keller pressure loggers were used. Such sensors measure water pressure, which was converted into water level by subtracting the atmospheric air pressure at the same time and date. The barometric data was recorded in or near the catchment. Since barometric data were only available for two locations at 1310 and 1545 m a. s. l., respectively, the actual values at the height of the two stations – approximately 1270 (C7) and 1410 (C6) m a. s. l. – had to be extrapolated using formula (1).

$$P_{\mathrm{corr}} = P * e^{\frac{-m_{\mathrm{Earth}} * g * \Delta_{\mathrm{Elev}}}{k * T}} \qquad (1)$$

where:

m_{Earth} = 0.0289644 kg/mol
g = 9.80665 m/s^2
Δ_{Elev} = difference in elevation between station and sensor
k = 8.31447 J/(mol*K)
T = air temperature

As C7 lies even below the lower barometric measurement station, only the data from the lower station were used for the extrapolation, except when there were no data from the lower station. For C6, which lies more or less in between the two barometers, the average of both extrapolated values were used. Only for two small time windows on the 18th and the 31st of August, only the data from the upper or lower station, respectively, were used because of the lack of data from the other station. Afterwards, the water level could be derived by subtracting the air pressure from the water pressure.

The intention was to use the water level measurements to create rating curves that connect the water levels to the streamflow measurements. For the three locations with weirs, this should have been straightforward However, I had too limited streamflow information from my own measurements to achieve this goal since I only managed to take measurements during low and, in some cases, medium flow conditions. Hence, I relied on older rating curves that had been developed in 2012. Since they chose the USBR (modified) rating curve, I used that one as well. That curve was created using the "Water measurement manual" edited by the United States Bureau of Reclamation in 2001. The equation is the following (United States Bureau of Reclamation, 2001):

$$Q = 4.28 * C_e * \tan\left(\frac{\theta}{2}\right) * (h_1 + k_h)^{\frac{5}{2}} \qquad (2)$$

where:

Q = discharge over the weir [ft^3/s]
C_e = effective discharge coefficient
h_1 = spill height [ft]
k_h = head correction factor
θ = angle of V-notch

The head correction factor follows a curve also included in the USBR's manual. The same goes for the effective discharge coefficient. For both factors, the values used in the existing rating curves were used to fit my data. To determine the spill height, the height of the V-notch's bottom had to be subtracted from the water level data, since the Odyssey loggers do not automatically account for this offset. Because of a lack of information on the V-notch height, I assumed that the lowest consistently recorded water level was equal to the V-notch height as I know that the streams almost stopped flowing during the measurement period. Additionally, since equation (2) uses feet instead of SI units, the equation applied to my data looks slightly different (3), as h_1 was converted to feet and the equation's result from cubic feet per second to litres per second:

$$\mathrm{Q} = 28.317(4.28 * C_e * \tan\left(\frac{\theta}{2}\right) * (\frac{h_1}{30.48} + k_h)^{\frac{5}{2}}) \quad (3)$$

To ensure the rating curve extracted from the data matched the few measurements, I compared it (USBR (modified)) with my data. Furthermore, I also used the rating curve mean discharge coefficients and k factors to assess the uncertainty of the discharge data. Ideally, the differences in using both rating curves would be minimal, thus corroborating the data's strength.

For the analysis of the streamflow data, it was necessary to compare it to rainfall data, which was obtained with a tipping bucket at a 10-minute resolution at the Erlenhöhe climate station, only a few hundred metres away from the Studibach. It is maintained by the WSL. Using python, I plotted the rainfall and the streamflow data for certain high-flow events, hence enabling me to extract response times for the different locations, which is defined as the difference between the timestamp of the event's maximum flow and maximum rainfall intensity. In other studies, the difference in time between start of rainfall and start of reaction is calculated (Skaugen et al., 2023), but in such a highly variable catchment like the Studibach and because some rain events show high inconsistency, I chose the simpler approach of difference in timestamps of maxima. For certain events, this approach had to be refined somewhat by creating subsets for each single rain burst during the event because the maximum rainfall does not necessarily lead to maximum flow if there is another rainfall event afterwards. For instance, there was an event on the 14th of November, when it rained in the morning and then again in the afternoon. Thus, the maximum flow of the entire day might have happened in the morning, even though maximum rainfall fell in the evening.

3.3 Sediment yield

To synthesise all the data recorded and calculated into the sediment yield – i.e., the amount of sediment flowing through the chosen locations in a given period of time, equation (4) was applied:

$$\mathrm{SY} = \mathrm{SSC} * \mathrm{Q} * \mathrm{T} * 86'400 \quad (4)$$

where:

SY = *sediment yield [g]*
SSC = *suspended sediment conc. [g/l]*
Q = *streamflow [l/s]*
T = *time step [d]*

Since Microsoft excel stores time and date in days, time steps were converted to seconds. They were either 300 s (5 min) or 600 s (10 min).

3.4 Time zones and time steps

The change in time step of the water level sensors in autumn also needed to be considered. Since the sensors' storage is not emptied over the winter, their measurement intervals of usually 5 minutes in summer are reduced to 10 minutes, lest the storages become full before the first data download in spring. Thus, in the data, there is also a change in time step, usually in late October. This leads to different values in sediment yield as the time step in equation (4) changes. Another time issue was the change from summertime (UTC +2) to wintertime (UTC +1) on October 29th. Since not all sensors handled this change equally, each data file was checked separately. Of the three sensor types used, the KELLER changed the time zone on their own, the Odyssey always measured in wintertime while the Cyclops-7 used summertime. In the end, wintertime was chosen as standard and the time stamps of all the measurements in summertime were converted to wintertime to avoid issues around the change of times at 3 AM on October 29th. Lastly, the Cyclops-7 sensors, for some reason, did not manage to synchronise their internal clocks with the ones of the field laptop, leading to some discrepancies among them. Thus, I noted their lag or advance in relation to the laptop's clock and then corrected their (winter) time stamps. Sadly, some of the sensors' time differences seem to have slightly changed over the course of my measurements, meaning that even the correction might not have removed all errors. However, the largest shift in difference noticed were two minutes, and can thus be neglected.

To achieve best comparability of the different collected data, all time stamps were rounded to the closest five minutes – after correction. For most sensors, this meant either no shift or only one of a single minute.

3.5 GIS analysis of catchment

For the analysis of the study site, I mainly relied on data provided by swisstopo (Swiss Federal Office of Topography) and pre-existing information in studies conducted in the Erlenbach catchment. The basis of the general topographical analysis were the layers included in "swissALTI3D", a highly precise digital elevation model of Switzerland (swisstopo, 2024). The parts covering the Studibach catchment were last updated in 2019. Other data by swisstopo are swissTLM3D, 10 cm orthoimages as well as a relief map at 1:10,000 scale. These data were all downloaded either directly from the swisstopo website or through GeoVITe (Geodata Versatile Information Transfer environment), a tool created by the Federal Institute of Technology Zurich (ETHZ) to facilitate access to geodata (ETH Zurich, 2019). Additionally, some additional map layers were incorporated, one of which was a simple polygon to crop other layers to as well as the stream network and all the measurement stations/sensor locations that are permanently installed in the catchment. The goal was to create map layers of the catchment containing the following: slope, aspect, land cover, elevation, geology. It was intended to use the slope to (partially) explain the temporal behaviour of sediment influx during a rain event, assuming that steeper slopes mean faster sediment movement. Land cover and geology, in contrast to aspect, should help explain spatial variations in sediment yield as the material characteristics at each location might have an influence on resistance to erosion. I assume land cover to have an impact as well, because different types of cover might strengthen or weaken the soils resistance to erosion. For instance, it can be expected less sediment (influx) in forested parts of the catchment compared to more open areas and especially the parts without vegetation in the landslide areas. Lastly, the elevation map's purpose is to give a general overview of the catchment and to derive characteristics such as the slope and aspect.

3.6 Technical issues

The most interesting location sediment-wise is C5 in the uppermost part of my study area. The sensor for that location was first installed about 20 m above the weir. Sadly, this put the sensor directly in a preferred spot of the buffalo being grazed there (fig. 5). Their activity was likely responsible for the sensor not working when I visited it two weeks after the first instalment. After retrieving it and bringing it back home for inspection, it suddenly started working again. Water might have managed to get into the sensor, shutting it down. After drying everything at home, that seemed to have restarted it. In consequence, I reinstalled the sensor about 20 m below the weirs, which put it outside of the buffalo's grazing ground, but also downslope of the weir. Thus, the correlation between streamflow and turbidity might not be entirely accurate if there was any influx of water in those 20 m, which was not the case during my visits, but could have happened during heavy rainstorms.

On the fourth visit to the catchment at the end of September, the sensor in the uppermost location had once again stopped recording. And exactly like the first time, it

Fig. 5: This image might show the buffalo responsible for shutting down the sensor in the uppermost location of the study area. The sensor lay exactly in the part of the stream visible in the photo. Judging from the buffalo's glistening hide and the water's murky texture, I would argue that the buffalo had just taken a bath. Probably on top of the sensor … (image taken by timelapse camera installed by me).

started working again once I had brought it home. There, it became clear that it had stopped recording almost exactly when I had been there the last time before. Thus, there are no values for the entire month of September, meaning that a very important piece of the puzzle is missing for much of the study period. Of course, this impairs my ability to draw any substantial conclusions.

Furthermore, other sensors also had their mishaps. First, the sensor at C7 was washed out by high flow during a heavy rain event at the end of August, meaning that the data between this event and the next visit on the 31st of August are unusable. Secondly, the same sensor once stopped working completely, which I only uncovered a month later, meaning that there is no data for the entirety of September at that location. That the sensor issue went undiscovered for so long is almost completely my own mistake for not visiting the catchment and checking on the sensors in September due to lack of rain. All other sensors malfunctioned also at least once, but usually for not as long a time as they stopped working only a few days before I went to the catchment again.

Additionally, the most severe issue encountered beside lack of data is unreasonable or simply unusable data. While weighing the filters with sediment after oven-drying, only three out of fourteen samples exhibited a positive weight difference, meaning that the other eleven were lighter with sediment than they were before. Since at least two of the three usable

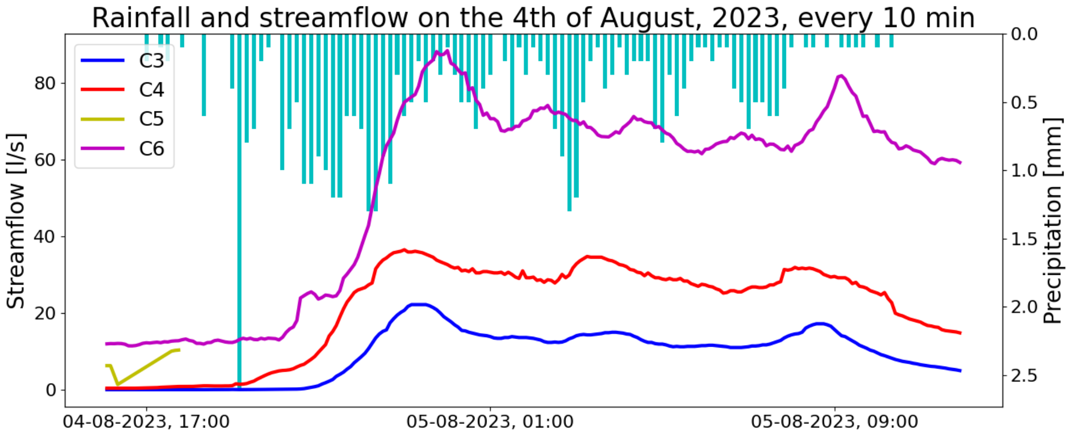

Fig. 6: Time series of streamflow and rainfall on the 4th of August. C7 will be missing in most graphs due to the described data issues.

samples and all others – which were set to have no sediment at all – formed a somewhat usable line, the data could still be partially salvaged (fig. 13). Nonetheless, the turbidity-SSC conversion needs to be treated with some caution as the data basis is dangerously slim.

Such unreasonable data was also recorded by the water level sensors in some cases. Since there was no easy way of repairing the data or interpolating anything useful, such data was usually simply ignored if it spanned over several hours. If only one or two values were missing, on the other hand, they were interpolated by calculating the averages of the values before and after the unreasonable (or missing) data. This was especially necessary around the times of data download which usually led to the missing of one or two intervals. Since water levels did not change much on the days of the visits, such simple interpolation can be deemed acceptable. The same procedure was applied to the turbidity sensors.

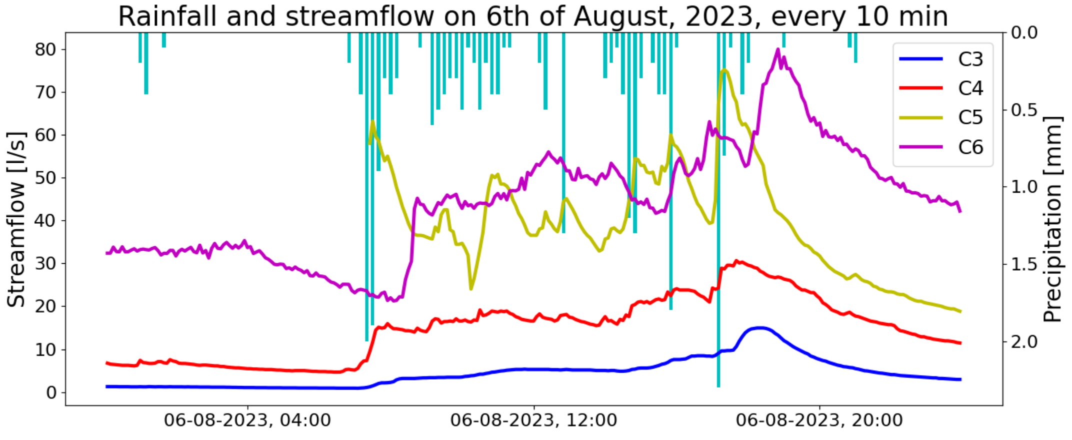

Fig. 7: Time series of streamflow and rainfall on the 6th of August.

4 Results

4.1 Streamflow

To start with, I need to emphasise that – for locations C3, C4 and C5 – I only looked at the streamflow values derived using the mean coefficients for the USBR method, as they lay usually closer to the measurement I took. Furthermore, the differences between using the mean coefficients and the location-specific ones were negligible. For instance, the difference between the means and medians of the USBR modified and USBR mean values ranged from less than 10 % to a maximum of close to 25 %. Even though the latter difference seems high, it must be kept in mind that this means a difference of, at most, a few decilitres per second.

4.1.1 C3

This location was characterised by generally low flow, with, at some times, virtually no flow at all. Although the mean flow was 1.1 l/s, the median flow lay clearly below, at 0.1 l/s. Looking at the data range which stretches from close to no flow at all to 52 l/s, it becomes evident why mean and median differ rather strongly: there are a few very high flow data points that pull the mean away from the huge majority of the data points. From the 26‘985 data entries a total of 22‘481 are lower than the arithmetic mean, amounting to 83 %. Thus, I tried to account for the uneven distribution of data over the range by disregarding the top and bottom 5 % each. However, the result was still a rather high mean of 0.4 l/s which led to 19‘873 values being lower than the mean, i.e. still 74 % lying below the mean. At the very least, this underlines even more strongly, how stark the variation can be. As for the behaviour of the streamflow over the entire study period, it behaved mostly in the way one would expect: Rather low variability on dry days, large, fast-rising spikes on rainy days with a longer receding curve after precipitation had passed. This

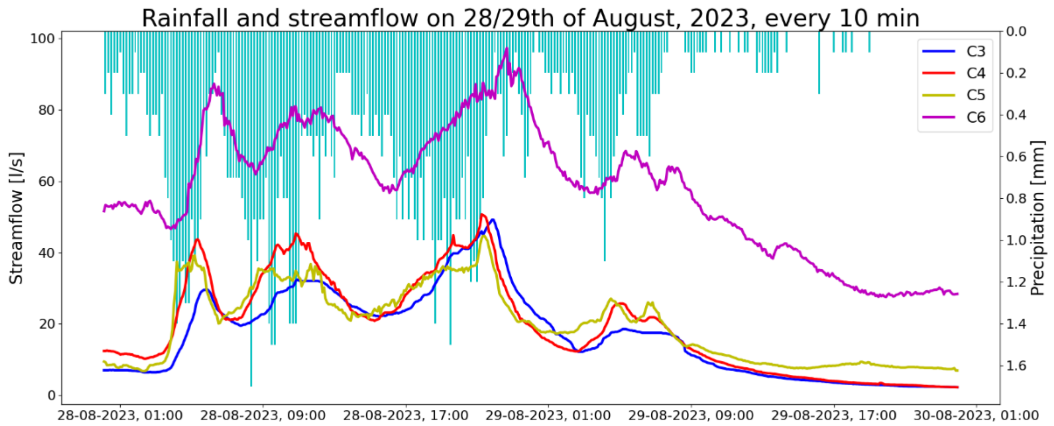

Fig. 8: Time series of rainfall and streamflow on August 28th and 29th 2023 for all sites, except C7 for which the streamflow was much higher.

Table 1: Peak streamflow and peak SSC values as well as their corresponding recording times. Missing or (probably) erroneous data is written in italics.

04.08.2023	**Peak Q [l/s]**	**Time of peak Q**	**Peak SSC [mg/l]**	**Time of peak SSC**
C3	22.2	23:10	69	22:20
C4	36.5	23:00	98	21:35
C5	no data	no data	no data	no data
C6	88.35	24:00	683	21:15
C7	300.1	23:45	2004	21:20
06.08.2023				
C3	14.9	18:15	45	18:15
C4	30.7	17:40	67	17:25
C5	75.3	17:25	690	17:05
C6	80.0	18:50	170	17:30
C7	305.0	19:40	*1018*	*20:20*
28.08.2023				
C3	49.2	21:55	107 (53)	05:45 (22:00)
C4	50.7	21:15	170 (260)	04:30 (21:25)
C5	44.6	21:20	794 (455)	04:15 (21:20)
C6	97.3	22:40	363 (167)	04:30 (21:20)
C7	552.4	22:50	*2353 (359)*	*02:25 (22:00)*
22.09.2023				
C3	6.5	07:20	66	05:30
C4	11.7	06:40	105	05:15
C5	26.6	05:05	790	08:45
C6	48.2	07:40	204	03:55
C7	246.9	07:35	no data	no data
21.10.2023				
C3	7.9	18:25	28	15:35
C4	12.2	18:25	48 (55)	14:20 (18:20)
C5	5.7	18:20	*no data*	*no data*

C6	23.2	19:45	87	14:05
C7	241.9	19:50	*no peak visible*	*no peak visible*
30.10.2023				
C3	11.5	23:20	81	23:20
C4	no data	no data	*no data*	*no data*
C5	17.5	22:20	*no data*	*no data*
C6	64.1	23:45	141	20:45
C7	321.0	24:00	*no peak visible*	*no peak visible*
14.11.2023 (1)				
C3	52	08:00		
C4	no data	no data		
C5	17.6	06:40		
C6	*no morning peak*	*no morning peak*		
C7	565.3	09:20		
14.11.2023 (2)				
C3	48.5	17:30		
C4	no data	no data		
C5	20.3	16:50		
C6	*27.3*	*14:40*		
C7	521.2	18:50		
15.11.2023				
C3	31.5	04:30		
C4	*no data*	*no data*		
C5	11.3	04:00		
C6	16.4	00:40		
C7	411.9	05:30		

effect is visible for all rain events recorded during the study period. A prime example for this behaviour is the high flow event on the 28th and 29th of August, when a strong rainfall caused water levels to rise (fig. 8). The stream's response time was only at about 01:40 h for the first rain input. For the other events, response times were not calculated, seeing as the water levels did not recede to baseflow in between, meaning that the actual response was diluted by the still enhanced streamflow. While the water level rose slowly in the beginning (from close to no flow to around 7 l/s), it spiked in the early morning hours of the 28th from under 10 l/s to 30 l/s. The largest spike reached 49 l/s. It then receded quickly, in less than 06:00 h, back to 12 l/s, but took then longer to abate further due to another small event. Only after approximately 4 hrs had the streamflow give or take reached back to lower levels. Still, it must be mentioned that the streamflow did not return completely to the baseflow before the event. Only after almost three days did it attain the low levels from before the event, albeit still slightly enhanced between 0.06 and 0.09 l/s, indicating a generally increased flow for the time being. Other high flow events were recorded on the 4th and 6th of August (fig. 6 and 7), with peaks at 22 l/s and 15 l/s, respectively. The response times for those two events lay at 04:00 h and 01:05 h. For the 4th, the receding time could not be calculated as another smaller event hit the next day. For that small event, the recession time was 04:00 h. For the 6th, on the other hand, the receding time was a little over 03:00 h, when streamflow stopped receding rapidly. In September, there were only small events leading to slightly more flow than usual, with peaks ranging from a little over 2 l/s on the 18th to over 6 l/s on the 22nd which responded in 04:40 h and receded over 04:00 h (fig. 9). In October, the weather became a little wetter, leading to more events with higher peaks. The highest value was recorded on the 30th, with a

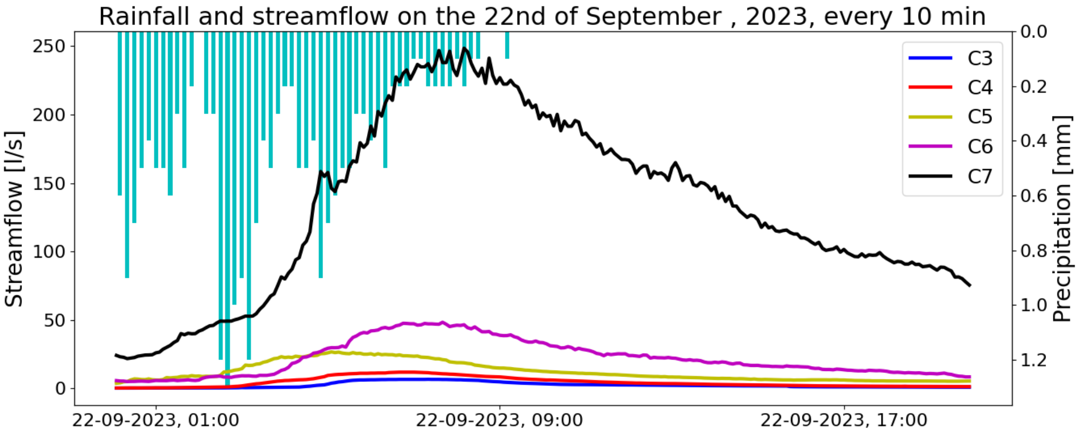

Fig. 9: Time series of rainfall and streamflow on the 22nd of September.

streamflow of 11.5 l/s and a response time of 01:30 h (fig. 11). For that event, the receding time was 06:00 h. The second larger event led to two peaks, the first on the 20th at 6 l/s and the second on the 21st at 7.9 l/s. For the latter event, the response time was 02:40 h, whereas the recession took 04:00 h. Still, there were some minor events in between with peaks at only a few litres per second. The highest flow registered in the middle of November (fig. 12), on the 14th, when streamflow reached the absolute maximum of almost 51.9 l/s. The recession time could not be extracted seeing as another event hit in the evening with a peak of 48.5 l/s. That peak's recession time can also not be estimated, seeing as several smaller events hit the next day. The response times, on the other hand, could be calculated, with 01:40 h for the morning event and 01:20 h for the one in the evening.

4.1.2 C4

Although the flow at this location seemed to be generally higher during my visits to the catchment, the statistics reveal values close to the ones seen at C3. The arithmetic mean of the streamflow lay at 1.5 l/s, while the median was much lower: 0.1 l/s. As with C3, the vast majority of values can be found below the arithmetic mean (20‘396 of 23‘440 recorded values, i.e. 87 %). By trimming the mean by 10 %, a new mean value of 0.5 l/s was found, reducing the count of values below mean to 18‘444 (= 79 %). The range of streamflow looked similar to the one found at C3: The lowest value was close to 0 l/s while the highest reached 50.7 l/s. The main difference to C3 was the location's behaviour during and after a rainfall event. Even though water levels still rose quickly on the 28th of August – comparable to C3 in speed and magnitude –, the water responded and receded faster. C4 attained its high flow 01:10 h after maximum rainfall and its baseflow after 05:00 h, before the next event hit. The behaviour in the next few days was comparable to C3, although C4 reached the very low flows almost a day earlier. Similarly, the baseflow remained increased after the event. While the consistent flow shortly before lay at around 0.07 l/s, it remained significantly higher afterwards, between 0.25 l/s and 0.4 l/s. These values are also clearly higher than the ones recorded at C3 after the rainfall event, indicating that the catchment area of C4 managed to store more water which it then released slowly after precipitation.

As for other events, the same ones as at C3 were recorded, except for the major one in the middle of November (fig. 12), since the sensor stopped recording beforehand. Interestingly, although the general behaviour is very similar to C3, the peak streamflow values differ greatly. For the two events on the 4th and the 6th of August

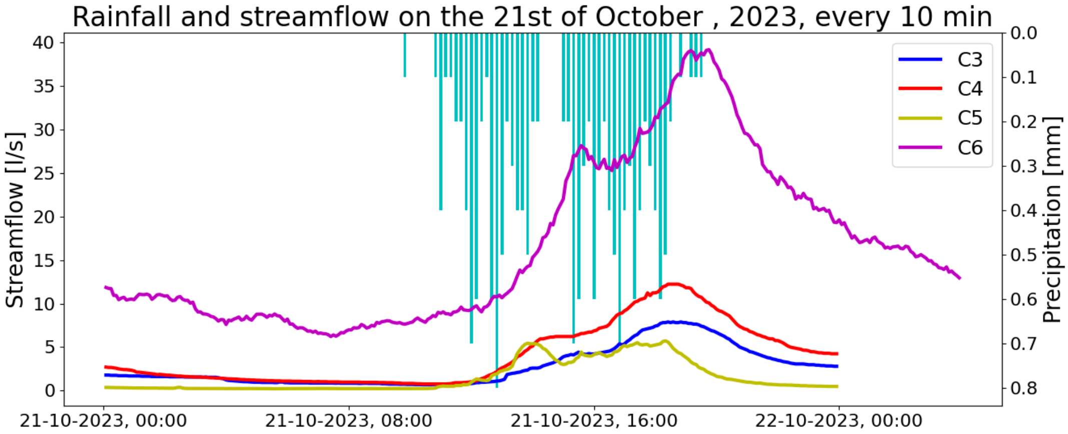

Fig. 10: Time series of rainfall and streamflow on the 21st of October.

(fig. 6 and 7), the peak streamflow values lay at 36.5 l/s and 30 l/s, respectively. On the 4th, the catchment reacted in 03:50 h, so slightly faster than C3, whereas on the 6th, the response time was 00:30 h and the receding time 03:30 h. Equally, the peak streamflow on the 22nd of September (fig. 9) was almost double to the 6.5 l/s at C3, with a value of 11.7 l/s. Response happened in 04:00 h and the recession took almost 03:00 h. The last event to have been recorded was the one on October 21st (fig. 10), when streamflow reached 12.2 l/s. Since the event consisted of two rain inputs in short consequence, the response time does not correspond to the event's absolute maximum, but to the first peak flow in the early afternoon, which was reached after 01:55 h. For the events on the 30th of October and 14th of November (fig. 11 and 12), data is sadly also missing as the sensor had malfunctioned during those events.

Comparing the times at which these peaks happened at the two locations close to each other, a rather clear temporal offset became visible. The maximum streamflow at C3 usually registered between 30 and 45 minutes later than at C4. Only the event on the 4th of August does not fit into the pattern as the offset was only 10 minutes then. Nevertheless, this can have two meanings: Firstly, that the rain simply moved from the southwest over the catchment, thus influencing C4's tributaries before it reached C3's. Secondly, it can mean that C4 simply reacts faster if one is to assume rain started in the entire catchment synchronously.

4.1.3 C5

Even though C5 lay much higher in the catchment, it exhibited significantly higher streamflow than the two other locations equipped with weirs. Its mean flow amounts to 2.6 l/s with a median at 1.3 l/s. Seeing as the mean is only twice the median – compared to fifteen times the median at C4 – less dispersion of data points could be assumed. This is further corroborated when

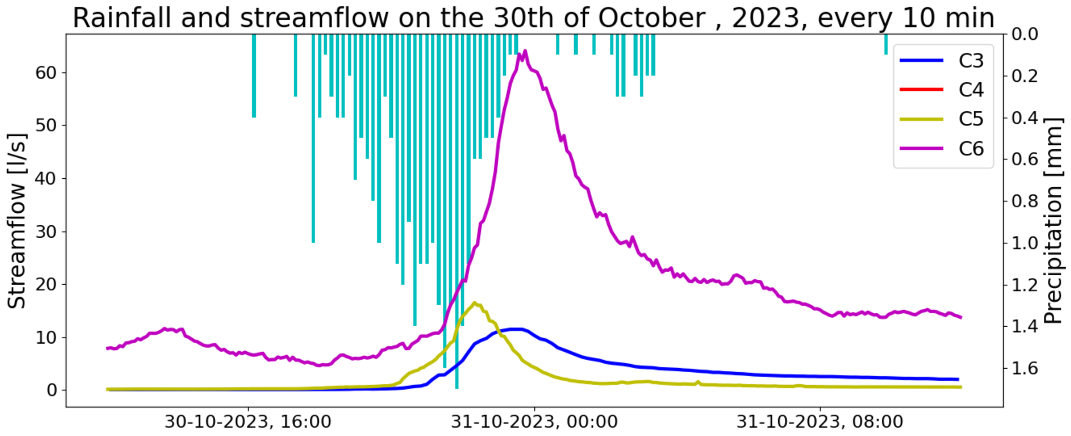

Fig. 11: Time series of rainfall and streamflow at the end of October.

looking at how many data points lie below the mean. Out of 26‘030 values, 20‘099 are lower than the mean, hence amounting to 77 % of values below average. Of course, this is still the vast majority, but in contrast to C3’s 83 % and C4’s 87 %, it is at least less. By trimming 10 % off the mean, a value of 1.7 l/s is found, reducing the number of values below the mean to 15 342 (= 59 %). The minimum value of 0.01 l/s coincides with the minima encountered at C3 and C4, whereas the maximum lies even higher at 75 l/s. These two values do not support the assumption that the values do not vary as much as at the other two locations with weirs. Rather, the flow is higher in general, which makes it take longer to dry out during rain-poor times. Thus, there are less values close to zero.

For the rainfall event on the 4th of August (fig. 6), data is sadly missing, as the sensor malfunctioned (probably due to the buffalo visible on fig. 5). For the 6th (fig. 7), a peak discharge of 75.3 l/s was recorded. The streamflow responded in only 00:10 h, then receded over the course of a little more than 05:00 h. As for the large event at the end of August (fig. 8), a peak of 44.6 l/s was measured. The recession cannot be estimated as another rain input halted it. The response time, in contrast, was 01:10 h. After said input, the streamflow abated in less than 06:00 h back to lower levels. For the 22nd of September (fig. 9), the peak discharge lay at 26.6 l/s, which was reached in 02:25 h and flowed through in 04:00 h. As for October 21st (fig. 10), the peak discharge registered at 5.7 l/s, with a response time of 01:00 h. For the event on October 30th (fig. 11), the peak discharge registered at 17.5 l/s with a response time of 00:30 h and a recession time of 01:30 h. The maximum discharge during the event in the morning of November 14th was 17.6 l/s, which was attained in 01:00 h (fig. 12). For the events in the afternoon and on the next day, response times lay at 00:40 h each. The peaks recorded were 20.3 l/s and 11.3 l7s,

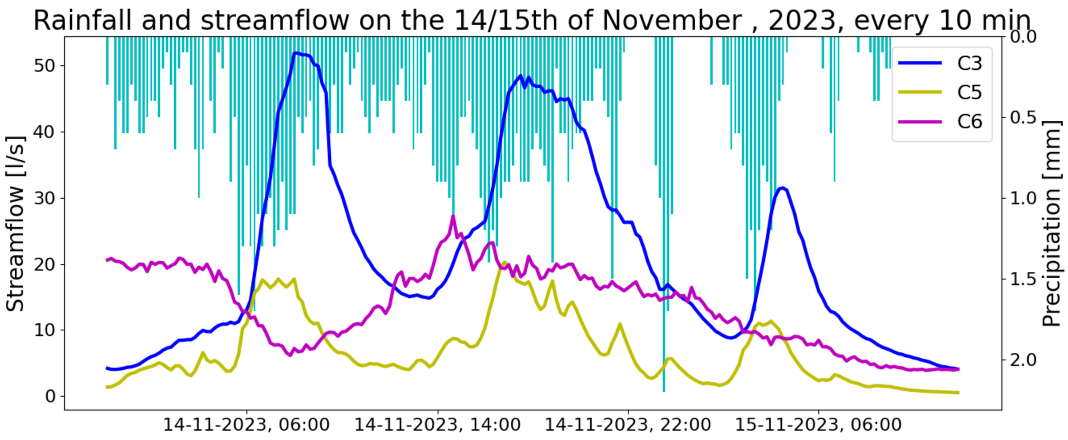

Fig. 12: Rainfall and streamflow on 14th/15th of November.

respectively. Due those two later events, recession time is impossible to estimate.

In comparison to C3 and C4, response times of C5 were generally shorter. Only on August 28th did the response times of C4 and C5 align. For all other events, C5 was at least 20 min (4th of August) earlier. For the 22nd of September it was even around 2 hrs earlier. However, seeing as all locations except for C5 have response times between 04:00 h and 05:30 h, it might also be a measurement or calculation issue instead of actual earlier response. Still, these observations implicate that the higher location generally reacts first. Furthermore, it nullifies the assumption made in the section about C4, namely that rain might have normally moved from the southwest, as C5 lies in the east of C4. On the other hand, values for C4 are missing for both the event at the end of October and the one in the middle of November, which might have helped corroborate any assumptions.

4.1.4 C6

C6 exhibited even higher flow rates than C5, with a mean flow of 11.3 l/s and a median of 7.1 l/s. As with C5, the number of values below average is lower than at C3 and C4, with only 73 % or 20‘955 out of 28‘873 values registering there. By trimming the mean the same way as before, this number is reduced to 64 % with a trimmed mean value of 9.2 l/s. Since mean and median are even closer together relatively speaking than the corresponding values at C5, more consistent flow can be assumed. This also coincides with the range that, albeit more widespread than at C5, does not encompass values that are close to no flow at all. The minimum flow recorded was 1.3 l/s, while the maximum reached 97.3 l/s.

The peak values on the 4th and the 6th of August lay at 88.4 l/s and 80.0 l/s, respectively, with response times of 04:50 h and 01:40 h (fig. 6 and 7). After the second event, the streamflow receded to base flow over the course of approximately 03:00 h. On the 28th (fig. 8), a peak streamflow of 97.3 l/s and a response time of 02:05 h registered. Again, its recession is somewhat diluted by smaller rain inputs afterwards, but the main part seems to have receded after 03:00 h. For the event on September 22nd (fig. 9), the peak lay at 48.2 l/s which took 05:00 h to be reached and almost 04:00 h to recede. October 21st exhibited a response time of 02:45 h which then led to a maximum discharge of 23.2 l/s and a recession time of 05:00 h (fig. 10). On the 30th of October (fig. 11), the maximum value recorded was 64.1 l/s with a response time of 01:55 h. That event’s recession took a little less than 03:00 h.

As for the month of November, the situation becomes inconsistent with the other locations. While C3 and C5 (C4 is missing data) exhibit clearly high flow events on the 14th, they show only small increases in flow in the days prior. C6, in contrast, shows large events starting in the night from the 9th to the 10th, which go up and down until they recede almost completely on the 14th, to increase again slightly around noon on the 14th. The peaks for the events on the 10th registered at close to 80 l/s, with another peak in the early hours of the 12th at a little under 70 l/s. The peak on the 14th was recorded – and that is even stranger – in the afternoon at 14:40 at 27.3 l/s. Compared to the other high flow events and the relationship between those values in contrast to the other locations, this peak is much lower and also late. However, it needs to be noted that the flow was increased around the time the other sensors registered their peaks on the 14th, it simply was not the highest flow C6 recorded on that day. Furthermore, another high flow event occurred on the 17th of November. Three peaks, each between 40 and 48 l/s, happened from shortly after noon until late in the evening. The last peak, reached on 20:20 h, receded rather slowly, over almost 08:00 h. Due to those inconsistencies, response times could not be confidently calculated.

Sadly, the response times that could be calculated do not exhibit a clear relationship to C3, C4 and C5. One might have expected the peaks at C6 to happen before the ones at C3 and C4, but after the ones at C5. Alas, C6 usually reacted second to last (only the outlet, C7, was even later). Sometimes it took C6 up to two and a half hours to reach the peak after C5 registered its own (as observed on the 22nd of September).

4.1.5 C7

Hardly surprisingly, C7, being the outlet, exhibited by far the highest flow rates compared to the other four locations. This becomes evident simply by looking at the mean flow of 62.7 l/s. This mean also seems comparatively representative for the entire study period as only 61 % (15‘163 out of 27‘724) of values lie below the average. By trimming by 10 %, a mean value of 54.7 l/s with 57 % below average is found. As can be seen, this is the only location where trimming the mean does only slightly increase the number of values above it, meaning the arithmetic mean is more representative for the entire data set than at other locations. The median flow value lay at 46.3 l/s. As for the range, there is a minimum value of 0 l/s and a maximum of 591.9 l/s. While the maximum sounds plausible, considering it is the entire catchment’s water that needs to move through that location, the minimum sounds too low. However, it is easily explained by insufficient data quality. As mentioned in the methods section, I had to work with an assumed offset of 7 cm for the water levels recorded by KELLER loggers (C6 and C7 are equipped with those). But since some values measured by the loggers were lower than those 7 cm, I had negative water levels in my corrected dataset. To avoid impossible negative flow values, I set them all to 0, i.e. no flow at all. Thus, the minimum flow was most likely very little flow, but due to my data processing was “corrected” to no flow. Therefore, I assume my minimum value to be wrong and suggest that it is ignored.

On the 4th and 6th of August, peaks of 300.1 l/s and 305.0 l/s were recorded, respectively, with response times of 04:35 h and 01:35 h. The second peak’s recession took over 04:00 h. For the major event on the 28th, the maximum value registered after 02:15 h at 552.4 l/s and then receded extremely quickly in a little over 01:00 h. The maximum value on the 22nd of September was drastically lower at only 249.9 l/s, while the response time was much longer at 05:30 h (fig. 9). That event’s recession cannot be extracted as another event hit in the late evening, thus diluting the receding flow. Still, the second peak of that minor follow-up event receded a little more slowly than the major August event, namely over 13:00 h. This slow recession was probably due to the release in stored water from the entire catchment, which would logically influence the outlet much more than the locations further upstream that are fed by much smaller catchment areas. The event on October 30th reached 321.0 l/s after 02:10 h and needed a little under 05:00 h to abate.

For November, the situation follows a similar pattern to C6: There are the same events as recorded at C3, C4 and C5, with two peaks on the 14th and one on the 15th. Of those, the largest reached 565.3 l/s in 03:20 h, while the second only attained 521.2 l/s in 00:40 h and receded in 04:30 h. The third, on November 15th, reached 411.9 l/s in 02:10 h. However, the increased flow already started on the 12th, which

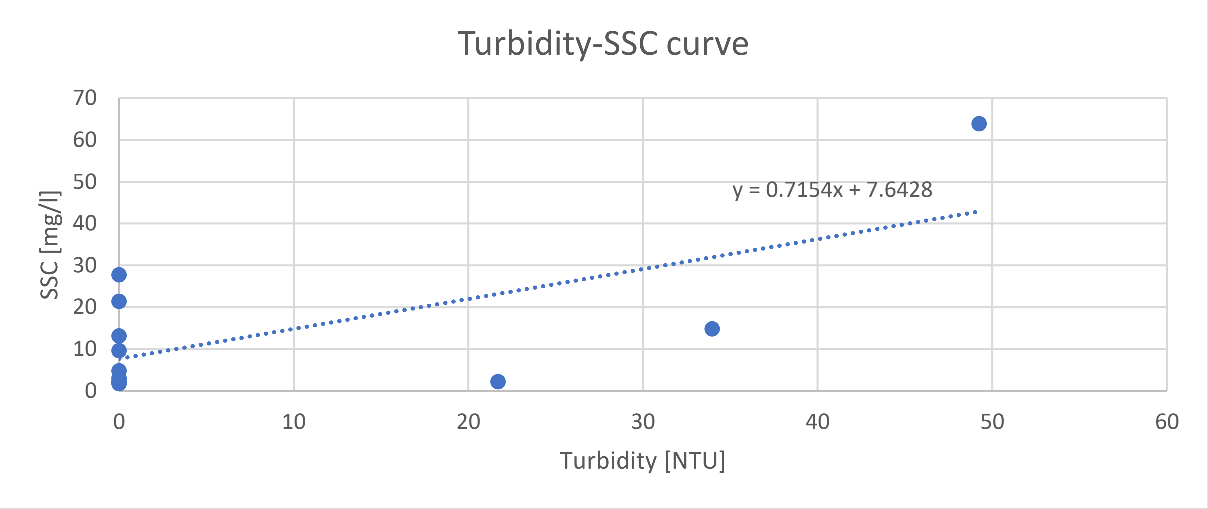

Fig. 13: Relationship between turbidity and SSC. As can be seen, the data basis is slim.

corresponds with a large reaction at C6 on that day. Interestingly though, the high flow registered at C6 on the 10th of November does not appear, or at least not very clearly, at C7. Seeing as the values recorded at C3, C5 and C6 (C4 was malfunctioning) do not even amount to a quarter of the water at the outlet, one must assume that there was either an input somewhere that did not flow through any single of my working sensors or that the value at one location must have been recorded wrongly. The most likely candidate would be C6, as it usually registered far higher flow rates than C5, which it strangely did not on the 14th of November. On the other hand, it is possible that the values at C7 are wrong, since I had to interpolate air pressure from two stations that were not located exactly on the same height as the sensor at C7.

As for the relationship of C7's response times to those of the other locations, they fit into the catchment's geography well. The peaks usually reached C7 the latest (exceptions: August 4th, when the response time of C6 was 15 min longer than C7's, and August 6th, when it was 5 min longer). Usually, the outlet registered maximum flow shortly after C6 did, indicating a strong influence of said location on the entire water flowing out of the catchment.

4.2 SSC

Using the water samples taken by the ISCO, the continuous turbidity measurements were transformed to SSC. The formula was derived from the trendline in fig. 13. However, the data basis is so slim that there is a considerable uncertainty.

The variation in suspended sediment concentrations was considerable. While there were values as low as only a few milligrams per litre, the highest recorded lay in the thousands. However, it needs to be noted that those maximum values are probably erroneous values. They stem from the sensor at C7 which I had, in the beginning, put at an unsuitable location full of bubbles, thus most likely distorting the values heavily. This is corroborated by the almost negligible variations in SSC during rainfall events after the sensor had been moved a little downstream into a small pond with almost no bubbles. Hence, I report C7's values before the relocation, but simply for completeness' sake. I strongly advise against using those values for anything else but underlining why turbidity sensors should not be put in bubble-rich locations. A similar issue might be present in C5's values. Although the location the sensor was put in after the buffalo shut it down the first time, it is possible that the second location was rich in bubbles as well. Judging from the imagery, the bubbles do not seem to reach the sensor all the time, but the water is rather turbulent all the same. In consequence, I deem that location's values to be more reasonable than C7's. Still, they should mainly be used to look at patterns than at numerical relationships. For that, their quality must be assumed to be too low.

As for the events recorded, I have data for the same events as in the streamflow section. Only the events in the middle of November are missing because I removed the sensors on November 12th, two days before the major event visible in my streamflow data.

4.2.1 C3

As with discharge, C3 exhibited the lowest values in SSC. The global minimum registered at 8.3 mg/l, whereas the global maximum reached 351 mg/l. On average, 14.9 mg/l were recorded. Seeing as the median was only at 10 mg/l, a rather uneven distribution of values must be assumed. The comparatively high maximum value underlines this further.

For the investigated high flow events, the following was observed: On August 4th, SSC rose synchronously with discharge. In contrast to discharge, however, it stopped rising much earlier and already started abating while water levels were still rising. After reaching the maximum of 69 mg/l, the levels receded to their pre-event state. Even the small discharge peak in the morning of August 5th did not lead to a new increase in SSC. In addition, even though streamflow stayed at around 10 l/s after the first rainfall (it was close to 0 beforehand), SSC remained extremely low, almost at the levels before the event. In short, it appears that a first surge in sediment was washed through the weir once the first rain had fallen, but then the sediment concentrations vanished almost completely. The next event on 6th of August displays almost the same pattern. After the first – small – increase in discharge, a slight elevation of SSC could be observed, but this receded almost immediately, even though discharge kept

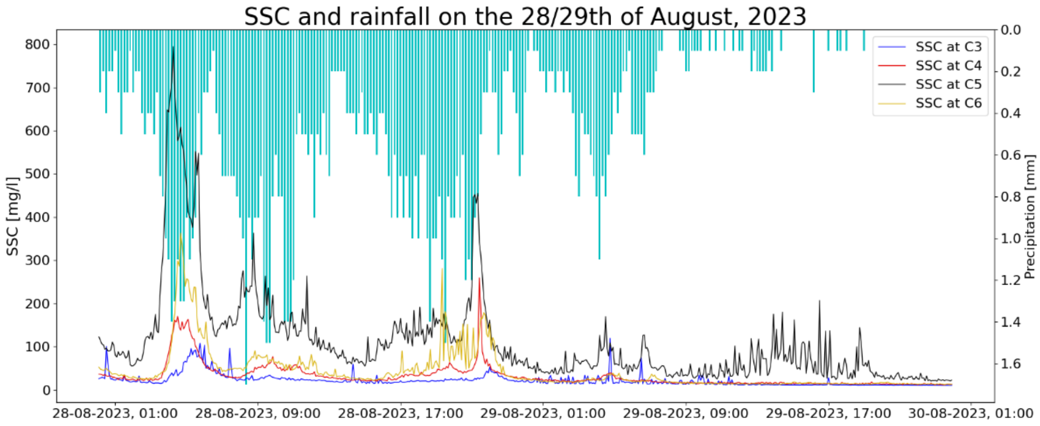

Fig. 14: Time series of SSC and rainfall for the major rain event at the end of August.

rising. Furthermore, in the evening, it took a rather strong and fast rising in streamflow to bring SSC to rise significantly as well. Still, the peak SSC only attained 45 mg/l. During the major event chain at the end of August, the situation becomes a little more dynamic. In the early hours of August 28th, the pattern follows the first two August events: SSC rises synchronously with discharge. In contrast to the other two events, it continues to rise until it reaches its peak at the same time as the discharge reaches its own. Afterwards, the pattern once again follows the first two events. SSC recedes (mostly) to its pre-event levels and only rises again when discharge increases enormously. However, even though the streamflow peak in the night from the 28th to the 29th was much higher than the one in the morning (fig. 14), SSC does not reach its peak levels from before. While it managed to climb to 107 mg/l in the early morning, it only became 53 mg/l in the late evening. In the early morning hours of August 29th, some small spikes in sediment concentrations were registered, but they were usually very short-lived and, except for two, did not reach the same levels as the major peak the day before.

The event on September 22nd displays the same pattern as the two events at the beginning of August. The SSC rises with streamflow, only to reach its peak before the discharge has stopped rising. Interestingly enough, SSC abates much more slowly than usually. This could be due to the plateau-like behaviour of the discharge. Usually, discharge attains its peak, then starts receding almost immediately, probably leading to deposition of sediment instead of further transport. However, this time, water levels remained on their peak levels for several hours, thus keeping more sediment in suspension than before and letting the SSC decrease more slowly.

On October 21st, C3's behaviour changes a little. Although SSC still rises with streamflow, it reaches its peak even earlier than on the other events. The maximum SSC of 28 mg/l registered while streamflow had not even reached half of its maximum. And SSC was back to around 20 mg/l when streamflow stopped increasing, almost five hours later. Also, the SSC peak was again rather short-lived, thus suggesting even further that sediment at that location is washed through in pulses. After a last short increase in SSC during the streamflow's peak, both values recede in sync. The event at the end of October displays behaviour not seen during the others. Usually, we saw an increase in SSC during rising water levels and then already a decrease while streamflow was still increasing. This time, however, SSC does not reach its peak well after streamflow had receded back to baseflow. The only connection visible between streamflow and SSC is the latter's fastest part of increase during the streamflow's rising limb. But then, even though streamflow recedes quickly, SSC continues rising – after a short plateauing – until it even exceeds the peak at around midnight of October 30th/31st. Thus, the peak of 81 mg/l recorded at 23:20 h on October 30th is not the maximum value recorded during those days. Nevertheless, I want to mention that SSC continued to rise for the next few days until the sensor suddenly stopped recording in the morning of November 2nd. Since there was almost no rain following the last two days of October, this seems rather unreasonable and leads me to believe the sensor started malfunctioning during that last recorded event. It could also be that the sensor, being placed inside the weir, was covered by sediment, thus recording values that are too high. In consequence, I discourage from using the data from after October 30th.

4.2.2 C4

C4 exhibited similar behaviour to C3. Additionally, the minimum (8.63 mg/l) and the mean (15.72 mg/l) are close to the values observed at C3. The median of 10.32 mg/l is almost exactly the same. The only large difference can be seen in the maximum, which lay at 942 mg/l.

On August 4th, a maximum SSC of 98 mg/l was recorded. When comparing it to C3, the value is about 50 % higher and it was registered 45 min before the peak at C3, indicating that C4 reacted slightly faster. This aligns perfectly with the behaviour already seen when investigating streamflow. As for the relationship between discharge and SSC, it compares to C3 nicely. SSC rises quickly with increasing streamflow, but it reaches its maximum and starts receding again long before the streamflow maximum is reached. There is, however, an interesting difference to C3 on that day. While C3's SSC remained on its pre-event levels even though streamflow stayed enhanced and even increased again slightly on the next day, C4 displays different behaviour: Like C3, streamflow remained at higher levels and exhibited two slight peaks in the early morning of August 5th, but contrastingly to C3, SSC also increased again after it had receded almost back to its pre-event levels late in the evening on August 4th. It appears that C4 experienced not one, but two sediment pulses during that event. On August 6th, on the other hand, the pattern we observe is the same as for C3. SSC levels increase, with a little delay, when discharge increases, only to decrease again before streamflow has even reached its peak. Contrarily to the first event, the second streamflow peak in the evening did only lead to a very small increase in SSC and not to a large peak like it did a day prior.

On August 28th/29th (fig. 14), we find a more varied situation. Whereas streamflow displays three rather large peaks on August 28th and a minor one on the 29th, SSC only exhibits two major peaks – the first in the early morning of the 28th and the second one late in the evening. The other two streamflow peaks (one around noon on the 28th and the other in the morning on the 29th) managed to increase SSC only slightly. The maximum values recorded during that event were much higher than before, with 170 mg/l during the morning input and 260 mg/l in the evening. Once again, the peaks both reached C4 before they reached C3. The difference was 1:15 h in the morning and 0:35 h in the evening.

C4's behaviour on September 22nd does not differ greatly from C3's. The only difference is the magnitude – a maximum of 105 mg/l was recorded – and the timing. While C3's peak registered at 05:30 h, C4's happened slightly earlier, at 05:15 h. Also, like C3, the SSC receded much more slowly than it did during other events, most likely due to the plateau-like behaviour of streamflow, with a much flatter rising and receding limb.

The event on the 21st of October exhibits the most striking differences to all other events. In contrast to C3, there were two major SSC peaks, the first of which happened 1:15 h before C3's and attained a level of 48 mg/l. The second peak registered at 55 mg/l, exactly four hours later. It coincides with the maximum streamflow. So, while C3's SSC was tendentially already receding again when the discharge reached its maximum, C4 had two maxima, one of which happened at the same time as the maximum streamflow. Hence, they seem to be more closely tied to each other than at C3.

For the event on October 30th, data is sadly missing as the sensor had started malfunctioning.

4.2.3 C5

C5 exhibited rather erratic behaviour, most likely linked to the probably not ideal location I put it in. Thus, all information concerning that location must be approached with caution. Nevertheless, I believe general patterns to be extractable, even though there might be much noise in the data. For the general characteristics of the data, I found a mean of 44.4 mg/l, while the median lay at only 16.9 mg/l. Seeing as the minimum was similar to C3's and C4's at 9.3 mg/l, while the maximum reached unreasonable levels of 1736.5 mg/l, one can easily see why mean and median differ so greatly. Due to the immense range recorded by the sensor, I suggest that one should use the median to assess the data distribution instead of the mean. This becomes even clearer when trimming 10 % of the data and then calculating the mean. This way, the mean is lowered to only 26.8 mg/l.

Since much data is missing for C5, its general behaviour is difficult to assess. For instance, the two events at the end of October lack any data, and for the 4th of August, I only have data until around 6 pm, before the rainfall hit. However, some small indication to C5's behaviour on the 4th can still be seen. Streamflow was in the process of rising when the sensor stopped working, and the same can be said for SSC. Just like C3 and C4, the SSC had also started receding slightly, even though streamflow levels were still rising, just not as fast as before. Considering this, I assume that C5 would behave similarly like C3 and C4 during that event. For August 6th, luckily, data was recorded. Peak SSC reached 690 mg/l at 17:05 h, thus 20 min before C4 and over an hour before C3 reached their peaks. When comparing the SSC's behaviour at C5 to C3 and C4, one can easily see its more erratic behaviour. Seeing as the streamflow was also much more dynamic during that event than it was at the other two locations with weirs, this is hardly surprising. The main difference to C3 and C4 is the close link between rising/falling streamflow and rising/falling SSC. When discharge increases, so does SSC, almost immediately. They appear to be much more closely related than at the other two locations. The only similarity to those two is the fast reaction of SSC to changes in discharge. As soon as the latter starts decreasing, the former decreases as well, usually even faster.

During the event at the end of August (fig. 14), the same pattern is visible. Each small increase or decrease in streamflow leads to an immediate and more pronounced reaction in SSC. Maximum SSC of 794 mg/l was attained at 04:15 h, 15 min before the peak at C4 and 1:30 h before the peak at C3. The second peak in the evening visible at C3 and C4 is also apparent here, with a value of 455 mg/l at 21:20 h, thus only 0:05 h before C4 and 0:40 h before C3. It appears that the event in the evening led to less delay between the three locations. Since I do not have any information on where the rain came from, I cannot assess whether that might have had an influence.

The last event I have data for at C5 is the one on September 22nd. Then, a maximum SSC of 790 mg/l was recorded, but over three hours after the peaks at C3 and C4 were registered. Also, when comparing SSC to streamflow, one sees that, in contrast to all other events, the SSC only rose after discharge had already started receding again. I must admit that I cannot explain this outcome. I checked the timestamps of the different sensors and did not find any time issues that would clarify this discrepancy. The only explanation that comes to my mind is that the weir was cleared before this event and thus retained more sediment than it would normally do. But seeing as the weirs at C3 and C4 are usually rather empty, as well, that does not seem entirely plausible.

4.2.4 C6

C6 moved in a similar range of values as C4. Its mean was a little higher, 18.9 mg/l, and the same goes for the median at 12.9 mg/l. The global minimum was also slightly higher with 9.8 mg/l, whereas the maximum almost 50 % lower at 682.7 mg/l. The overall behaviour of C6 is characterised by a generally more pronounced dynamic than both C3 and C4, but less so than C5. It also depends on the intensity of the rainfall causing changes in SSC.

For instance, on the 4th of August, the SSC peak was much higher (683 mg/l) than on the 6th (170 mg/l). What was similar between those events, on the other hand, was the quick response of SSC to increased streamflow. As with the other locations, the rising of SSC coincides with the rising in streamflow, but the peak is reached and the recession begins long before the discharge is even close to its peak. Especially on the 4th, SSC has already fallen almost completely back to its pre-event levels while streamflow is at its maximum. Even the heightened water levels persisting until later on the 5th did not incite another significant sediment response. Only small peaks (< 50 mg/l) are visible for the 5th, even though discharge remained at far over 60 l/s (compared to almost no flow before the event). Over the course of the 5th, SSC recedes to very low levels, before it increases again in the early morning of the 6th, although much less intensely than on the 4th. This is rather surprising, considering that the streamflow levels are only marginally lower than two days prior. Only the rapid increase in streamflow around 8 am seems to have eroded enough sediment to visibly increase SSC for a short time. The rest of the day, only small variations in SSC can be seen, usually shortly after water levels have started increasing again. The last larger peak, almost on the same level as the one in the morning, registered during the second-to-last streamflow peak’s recession. Interestingly, the last peak’s rising limb does not seem to have incited another increase in SSC, but only managed to slow the last SSC peak’s recession. The peaks’ timestamps fall in line with the ones at C4, happening usually around the same time or only shortly later. The time lag of C3 to C6 lies between 0:45 h and 1:05 h. As with the other locations, the event on the 28th and 29th of August stands out (fig. 14). While the discharge exhibits at least three major peaks and a minor one in the early morning of the 29th, SSC only displays two major peaks that coincide with the first and third streamflow peak, which also happen to be the maximum discharge levels of the event. The intermediate peak in between the two largest ones did incite a response in SSC, but only a very small one with SSC levels around 100 mg/l. The maximum values for the other two peaks are 363 mg/l and 167 mg/l, respectively. The minor increase in streamflow during the largest peak’s receding limb on the 29th did not lead to a significant response in SSC. It only increased slightly. When comparing the timestamps of the SSC maxima, one can see that C6’s maxima usually coincide temporally with the ones at C4 and C5. The time differences move between 0 min and 15 min. Only C3 seems to be reached by the sediment clearly after all the others.

Unsurprisingly, the September event is the least dynamic one. Streamflow exhibits only one large peak which leads to a single response in SSC. This response reaches its maximum long before streamflow does and has already almost completely receded once the streamflow starts decreasing again. However, SSC did not decrease consistently during that event. While it started going back down after its maximum, it increased once again for a short time once streamflow was close to its own maximum. Afterwards both decreased quite consistently. The peak SSC registered was 204 mg/l, recorded long before the other locations. The closest one was C4, which still recorded 1:20 h later than C6.

On October 21st, C6’s behaviour remained the same. Just when discharge starts increasing, SSC rises extremely fast and reaches its maximum of 87 mg/l even before streamflow levels have accomplished half of their increase. After that, SSC abates almost immediately, but not entirely. Since streamflow starts decreasing for a very short time before increasing once more and even further, SSC also increases again, although only slightly, to about 40 mg/l. After that, SSC recedes noisily while streamflow does as well. When looking at the timestamps, a difference to before is unveiled. Before, C6 reached its peaks usually at about the same time as C4 or even a little later. This time, in contrast, C6 is the first to get to its peak (for C5, there is sadly no data, and C7 does not exhibit any peaks worthy of mention), although only by 0:15 h. For October 30th, a timestamp comparison is not possible as I only have values from C3 and C6. Still, the peak on the 30th of 141 mg/l happened 2:35 h before the one at C3. In addition, it is interesting to notice that SSC seems to have concluded most of its rise before streamflow rising has even really picked up its speed. SSC has already receded to about half of its maximum when streamflow levels were at about their own peak's half. In contrast to other events mentioned, the streamflow's peak did not incite a new response of SSC. Seeing as the maximum discharge was only attained for a very short period, this does not come as a huge surprise.

4.2.5 C7

C7's behaviour can best be described as noisy, at least up until the point where I moved the sensor to a less bubbly location. Thus, the information for the events in August must be approached with care. At least the patterns align with the ones seen at the other four locations. C7's statistics underline this further. While the minimum is the lowest of all five locations (7.7 mg/l), the maximum goes far beyond anything even C5 recorded: 3'615.6 mg/l. Also, the mean lies at 48.3 mg/l, while the median is only 10.1 mg/l, indicating even further how dispersed the values are.

For the 4th of August, a peak SSC of 2004 mg/l was recorded. Seeing as this happened *before* the peaks at both C3 and C4, which contribute at least a considerable part of the water flowing to the outlet, this seems rather unreasonable. Still, the major part of the SSC increase happened, as we have seen many times now, mostly before streamflow was at its highest. Once discharge levelled out at around 250–300 l/s, SSC had already receded back to values between close to 0 and approx. 300 mg/l. Only in the morning of the 5th of August did SSC increase again to close to 1000 mg/l. For the 6th of August, the data become even more noisy. It spikes, usually for a single data point, to values sometimes over 1'200 mg/l, only to fall back down to below 100 mg/l. The evening peak present at the locations upstream is also visible here, at 1'018 mg/l recorded at 20:20 h, more than 2:00 h after C3 and more than 3:00 h after C5. A pattern cannot be extracted here as the data is simply too noisy.

The situation does not ameliorate for the end August event (fig. 14). At least, it shows that SSC once again increases mainly before streamflow reaches its highest levels. The overall peak was reached at 02:25 h – almost 2:00 h *before* C5 – with a value of 2'353 mg/l. The evening peak was much

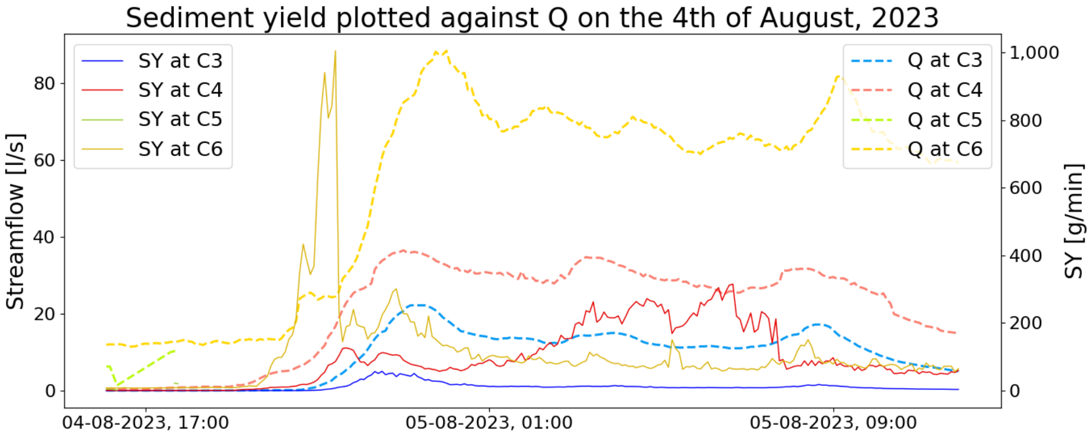

Fig. 15: SY plotted against Q on the 4th/5th of August.

lower, at 359 mg/l and happened at the same time as the one at C3, but around 0:40 h later than the other locations' maxima.

For the September event, data is sadly missing.

In October, the sensor had already been moved to a more suitable location, leading to vastly different results as before. Now, SSC rarely exceeded 20 mg/l. Even during the event on the 21st of October, the peak lay at only 18 mg/l. Interestingly, this happened long before streamflow even started increasing and the other locations got to their maxima. Only the large increase in streamflow in the evening led to another increase in SSC, albeit for a very short time and much less pronounced than before (around 16 mg/l). It looks similar on the 30th of October. Although SSC increases slightly with heightened streamflow, it does not do so even closely as much as the SSC at other locations. The peak was even lower than on the 21st, it did not even reach 15 mg/l. The question now remains, if the values from the bubbly location are entirely wrong or if these low values are wrong as well. Meaning the truth would lie somewhere in the middle. There are some streams flowing into the outlet which were not equipped with sensors. Because of this, I cannot accurately assess whether they might have brought the vast amounts of sediment suggested by the earlier values. It could also be that they transported large amounts of almost clear water necessary for the lower values in the end.

4.3 Sediment yield

First of all, since sediment yield is time-dependent, its values are always reported 5-minute steps. Since the streamflow sensors at some point were put to 10-minute intervals, those values are simply halved to receive the average 5-minute values. For C4 and C5, there are no 10-minute values since the turbidity sensors stopped working before the water level ones were programmed to 10-minute intervals. When looking at fig. 15, it becomes evident that sediment yield does not seem to follow streamflow as nicely as one would expect. This remained so for most of the other events as well.

4.3.1 C3

In contrast to the above statement, on August 4th, C3's sediment yield seems to have depended more on streamflow than on the SSC. This becomes evident when looking at the delay in sediment yield compared to SSC. The former reaches its peak just as the latter starts decreasing again. When looking at the streamflow, it becomes clear why. Streamflow rises quickly and strongly, thus transporting more sediment even though the SSC is already decreasing. The large spike in the waning hours of August 4th and the early hours of August 5th transported approximately 7.7 kg of suspended sediment. A similar value of 6.5 kg can be found for the event on the 6th of August (fig. 16). Although the sediment yield is generally lower, the event lasted longer and thus still achieved similar amount of transported sediment. In contrast to the first event, sediment yield now nicely follows the SSC, although somewhat diluted and much less pronounced. On August 28th/29th (fig. 17), this becomes even more visible. Sediment yield looks like an almost exact mirror image of SSC, simply a little bit lower with less shard spikes. During those days, 78.4 kg of suspended sediment were transported through the weir. Due to the only short pauses between separate events, it is hard to extract single events. Still, the major spike in the morning of August 28th transported 19.1 kg in only five hours. Since streamflow was not that variable on those two days (at least for the most part), there is almost no disturbance of the SSC pattern in the sediment yield data visible.

On the 22nd of September, this changes slightly. Since streamflow does not start rising before 04:25, sediment yield also remains very low despite SSC tendentially rising since midnight. Only when streamflow – and SSC – pick up fast, so does sediment yield. It increases quickly and then recedes very slowly. The graph reminds heavily of a storm flow graph with steep rising and flat receding limb. Since C3's discharge on that day looks quite nicely like such a graph, it is not surprising that SSC and sediment yield follow this pattern as well. The event transported 4.2 kg of suspended sediment over the course of almost 16 h.

On the 21st of October, discharge seems to have more of an influence than usually. Although sediment yield still follows SSC, the spikes are sometimes almost invisible (cf. around noon) and those that are, are vastly less pronounced. Still, the suspended sediment transported amounted to 3.3 kg over the span of 12 h. On October 30th, it becomes increasingly difficult to estimate the amount of sediment transported due to the inconsistencies in the SSC values already reported. Thus, I only describe the general characteristics of the event's rising limb. In contrast to the other October event, the sediment yield now again follows the SSC almost perfectly and mirrors its rising and lowering in sync. Only after the major part of the event is over, when the turbidity and thus the SSC data becomes unreasonable does the sediment yield seemingly decouple from the SSC, most likely because of the almost non-existent streamflow.

4.3.2 C4

In general, C4's sediment yield follows its SSC even better than C3's. However, I also only have five events to look at, the one on 30th of October sadly lacks data from C4. For August 4th, that location transported 112.3 kg of suspended sediment in half a day. The major part of the transport actually happened after midnight on the 5th, when SSC reached its maximum and thus also the sediment yield. On the 6th (fig. 16), on the other hand, "only" 58.6 kg were transported in two large spikes, the first of which does not appear visibly at C3. This aligns with the behaviour of discharge on that day. While C3's streamflow did not increase significantly before noon, C4 exhibited already a strong increase in the early morning, hence probably eroding more sediment. C4's behaviour on the 28th/29th does not differ greatly from the other two events (fig. 17). The only main difference is the amount of sediment transported, which lay at 138.2 kg from midnight 27th/28th to 9 am on the 29th.

As with C3, the 22nd of September shows some interesting differences to the August events. Namely, the sediment yield's rising limb does not follow exactly the pattern of SSC, which rises quickly, decreases a little, then increases swiftly to its peak. Sediment yield, in contrast, only levels out shortly during its rise. This is linked to the streamflow which increases more or less undisturbed. In short, the sediment yield still does follow SSC, but with some interference from streamflow. Afterwards, it starts mirroring the concentration again. During this event, the stream transported a total of 12.7 kg in 15 h.

On October 21st, the erratic behaviour of SSC led to some erratic data in sediment yield as well, but not as pronounced as the SSC because of streamflow's more consistent nature. During that event, around 8.8 kg of sediment were transported during the main spike in sediment yield, so, much less than during all other events.

4.3.3 C5

Sadly, for C5, there is only usable data for the event on the 6th (only starting from

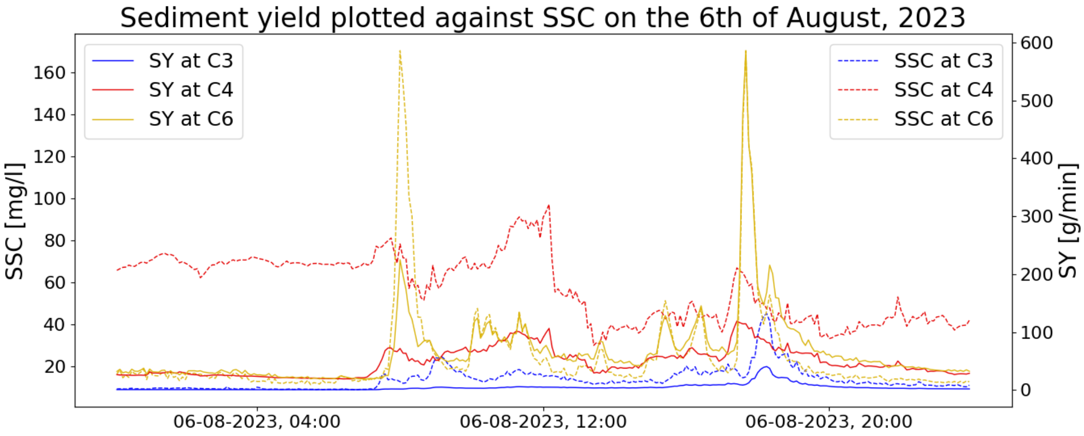

Fig. 16: Sediment yield plotted against SSC on the 6th of August.

07:25, fig. 16)), the 28th/29th of August (fig. 17) and for the 22nd of September. Still, some general observations can be made. First of all, C5 exhibits much stronger variation than both C4 and C3. Since this remains even after moving the sensor out from buffalo territory, I assume this to be true and not based on erroneous measurements, although the bubble situation might have increased noise in the data. As for the relationship between SSC and sediment yield, it appears to be the same as for C4, meaning that sediment yield almost perfectly mirrors SSC's behaviour.

This can be seen best on the 6th of August, where SSC and sediment yield are often almost indistinguishable from each other. This leads to a sediment transport of 162 kg for that event. Although I first thought this value to be unbelievably much, seeing as the weir is full of sediment after each single rain event, it is possible. Of course, due to the rather thin data basis of my turbidity-SSC conversion, there is considerable uncertainty. For the event at the end of August, the amount of sediment was even larger, namely 489.7 kg over the span of one and a half days. The largest spike in sediment transport in the morning hours of August 28th brought down 149 kg on its own.

On September 22nd, the amount of sediment transported was only 77 kg because, firstly, the event did not last for as long as the one before and, secondly, both SSC and discharge were at lower levels.

It is telling that this location, even though it is not the one with the most streamflow, seems to transport the largest amounts of sediment. The high values in SSC have already hinted at that. Considering C5 lies close to a recent and not yet overgrown landslide, this was to be expected.

4.3.4 C6

C6 generally exhibits lower or similar sediment yield values as C5. The main difference is the less extreme variation.

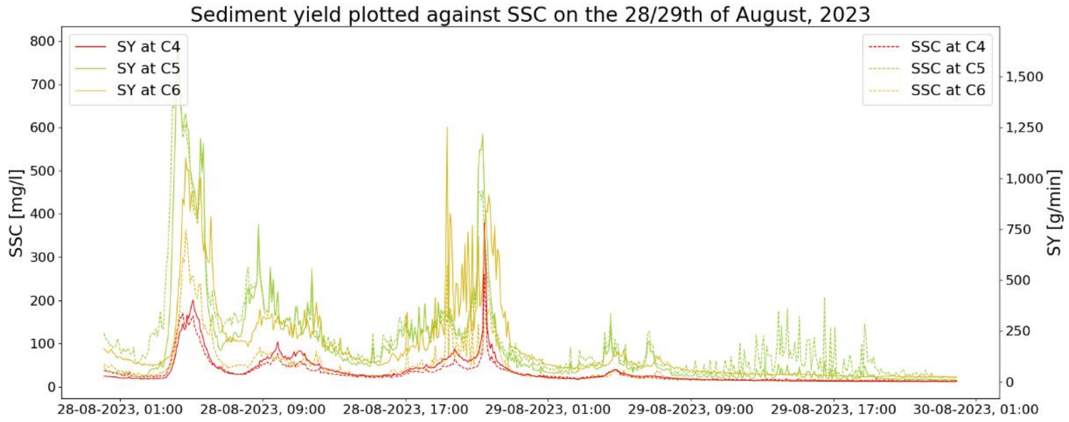

Fig. 17: Sediment yield plotted against SSC at the end of August.

On the 4th and 5th of August, for example, there is one major and some minor peaks in sediment yield, but the rest in between remains rather constant. As such, of the approximately 122.1 kg of sediment transported during that event, 51.8 kg came down only in the spike in the evening of August 4th. This supports my assumption that the sediment seems to move in pulses because, although rain peaked during that sediment yield maximum, it was generally rather consistent for the rest of day. On the 6th of August (fig. 16), 81.2 kg of sediment were transported over 16 h. There were two major spikes, both of which did not dominate the sediment yield as much as the maximum on August 4th, because they usually only lasted for a very short time (i.e., one single value, which might also be an outlier). In general, the sediment yield displays much variation on that day, which is explained by the highly variable SSC. This continues on to the end of August (fig. 17), where highly variable SSC leads to highly variable sediment yield. However, the peaks are now longer-lasting and thus dominate the sediment yield more. To a total of 450.4 kg of sediment transported, the first spike contributed 135.5 kg and the second one 146.2 kg. So, together they amount to almost two thirds of this event's entire sediment load.

The single-input nature of the September 22nd event again led to a rather simple behaviour in sediment yield. It reacts in a delayed manner to SSC, meaning it is influenced by streamflow rising slightly after SSC. In total, 63.6 kg of sediment were transported. The graph has, just like the streamflow on that day, a steep rising limb and a rather slowly falling receding limb.

For the 21st of October, the plot looks similar, albeit with two peaks, thus diluting the first peak's receding limb. In total, 30.1 kg of suspended sediment were transported. On October 30th/31st, it were 42.3 kg in one single spike. The interesting here is the rather steep receding limb, giving the sediment yield a symmetric look. Only close to baseflow does the receding limb start to really flatten out. Seeing as streamflow did not exhibit a strong reaction to that day's rainfall, but SSC did, this explains why the sediment yield fell so quickly.

4.3.5 C7

For C7, there is information for the events in August and the ones in October. Expect huge differences between the first three and the latter two because of the turbidity sensor's relocation to a less bubbly location.

Even though streamflow shows not much noise on the 4th and 5th of August, SSC and thus sediment yield do. They both jump from very high to rather low values in just a few minutes. Thus, extraction of single spikes is hard to accomplish with any certainty. However, I can say how much sediment seems to have been transported: 5164 kg. Although it might be possible for the outlet to move over five tons of suspended sediment along over the course of half a day, but it seems quite implausible. The data becomes even more noisy on the 6th of August. Generally, sediment yield seems less variable than SSC, since discharge somewhat counters the SSC's erratic behaviour. In total, 4626 kg of suspended sediment were transported. On August 28th/29th, the values become entirely unrealistic. According to the data, over 9000 t of suspended sediment were transported over one and a half days. I do not think I need to explain why that is implausible.

For the October events, sediment yield values become much more reasonable. The spike on October 21st and the early hours of October 22nd transported 114.7 kg of suspended sediment, thus aligning much more nicely with the sediment yields recorded at C3 and C4. Also, this event is the first to show clearly how much higher sediment yield generally is at the outlet due to higher streamflow. Although SSC is similar to other locations during normal or low flow, sediment yield is much higher at around 300 g/5 min. As for October 30th and 31st, a total of 113.7 kg of suspended sediment was transported. For the first time for C7, a clear, steep rising limb and a slowly falling receding limb are visible. On October 21st, the rising limb was not that steep because of only slowly rising streamflow.

5 Discussion

The main goal of this study was to investigate the behaviour of sediment transport in a small mountain stream, because the high variability in such catchments means that inferring information from neighbouring catchments might not yield accurate results.

5.1 Response time of SSC

5.1.1 Temporal variability

First of all, it is important to note that for rainfall to incite a sediment response, that rainfall needs to create runoff. As that requires the rainfall to exceed the soil's storage capacity and / or its infiltration capacity, a certain threshold of intensity and / or rainfall duration must be exceeded (Dugan et al., 2009). Since I did not investigate either of those factors, I can only rely on assumptions and earlier work, which was mainly conducted in the neighbouring Erlenbach catchment, hoping that that catchment's characteristics match up with the Studibach's. As already mentioned in the introduction, the soil was usually very wet, leading me to believe that soil storage was, for the most time, rather full. This lines up with the fact that the water table in the Erlenbach catchment is usually close to the surface, thus creating a generally wet environment that lets precipitation quickly contribute to runoff (Van Meerveld et al., 2018). This factor is important to keep in mind when looking at the response times calculated (tables 4 and 5 in the appendix). It is striking that the SSC responded much more slowly on the 4th and 28th of August (in the evening) and on the 22nd of September than during all other events. While response times for locations like C5 and C6 usually registered at under 30 min, even they took several hours to react on the aforementioned days. For the 4th, this can be easily explained by the lack of substantial rain in the days prior to the event. There was some rain, especially on the 2nd of August, but not much. Seeing as it was also mostly dry on the last day of July and that the soil storage in the Erlenbach and, thus, likely also in the Studibach catchment, is low (Van Meerveld et al., 2018), the storage empties quickly. This then leads to a storage deficit that first needs to be filled before rainfall can contribute to streamflow and, in consequence, increase erosive capacity, which would then cause the rising in SSC. Similar reasons can be put forward for the catchment's slow reaction in September, considering it did not rain in the two days prior and even the rain on the 19th was only little. The last significant rainfall had happened on the 18th, before which only short precipitation events happened. Thus, soil storage was probably rather empty and needed to be filled first before the rain could contribute to streamflow. Of course, had the intensity been high enough to completely exceed the soil's infiltration capacity, discharge would still have increased more quickly. This can be seen nicely during the two events on August 6th. Rainfall was rather intense (and soil storage can be assumed to have been satisfied as it had also rained on the 5th), thus almost immediately increasing streamflow and, in turn, the amount of sediment in the streams. The evening event on the 28th, however, does not fit into this reasoning. While the morning and the afternoon event both led to quick reactions due to long-lasting and intense rainfall, the evening precipitation took much longer to lead to a sediment response. Several studies have reported that not all sections of the catchment are connected to each other at all times, depending on the flow conditions (Kiewiet, van Meerveld, & Seibert, 2020; Van Meerveld et al., 2018). Following those results, I suggest that this (dis-) connectivity had an influence on this delayed reaction. After the two rainfall events in the morning and the afternoon, the connectivity was probably close to its maximum, meaning that the first sediment pulses even from further locations had already passed. The new and less intense input in the evening took longer to reach the parts of the catchment I investigated because the newly contributing areas increased the maximum amount of sediment by such a large margin that it simply took the stream much longer to reach maximum SSC, even though the rate of increase was comparable. This is supported by the behaviour of SSC in the evening at all locations except for C3. Although the peak in the morning hours was clearly the largest for all locations. This is hardly surprising considering the intense rainfall and the large area probably still disconnected from the main streams of the catchment because of the long dry period beforehand. In contrast, the peak in the evening looks much smaller, but it is still clearly more intense than the one in the afternoon. Thus, it is possible that the SSC simply took longer to reach its maximum because there was a larger area providing more sediment than in the afternoon. Additionally, it is possible that the flow, which reached its maximum during the third event on August 28th, led to the collapse of channel banks and, in consequence, to increased influx of sediment material. Since the channels are deeply incised at many locations and thus susceptible to erosion, this is not unlikely. Several studies at other rivers have found such microscale events to be important drivers of SSC (Carter et al., 2003; De Girolamo et al., 2015; Yellen et al., 2014).

Interestingly, the 21st of October shows even more differing behaviour. While streamflow exhibits a more or less linear rise with one intermediate peak that stops the linear increase for a short moment, SSC displays two distinct peaks, of which the second is significantly smaller. This is unexpected, because in streamflow we see the second peak to be much higher. The dip in the hydrograph is easily explained by the short break in rainfall. The difference in peaks, however, is less clearly explained. The most likely explanation is that the large sediment pulse shortly before exhausted sediment stores, meaning that there was no easily available sediment to be moved anymore, even though streamflow reached higher levels. In addition, the enhanced flow over a certain period of time might have led to dilution of the already present sediment (Vercruysse et al., 2017). Since the streams are very small and the flow was not increased for a longer period of time than during other events, I favour the first possibility.

In short, I can neither confirm nor completely reject my hypothesis about immediate reactions of SSC to rainfall. Although there are some locations that did react almost immediately to rainfall on certain occasions (e.g. C5 and C6), there is not enough evidence for an absolute claim. The only thing I can confidently say is that the locations further upstream seem to react quite quickly if the soil is already sufficiently wet and / or the rain event is intense enough. Of course, when looking at the data provided here, C7 seems to counter my claim. However, C7's data quality is extremely bad for all events in August (bad positioning in the stream) or simply unavailable (e.g. on September 22nd). Consequentially, its input should largely be neglected. Only for the 21st of October in the evening does it provide any useful information. Although it reacts faster than almost all other locations, it fits into my assumption well, considering that its peak is considerably smaller, comparatively speaking, than the other locations'. Furthermore, it is fed by at least two more rather large streams that have not been equipped with sensors. Hence, it is likely that they diluted the other locations' influence on C7's behaviour so strongly that the seemingly unfitting response time could be attributed to that lateral influence.

5.1.2 Spatial variability

Compared to the temporal variability in SSC response times, the spatial variability of those values is even more confusing. My assumption that the sub-catchments further upstream react differently from those further downstream is not entirely confirmed nor is it completely rejected. C5, being the sensor location furthest upstream does exhibit some of the quickest and most extreme responses. Although its streamflow is usually surpassed by all other locations except for C3, it consistently recorded the highest SSC and thus also the highest sediment yield (I ignore C7 in this because of the mentioned issues with that turbidity sensor's data quality). This agrees with the notion that steep or geomorphologically unstable terrain leads to more sediment influx. C5 is the sensor that was located most closely to the recent landslide that was not yet entirely regrown, meaning that there was much easily erodible sediment available. Furthermore, there is large swaths of steep terrain upstream of C5, meaning that rain falling down there eroded sediment much more quickly and more easily than in flatter parts. However, since there is flat terrain in between C5 and those steeper parts, the sediment stemming from that less flat terrain might simply have been deposited before actually reaching the stream. Since the other locations, even those influenced by steep slopes like C6 and C4, did not display even remotely similar SSC values – even though streamflow was usually clearly higher – I assume the geomorphological instability caused by the landslide to have a greater impact on the amount of sediment in the water than the steepness. This is further corroborated by experience. Several people also doing research in the Studibach catchment confirmed independently from each other that the weir at C5 only started needing extensive emptying after the landslide went down and thus clearly increased the sediment availability to the stream.

Summarising, it seems appropriate to attribute a high sediment input to the presence of easily erodible sediment from locations without or with only sparse vegetation cover. Besides the obvious landslide, those could be collapsed channel banks.

5.2 Response intensity of SSC

5.2.1 Q-SSC-relationship

Following one’s intuition, it is to be expected that a higher streamflow is by some relationship connected to higher SSC, which can also be observed quite often (De Girolamo et al., 2015; Kisi, 2012; Oliveira & Quaresma, 2017). The reason for such behaviour is the increased amount of water and its increased power due to usually higher flow speed. By being more abundant and faster, there is more fluid for sediment to be suspended in and the water has a higher potential of eroding sediment which was not erodible before. However, there are also datasets showing that the relationship between streamflow and SSC is by no means constant or even ubiquitous (Rasmussen et al., 2009). This means that, depending on the stream, there is no clear relationship between discharge and SSC. My data (fig. 18) displays this perfectly. Although an increase in streamflow generally leads to an increase in SSC, this relationship is by no means clear-cut. There can be high values during little flow – the most extreme SSC values during almost no flow must be considered as outliers – or little sediment while streamflow is high. This agrees with the notion of sediment stores of different availability and size. If a sediment store is large and easily accessible, i.e., easily eroded, then SSC might rise quickly even during only slightly enhanced discharge. But if sediment stores are exhausted due to long-lasting rainfalls and thus constantly increased water levels, then SSC will start to recede even though the water still holds much erosive power. Only by once again increasing sediment availability, for instance through sediment bank collapse or new landslides may SSC increased again during that same event. In short, there does not appear to be any clear relationship between streamflow and SSC.

5.2.2 Peak SSC

The peak SSC compared to peak streamflow further discourages from assuming a direct relationship between those two factors (table 1, fig. 18). Although, in general, higher peaks lead to higher SSC, this is not always the case. For instance, the peak streamflow at C3 on September 22nd was not even a third of its streamflow on August 4th, but those events' peak SSC almost match up. That there is no clear relationship becomes even more apparent when looking at August 6th: On that day, C3's streamflow was *higher* than it was on the 22nd of September, but SSC was higher on the latter date. Similar observations can be made for all other sensors as well. Especially the event on August 6th seems to have mobilised comparatively little sediment. Following the reasoning of sediment stores, it is probable that the rain over the two days prior has removed most easily accessible sediment from the catchment, thus depriving the streams from higher concentrations, even though streamflow was similar to the 4th.

As for the geographic variability of peak SSC, one can clearly see that – excluding C7 – C5 displays, by far, the highest SSCs. Those values then decrease further downstream until they reach their minima at C3 and C4. Looking at fig. 2 and 3, we can see that C5's water flows through C6 with some more input from the southeast. Then, it moves further and becomes part of both C3's and C4's input. The question remaining now is how it can be that the extremely high sediment values found at C5 dilute this quickly. There are several explanations possible.

The first, the simplest one, can be found by looking at the stream network. There are many tiny streams bringing more water to the locations further downstream that are entirely disconnected from C5. For instance, more than half of C6's catchment does not affect C5 but the stream network south of it. Similar things can be said about the two weirs C3 and C4. If there is more water input from those parts of the catchment, which I could not investigate, than there is sediment input, this would lead to a dilution of sediment input from C5. This might hold true for C6, seeing as all

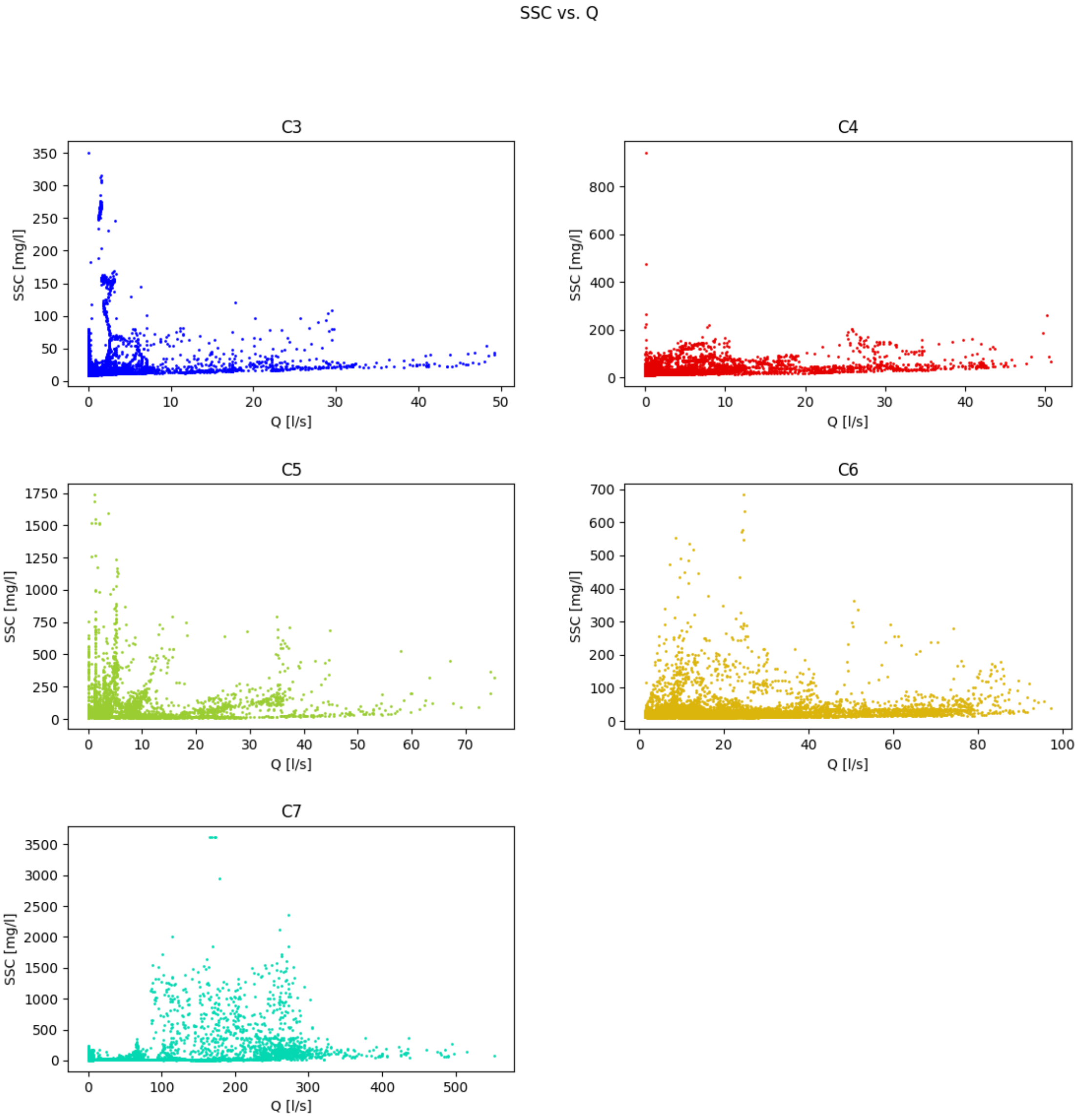

Fig. 18: SSC plotted against streamflow. As can be seen, there is no clear relationship in my data between these two factors.

water from C5 should move through C6, so, without any deposition in between, dilution would be the only answer to how SSC could decrease this quickly. However, for C3 and C4, this does not work, at least not entirely. Streamflow values at those two weirs are usually not much higher than at C5, meaning that dilution can only be part of the answer. It is possible that some of C5's water, and thus also of its sediment, flows *past* the two weirs. After C6, the stream network subdivides in several smaller networks, some of which bypass the weirs, perhaps moving some of C5's sediment along without it ever being registered.

Another possibility is dysconnectivity of sediment pathways. If there is sufficient resistance to transport, for instance, through streamflow deceleration in flatter areas or increased channel roughness, some of the sediment might be deposited between two transport locations (Fryirs, 2013). In this case, those would be C5 and the other sensor locations. Looking at the slope (fig. 3) between C5 and C6, as well as between C6 and the other two weirs, we can easily notice that both sections contain steeper parts intermitted by flatter terrain. Especially the route from C6 to C3 contains an almost entirely flat portion, probably explaining why C3's SSC is generally lower than C4's, even on August 28th, when streamflow was comparable at those two locations. Of course, it might also be that C4 receives more sediment input from the southern part of its catchment which was not investigated in this study. Furthermore, both C3 and C4 have a rather flat stream shortly before the actual measurement station, meaning that some sediment might be deposited right before it reaches the sensors. C6 has a rather steep channel leading up to it, thus transporting all the sediment that moved through the flat part between it and C5. The latter also has a quite flat portion of the stream leading up to it. Still, sediment concentrations are extremely high, most likely due to the already mentioned high availability of easily erodible sediment from the landslide.

To summarise my answer to my second research question: I fail to reject my hypothesis about the influence of landslide activity. Although I cannot be entirely sure as I did not analyse sediment sources in my samples, it is highly likely that the landslide increased the amount of sediment present in the stream. Furthermore, the slope of the terrain does seem to influence sediment transport by deciding whether sediment remains in suspension or is deposited. However, if the slope also influences sediment availability and erodibility in general, I cannot safely say. I think it to be probable, but my data does not suffice to claim it with confidence.

5.3 Possible improvements

Some issues or limitations have already become abundantly clear, especially the almost unusable data from C7. However, there are some more things on which a follow-up project could certainly improve. First of all, it would be necessary to investigate the entire Studibach catchment. For instance, there is no sensor upstream of C4 that monitors the southern part of C4's sub-catchment. The same goes for the large southern section of the catchment flowing towards C6. Possible locations for such additional sensor stations are marked in fig. 19. Using such an approach, possible dilution effects from those parts of the catchment could be isolated or disproven. To further improve data availability in the catchment, it would be necessary to analyse sediment samples. In doing so, it could be investigated where sediment stemmed from, so that the influence of landslide activity could be better assessed. This would also make it possible to quantify how

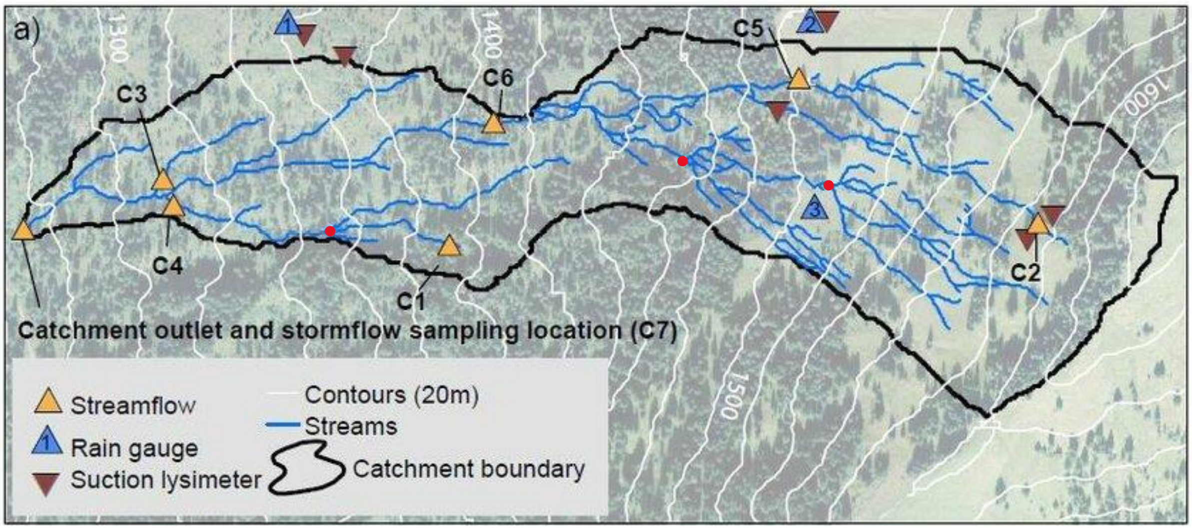

Fig. 19: Map of the Studibach catchment including suggested additional locations to investigate (red dots) (Kiewiet, van Meerveld, Stähli, and Seibert, 2020, 3384; the map originated from the preprint; thus, it looks slightly differently from the published version).

much sediment comes from which stream. Especially for C3 and C4, which receive inputs from several sub-networks, this could be interesting.

Additionally, it could be interesting to investigate the behaviour of the stream network during another season (or the entire year). Especially the snowmelt in spring might have an impact on the sediment transport not anticipated. For Arctic catchments, snowmelt has been shown to be an important driver of SSC, although rain events must not be neglected (Dugan et al., 2009).

Furthermore, to increase the ability to explain inter-event differences in response times of both streamflow and SSC, analyses of soil storage and infiltration capacity would be suitable. By assessing how much water can be stored in the catchment and how quickly this drains during dry days, it should even become possible to predict streamflow and maybe even SSC. However, such analyses would be extremely time-consuming because the catchment is not uniform, meaning extensive sampling would be necessary in order to achieve even a remotely useful grid of information about soil properties. Lastly, there is always a scale issue present in sediment analyses. Although my time series has a high resolution and covers most of summer, the entire autumn and the beginning of winter, it still only covers a few months and I analysed almost exclusively on event-basis. Meaning that longer-lasting trends are invisible. If one were to combat this, data collection over longer periods of time would be necessary. Only then could the catchment's sediment transport behaviour be investigated on different time scales (Vercruysse et al., 2017).

6 Conclusion

This study's aim was to better understand the characteristics of suspended sediment transport in a (pre-) Alpine catchment. Such catchments are characterised by high variability and low data availability. Due to those factors, already conducted studies in other catchments can only partially be transferred to other similar catchments. Thus, it is imperative to survey each catchment on its own, even though that uses up a lot of resources. The Studibach was a prime choice for such a project because it is, for a small mountainous catchment, already well-equipped with sensors. Water level, air pressure and rainfall data were all already collected and thus I did not need to install sensors for those values as well. Hence, I could focus entirely on turbidity, water sampling and measuring streamflow to get my rating curves. Thanks to the pre-existing data, I could still finish my study even though the data quality of my water samples was far from ideal.

Using this approach, I found that the Studibach generally does not react as fast to rainfall as I would have expected, especially if it was dry the days before an event. Furthermore, suspended sediment concentrations did not follow streamflow as perfectly as I would have hoped. Sometimes, suspended sediment even behaved seemingly completely decoupled form streamflow. My assumptions on topographical or geomorphological factors impacting sediment transport, however, could be partially corroborated. It appears that open areas without vegetations, which are prevalent in a landslide area, vastly increase sediment availability and thus also the suspended sediment concentrations during an event. In contrast, those high concentrations do not propagate through the entire catchment. Either by dilution from other parts of the catchment not investigated in this study or by deposition of sediment in flatter sections between two sensors, the sediment concentration gradually decreases when moving through the catchment.

For further research about similar topics in the area, it will be of utmost importance to install more sensors to cover more sub-catchments and better dissect the different signals. Also, the turbidity sensors need to be checked more often as they seem to be rather prone to malfunctions or even complete failures – especially if buffalo are involved in any way.

7 Acknowledgments

I thank my supervisor, Dr Ilja van Meerveld, who helped me outline my project and accompanied me along the way with insight and constructive criticism. She was also always readily available to propose a solution if my data was not as useful as anticipated. Secondly, I thank my co-supervisor, Victor Gauthier, for helping me set up my equipment in the field and sacrificing his time to answer my questions or providing me with material and additional data. Neither my data collection nor my data analysis would have been possible without his support and instruction. Next, I would like to thank Anna Leuteritz, who, although not officially involved with my thesis, helped me get additional material and answered questions I could not answer myself. Further, I would like to thank Anna Czerniejewska, who let me borrow the laptop used to read out the data from the pre-installed sensors in the catchment after I failed to finish my data collection before those sensors were read out the last time before the beginning of winter. My data range would have been severely limited had she not helped me. Lastly, I would like to thank everybody who took the time to read through my thesis and point out to me when my English went completely off the rails or was so convoluted that it became incomprehensible for anybody not used to the never-ending sentences of a Cicero or a Virgil.

8 References

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8.1 Data sources for GIS analysis

Swisstopo:

- swissALTI3D2019 (accessed through geovite.ch)
- swissTLM3D (https://www.swisstopo.admin.ch/en/geodata/landscape/tlm3d.html)
- Orthoimages, 10 cm, (https://www.swisstopo.admin.ch/de/geodata/images/ortho/swissimage10.html)
- Map with relief, 1:10000 (accessed through geovite.ch)

Assendelft, R. S. and van Meerveld, H. J. (2019). Studibach stream networks. Zenodo.org. https://zenodo.org/record/3543674:

- Catchment boundaries and stream network:

9 Appendix

9.1 Tables

Missing or likely erroneous data is written in *italics*.

Table 2: Peak sediment yield (SY) values and their timestamps during certain rain events in the Studibach catchment.

04.08.2023	**Peak SY [g/min]**	**Time**
C3	56.4	22:20
C4	126.3	21:40
C5	no data	no data
C6	1’005.3	21:25
C7	13’769.6	*21:20*
06.08.2023		
C3	21.8	18:40
C4	119	17:25
C5	1857.3	17:05
C6	586	17:40
C7	*9828.7* *9665.9*	*15:25* *(17:00)*
28.08.2023		
C3	180.7	06:00
C4	400.8	05:05
C5	1318.1	04:40
C6	1101.9	04:40
C7	*23’152.3*	*04:35*
22.09.2023		
C3	20.8	06:10
C4	76.2	05:10
C5	812.4	08:15
C6	250.4	04:35
C7	*no data*	*no data*
21.10.2023		
C3	11.5	18:15
C4	39.9	18:20
C5	*no data*	*no data*
C6	77.9	18:50
C7	191.8	18:10
30.10.2023		
C3	53.5	23:50
C4	*no data*	*no data*
C5	*no data*	*no data*
C6	272.4	22:50
C7	222.9	24:00

Table 3: Response times of the different locations during certain rainfall events. The response time is given in hh:mm. For the 14th and the 15th of November, the values of C6 were not included because the location seems to have behaved completely decoupled from the rainfall, thus leading to erroneous values.

	C3	**C4**	**C5**	**C6**	**C7**
04.08.	4:00	3:50	*no data*	4:50	4:35
06.08.	1:05	0:30	0:10	1:40	1:35
28.08.	1:40	1:10	1:10	2:05	2:15
22.09.	4:40	4:00	2:25	5:00	5:30
21.10	2:40	1:55	1:00	2:45	2:55
30.10.	1:30	*no data*	0:30	1:55	2:10
14.11. (1)	1:40	*no data*	1:00	*n/a*	3:20
14.11. (2)	1:20	*no data*	0:40	0:10	0:40
15.11.	1:10	*no data*	0:40	*n/a*	2:10

Table 4: Response times to peak rainfall for SSC. For those events where SSC seemingly reacted too fast, response time was put to "n/a". Those are mainly the events where peak rainfall was reached late in the rainfall.

	C3	**C4**	**C5**	**C6**	**C7**
04.08.	3:10	2:25	*no data*	2:05	2:10
06.08. (1)	1:50	*no reaction*	0:10	0:40	0:50
06.08. (2)	1:05	0:15	n/a	0:20	3:10
28.08. (1)	1:35	0:20	0:05	0:20	*data too erratic*
28.08. (2)	*no reaction*	1:30	0:25	0:40	*data too erratic*
28.08. (3)	3:20	2:45	2:40	2:40	3:20
22.09.	2:50	2:35	*5:35*	1:15	*no data*
21.10. (1)	1:40	1:40	*no data*	1:25	*no reaction*
21.10. (2)	2:20	2:20	*no data*	1:35	1:35
30.10.	1:10	*no data*	*no data*	n/a	*no reaction*

10 Personal declaration

Personal declaration: I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

Date:

28.06.2024

Signature: