Interaction of turbidity currents and contour currents in flume-tank experiments; deposits, grainsizes and turbidity current concentration profiles linked to contour current velocity

Master thesis: Jesse Bleeker
Student number: 6122094
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Department of Earth Sciences
Faculty of Geosciences
Utrecht University

First supervisor: Dr. Joris T. Eggenhuisen
Second supervisor: Pelle Adema MSc.

Abstract

Turbidity currents carry large amounts of sediment, nutrients, organic carbon, and even pollutants and plastics to the deep sea and store them in basin-floor fans forming the largest sediment accumulations on Earth. Continental slope environments are rich in dynamic processes such as tides, waves and contour currents. Turbidity currents can interact with other water masses, resulting in a combined flow field, forming e.g. a mixed turbidite-contourite system. These combined flows deposit large volumes of sediment along the continental slope, hosting important archives of Earth's climate, potential reservoirs for hydrocarbons and a sink for carbon and micro-plastics. Several conceptual models have been published that hypothesize how this interaction works and how this affects depositional patterns. These models remain largely untested. Furthermore, a clear link between process and deposit is missing. Experiments can add to the understanding of depositional patterns of mixed systems by linking the flow dynamics to turbidity current concentrations and deposits, which is often impossible in field measurements. This study focused on three-dimensional flume experiments of turbidity current – contour current interaction conducted in the Eurotank flume facility of Utrecht University. Two parameters are tested in ten experiments. Channel depth and contour current velocity are varied to find out how they affect: (1) locations and amounts of sediments deposited, (2) grainsize distributions inside and outside the channel, (3) concentration of the turbidity current at different elevations above the bed, inside and outside the channel. The results show, Firstly, that turbidity currents are better confined in a 10 cm deep channel compared to a 4 or 7 cm deep channel. Second, more sediment is deposited in the channel and on the downstream overbank when a contour current is present. Third, the grainsize of the deposited sediment is larger in the channel and smaller on the downstream overbank when a contour current is present. It is seen that not a strong but a weak contour current results in most sediment and finest sediment on the downstream overbank. Fourth, the concentration profiles show that the turbidity current becomes thicker and has a higher concentration above the downstream overbank when a contour current is present.

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Introduction

Turbidity currents are sea-bed hugging flows that flow down a slope to the deep sea under the influence of gravity, mostly through a channel. These flows carry large amounts of sediment, nutrients, pollutants, organic carbon (Galy et al. 2007) and even plastics (Pohl et al. 2020) to the deep sea and store them in basin-floor fans that form the largest sediment accumulations on the planet (Azpiroz-Zabala et al. 2017; De Leeuw et al. 2016; Pohl et al. 2019).

Contour currents are long lasting (up to millions of years) currents driven by tidal, wind, wave or thermohaline forces. These contour currents typically flow parallel to the slope, i.e. approximately perpendicular to turbidity currents (Shanmugam et al. 1993). Contour currents rework sediments and create deposits called contourites. Contourites provide valuable information about ocean currents, determined by atmospheric forcing (Alonso et al. 2021), which play a critical role in shaping our planets' (Kuhlbrodt et al. 2007) or regional (Toucanne et al. 2007) climate and ecosystem. Additionally, contourites can have economic significance as potential sources of oil, gas, and mineral deposits (Viana 2008). Understanding their formation and distribution can aid resource exploration and management. Contour currents represent bottom currents such as geostrophic currents or currents affected by Coriolis force. Geostrophic contour currents involved in the deep thermohaline circulation appear to be a very important control on the shape of many sediment bodies (Heezen et al. 1966). Also, currents forced by the Coriolis force can results in significant asymmetry in the heights of their levee banks (Cossu et al. 2010).

This research comes from a change in perspective from turbidity currents flowing in to still standing water to the interaction between turbidity currents and other dynamic water masses, e.g. contour currents. A mixed system, interacting turbidity currents and contour currents, can result in different depositional bedforms, stacking patterns and channel migration directions. Multiple depositional options are possible for mixed systems depending several parameters. For example the bathymetry and the velocity of the turbidity current and contour current. It is possible to get large drifts, channel-levee and lobe deposits or a combination (Hernández-Molina et al. 2008; Pohl et al. 2019) which can form, but also disappear due to erosion (Laberg and Camerlenghi 2008). These different patterns can serve as records of past ocean circulation and climate change or paleoclimatic reconstructions, for example in the Mediterranean (Alonso et al. 2021; Bahr et al. 2014; Smillie and Stow 2017). With more knowledge about the interaction of turbidity currents and contour currents a better climate reconstruction can be made.

Turbidite-contourite systems are investigated on different scales and with different scientific approaches. Fieldwork with the study of actual rocks or cores (Fonnesu et al. 2020), the use of seismic data (Hernández-Molina et al. 2017; Normandeau et al. 2019), the use of numerical modeling (Huang et al. 2005; Huang et al. 2007) and experiments (Miramontes et al. 2020). Much research is done on turbidite-contourite systems of existing channels on different places on Earth with the use of field observations and seismic data. For instance offshore of Canada or Tanzania (Normandeau et al. 2019; Sansom 2018), where the morphology of bedforms and channels are investigated respectively. Most research is done by observations of deposits. However, the record of the process and so, the link between the process and the deposit is missing.

Experimental research can be used to help making this link more clear. On experimental scale, little research has been done. The only experimental research on turbidity currents together with contour currents is the work of Miramontes et al. 2020. In their research the Eurotank is used. It is a scaled experiment of a turbidity current flowing down a slope interacting with a contour current. The results of this study showed that contour currents can indeed deflect turbidity currents. Also, the channel-levee architecture changed during this experiment. The downstream levee grew larger than the upstream levee. The increase in contour current velocity increased the asymmetry of the channel-levee system. Downstream of the contour current the levee was wider and there were unwanted bedforms. In the work of Miramontes et al. (2020) the long term migration of the channel was suggested to be against the direction of the contour current. However, this is not always the case. Gong et al. (2020) suggest that the channel migration can be both upstream or downstream of the contour current.

Previous studies suggest conceptual models with most deposition on the upstream overbank (Chen et al. 2020; Fonnesu et al. 2020; Gong et al. 2013; 2016; Rasmussen et al. 2003) or on the downstream overbank (Chen et al. 2020; Fonnesu et al. 2020; Fuhrmann et al. 2020; Rasmussen et al. 2003; Rodrigues, Hernández-Molina, and Kirby 2021; Rodrigues et al. 2022; Sansom 2018). The migration direction of the channel is strongly related to the locations of sediment deposition, however in our research it is difficult to get information on the migration direction out of the data, since the experiment is not made for that. The models of Chen et al. (2020), Gong et al. (2013), and Rodrigues et al. (2022) show possibilities for both sedimentation on the downstream and the upstream overbank. Lateral accretion is seen on the upstream overbank when the migration direction is equal to the direction of the contour current (Chen et al. 2020). Rasmussen et al. (2003) and Rodrigues et al. (2022) show that in a single mixed system the location of deposition can change, depending on the strength of the turbidity current and contour current. Rodrigues et al. (2022) argues that the direction of migration may depend on several factors, such as the velocity and persistency of bottom currents and the velocity and frequency of turbidity flows. In systems with strong and persistent bottom currents (>25-30 cm s^{-1}), a down-current migration is expected. In systems built under weak to moderate bottom currents, an up-current migration appears to be more dominant. The migration of mixed systems may also be influenced by surrounding morphologies, seafloor irregularities, and the dimensions of the channel-drifts and submarine channels (Rodrigues et al. 2022). Fuhrmann et al. (2020) discusses that when the contour current is dominant there should be more sediment deposited on the forming drift and when the turbidity current is dominant the channel would fill in with more sediment.

It is a problem for everyone working on turbidity and contour current interaction that a link between the process and deposit is missing in field-based studies. Nobody really knows what the flow field of combined turbidity and contour current flow looks like together with the concentrations of the turbidity currents and the deposit distribution. Despite the lack of the link between the process and deposit, which can be made by sufficient experimental research, there are many conceptual models (Fonnesu et al. 2020; Shanmugam et al. 1993) that suggest how the interaction works, but these models remain untested. I will test these conceptual models with experiments.

It is worthwhile to study turbidity currents and contour currents on experimental scale for multiple reasons. Firstly, this research can help other researchers. The results of the experiments can provide new insights in the interaction of turbidity currents and contour currents. My work will focus on the deposits and sediments resulting from the interaction of turbidity currents and contour currents by the use of experiments. My work can contribute to the paleoclimate community in a broader sense and to the deepwater sedimentology community because it is complementary to field measurements which are very limited in the measurements they can do in situ. The second reason is that turbidity currents and submarine landslides can cause damage to under water infrastructure and cable networks (Carter et al. 2014; Pope et al. 2017). My results can inform other researchers and provide new findings to these relevant societal problems.

This research is about the deposition and concentration of turbidity currents during and after interaction with contour currents. The question how changes in the velocity of the contour current and channel depth result in changes in the deposits of turbidite-contourite systems is a major question in the deep sea sedimentological research community. I want to contribute to answering this question by making a link between the process of a mixed system and the deposit on experimental scale. I will investigate the deposits and sediments after deflection and overspill of turbidity currents over the channel overbanks under the influence of contour currents during and after experiments. The experiments are executed in the Eurotank at Utrecht University. The Eurotank is an 11x6x1.20 m flume tank which can be used to make experimental turbidity currents together with contour currents. To link the process of the interaction of turbidity currents and contour currents to the deposits, I analyzed 1. laser scans, cross sections and calculated volumes of the deposition, 2. Grainsizes of the deposits and siphon samples, and 3. concentration profiles of the turbidity currents that results from laboratory experiments. With these results, depositional patterns are clarified. This helps the understanding and supplies physical justifications to the already existing models of the interaction of turbidity currents and contour currents. These data is used to answer the main questions of the study: 1. How do contour currents with different velocities affect the location and amount of sedimentation? 2. How much of what sediment grainsize is deposited where? And 3. How do the concentrations of the turbidity currents differ inside and outside the channel? To answer these questions, ten experiments are executed in the Eurotank. In the experiments I will test two parameters, namely the channel depth and contour current velocity.

Materials and Methods

Before the experiment - Flume tank setup

This experimental study made use of the Eurotank, which is located at Utrecht University. The Eurotank is an 11×6×1.20 m flume tank that can hold 70,000 liters of water. It is equipped with an inlet for sediment mixtures to conduct sedimentological experiments. Both the current conditions as well as the morphology of the deposit can be studied. In the flume tank, before each experiment, we leveled a slope of 5° with the aid of two stainless steel bars which were dug in to the slope and allowed us to prepare a surface of loose, fine to coarse sand that is parallel to the top of the bars (Figure 1). This ensured that the slope angle remained the same for all successive experiments. The slope of 5° and the grainsize of the sediment in the turbidity current is chosen so that the turbidity current velocity had a maximum of ~0.5 m s^{-1}. This ensured that the stable part of the experiment lasts for more than 100 seconds. A 100 seconds constant velocity of the turbidity current was needed so that there was enough time for the velocity measurements at different locations inside and outside the channel. The Froude number during the experiment was calculated for the most extreme possibilities and has a value of 1-1.7 (P.H. Adema, personal communication, 2023). On the sediment surface, we made a flat bed and after that we dug an 80 cm wide and 5.5 m long channel in the middle of the surface (Figure 1), using a template. For different experiments, different channel depths were made (4, 7, and 10 cm). With a channel depth of 4 cm the turbidity current is poorly confined, and with a channel depth of 10 cm the turbidity current is approximately confined (Pohl et al. 2019), since the height of the turbidity current ranges from 10-12 cm (Figure 2). After the channel was made the bathymetry was scanned with a laser scanner and then the tank was filled with water. Filling the tank with water takes 16 hours.

Contour current - turbidity current measurements

In the Eurotank we can produce currents perpendicular to the input of the sediment mixture that are an analog for contour currents. The velocity of this perpendicular current can be varied by means of two pumps that result in contour current velocities of 5 and 9 cm s^{-1}. These velocities are chosen because we have 3 pumps with a certain strength that can generate these velocities. Only two pumps were used because it is not realistic if the contour current exceeds 10 cm s^{-1}, because the speed of the contour current then becomes much to large compared to the turbidity current in comparison to nature, since the turbidity current has a maximum velocity of around 50 cm^{-1}. A contour current made with one pump is called a weak contour current and a contour current made with two pumps is called a strong contour current. The contour current flowed in a circular motion through the flume tank.

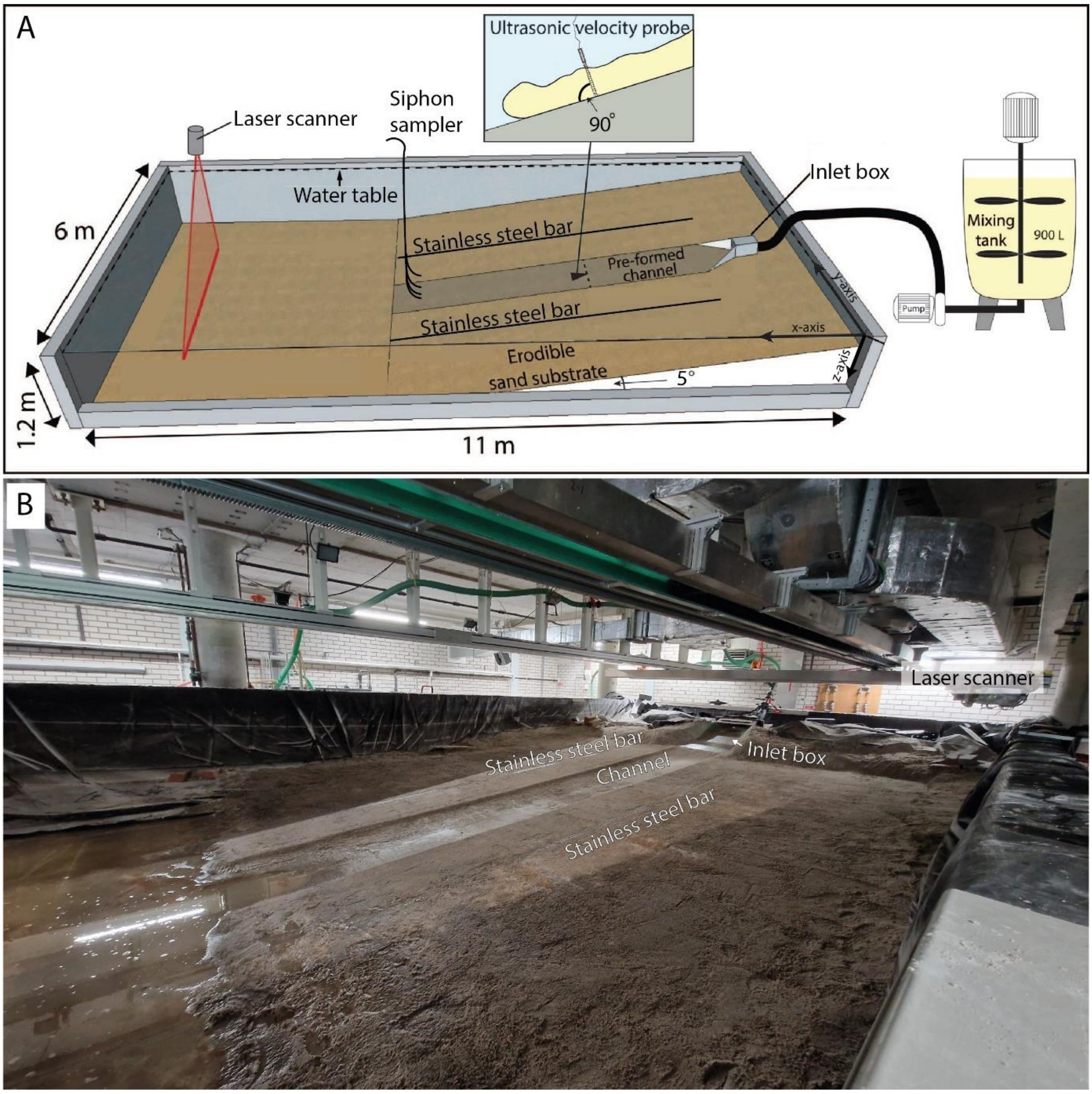


Figure 1, A: overview of the experimental setup, figure modified from de Leeuw et al. (2018). B: photo of the setup before the experiment has run.

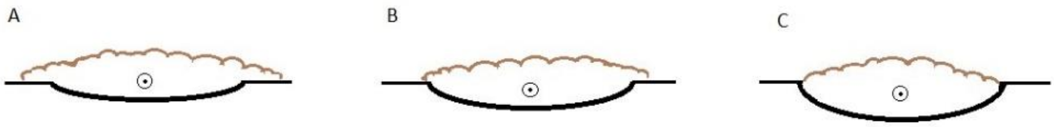


Figure 2, Different channel depths, A = 4 cm, B = 7 cm, and C = 10 cm, where A is the least confined and C is the most confined.

We carried out a series of current velocity and direction measurements with one and two pumps to determine the position in the tank, where the current was most perpendicular to the turbidity current coming from the inlet box. The velocity and direction of the contour current was measured using an Ultrasonic Doppler Velocimeter (UDOP). With this technique velocities are derived from shifts in positions between pulses. The advantage of this technique is that pulsed doppler ultrasound offers instantaneously a complete velocity profile ("Technique Background of UDV" n.d.). The UDOP was positioned 30 cm above the bed, inside and outside the channel. The UDOP measures the direction and velocity of the flow of the contour current in three dimensions, called the x, y, and z direction. Figure 3 shows a plot of the flow measurements of only the contour current on multiple positions in the experimental setup. At the location where the turbidity current comes inside the tank, the contour current crosses the channel and turbidity current perpendicular (Figure 3). It is seen that inside the channel, the direction of the flow is perpendicular to the channel. When measuring outside the channel it is seen that the direction of the flow followed a circular motion and becomes less perpendicular to the channel. The UDOP was also used to measure single turbidity currents and combinations of contour currents together with turbidity currents.

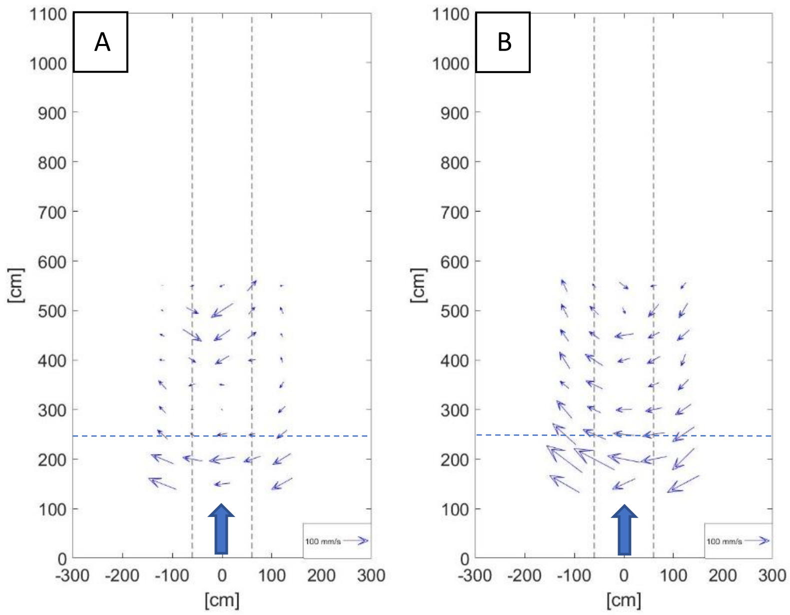


Figure 3, Velocity field of the contour current with one (A) and two (B) pumps. The Big arrow indicates the inlet of the turbidity current. Vertical dashed lines indicate the channel and horizontal dashed line indicates the position of the UDOP.

Sediment mixture preparation

Before we started each experiment the contour current was switched on and then the turbidity current mixture was made. The turbidity current mixture consisted of water and sediment. It was homogenized in a mixer with a maximum volume of 900 liters. As sediment we used a glass granulate. We bought the sediment from the company 'Kuhmichel'. The grains have a density of

2300 kg m^{-3}. The grainsize was determined in the lab using the Malvern Mastersizer 2000 and is 0-110 µm (Figure 4). The grains of glass granulate are of silt size, so from now on the grains are called silt. We used 145 kg silt for every experiment to reach a concentration of 6.1 %Vol of the mixture. The mixture was pumped through a diffuser into the inlet box (Figure 1) of the flume tank and released to flow down slope under influence of gravity. The diffuser ensures that rotational flows of the turbidity current disappear and that there is a lateral spreading to slow down the turbidity current. This is the start of an experiment. The pump had a constant discharge of 23-24 $m^3 h^{-1}$.

Experiments of a turbidity current only, as well as experiments of a combined turbidity current with a contour current were executed. The sequence of the different experiments that were executed are shown in table 1.

	CD = 4 cm	**CD = 7 cm**	**CD = 10 cm**
No CC	8	1/3	10
1 CC	7	2	5
2 CC	9	4	6

Table 1, Executed experiments, CD = Channel depth, No CC = No contour current, 1 CC = 1 pump contour current/weak contour current, 2 CC = 2 pumps contour current/strong contour current. The numbers indicate the order of the experiments.

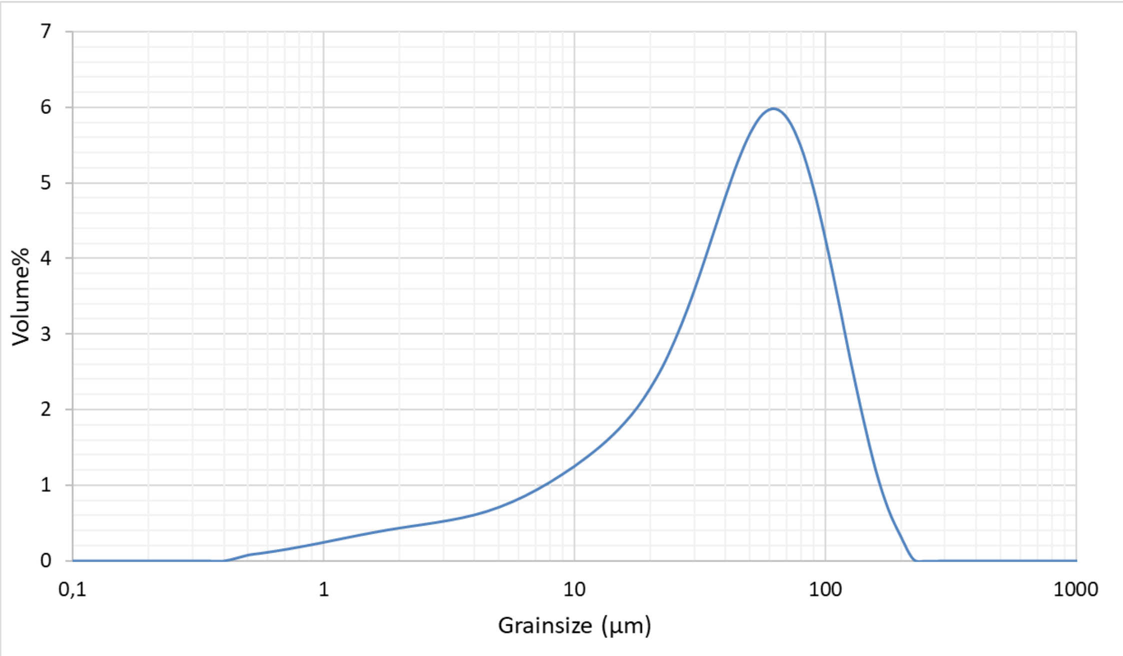


Figure 4, Grainsize distribution of the used silt.

During the experiment - Siphon sampling

During the experiment the turbidity current was siphoned with a custom-made siphon sampler (Figure 1A). With these siphon samples the concentration of the turbidity current could be determined. The siphon sampler consists of four tubes at four different elevations above the bed (viz., 1, 2, 4, and 8 cm). The four tubes were connected to four hoses. Under the influence of gravity, the sediment mixture flowed from the tank through the tubes and hoses into measuring cups. The technique of Pohl et al. (2020) was used. The sampling of the sediment mixture took 40 seconds. Since we know the diameter (8 mm) of the tubes, the discharge and the velocity inside the hoses could be calculated. This turned out to be 50 cm s^{-1}, which is in the same order of magnitude as the velocity of the turbidity current. Thus, there was barely any acceleration or delay of the mixture when it enters the tubes. This leads to a negligible effect of the sampling technique on the behavior of the turbidity current and the sampling. The measuring cups were filled with about one liter of the mixture. The total volume was read from de scale on the measuring cup and the mass of the total volume was measured with a scale accurate to the gram. After the experiment, the concentration of the silt in %Vol was calculated using 2 equations:

$$C_s\rho_s + C_w\rho_w = C_b\rho_b \tag{1}$$

$$C_w + C_s = C_b \tag{2}$$

Where C_s = concentration silt, ρ_s = density silt, C_s = concentration water, ρ_w = density of water, C_b = bulk concentration, which is the total concentration of water and silt and so is 1, ρ_b = bulk density. The density of the silt is 2300 kg m^{-3} and the density of water is 998 kg m^{-3} at 20 °C. Equation 2 can be substituted into equation 1, this gives the following equation:

$$C_s = \frac{C_b\rho_b - \rho_w}{\rho_s - \rho_w} \tag{3}$$

When using C_b = 1, the densities and the equation for density the following equation appears:

$$Cs = \frac{\frac{m_b}{V_b} - 998}{2300 - 998} \tag{4}$$

where m_b = bulk mass and V_b = bulk volume. This equation was used to calculate the concentration.

In our experiments the concentrations were measured in the channel and on the downstream overbank. In first instance we wanted to siphon the turbidity current also on the upstream overbank. However, due to the contour current, the turbidity current was deflected and did not reach the siphons on the upstream overbank. this could be remedied by hanging the siphons closer to the channel, but we decided not to do because than the location of the siphon was so close to the edge of the overbank that this might influence the siphoning.

After the experiment - Difference maps and sampling

After the experiment the tank was drained and the bathymetry was scanned with the laser again. A difference map was created using the two scans before and after the experiment. With these difference maps very subtle differences in elevation change are visible. Figure 5 shows the results of a difference map for an experiment with and without a contour current. In Figure 5A there is no contour current and in Figure 5B there is a contour current, indicated with the blue arrow. This figure shows that with a contour current more sediment was blown to the downstream overbank. After 4 meter also on the upstream overbank there is sediment deposition, however, this is not our area of interest, because the contour current is not representative and has multiple directions (Figure 3). Figure 6 shows the areas in a two-dimensional view. Yellow colors indicate sedimentation and blue colors indicate erosion (for figures of the elevation for all the experiments, see the supplementary figures). To quantify the amount of deposited sediment, the mean elevation in the areas of interest was calculated, indicated with the black squares. The length of the black squares is two meters, from 2-4 meters from the inlet box. The width of the black squares is 1.5 meter. With the calculated elevation change, the different experiments were compared to each other.

After scanning the bathymetry also samples were taken at the same locations as our areas of interest. A sampling grid was defined that consisted of sampling rows in the length and width of the tank to get an overview of the deposition in multiple directions (Figure 7). At each sampling spot, a sample was taken for grain size analysis. The grain size distribution of the samples was subsequently determined in the lab using the Malvern Mastersizer 2000. Also, the grainsize of the collected siphon samples were measured in the lab. After the samples were taken the surface was prepared for a new experiment.

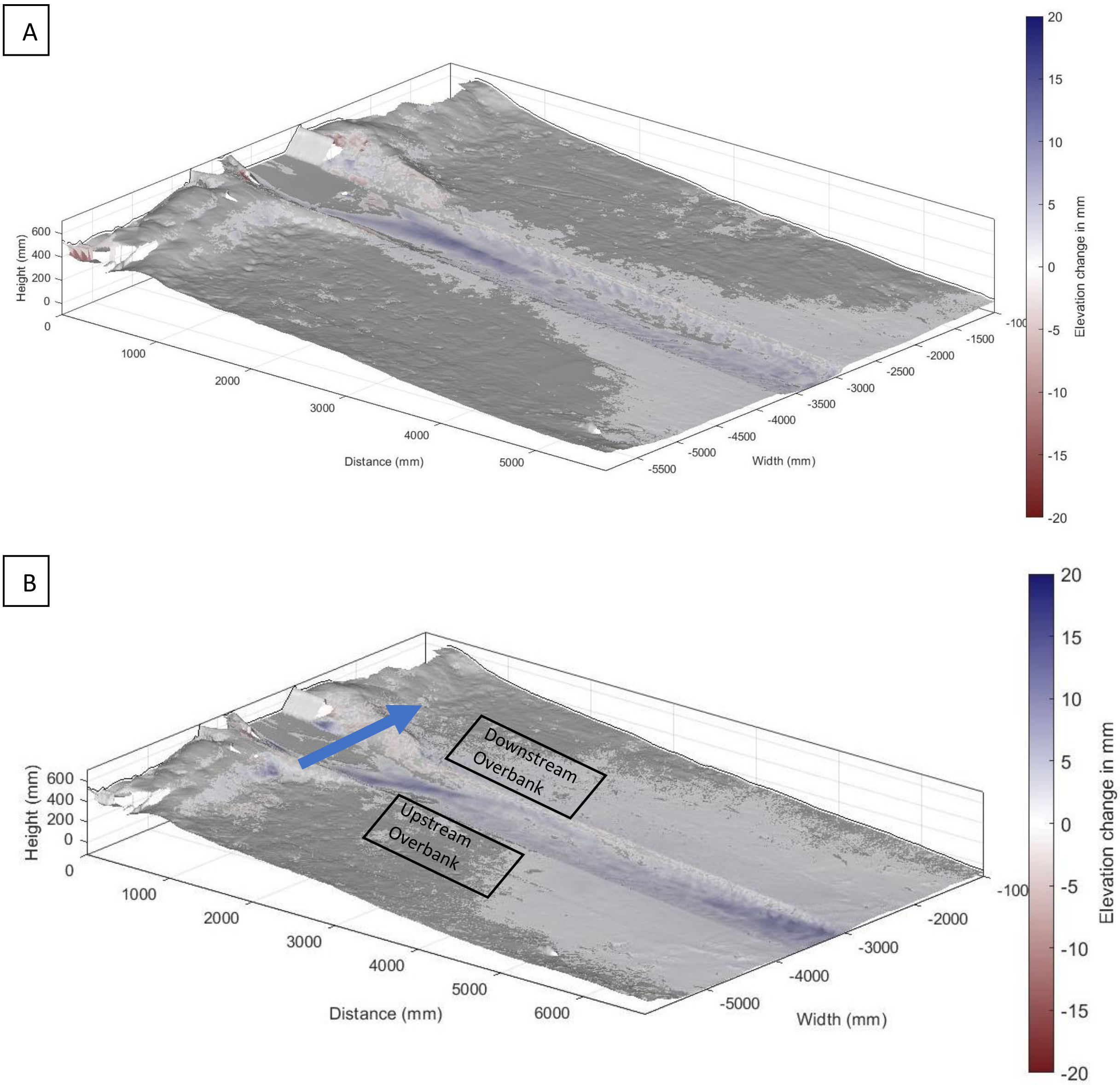


Figure 5, Result of the laser scan in a three dimensional display without (A) and with (B) a strong contour current. In figure B the areas of interest are indicated with the black squares. Figure B shows that more sediment ends up on the downstream overbank when a contour current is present. The channel depth for both figures is 7 cm.

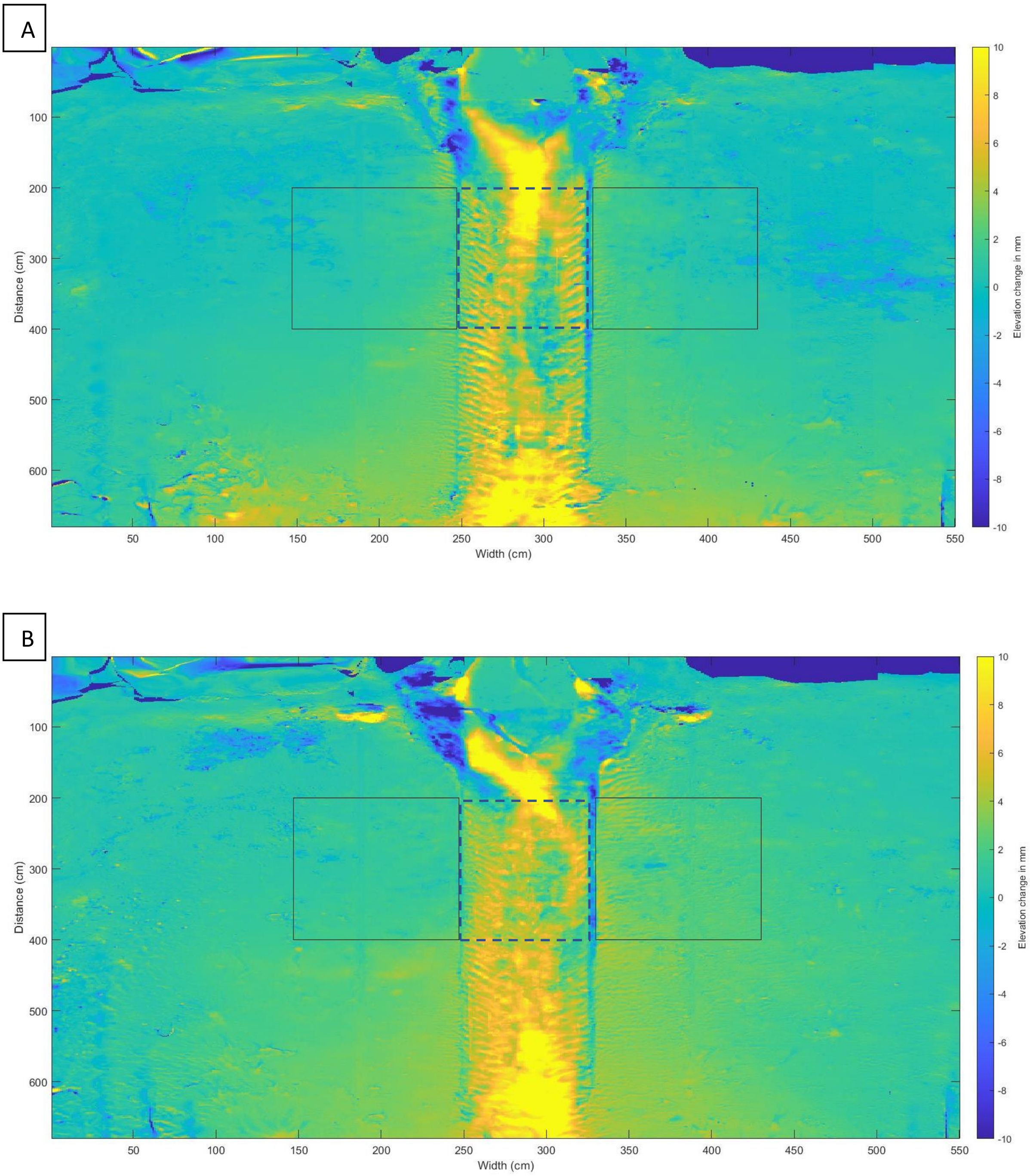


Figure 6, Results of the calculated volume difference of the laser scan of figure 8. The yellow color indicates a positive volume change, so, a sediment deposition. The black squares indicate the areas of interest on the overbanks, the dashed black square is the area of interest inside the channel. For the black squares the mean volume change is calculated. Channel depth is 7 cm. A has no contour current and B has a strong contour current. See all the scans in the supplementary figures.

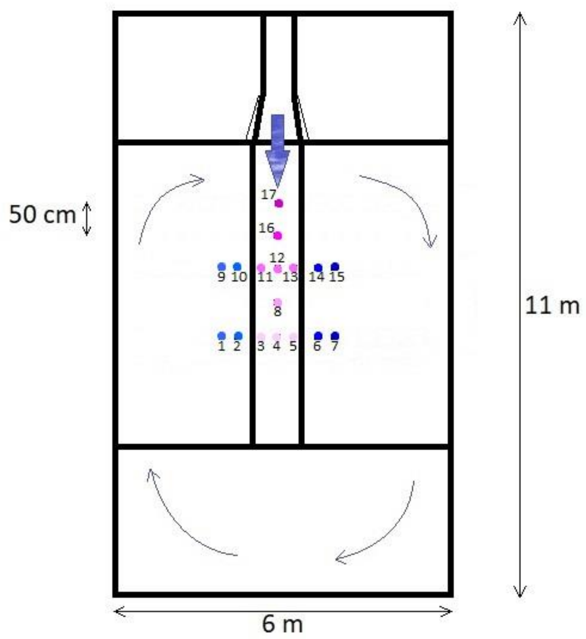


Figure 7, Overview of the flume tank. The dots are the sampling locations, numbered 1 to 17. In the vertical direction, the distance between the sampling locations is 50 cm and in the horizontal direction this is 30 cm. The different colors are also used in Figures 16 and 17 to show which measured sample comes from which sampling location. The big arrow indicates the inlet of the turbidity current. The thin arrows indicate the flow of the contour current.

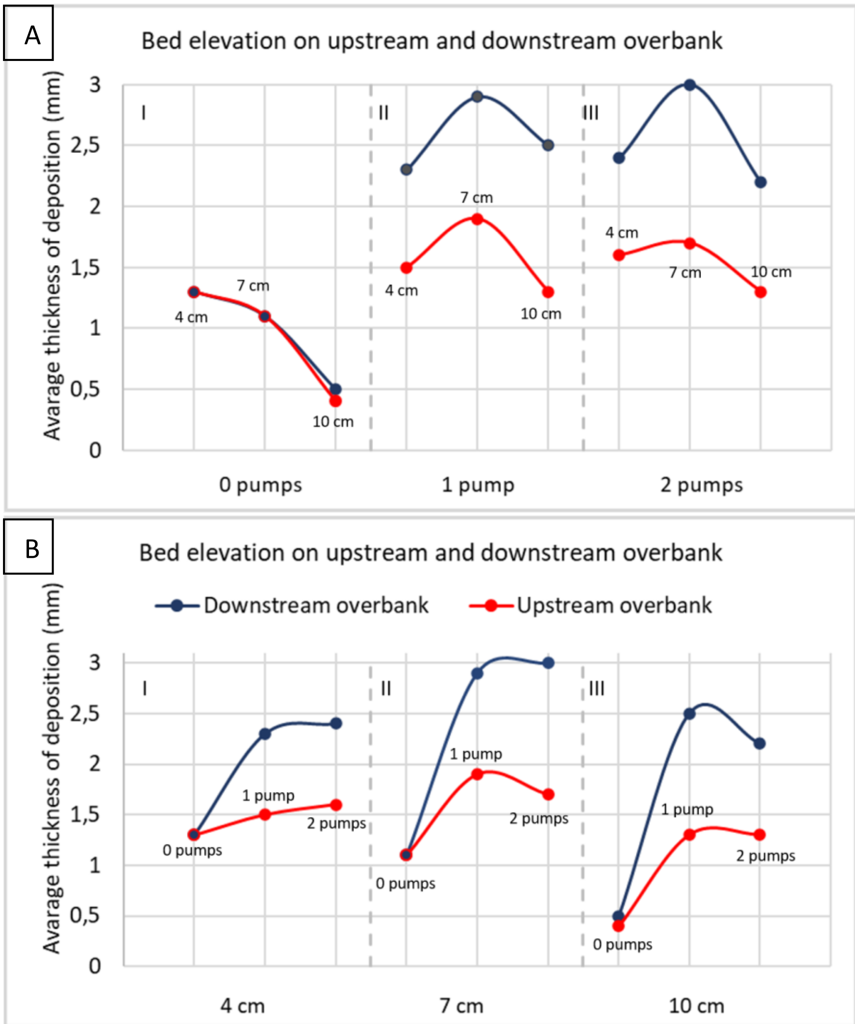
Results

Depositional patterns and volumes according to scans and cross sections

For all the experiments, the volumes of deposited sediment on the overbanks and in the channel are calculated according to the laser scans (Figure 8 and 9). Figure 8 shows that no contour current results in the same elevation on the upstream and downstream overbank (figure 8A I). Figure 8A I also shows that the mean elevation change decrease when the channel is deeper.

Figures 8A II and 8A III show that with a weak and a strong contour current, more sediment is deposited on the downstream and upstream overbank. Only subtle differences can be seen for the differences between a weak or strong contour current. On the downstream overbank more sediment is deposited than on the upstream overbank. Figures 8A II and 8A III also show non-monotonous behavior. It is seen that a change in channel depth from 4 to 7 cm results in more deposition on the downstream and the upstream overbank. However, with an increase of the channel depth from 7 to 10 cm a decrease in deposition is seen. So, a channel depth of 7 cm seems to be optimal for transporting sediment from the channel to the overbank directly next to the channel.

Figure 8B shows that the elevation change on the upstream overbank increases when the pump intensity increases at a channel depth of 4 cm (Figure 8B I). Also with a channel depth of 7 cm, more sediment is deposited on the downstream overbank (Figure 8B II) with a stronger contour current. The upstream overbank shows non-monotonous behavior again. A strong contour current doesn't increase the deposition on that overbank compared to a weak contour current. With a 10 cm deep channel, also on the downstream overbank non-monotonous behavior is seen. The weak contour current results in the most sedimentation on the downstream overbank (Figure 8B III).



	CD = 4 cm	CD = 7 cm	CD = 10 cm	
No CC	8	1/3	10	Figure A I
1 CC	7	2	5	Figure B II
2 CC	9	4	6	Figure C III

	CD = 4 cm	CD = 7 cm	CD = 10 cm
No CC	8	1/3	10
1 CC	7	2	5
2 CC	9	4	6
	Figure A I	Figure B II	Figure C III

Figure 8, Elevation on the downstream and upstream overbank. Figure A shows the different contour current intensities and figure B shows the different channel depths. During the experiment with a channel depth of 7 cm and 2 pumps 240 liters of sediment mixture was left in the tank. So, the amount of sediment is calculated as for a normal full tank.

Figure 9 shows the elevation of the bed on the downstream overbank and in the channel. This figure shows that when a contour current pump is switched on, there is more deposition on the downstream overbank as well as in the channel.

With a 7 or 10 cm deep channel, more sediment is deposited inside the channel when compared to an experiment with a channel of 4 cm when the contour current is switched on. The increase in sedimentation in the channel is due to reduced overspilling for deeper channels due to a better confinement (Figure 3).

It is seen that with a channel depth of 7 or 10 cm there is more sediment deposited in the channel with a weak contour current than with a strong contour current.

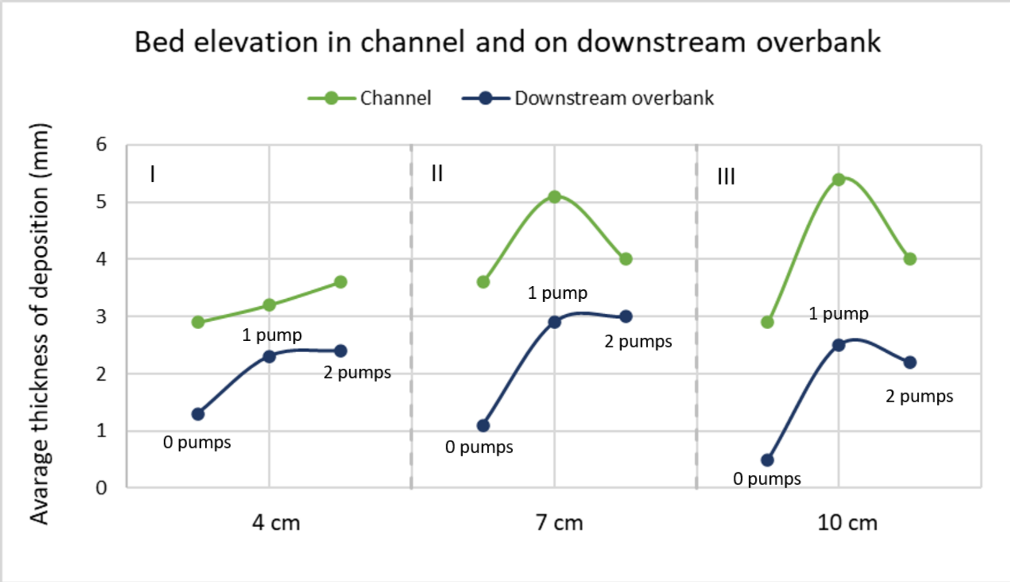


Figure 9, Elevation on the downstream overbank and in the channel.

I made cross section according to the laser scans, to see if there is also erosion in addition to deposition. Figure 10 shows the locations of the cross sections of figures 11-13. Figure 11-13 show experiments with a 10 cm deep channel and with no, a weak or a strong contour current respectively. The blue circles in figures 12 and 13 indicate locations of erosion compared to the experiment without a contour current (Figure 11). It is seen that most of the erosion takes place on the downstream overbank. Mainly with a weak contour current (Figure 12) the erosion on the downstream overbank turns out to be more present. Also, with a strong contour current (Figure 13) the downstream overbank erodes, but not as much as in the experiment with a weak contour current.

The green circles (Figure 12 and 13) indicate locations of additional deposition compared to the experiment without a contour current (Figure 11). The green circles in Figure 12 and 13 show that mainly on the downstream overbank the deposition increases when a contour current is present (which is also seen in Figure 8). This is in accordance with the results in Figure 8 and 9. Figure 13 shows that inside the channel, the sediment deposition is mainly on the sidewall of the upstream overbank, where in figure 12 the sediment deposition is on the sidewalls of both overbanks and in the middle. This indicates that with a stronger contour current more sediment is deposited on the wall of the upstream overbank. For all the scans and cross sections, see the supplementary figures.

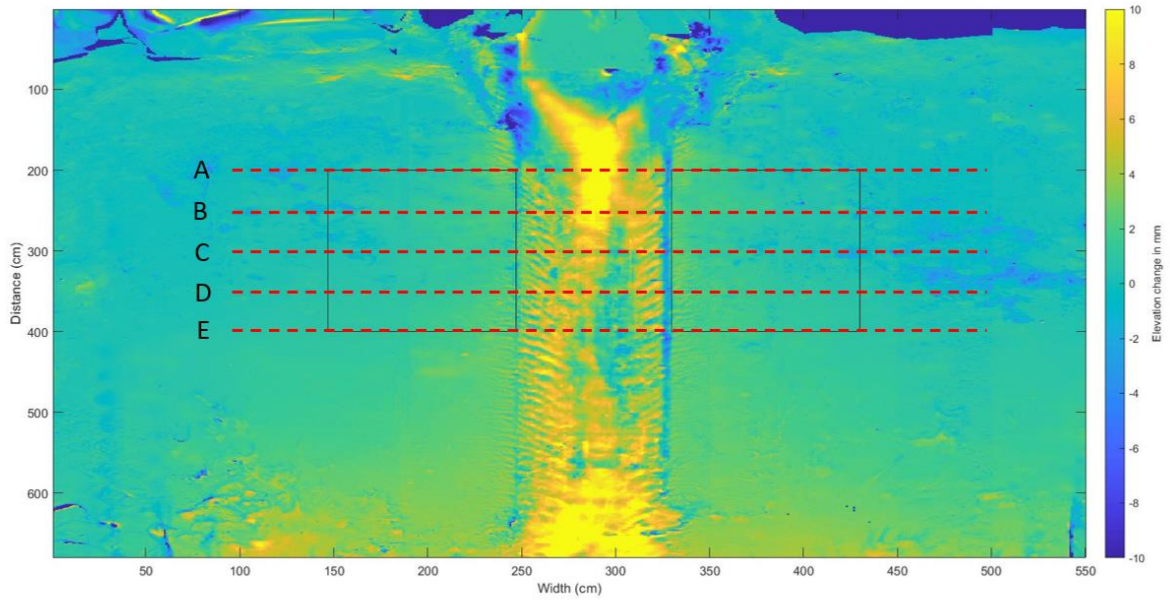


Figure 10, Difference map resulting from the laser scans. The red lines indicate the locations of the cross sections.

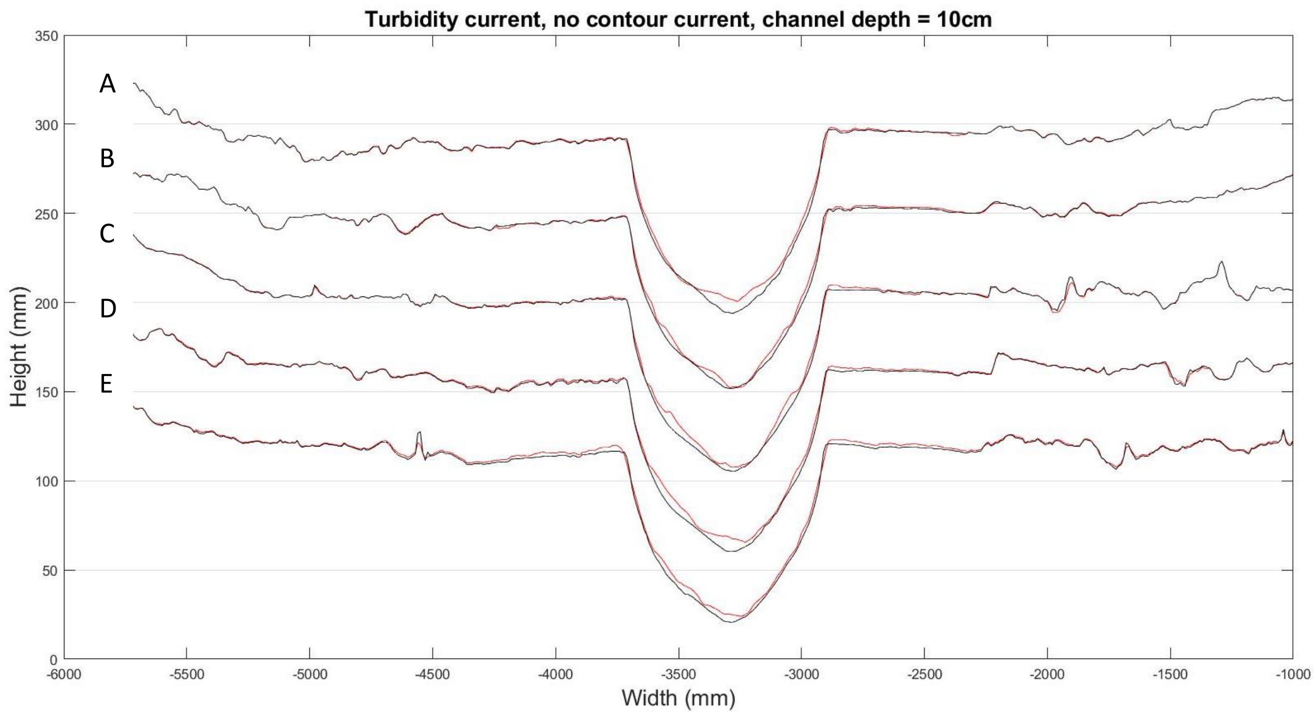


Figure 11, Cross sections through the channel. Cross sections A-E correspond to the locations indicated in figure 18. Turbidity current only, Channel depth of 10 cm.

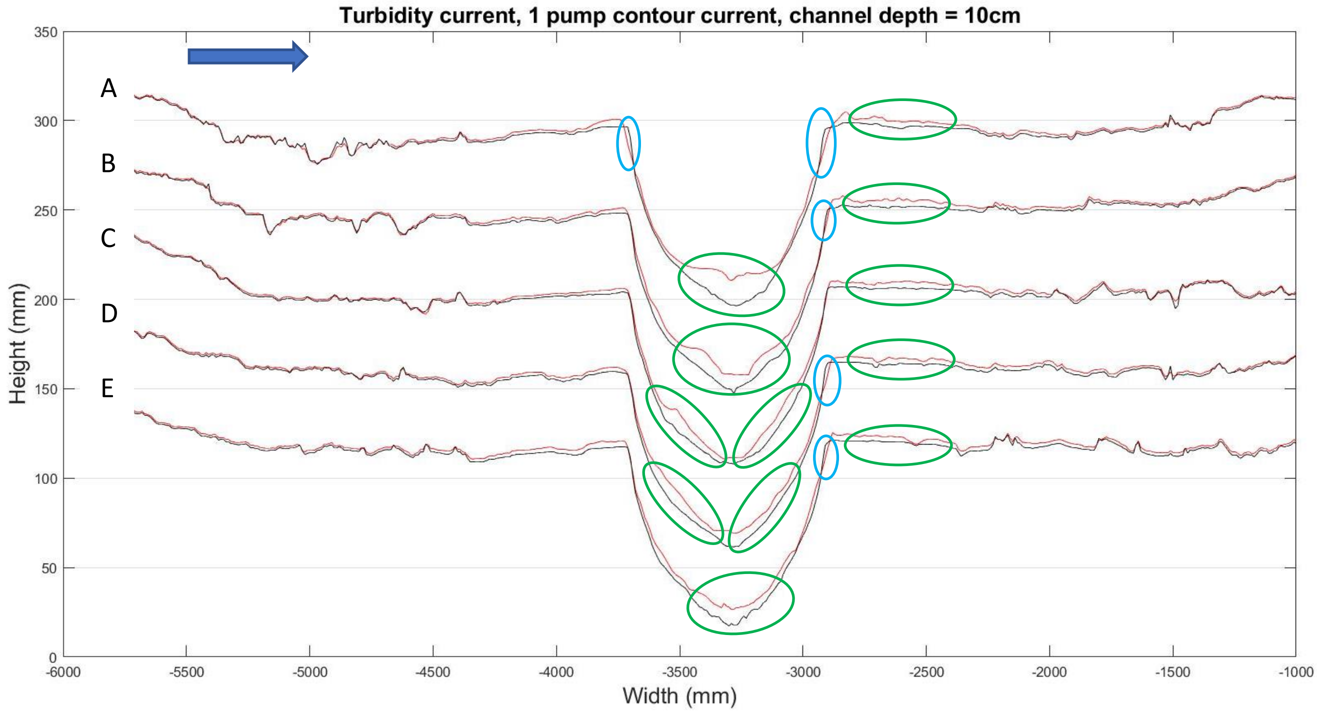


Figure 12, Cross sections through the channel. Cross sections A-E correspond to the locations indicated in figure 18. Turbidity current with a weak contour current. Channel depth of 10 cm.

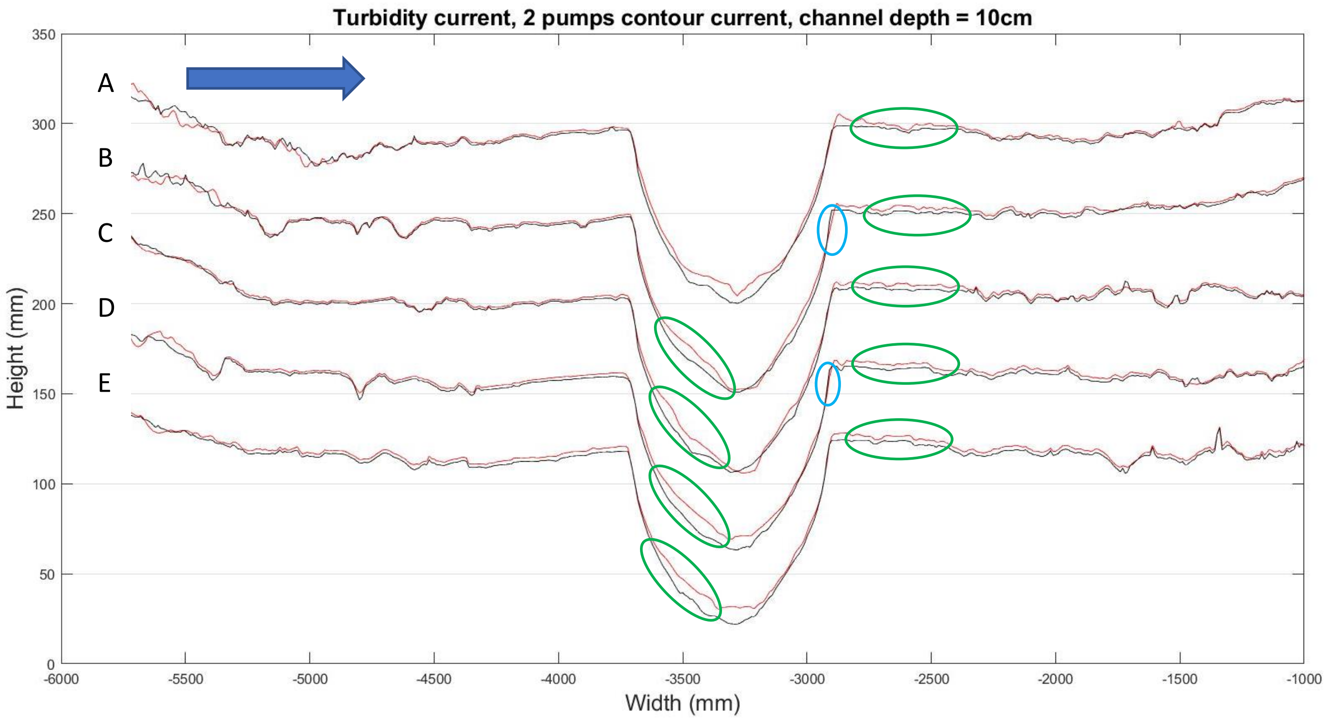


Figure 13, Cross sections through the channel. Cross sections A-E correspond to the locations indicated in figure 18. Turbidity current with a strong contour current. Channel depth of 10 cm.

Grainsizes of the samples

Figure 14 shows the grainsize distribution of all the sampling locations of the experiment with a weak contour current and a channel of 7 cm deep. Figure 14 shows that a clear segregation can be made for the grainsizes of the grains inside or outside the channel. The grains inside the channel have a size of 65-80 µm and outside the channel the grains are 35-55 µm. Also the grains on the upstream overbank are smaller than on the downstream overbank. The yellow profile indicates the initial grainsize of the silt and the red profile is the silt that was still in the water column after the experiment. It is seen that the grains in the channel are larger than the initial grainsize and that the grains on the overbanks are smaller than the initial grainsize. The grains that stay behind in the water column are the smallest grains. The red line indicates the grainsize of the mode for one single sampling location. The software of the Malvern gives de mode directly and so for every sample the mode can be used to plot in figures. The mode is used so that for every sample location a point can be plotted instead of a line (Figures 16, 17, and 21). This makes a comparison between the different experiments more easy.

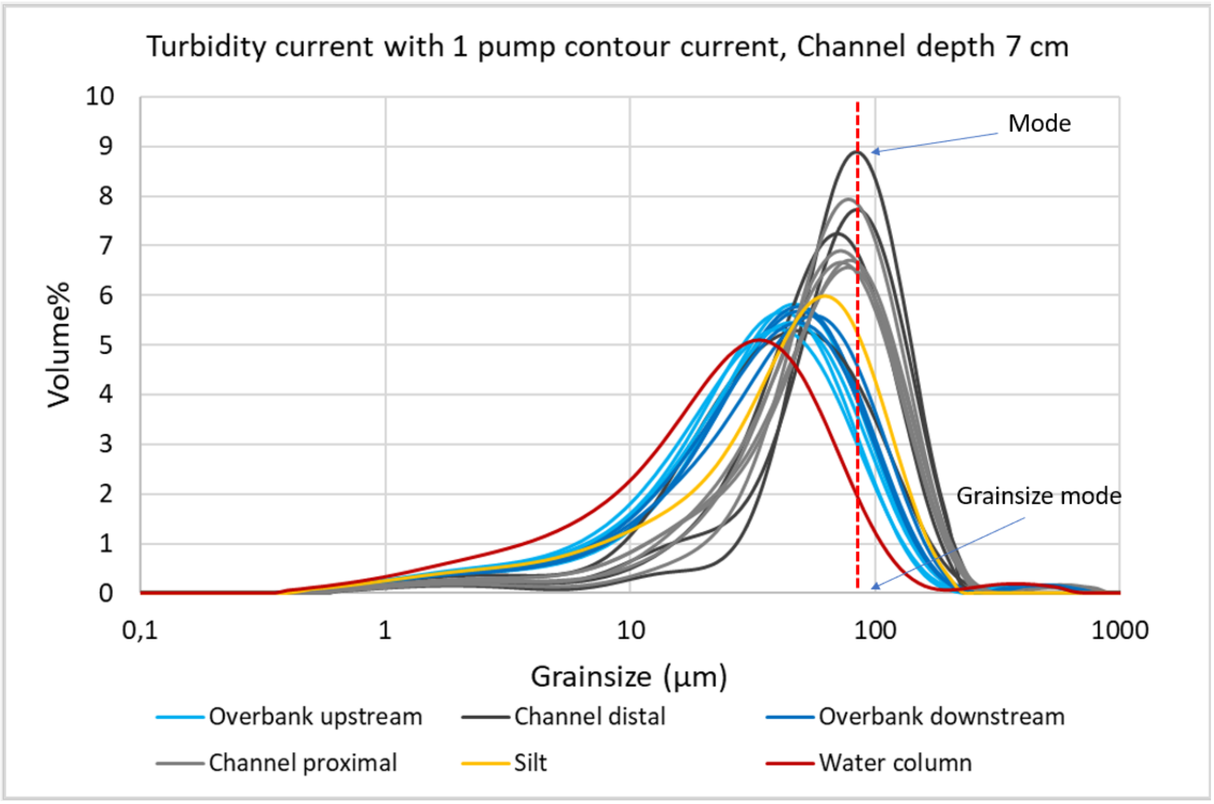
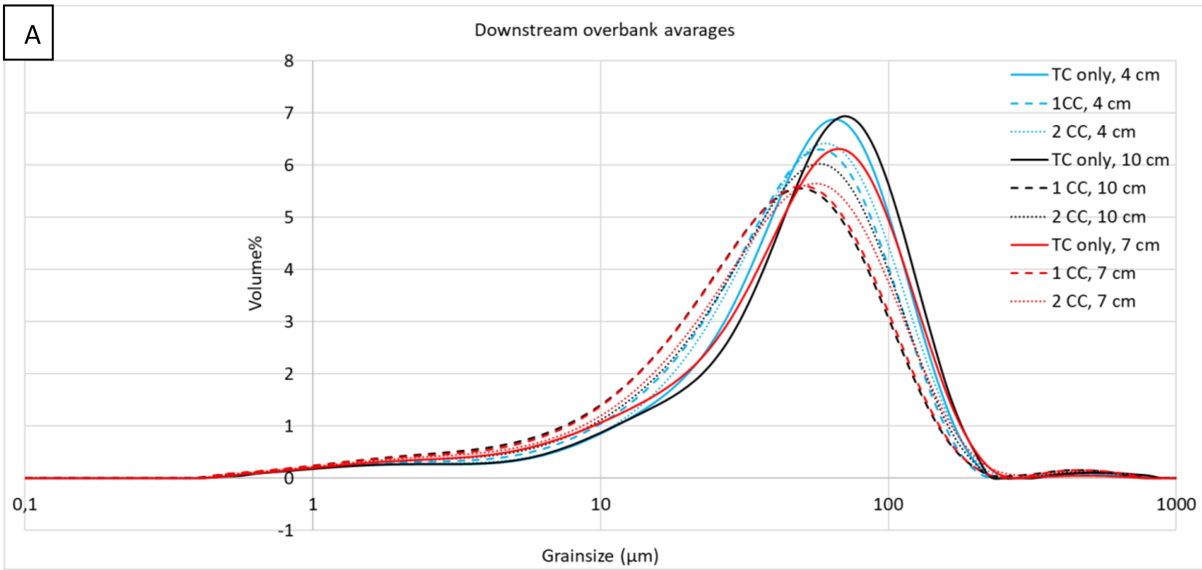


Figure 14, Grainsize distribution of one experiment. The yellow line indicates the grainsize distribution of the silt prior to the experiment. The dark red profile indicates the sediment that is in suspension in the water column after the experiment (the mode of this profile is around 32 µm). The dashed red line indicates the position of the mode of one sample. The mode is used to make Figures 10, 11, and 13. The figure shows that The grainsizes in the channel are larger than the grainsizes on the downstream overbank.

Figure 15 compares the grainsizes on the downstream (Figure 15A) and upstream (Figure 15B) overbanks. The main learning from Figure 15 is that grainsize is coarsest on both overbanks in absence of a contour current. Secondary, the overbank grainsizes are finer on the upstream overbank compared to the downstream overbank when the contour currents are present. On the upstream overbank, there is little difference in grainsize for either a weak or strong contour current. On the downstream overbank there is a difference of maximum 10 µm in deposited grainsize for a weak or strong contour current (Figure 15A). The figure shows that with weak contour current, the grainsize on the downstream overbank is the smallest. With a strong contour current, the grains on the downstream overbank are a bit larger than with a weak contour current. Also, the channel depth has an influence on the grainsize that ends up on the downstream overbank. With a deeper channel, the amount of coarse grains that ends up on the downstream overbank decreases. This will result in a smaller grainsize on the downstream overbank for a deeper channel. Figures 16 and 17 show even more detailed figures of the grainsizes inside and outside the channel.



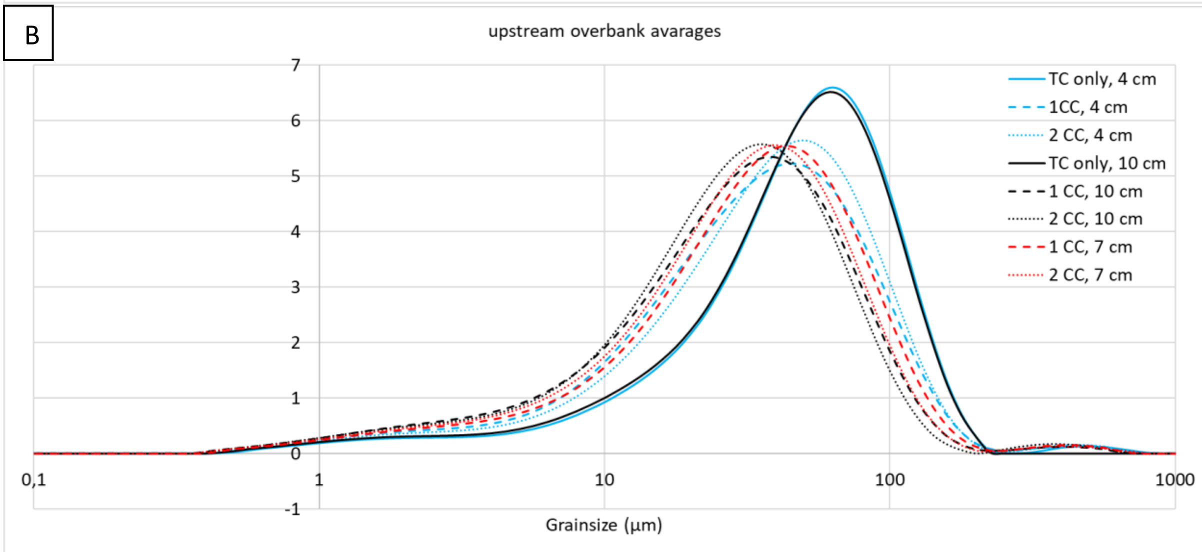
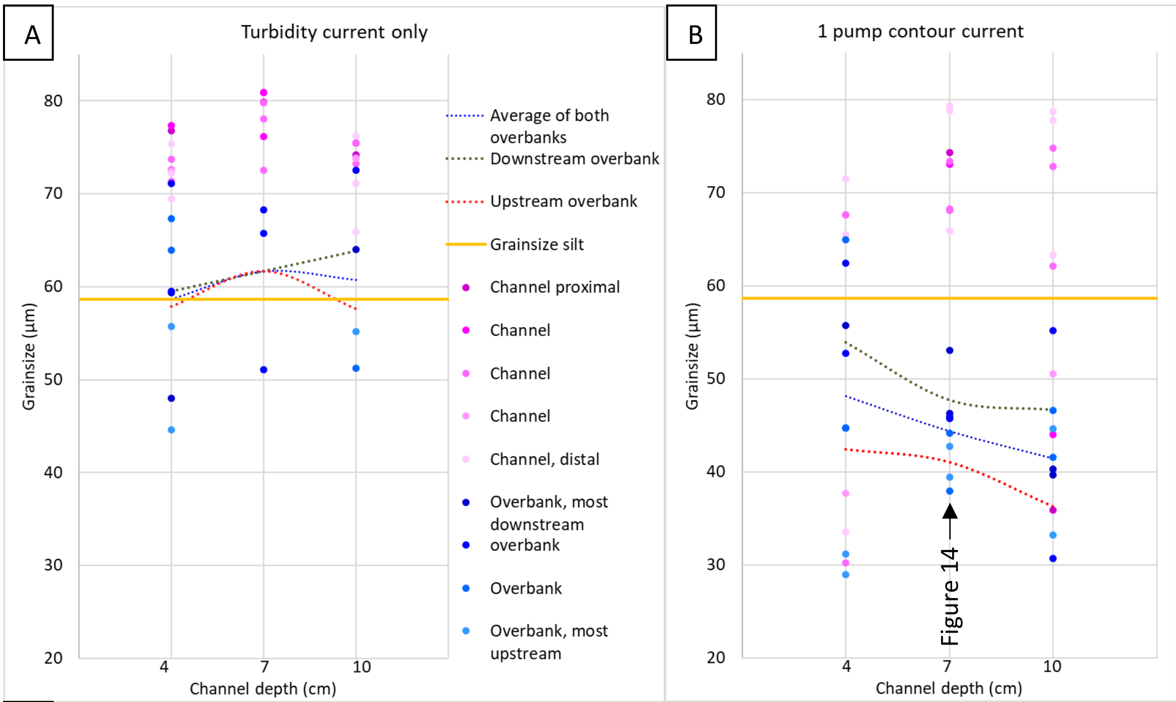
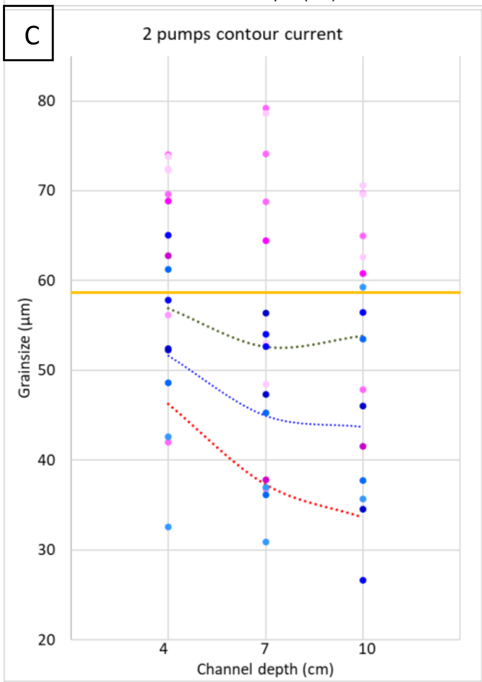


Figure 15, A and B show averages of the grainsize distribution for all the samples taken on the downstream and upstream overbank respectively.

Figure 16 Shows the results of the grainsize analysis of all the experiments. In figure 16A, no contour current is present, in figure 10B there is a weak contour current and figure 16C shows the result for a strong contour current. Figure 16 shows again that with the absence of a contour current, the grainsizes that end up on the overbank are larger than with a contour current. The sediment that ends up on the overbank is almost the same as the starting grainsize of the silt without a contour current. The starting grainsize distribution of the silt is indicated with the yellow line. When a weak or strong contour current is present, the grainsizes on the overbank decrease below the yellow line of the silt. Also, it is seen that the grainsizes decrease when the channel depths increase.

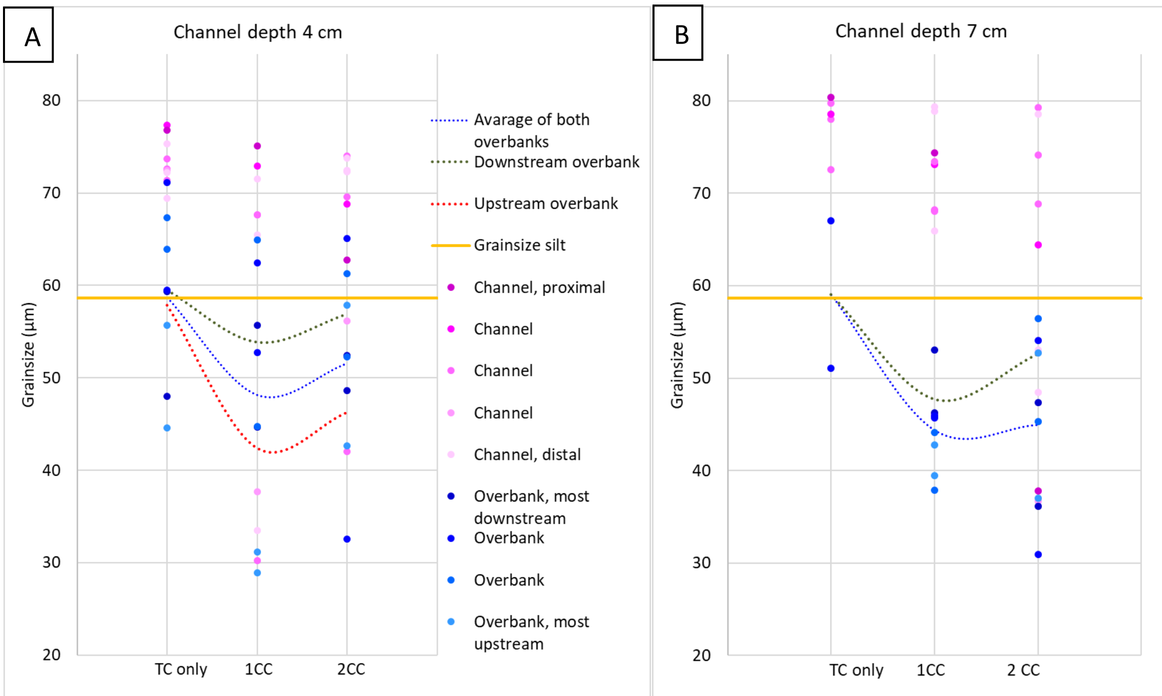


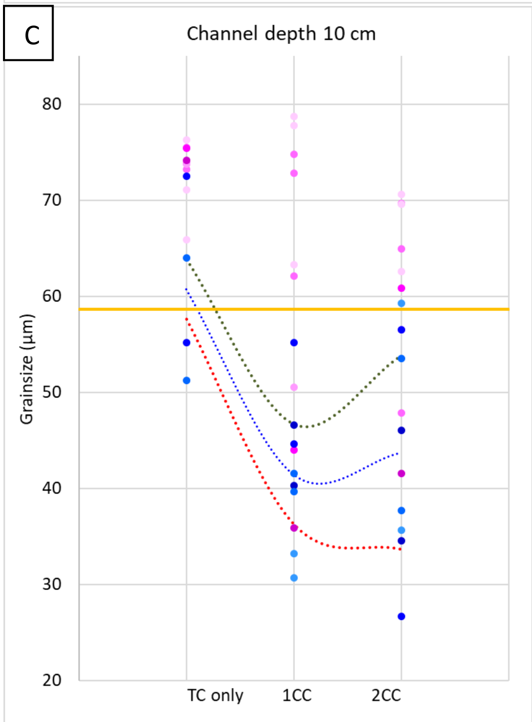


	CD = 4 cm	CD = 7 cm	CD = 10 cm	
No CC	8	1/3	10	Figure A
1 CC	7	2	5	Figure B
2 CC	9	4	6	Figure C

Figure 16, A Shows the mode of the grainsizes of the experiments of only a turbidity current. B shows the mode of the grainsizes of the experiments with a weak contour current. C shows the mode of the grainsizes of the experiments with a strong contour current. The yellow line indicates the grainsize of the silt before using it for an experiment. The colors of the data points correspond to the colors in Figure 7.

Figure 17 shows three graphs with a difference in contour current strength at one channel depth. When there is no contour current, the graphs show that the mean grainsize on the overbank is almost equal to the initial grainsize of the silt when looking at the blue line. With a contour current, the grainsize decreases (Figure 17). The green line shows the mean grainsize of the downstream overbank. It shows that the grainsize on that overbank decreases when a weak contour current is present. It also shows that with a strong contour current, the grainsize increases again a bit (Figure 17). Also, it is seen that the differences between no contour current or a contour current are larger when the channel depths become larger.





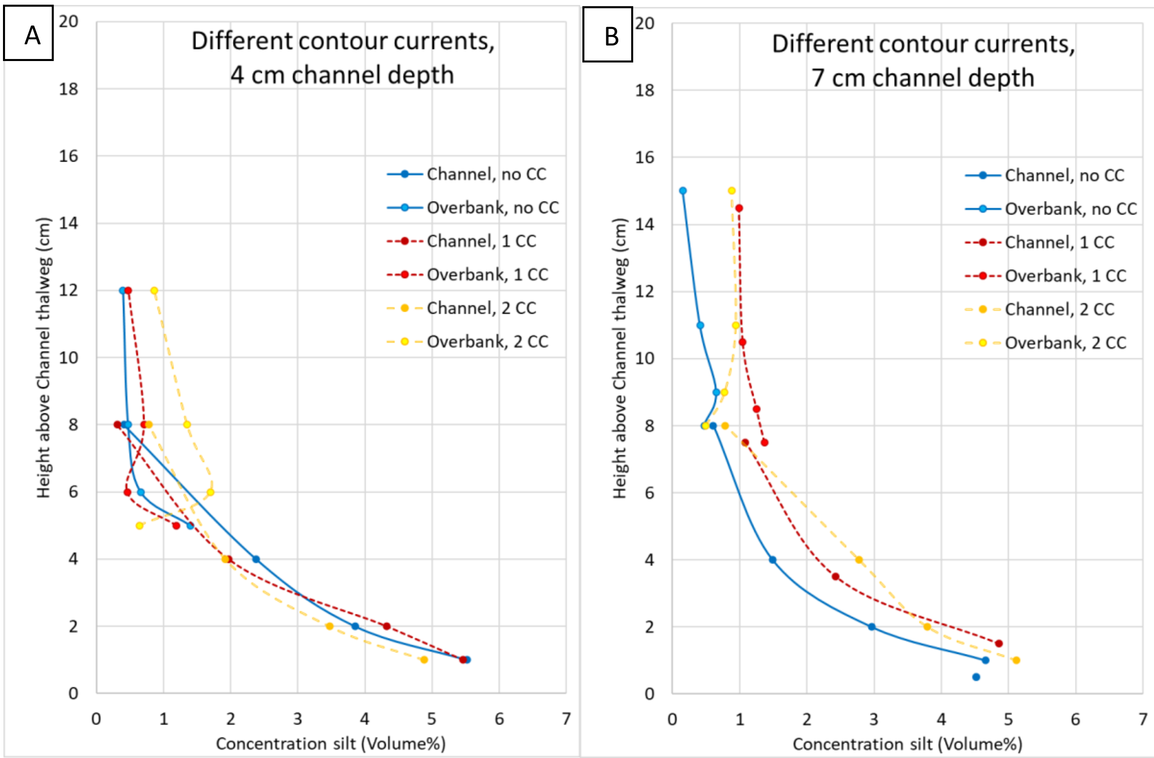
	CD = 4 cm	CD = 7 cm	CD = 10 cm
No CC	8	1/3	10
1 CC	7	2	5
2 CC	9	4	6
	Figure A	Figure B	Figure C

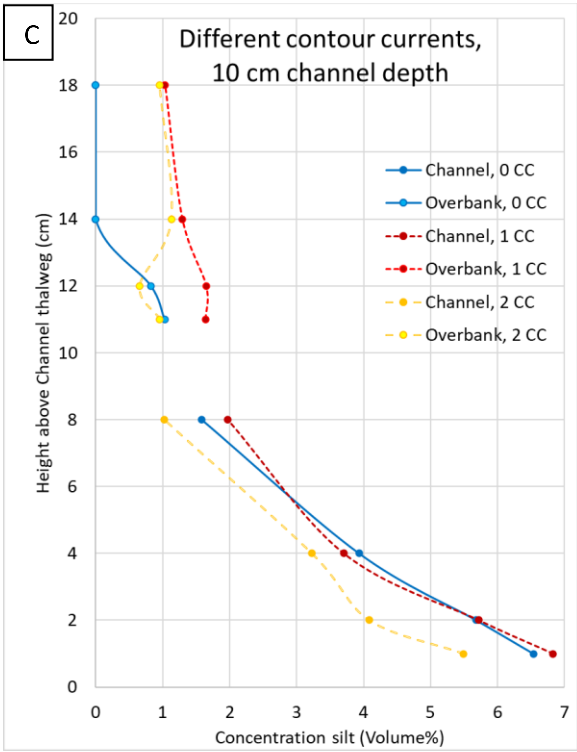
Figure 17, A Shows the mode of the grainsizes of the experiments with a channel depth of 4 cm. B shows the mode of the grainsizes of the experiments with a channel depth of 7 cm. C shows the mode of the grainsizes of the experiments with a channel depth of 10 cm.

Siphon samples and concentration profiles

Firstly, the results for the different channel depths are compared (Figure 18). These figures show that a stronger contour current with one or two pumps result in larger concentrations of the turbidity current on the downstream overbank. Especially, for a channel depth of 7 and 10 cm it can be seen that all the way up to the 8 cm syphon the concentration in the turbidity current is still around 1 %Vol. Also, in the 4 cm deep channel it is seen that for the highest contour current velocity a large amount of sediment is blown out of the channel.

In the channel it is seen that the concentrations are up to almost 7 %Vol when the channel depth is 10 cm, where for the experiments with channel depths of 4 and 7 cm the maximum volume% is around 5. The reason for this is that the turbidity current in a channel of 10 cm depth is more confined. The influence of the contour current is less strong and lateral spreading is more difficult. Most of the turbidity current will not be blown out and stays in the channel.

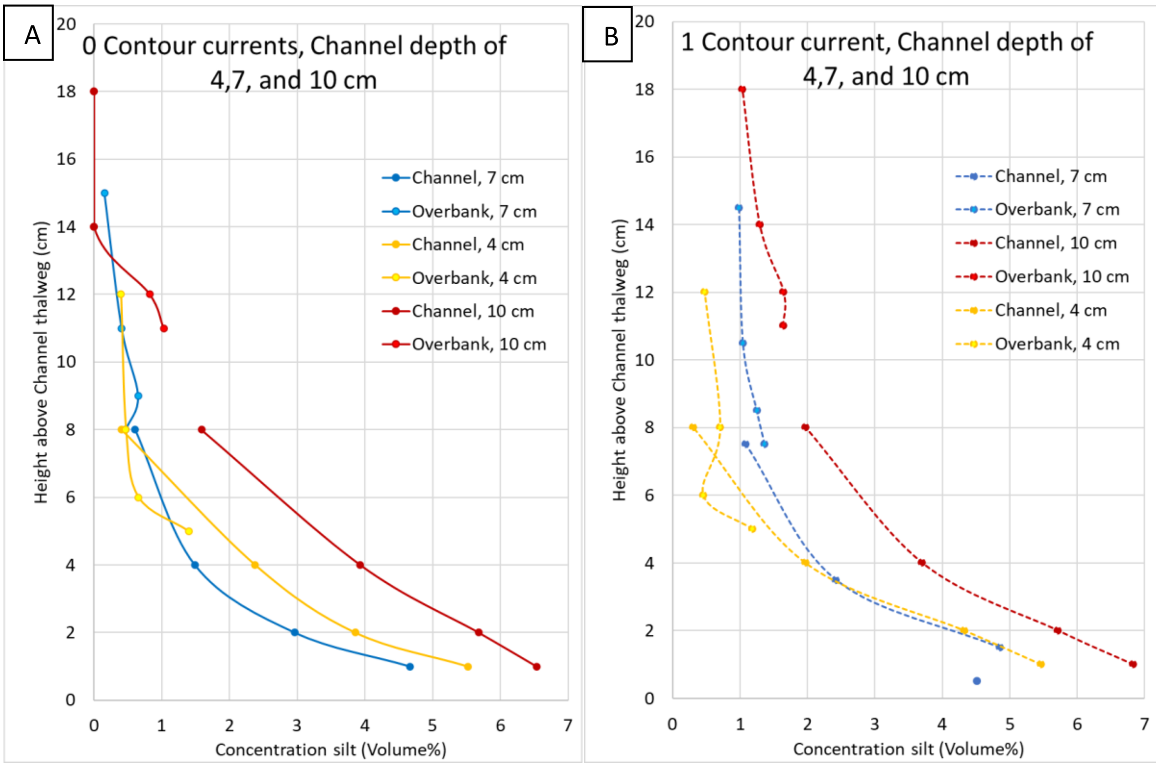


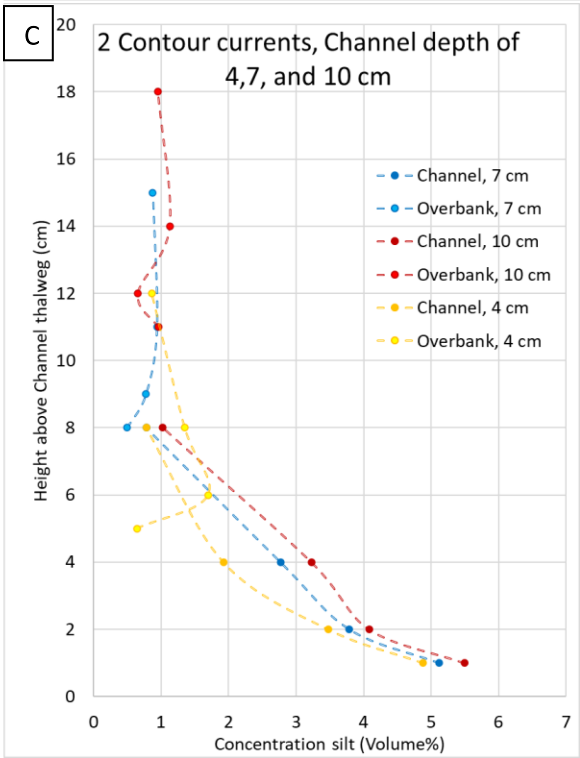


	CD = 4 cm	CD = 7 cm	CD = 10 cm
No CC	8	1/3	10
1 CC	7	2	5
2 CC	9	4	6

Figure 18, Concentration measurements compared for different channel depths. Figure A shows the results for a 4 cm deep channel. Figure B shows the results for a 7 cm deep channel. Figure C shows the results for a 10 cm deep channel. Note that in figure B the solid line is not plotted through the lowest point, this is because the siphon tube was clogged with sediment. The matrix shows which experiments have been shown.

In Figure 19 the same results as for Figure 18 are used but they are shown different, in one subfigure, now the concentrations are shown for a weak, strong or no contour current. Figure 19A shows that without a contour current there is small amount of sediment blown out of the channel. With a 10 cm deep channel there is even no sediment in the two highest tubes on the channel. On the overbanks of a 4 or 7 cm deep channel only 0.5 volume% ends up in the tubes on the overbanks.





	CD = 4 cm	CD = 7 cm	CD = 10 cm
No CC	8	1/3	10
1 CC	7	2	5
2 CC	9	4	6

Figure 19, Concentration measurements compared for different contour current velocity (Figure A, B, and C). Figure A shows the results for a turbidity current without a contour current. Figure B shows the results for a weak contour current. Figure C shows the results for a strong contour current. The matrix shows which experiments have been shown.

With both a weak and strong contour current the amount of sediment in the tubes increases over 1 volume% (Figures 19B and 19C). Figure 19B shows that the concentration on the downstream overbank increases when the channel becomes deeper. Figure 19C shows almost vertical lines of the concentration on the overbank. This indicates that the contour current is so strong that the turbidity that is blown out of the channel has a constant concentration over the height of 8 cm.

Grainsizes of the siphon samples

Figure 20 shows the grainsizes of the siphon samples. It shows that the grainsizes in the turbidity cloud are larger inside the channel than on the overbanks. In the channel it is seen that the largest grainsizes are at low elevations of only 1 or 2 centimeters above the bed. There is no gradual decrease of grainsize compared to the height inside the sediment cloud. On the overbank there is not even a decrease in grainsize. It seems that the grainsize increase towards the top. When a contour current is switched on, the grainsizes on the overbank are larger than without a contour current. Within the channel this increase cannot be noticed.

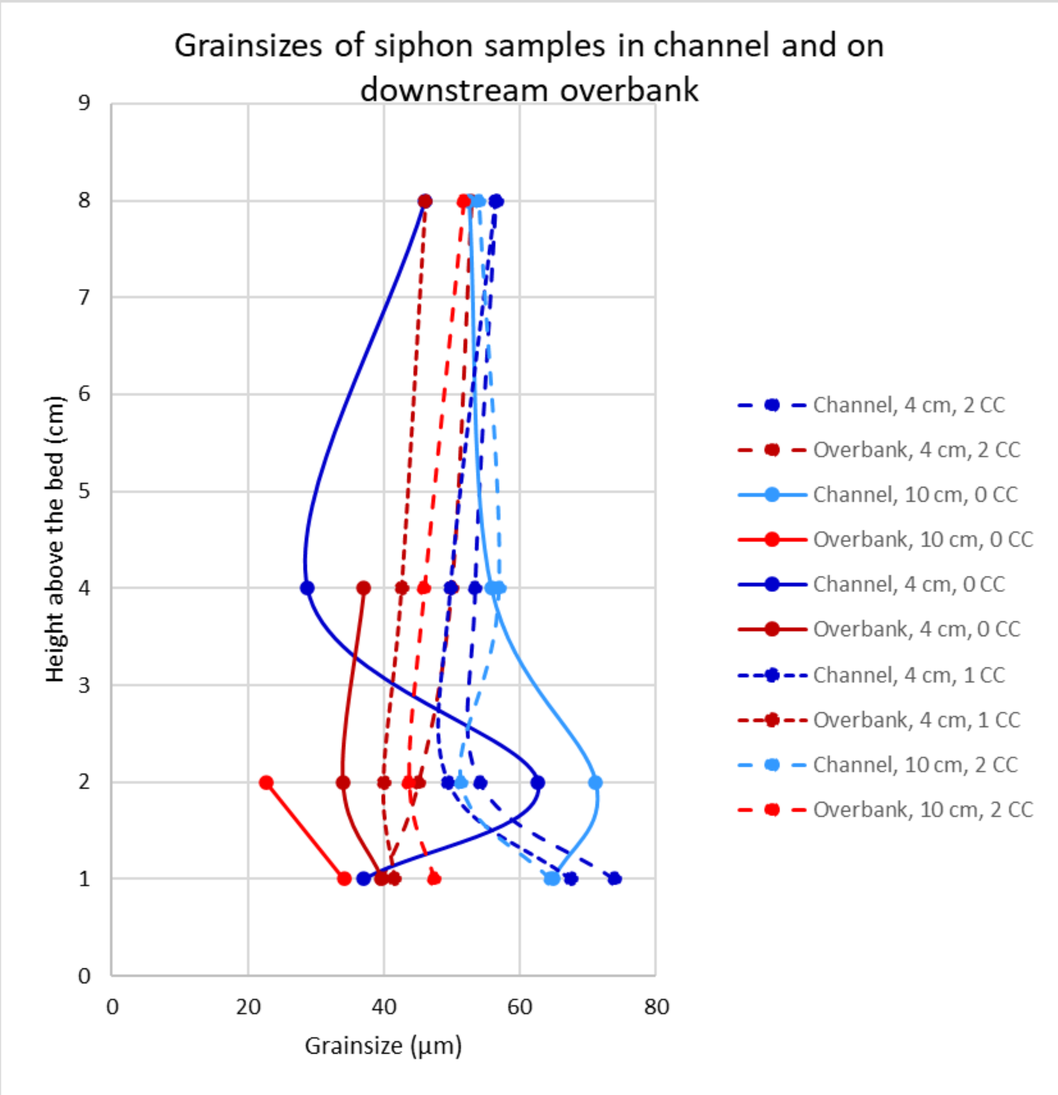


Figure 20, Grainsizes of siphon samples inside the channel and on the downstream overbank.

Figure 21 compares the different experiments with each other. All the different measurements are plotted as points again for a better comparison between the experiments. It shows that the grainsize in the siphons on the overbank increase when a weak or strong contour current is present. With a 4 cm deep channel the grainsizes in the siphons in the channel increase as well, however, in the 10 cm deep channel the grainsizes decrease a little bit.

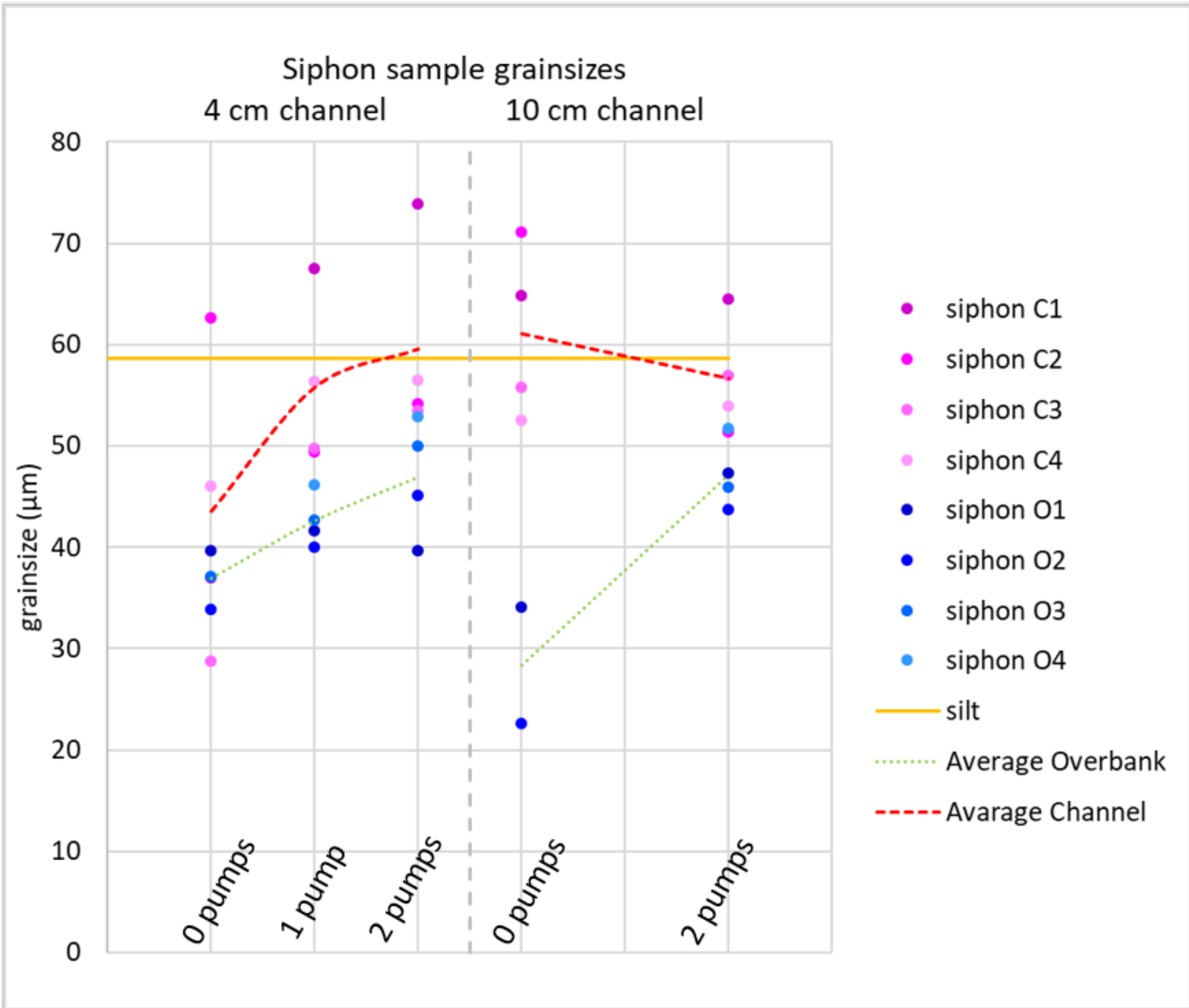


Figure 21, All the colored dots indicate the mode of a different siphon height. Siphon C1 is the lowest siphon in the channel, so 1 cm above the bed. Siphon C2 is 2 cm above the bed. Siphon C3 is 4 cm above the bed and siphon C4 is 8 cm above the bed. Siphon O1-O4 are at equal height above the bed, but on the downstream overbank.

Discussion

Depositional patterns and volumes according to scans and cross sections

The results shown in figure 8 can be related to the degree of confinement. When the channel is deeper the turbidity current is more confined and the volume that is able to be transported out of the channel is lower. This is seen when no contour current is present (Figure 8A I). The deepest channel results in to lowest amount of deposited sediment on both the downstream and upstream overbank. At the 10 cm channel, little is deposited on the overbanks when no contour current is present, this is because the turbidity current is well confined and hardly overspills onto the overbanks. But also when a contour current is present (Figure 8A II and 8AIII) the lowest amount of sediment is deposited on the upstream overbank when the channel is 10 cm deep. This also relates to the confinement, when the turbidity current is less confined, more sediment can escape the channel on the upstream overbank. This can also be seen from the velocity data (Figure 22). With a stronger contour current or with a deeper channel, the velocity profile does not show any velocity on the upstream overbank.

For a 7 or 10 cm deep channel, the velocity profiles also show that the turbidity current is fastest when a weak contour current is present (Figure 22). It is expected that when the turbidity current is faster, it is more difficult for the contour current to blow sediment out of the channel. However, the turbidity current is also thicker, and so, less confined, which can result in more sedimentation on the downstream overbank. For a 4 cm deep channel this is not the case, the profile with a strong contour current is the highest, this can result in the most sedimentation because the turbidity current is the least confined.

It is also seen that more sediment is deposited on the upstream overbank when a contour current is present compared to the experiments without a contour current (Figure 8). This is not expected. I would expect that more sediment is deposited on the downstream overbank but not on the upstream overbank. This result is interpreted as sediment that was in suspension and is deposited after a while of circulating in the tank. The grainsize data supports this, since the grainsizes of the most upstream samples is around 30 µm (Figure 16 and 17) and this is almost equal to the grainsize inside the water column after an experiment (Figure 14).

When comparing the sedimentation in the channel and on the downstream overbank (Figure 9) it is seen that when a contour current pump is switched on, there is more deposition on the downstream overbank as well as in the channel. So, when there is no contour current, the turbidity current is bypassing over a longer distance. A higher downstream velocity of the turbidity current is expected, however, the velocity data (Figure 22) does not show higher velocities when no contour current is present, contrary, we find the highest velocities when a weak contour current is present for channels of 4 and 10 cm deep. When comparing the deposition inside the channel (Figure 11-13) to the models of Chen et al. (2020) there are characteristics of lateral accretion on both the upstream and the downstream overbank. With a 10 cm deep channel most of the deposit is on the sidewall of the upstream overbank and with a 4 cm deep channel most deposition is on the downstream overbank. In our experiments it is seen that on the downstream overbank more sediment deposited when the contour current is switched on. However, in our experiments there is also more channel infill when the contour current is switched on, which is in contrast to the statement of Fuhrmann et al. (2020). They suggest that that when the contour current is dominant there should be more sediment deposited on the forming a drift and when the turbidity current is dominant the channel would fill in with more sediment.

The volume calculations (Figures 8 and 9) and the cross sections (Figures 11-13) both show that most sediment is deposited in the channel and on the downstream overbank. However, the cross sections also show that the downstream overbank is eroded more than the upstream overbank for a channel of 10 cm deep (Figure 12 and 13). This erosion can be explained by the steepness of the sidewalls of the channel. The sidewalls of the 10 cm deep channel are steep and likely to erode compared to a 4 cm deep channel. The 4 cm deep channels are less steep and so they are more suitable for deposition on the sidewalls (Figure 13-15 of Supplementary Figures). The sidewalls of the 10 cm deep channel become less steep when they are eroded and on that sidewalls deposition can be expected. These patterns of erosion and deposition may indicate the direction of channel migration. However, we should be careful to write an interpretation on channel migration directions based the erosion and deposition seen in these cross sections. The sediment used for channel preparation was a mix of silt up to coarse sand of which the grainsize is not known and in shaping the channel it was pushed together with the template. Also with the low Froude number turbidity currents that were made are these experiments not set up for studying channel migration. An option for future studies on the channel migration direction would be to execute multiple experiments in succession to show if any channel migration patterns are possible in this experimental setup.

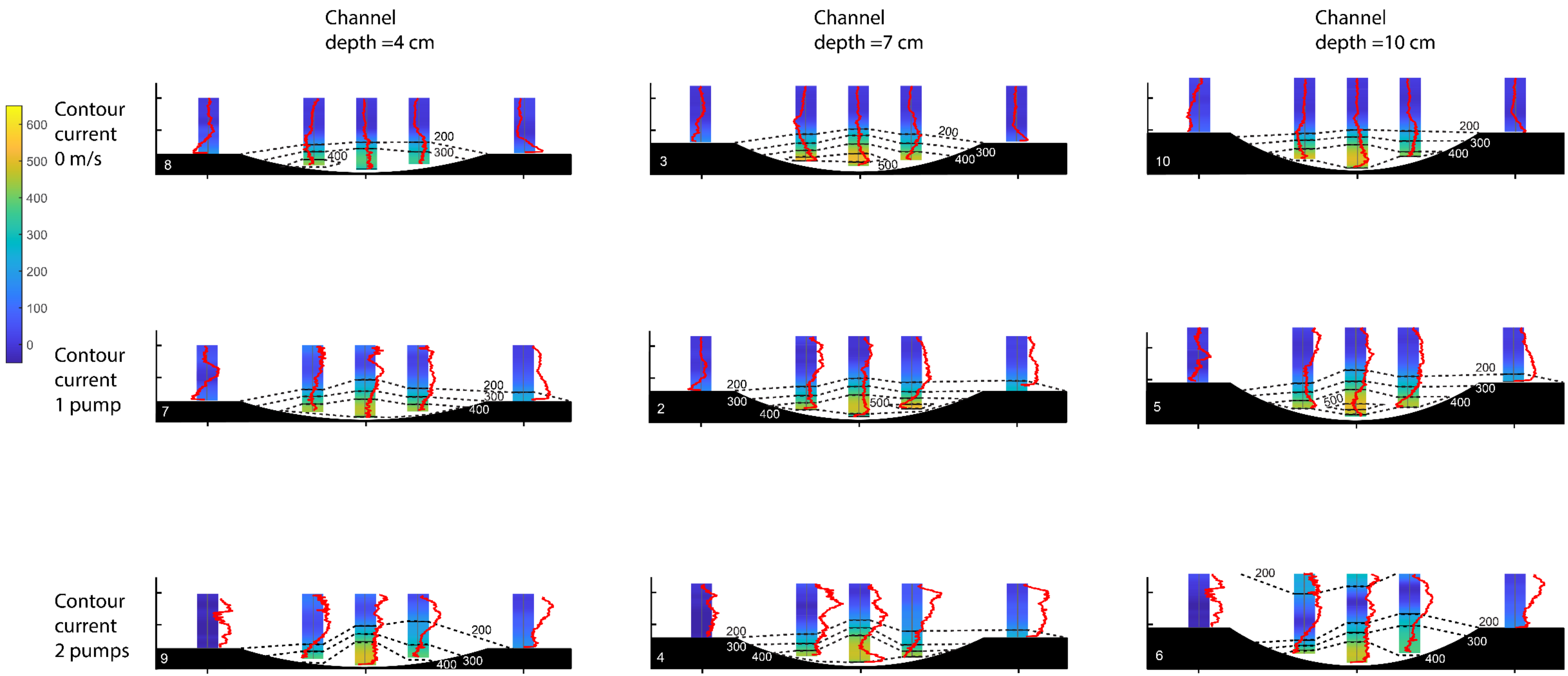


Figure 22, Velocity profiles measured by P.H. Adema with the UDOP (unpublished). When a contour current is present it flows from left to right. Blue to yellow colors indicate the downslope velocity of the turbidity current. Red profiles indicate the across slope velocity of the turbidity current deflected by the contour current.

The scans and cross sections (see all the scans and cross sections in the supplementary figures) also show that more sedimentary structures are present on the downstream overbank, Which is in agreement with Fonnesu et al. (2020) and Normandeau et al. (2019), where they also found structures on the downstream overbank. According to Stow et al. (2009) and Rebesco et al. (2014) straight, undulatory, and starved ripples can be found with the flow velocities of maximum 0.5 m s^{-1} and the grainsizes we used. On the downstream overbank these structures were found.

Grainsize analysis of sediment samples

Figure 15 shows little difference in grainsize on the upstream overbank for either a weak or a strong contour current. This is maybe possible due the circular flow of the sediment. In 150 seconds the sediment can travel one circle in the tank. So, the sediment that is deposited on the upstream side of the channel can also be sediment that was is suspension and was deposited later. This results in small grainsizes on the upstream overbank.

Figures 16 and 17 show that with a weak or strong contour current the grainsizes of the sediment on the overbanks decrease. There is no (or hardly any) sorting between the channel and the overbank in absence of a contour current. The grains on the overbanks after an experiment without a contour current are almost the same size as the size of the starting silt (Figure 16A) because there is no contour current that can affect the turbidity current. It could be that there is another sorting mechanism than with a contour current, although the sorting could be more subtle. Our observations are in line with Fonnesu et al. (2020), who shows that there is a dense flow in the channel that consists of coarser material. The large suspension cloud that reaches the downstream overbank consists of finer grains. This results in accumulation of fine-grained sediments on the downstream part of the channel complex. The mechanism responsible for this sorting of grains is winnowing (“Definition of WINNOW” 2023). This mechanism means that due to the contour current, the smaller grains can be blown out of the turbidity current cloud (Figure 23). However, there is a difference in grainsize on the downstream overbank when comparing experiments with a weak contour current to a strong contour current. The smallest grains on the downstream overbank with channels of 7 and 10 cm deep are found with weak contour currents. The strong contour current is so strong that also bigger grains can be blown out of the channel, so the winnowing process is poorer. With a strong contour current the ratio large/small grains increases on the downstream overbank and decreases in the channel (Figure 17) because more big grains are blown out of the channel. The smaller differences with the channel of 4 cm can be explained by the fact that the turbidity current is the least confined. More overspill is possible and larger grains can end up on the overbank when a contour current is switched on.

Grainsize analysis of siphon samples

In our experiments, the grainsizes in the siphon samples do not decrease towards the top (Figure 20) as is seen in De Leeuw et al. (2018). In the channel, the decrease is far from exponential what is seen in De Leeuw et al. (2018). On the overbank, the grainsizes even has a little increase towards the top. It must be taken into consideration that the profiles in De Leeuw et al. (2018) are made after a two-dimensional experiment. Also, the grainsize of the sediment they used was larger than that of the sediment we used. The two-dimensional experiments together with the larger grainsizes makes the increases of the stratification more expected.

The profiles in Figure 20 show that the grainsizes in the turbidity current above the overbank do not become smaller when a contour current is switched on compared to an experiment without a contour current. However, this is expected with the mechanism of winnowing. Nevertheless, the grainsizes of the deposits show smaller grainsizes on the overbank when a contour current is present

(Figure 16 and 17), which does not match the grainsizes of the siphons. It is possible that the turbidity current becomes thicker when a contour current is present. The siphons cannot sample the upper part of the turbidity current and this can explain that there would still be many small grains deposited on the overbank.

For the 4 cm deep channel we observed larger grains in the siphon samples with a stronger contour current. This is against the mechanism of winnowing. Then you would expect that the grainsizes decrease when the contour current becomes stronger which is seen in the deposits. If it is a closed system I would expect opposite trends of the grainsize for the channel and the overbank, but this is not seen. However, in the channel, the grainsize increases with a stronger contour current and this can be linked to winnowing. More small grains are being blown out of the channel. More big grains stay behind which results in a larger grainsize.

These larger grains in the siphon samples are difficult to match to the smaller grains in the samples of the deposits. The smaller grainsize in the deposits can be related to small silt that stays for a longer time in suspension. This silt flows around in the tank until it is deposited. This silt is deposited in both the channel as on the overbanks. however, the amount of deposited sediment from the turbidity current in the channel is larger, so the influence on the grainsize inside the channel is less. The amount of deposited sediment from the turbidity current on the overbank is smaller, so the influence of the silt deposited from suspension is larger compared to the samples inside the channel. This results in a smaller grainsize on the overbank.

For future experiments on differences in grainsize deposition, I would recommend to use a larger distribution of grains. Larger grains are also found in natural mixed systems (Fonnesu et al. 2020). Experiments with mixtures of silt together with fine sand up to 250 µm could be executed for optimal results. It makes small differences more clear compares to the small grainsize distribution we used (10 – 110 µm, Figure 1). A larger grainsize distribution would enhance the differences in grainsize for the siphon samples and on the sample locations. However, our grainsize was so chosen that we could create a slow turbidity current that is comparable to natural systems. This resulted in deposits that can be interpreted to a certain extend and not beyond.

Also, the length of the sorting of the silt is relatively short. Culp et al. (2021) shows that sorting over an advection length of more than 9 meter gives satisfactory results, but, our silt has less than one meter to sort out. However, in the flume tank we used, such a length is impossible. When the sorting of the silt is better it can also be used as a better sortable silt proxy (McCave et al. 2017).

In nature, the deposition and sorting of grainsize is important for the reservoir properties of the system. Both coarse grained channel fills as well as thin bedded turbidite deposits have a large reservoir potential (Fonnesu et al. 2020; Hansen et al. 2015). When a contour current is present, the grainsize of the deposits further away from the channel become smaller. These sediments have poor reservoir properties (Fonnesu et al. 2020). This is also seen in our experiments. Coarser materials are present in the channels and the fines end up on the downstream overbanks.

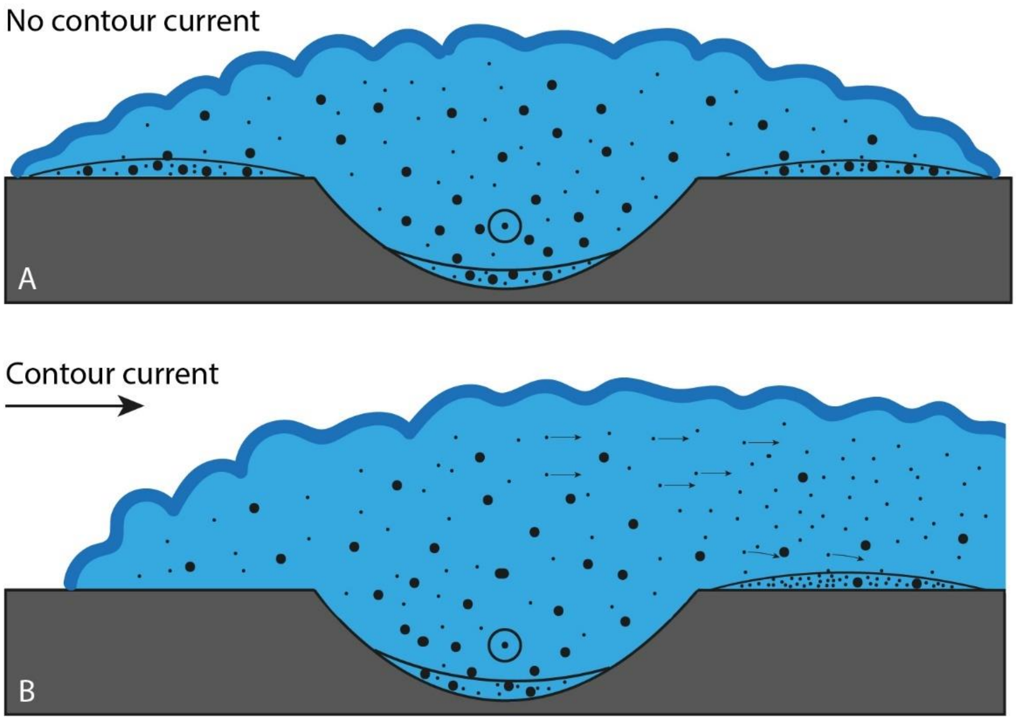


Figure 23, A shows a turbidity current without a contour current. On both overbanks an equal amount of sediment is deposited and the grainsize is equal to the initial grainsize of the silt. B shows the mechanism of winnowing. More finer sediments are blown out the channel due to the contour current. On the downstream overbank the deposit contains more fine sediment.

Concentration measurements and profiles

We are the first who succeeded in measuring concentrations in three-dimensional experimental turbidity currents. Previous experimental studies only measured concentration in two-dimensional experiments (De Leeuw et al. 2018; F. Pohl et al. 2020). Our three-dimensional experiments result in much lower concentrations compared to two-dimensional experiments, especially close to the bed. The concentration in the experiments of Pohl et al. (2020) has values up to 20-30 %Vol at 1 cm above the bed with an initial concentration of 17 %Vol of the mixture. It is seen that the concentration close to the bed becomes higher than the initial concentration which can be explained by the fact that gravity acts on the particles. Sediment from higher elevations in the turbidity current sink to the lower parts. In our experiments the turbidity current has the opportunity to spread laterally. The turbidity current can overspill the channel and end up on the overbanks. This results in relatively low concentrations close to the bed compared to two-dimensional experiments (F. Pohl et al. 2020). This is supported by our data since the concentration in the turbidity current is only 5-6 %Vol at 1 cm above the bed. We started with a concentration of 6.1 %Vol, so the concentration in the lowest part of the current is only equal or lower than the initial concentration. Also, we used silt in our experiment, which is more easy to keep in suspension than the coarser sediment used by De Leeuw et al. (2018) and Pohl et al. (2020).

I experienced that during the calculations of the concentrations small differences in reading the volume from the measuring cup and only a difference of one gram on the scale could result is a major difference in concentration. So for future experimental studies on the concentration of turbidity currents I suggest to use a measuring cups that are very precise, accurate to the millimeter and a scale accurate to 0.1 gram.

The results of the siphoning in the channel and on the downstream overbank gave us the results shown in Figure 18 and 19. With these results, Figure 24 is made. This figure shows that on the downstream overbank the turbidity current becomes thicker when a contour current is present. Also, the concentration becomes higher on the downstream overbank. Together with the strength of the contour current, the sediment can be deposited much further away from the channel.

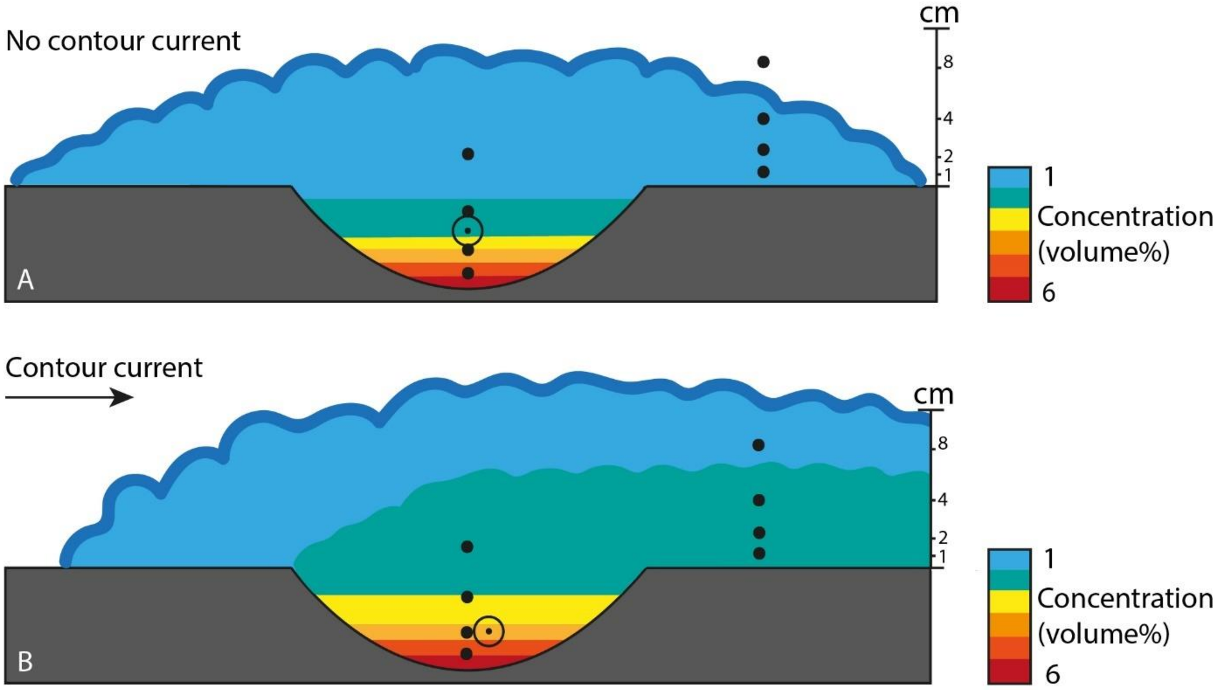


Figure 24, A shows a turbidity current without a contour current. B shows a turbidity current with a contour current. The figure shows that on the downstream overbank, the turbidity current is thicker when a contour current is present. Also, the concentration on the downstream overbank is higher. The black dots indicate the siphon samples at 1, 2, 4, and 8 cm above the bed.

Conclusion

The link between the process and deposition in turbidity current – contour current mixed system models is often missing in field based studies. Experiments can help understanding and can supply physical justifications to the already existing models of the interaction of turbidity currents and contour currents. This research provides the results of ten scaled flume tank experiments. The experiments mimics a turbidity current that brings sediment to the deep sea that is deflected by a contour current. In this research two parameters are tested, channel depth and contour current velocity. The results show volumes of depositions, grainsizes of depositions and of the suspended turbidity current, and concentration profiles.

The calculated volumes according to the laser scans show that no contour current results in the same elevation on the upstream and downstream overbank, despite the channel depth. But it is seen that with a deeper channel, less sediment is transported out of the channel. This is related to the rate of confinement of the channel. With a deeper channel, the turbidity current is more confined and sediment transport out of the channel is more difficult.

It is seen that when a contour current is switched on, the amount of sedimentation increases in either the channel and on the upstream and downstream overbank. It is seen that with a channel depth of 7 cm, most sediment is deposited on the upstream and downstream overbanks, compared to channels of 4 and 10 cm. There is also more deposition on the downstream overbank than on the upstream overbank when a contour current is present. The difference in a weak or small contour current, only gives small differences in the amount of deposited sediment.

Sorting of sediment grains is seen when a contour current is present. Small grains end up on the overbank and large grains stay behind in the channel. It is seen that on the downstream overbank the grains are smallest with a weak contour current for all three channel depths. However, in the siphon samples, larger grains are found with an increasing contour current strength.

The concentration profiles show highest concentrations in the channel when the depth is 10 cm deep. This is because the channel is most confined and most sediment stays in the channel. In the absence of a contour current the concentrations on the downstream overbank are the smallest, with even no measurable turbidity current in the highest siphons with a 10 cm deep channel. This is also because of a good confinement of the turbidity current. A strong contour current results in highest concentrations on the downstream overbank with constant concentrations over the 8 cm that is siphoned. Also the turbidity current becomes thicker above the downstream overbank when a contour current is present.

For future experimental research on the grainsize distribution of deposits of a mixed system I would suggest to use a mixture with silt together with fine sand. The larger distribution of sediment sizes would result in a better sorting of sediment and it would be better recognizable in the deposits and in the siphons. For a better understanding of channel migration direction multiple experiments could be executed is succession to see a better sequence of changes in channel morphology.

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