Rapport de stage individuel

4ème année

Study of a constricted vegetation-less meander river

Company supervisor: Bruce Macvicar, PhD., P.Eng

Function: Associate Professor

Academic supervisor: Pierre Peeters

Clara Tremblais

IMA

2024-2025

Clara Tremblais
2024-2025

Study of a constricted vegetation-less meander river

Experiment in flume

Abstract:

The urban development is a threat to the natural space that a meander river needs to naturally migrate in time. It can cause the river's morphology to change, and ecosystems to be endangered. In this study, we run a sequence of floods in a flume where a constricted vegetation-less meander river is modeled. After the floods, is analysed evolution of flume is morphology. The general morphology of the modelled river did not drastically change. The already existing bars and island were maintained and still here after the storms. The main evolution in the flume is a general incision of the riverbed as well as a width enlargement all along the channel.

Key words: Meander River, meander confinement, river hydraulics, fluvial geomorphology

University of Waterloo, Civil and environmental engineering department
University of Waterloo 200 University Avenue West Waterloo, Ontario, Canada, N2L 3G1

Company supervisor: Bruce Macvicar, PhD., P. Eng
Associate Professor

Academic supervisor: Pierre Peeters

TABLE OF CONTENTS

ACKNOWLEGMENTS

First, I would like to thank my supervisor Bruce Macvicar for giving me the opportunity to run these experiments, helping and guiding me through the process. I would also like to thank Rachael Messenger-Lehmann who ran all the previous experiments and created the flume. Her precious advice was appreciated. Many thanks to Huaiyuan Weng and Chul Min Yeum for helping us scan the flume. Finally, thank you to the whole research group of Bruce, for being very welcoming during these few months.

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Floodplains play a major role in the proper functioning of a river. They lower the energy of the river during floods by dissipating the water in the floodplain. It holds a rich ecosystem, home to many faunal and floristic species. It also corresponds to the zone of freedom for meander rivers. Indeed, these will evolve and naturally migrate in space. At the same time, floodplains are highly sought for industrial and urban development. However, the constructions are weakened by erosion. The most common solution to remedy this created weakness, is to install riprap, which can be described as hard engineering. However, there are other ways of dealing with the problem. Currently, the city of Calgary located in Alberta, is being affected by these issues and has set up a "green belt" around its river, the Bow River. A green belt is a non urbanized space kept all along the river to allow its natural migration. The width of the belt is 50 metres around the Bow River. For a scenario for over 1,000 years of evolution of the Bow River, 500 metres of belt would be necessary. Nevertheless, such a change would have wide-ranging impacts on the economy and development projects already underway. On the other hand, an important economic driver of the city of Calgary, the recreational fishery has been valued between $24.5M - $114M annually (CRUA, 2016 and Christensen et. al., 2020).. Protecting the floodplain of the Bow River even more and allowing space for the natural migration of the river would protect and create new fish habitats. It would also save money on potential hard erosion mitigation projects.

Thus, research in the field will help justify such measures and encourage policy decisions. Some research has been done in the past, such as the description of the plan geometry and migratory behaviour of a set of confined meandering rivers (Nicoll and Hickins, 2010), and the effects of confinement on the hydrodynamics of a cohesive meander channel (Parsapour and Rennie, 2018). However, these projects were limited in scope and did not address the question of how floodplain width affects the long-term sustainability of rivers. To answer this question, the city of Calgary has been collaborating on this research with the University of Waterloo.
The internship is taking place at the University of Waterloo in Waterloo, Ontario, Canada, under the supervision of Professor Bruce Macvicar at the Department of Civil and Environmental Engineering. The aim of this work is to complete the study done on the physical model constructed at the University of Waterloo, including analysing the river's morphology and hydraulic consequences on a river such as the Bow River. This research will participate in a better understanding of long-term effects on confinement of an urban river in general. More specifically there, when the vegetation is removed to look further into its effects on the morphology. Thus, a series of experiments was held in the hydraulic lab of the University in order to collect morphology and hydraulic parameters prior to analyse. The experiments consisted of removing the vegetation from the flume and running a sequence of floods.

I. CONTEXT AND LITERRATURE REVIEW

The Bow River is a meander river located in Calgary, Alberta, Canada. Prior to the construction of dams, bank stabilization and the lack of significant floods for eighty years, the river was characterised by complex forms and morphology with a multi-threaded channel and several islands. Today, the channel through and downstream of Calgary is simplified and relatively static (Figure 1). In response, the riverbanks have become densely vegetated mainly by poplars and willows. Eventually, the erosion pattern is highly modified, due to the disappearance of unstable point bars (Rood and Kaluthoda, 2017).

Figure 1: Aerial imagery from 1924 and 2020 of the Bow River flood plain near Heritage Meadows. Note the complex diversity of riverine habitat that existed prior to development. These types of habitats can no longer be created here due to the river being constricted

:

To begin this work, it is necessary to investigate the literature and understand what is known about river migration and urban constricted rivers.

1. Constricted rivers

Firstly, it is relevant to clarify what a constricted meander river is. It mainly refers to a meandering river where the horizontal migration is constrained by valleys on both sides of the river and the plane shape cannot be fully developed (Li et al., 2024). Constricted meander rivers are less studied and there is less knowledge on them. However, a few studies have investigated these kinds of rivers.

A 2024 studyhad for objectives to analyse and compare the plane morphological characteristics of the constrained meandering river of the Loess Plateau in China. In order to do so, they compared 19 constrained meandering rivers to 19 original alluvial meandering rivers analysed in a previous study (Guo et al., 2019). The method used is based on Landsat 8 imagery. Through this work, they were able to make several observations. They concluded that the constrained rivers alternate between straight and meandering channels, influenced by the surrounding mountains. They observed that the bends cannot fully develop due to the constraints on the sides. The meandering wavelength in the long time tends to be longer in unconstrained meandering rivers. It was also observed that the constricted meandering rivers on the Loess Plateau show predominantly upstream skewness.

Another study led by Tami J. Nicoll and Edward J. Hickin published in 2022, was based on constrained rivers in Canada. The objectives of this research were to analyse the plane geometry and migration rate of 23 rivers located in Alberta and British Columbia. Then, finding a possible relation between these rates and hydrological and geomorphological factors. To do so, the team used historical aerial photography analysed by GIS (Geographic Information System).

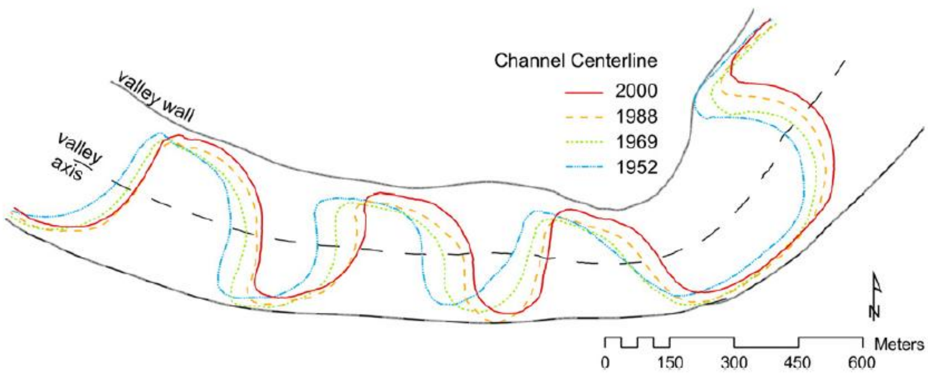

Figure 2: Successive channel centrelines showing channel migration (1952-2000) along a reach of the Beaver River, AB. (Nicoll et Hicking, 2022)

As shown in **Erreur ! Source du renvoi introuvable. Erreur ! Source du renvoi introuvable.** above, it appears that the river meanders generally tend to translate downstream as a package, cutoffs are relatively uncommon compared to free meandering rivers.

Through the author's analysis, constricted meander rivers, even though the unique geometric characteristics due to their confinement, the authors suggest to not categorized constricted rivers differently from the free meander rivers. Their migration behavior is very similar to the unconstrained river systems. Relations have been found between environmental factors (stream power, width, slope and discharge) and migration rate, similar to the ones observed on free meandering rivers.

2. Vegetation and meander rivers

Vegetation in meander rivers plays a non negligible role in the morphology and evolution of these types of rivers. A common hypothesis is that meandering rivers don't exist without it. A study conducted by Alessandre Lelpi, Mathieu G. A. Lapôtre, Martin R. Gibling and C. Kevin Boyce published in 2022, analysed the impact of vegetation on meandering rivers. To evaluate this matter, evidence was used from rock records. Indeed, the meander rivers have a unique dynamic where the outer banks in bends are eroded, also deposition on the inner banks. This phenomenon creates specific depositional records that can be identified in sedimentary successions. In this paper, the authors explain that in the geological field, a coincidence between the "protracted spread of land plants in the early to middle Paleozoic and the rise of sedimentological indicators related to lateral accretion in meandering rivers" is described. In the paper's conclusion, meandering-rivers can emerge without vegetation. However, plants provide "stable meandering systems through retention of floodplain mud by sediment baffling and associated processes, resulting in mechanical strengthening of channel banks. »

II. EXPERIMENTAL MODEL

As previously mentioned, this project is conducted for and with the city of Calgary. When the experimental model was built in the laboratory at the University of Waterloo, it turned out that the dimensions of the river were too big to replicate in the flume of the laboratory. Thus, a decision was taken in conversation with the city of Calgary to model the Jumping Pound Creek, a tributary to the Bow River but smaller in scale. This creek was chosen because of its similarities with the Bow River and to the data available (discharge, depth, previous flood data, …).

1. Flume set-up

The experiments were held in the flume in the hydraulic lab at the University of Waterloo. The flume is 13.2 metres long and 2 metres wide. The slope is about the same as the Jumping Pound Creek, which is 0.49%. It is equipped with an air compressor valve and an in-pipe flowmeter to control and measure discharge. The flume has been set up with a re-circulating water supply system. More specifically, there is a tank placed towards the end of the flume and inside it, there is a pump which collects the water and returns it to the valve. The water is changed every 2 experiments to keep a relatively clean water. The flume has a movable camera cage as well as a movable bridge. The movable camera cage contains four halogen lights installed as well, to make sure the light is homogeneous. A video camera is also present in the camera cage, and two other cameras are used to take pictures of the flume. The cameras and computer are both connected to the camera cage, in order to transfer directly photos and videos to the computer once they are taken. Below is a schematic of the flume (Figure 3).

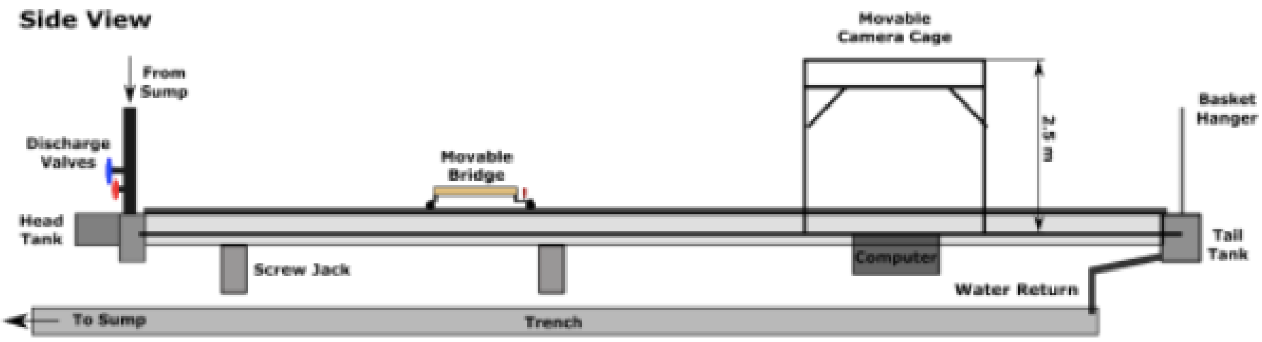

Figure 3: Flume schematic (Rachael Messenger-Lehmann, 2025)

Additionally, there are twenty-three targets installed along the outer edge of the flume to support image analysis. These targets are spaced 1 metre apart on both sides of the flume. This resulted in a target every 0.5 metre. The targets overhung the flume as they are positioned 20-30 cm above the flume bed (Figure 4: 3)

The last intervention on the flume is to cut the Alfalfa, the vegetation in the flume, within the walls since the objective of these experiments was to simulate floods without any. To do this, a few methods were considered: using an electric cutting tool, scissors, or pulling it off by hand. Eventually, a combination of using scissors and pulling the alfalfa off by hand where used. The sand stayed in place despite the pulling. Figure 4 shows a photo of the flume after the last experiment of the previous master's student, which was in February 2025. The second photo shows the flume in May 2025, where the vegetation is dead (Figure 4: 1) and cut within the walls (Figure 4: 2).

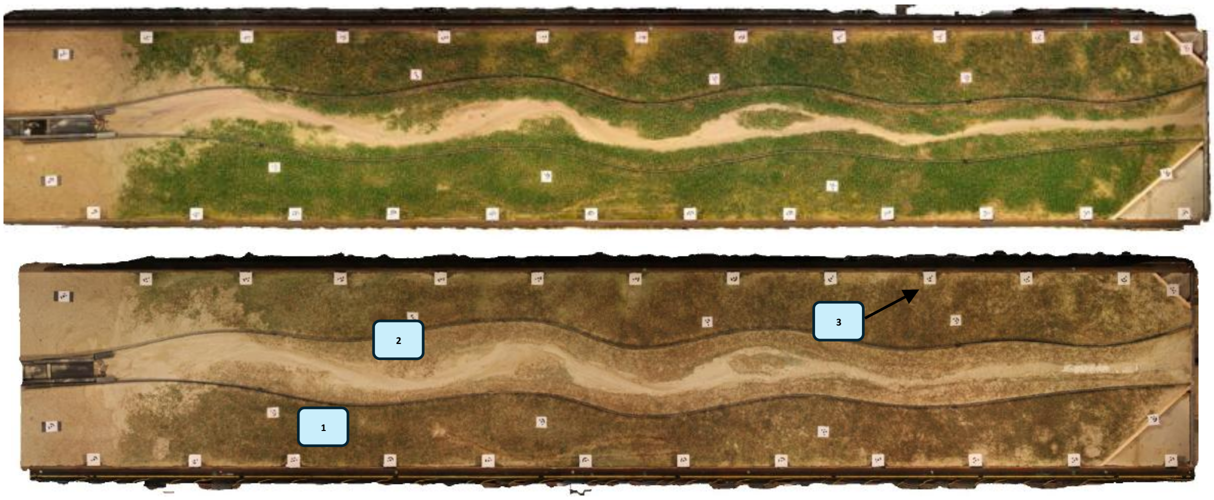

Figure 4: Photos of the flume before and after vegetation removal (1: Dead Alfalfa; 2: Alfalfa cut; 3: Target)

The vegetation removal mostly removed the aerial part of the plants. Most of the alfalfa's roots were still in the sand. There is a possibility that the root system could still exert a force on the bank and prevent major sand movement.

2. Sediment supply

To properly simulate the Creek, a sediment supply during the floods was needed. The sediment supply was previously calculated by the master's student (Rachael Messenger-Lehmann, master's student at the University of Waterloo,) who began the experiment in this flume. Output quantities were measured in the Jumping Pound Creek to estimate the sediment input quantities. Then, the Meyer-Peter-Müller equation is applied to calculate the sediment transport (Meyer-Peter & Müller, 1948).

The flume was fed sediment manually at its top for the 25-, 50- and 100-years floods. The sediment quantities calculated for the 5-year floods were insignificant, thus none were added during the two specific experiments. The different quantities are detailed in *Table 1.*

Table 1: Detailed quantities of sediment input during floods

Time (min)	**Sediment input (g)**		
	25-yr	**50-yr**	**100-yr**
0-50	0	0	0
60	0	7.32	4.02
70	1.46	44.89	41.59
80	17.09	110.33	126.42
90	47.15	187.66	231.96
100	89.28	277.94	359.58
110	138.43	390.78	515.77

120	195.57	514.67	689.91
130	212.19	537.8	781.23
140	177.94	478.62	728.05
150	153.41	422.24	636.74
160	130.52	357.53	550.17
170	101.75	306.15	456.25
180	75.5	258.02	368.42
190	57.33	203.75	296.52
200	41.45	161.59	230.77
210	22.95	123.47	162.4
220	8.77	88.3	102.69
230	1.47	58.09	58.09
240	0.01	27.83	24.53
250	0	8.77	4.02
260	0	1.46	0
270-360	0	0	0
Total	**1472.27**	**4567.21**	**6369.13**

The sediment size distribution was the same for the bed. As well as the feed, which is a D_{50} of 0.76mm (Figure 5). The sediment contained a small proportion of UV-painted particles: 1% of green (1 mm) and 1% of pink (0.71 mm). These coloured particles were added to allow to take videos under UV lights during the experiments, to see the modalities of transport with the help of a specific program.

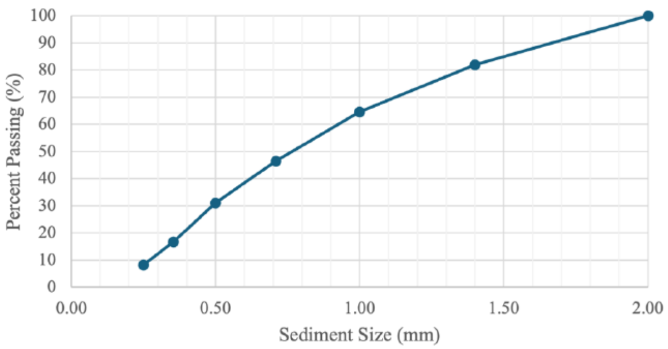

Figure 5: Bed and feed sediment size distribution

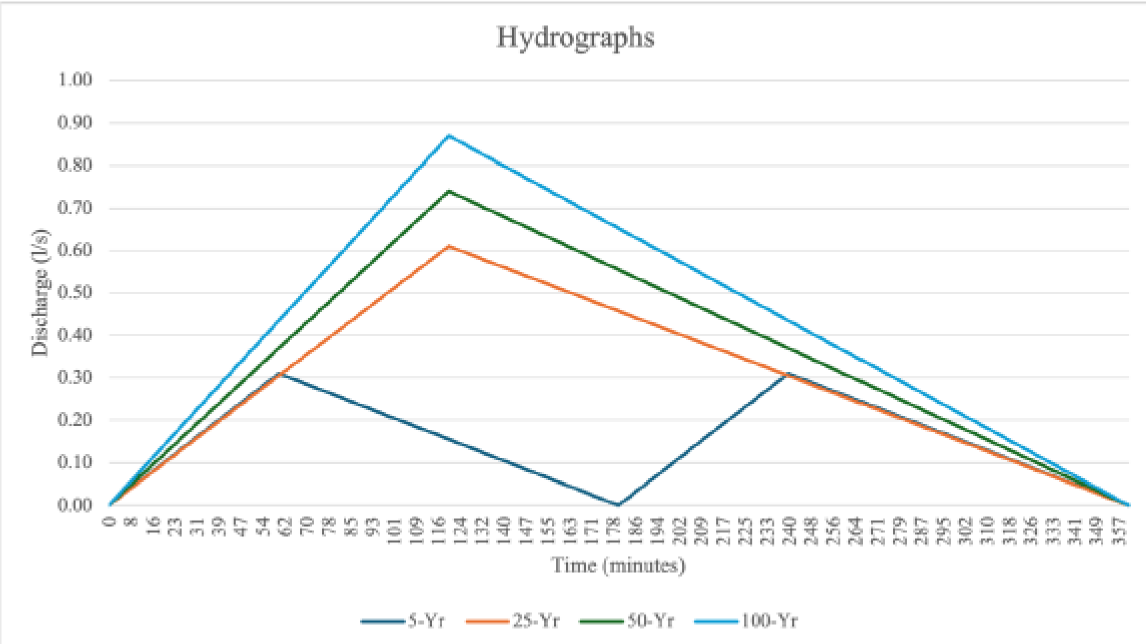

Figure 6: Hydrographs of the floods

Figure 7, the discharge of the 5-year floods has two peaks. However, in the lab this hydrograph could not be run by the instrument of the University due to their low value. The solution was to put a content discharge of 0.32 L.s^{-1}.

3. Data collection

3.1. Aerial imagery, scan and videos

Before the first experiment and then after each experiment, a series of photographs was taken. The photos were taken every 25 centimetres by moving the camera cage, starting from upstream to downstream of the channel. To properly account for the topography, the photos were taken at least a day after the storm to let the water drain. The cameras used were Canon ESO REBEL t5i placed in the movable cage.

A more accurate technique of analysing topography was introduced during the experiment. The Pro S enhanced camera which is a ©Mech Eye 3D non-laser camera. This camera uses a light pattern which is not a laser. With the light returning to the camera, it can scan the topography. Usually, this type of camera is used to scan exterior places such as bitumen. Such technology provides opportunities for more detailed Difference of Elevation Models (DEMs). Thus, a more detailed investigation with a better characterization of riverbed topography.

A series of 3D markers was printed and installed on the walls of the flume with paper clips (Figure 7). To make sure the markers were put in the exact same place every time, marks were made on the PVC walls. This configuration allowed to remove them easily for when we would take the pictures. The 3D camera has an elevation accuracy of 0.05 mm and can scan from a height between 500 and 1000 mm.

This means that in our case and with the camera put at 1 metre high, it would scan a surface of 63*43cm^2. Therefore, we would be able to see the flume from its two PVC walls.

Figure 7: Photograph of a 3D marker

Additionally, a video camera recorded videos every 20 minutes during each flood. This camera is also placed in the movable cage which was lit by UV (Ultraviolet) light placed inside the studio. To be able to compare all the videos, six 5-millimetre fluorescent pink painted pebbles were placed on the bank (Figure 8).

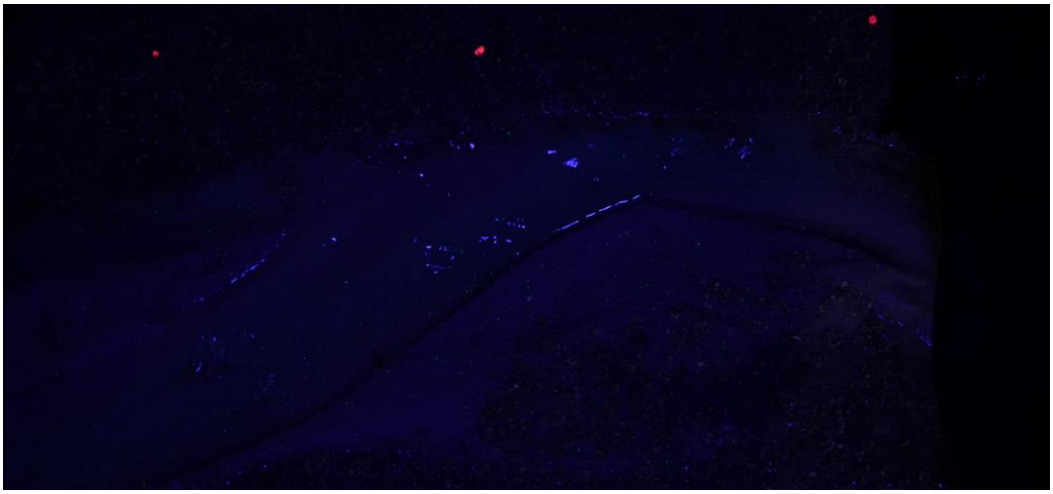

Figure 8: Screenshot of a video shot with UV light

3.2. Sediment collection

At the downstream end of the flume, there are 2 baskets that collect sediment during the experiments. The bottom of the sediment collection basket was made of thinly meshed tissue, that allowed the water to drain. It can be noted that the baskets collected not only sand but vegetation debris as well. All the sediment collected were placed in plastic bags for later analyse. The sediment was collected after the rising and falling peak of each storm.

3.3. Depth and measurement

To measure the depth of the bed and the water elevation, we used the movable bridge by placing marks on it at different location of the bed. The depth was measured on the edges of the two PVC walls, then starting from each edge of dead vegetation, and every five centimetres the depth was measured. Figure 9 shows a schematic of the flume where all the measurements were taken. In total, ten measurements were done every 30 minutes during every experiment. The channel width considered for the measurements was from the edges of the water flow.

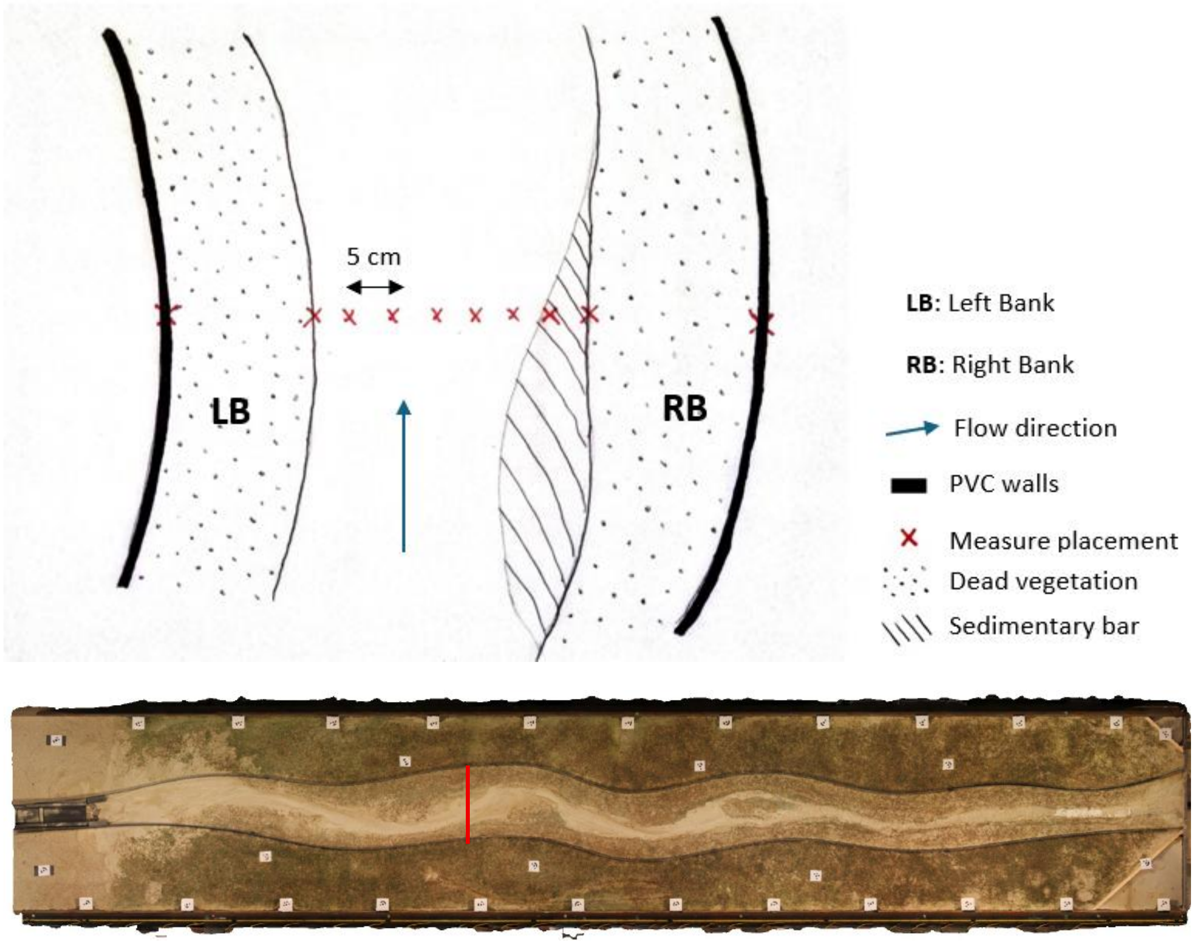

Figure 9: Schematic (above) and location (under) of the depth measurement

4. Data analysis

4.1. Sediment and depth analysis

The first step in the sediment analysis was to place all the sediment collected during all the experiment into a 110°C furnace for 24 hours to dry the sand. Then, every sample from each experiment was weighed and sieved. To sieve the samples, a screen shaker was used. Screen shakers use vertical vibration to sieve sediments through screen trays. The screen tray sizes that were used are are the following: 1.41mm (No.14), 1.00mm (No.18), 0.71mm (No.25), 0.5mm (No.35), 0.35mm (No.45), and 0.25mm (No.60).

The data of depth collected during each experiment was put in an Excel file.

4.2. Morphology analysis

To analyse the morphology evolution (channel width, meander wavelength, and sinuosity) of the modeled river throughout the floods, a drawing software named AutoCAD© was used. Figure 11 shows a screenshot of the different measurements done on the software. The reference used to scale the photographs of the flume was the distance between two targets, which was close to one metre.

The width was measured every 50 centimetres, which is represented by the orange lines. The thalweg was traced with an estimate by looking at the lowest point of the channel in the photograph. To calculate the sinuosity (symbolisedS), the length of the straight line was divided by the length of the thalweg. According to the classic system of class for the sinuosity, which is:

- S < 1.05: Nearly straight
- 1.05 < S < 1.25: Sinuous
- 1.25 < S < 1.5: Very sinuous
- S > 1.5: Meandering

4.3. Topography analysis

To reconstruct the flume, the images taken by the two Canon cameras were stitched together using the ©Agisoft Photoscan 1.4. The software uses the targets installed within the flume. It then process the overlapping images to generate 3D data, resulting in both stitched photo mosaics and digital elevation models (DEMs) of the flume surface.

To be able to analyse the data, it is run through a customized code on MATLAB and used through an interface shown in Appendix 1. To correct the tilt of the flume, the DEMs were detrended. From the corrected surfaces, Differences of DEMs (DODs) were created to be able to see areas of deposition and erosion. Some masks were then applied to allow more specific area analysis and the reduction of data to accelerate the process.

III. RESULT AND DISCUSSION

The photos stitched together on Agisoft did not perform well during the data processing phase. Indeed, the estimated vertical error of the software, called Z error, was particularly high for all experiments except the first series of photos of the flume just after the vegetation removal. This error was of the order of 3 centimetres whereas in normal times it should be more of the order of a millimetre (ideally 2 mm compared to the scale of the flume). According to the reports produced by Agisoft, it is the targets located at the downstream and upstream of the flume that cause a problem. Indeed, for technical reasons these areas had fewer photos. The solution considered to resolve this

problem was to delete the pictures of the beginning and end of the flume in order to decease the error value.
For this reason, these areas won't be in the following analysis.

1. Sediment transport analysis

Throughout the two 5-years floods, a few sediments were collected. Most of the sediment collected was vegetation debris. The vegetation removal made a lot of organic waste that fell into the flume, especially Alfalfa leaves. For this reason, it was considered that the sediment collected was insignificant, resulting in impertinency to sieve it. However, Table 3 shows the wetted weight of the sediment collected for the first and second half of the two 5-year experiments.

Table 2: Dry weight of sediment collected during the floods

	Experiment	**Dry mass of sediment RISE storm (kg)**	**Dry mass of sediment FALL storm (kg)**	**Sediment mass added (g)**
LMR_exp37 (wet weight)	First 5-year	0.08	0.05	0
LMR_exp38 (wet weight)	Second 5-year	0.04	0.02	0
LMR_exp39	25-year	5.2	6.8	1472.27
LMR_exp40	50-year	3.8	4.7	4567.21
LMR_exp41	100-year	4.2	4.2	6369.13

The 25-years experiment has the highest mass of sediment collected for both after the rising and fall compared to the other next two storms. It is 5.2 and 6.8 kilograms collected during the 25-years flood. For the next two storms, we can see that less sediment is collected. These numbers suggest that the 25-years one had more erosion and less for the last two experiments. There was even possibly a deposition during these latter.

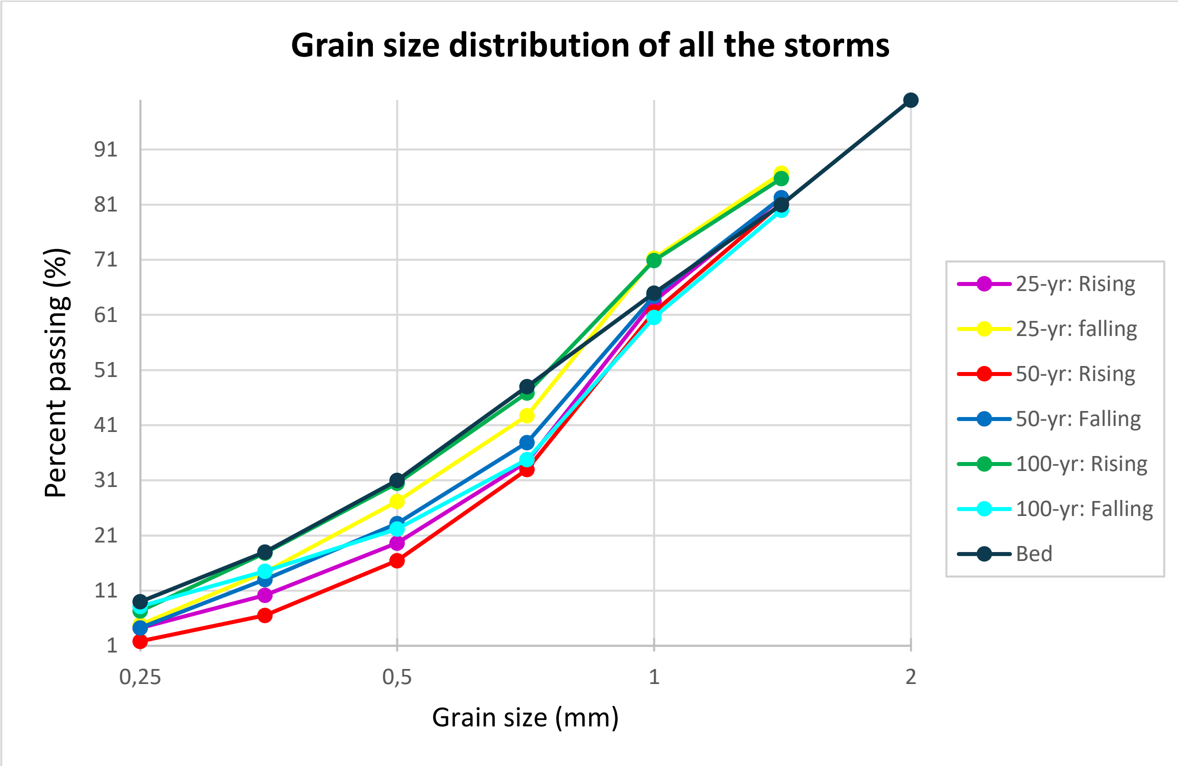

Figure 10: Grain size distribution after the rising and fall of the experiments and the initial bed and feed sediment size distribution (black line)

For every sample sieved except, the grain size distribution after the rising storm of the 100-year storm, it has a D_{50} higher than the one of the sediment grain size distributions of the flume bed and sediment feed. It means that during the floods, the sediment transported contained a proportion of larger sediment.

Even though there was no sieving of the two 5-year floods for the reasons explained above, the little sediment collected was fine sand of the order of 0.25mm according to visual interpretation. It suggests that the other floods, which are more intense, were able to transport larger sediment.

The Uniformity Coefficient (C_u) was calculated by dividing the D_{60} by the D_{10}. The results are shown in Table 4.

Table 3: Uniformity coefficient after the rising and fall of the 25-year, 50-year and 100-year storm

	D_{60}	D_{10}	C_u
25-year - Rising	0,95	0,35	2,71
25-year - Falling	0,9	0,3	3,00
50-year - Rising	0,98	0,4	2,45
50-year - Falling	0,95	0,35	2,71
100-year - Rising	0,85	0,28	3,04
100-year - Falling	1	0,24	4,17

All the uniformity coefficients have a value lower than 4, which means that the samples and so the sediment transported during these three floods are uniformly graded. However, the coefficient of the sediment collected after the fall of the 100-years storm has a value slightly over than 4, which signifies that the sample was less uniform than the other.

2. Scans and videos

The scans of the flume and the videos taken during the experiment. The scans needed some more processing and are going to be used in the future, with the continuation of this project.
The code for the analysis of the video is still being worked on, as well as the scans, it won't be analysed in this report.

A few results can however be shown here to give some context. Figure 11 shows the colorized scans of the flume.

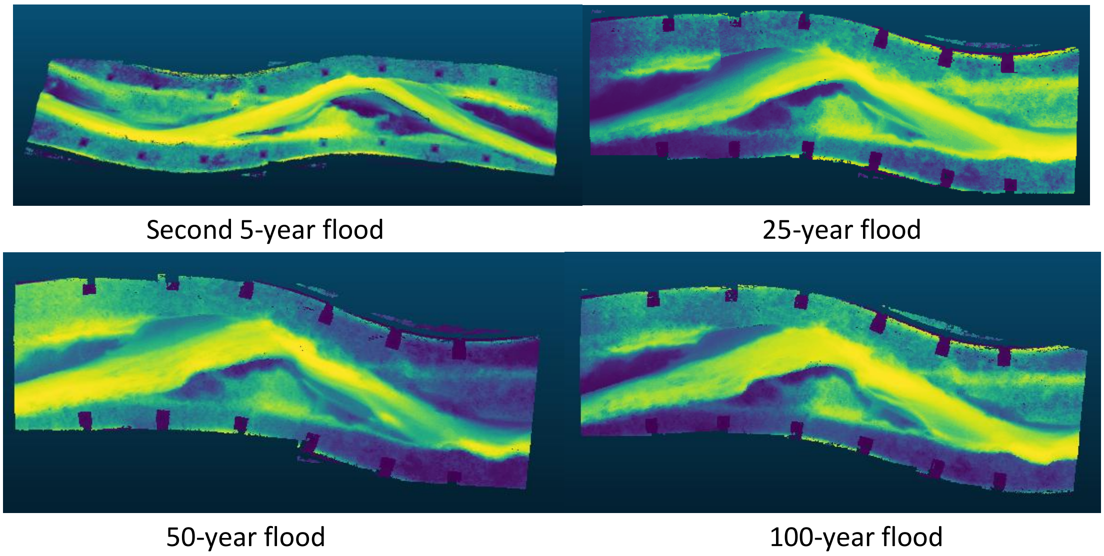

Figure 11: Colorized scans of the four last experiments

The absence of scale is due to the in-process analysis of the scans. However, the appearance of the colorized scans seems to show an erosion of the bar throughout the passing of the storms.

3. Morphology and elevation analysis

The process of the morphology analysis of the flume before and after the experiment done on ©AutoCAD is shown in Figure 11. The red lines represent the thalweg and the straight length from upstream to downstream of the flume. The orange lines and their associated numbers show the different locations of the channel width measurement on the flume, which was taken every 50 centimetres. The purple lines and circles indicate the three wavelengths numbered from 1 to 3, which were estimated by measuring the furthest point on the thalweg of each meander.

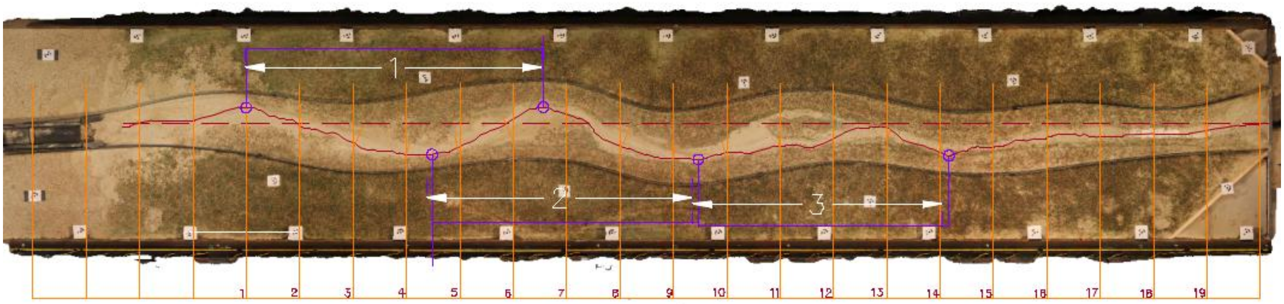

Figure 12: Morphology measures of the flume before the experiments

The channel had a sinuosity of 1.05, and remained stable after running the sequence of flood. The river stayed sinuous.

Table 4: Wavelength of the meanders of the flume

Wavelength (m)	Initial flume	Flume after the storms
1	2.78	3.14
2	2.49	2.48
3	2.35	2.47

On Table 5, we can see that the first wavelength and third one has grown by 0.12 and 0.36 metres after the floods.

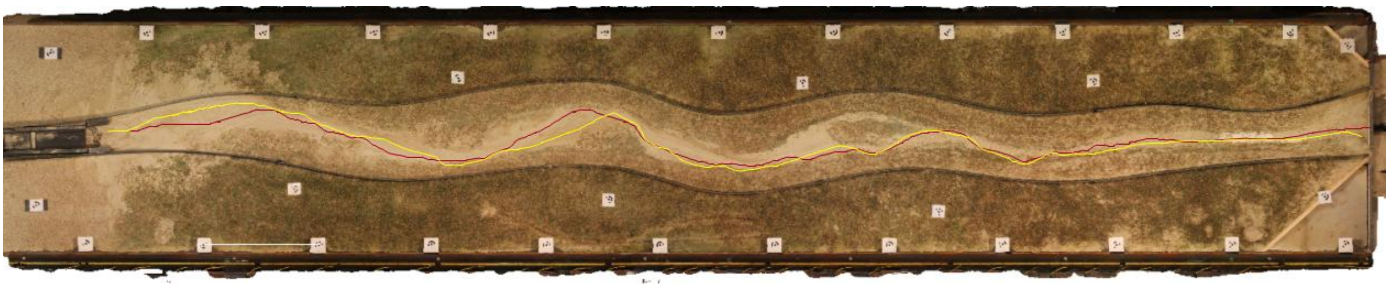

Figure 13: Flume photograph that sows the evolution of the thalweg before and after the flood (Red line: initial thalweg; yellow line: thalweg after the floods)

In Figure 13, the evolution of the deepest point of the channel after the vegetation removal and after all the experiments run in the flume is shown. The red and yellow lines overlap each other in the second half of the flume. It suggests that the water flow in this area didn't change even after the run of the five floods. However, it is from upstream to the second meander the thalweg has moved closer to the left wall one metre from the beginning of the flume. The other area where the thalweg has moved as well is on the second meander: the thalweg shifted laterally to the outer bend of the meander. The shift suggests erosion on the outer banks and deposition on the inner banks, a typical behavior in meandering river systems. The thalweg movement in this area also shows a slightly more sinuous channel here.

Water and channel width

For the 5-year experiment, the mean water width measured was between 15 and 16 centimetres. For the three other floods, as expected, the water width was higher. The mean width for the other flood was:

- 25-year flood: 24 cm
- 50-year flood: 29 cm
- 100-year flood: 26 cm

The water width is 2 centimetres larger than the 25-year to 100-year flood. It can be noted that during the 50-year flood, the water width was wider than in both other floods.

Table 5: Channel width: before and after the running of floods

Width	Before floods (m)	After floods (m)	Width difference (cm)
1	0.155	0.231	7.6
2	0.113	0.145	3.2
3	0.218	0.225	0.7
4	0.132	0.167	3.5
5	0.149	0.104	-4.5
6	0.213	0.239	2.6
7	0.131	0.198	6.7
8	0.262	0.247	-1.5
9	0.141	0.139	-0.2
10	0.142	0.171	2.9
11	0.102	0.108	0.6
12	0.133	0.13	-0.3
13	0.14	0.09	-0.5
14	0.118	0.12	0.2

15	0.073	0.093	2
16	0.159	0.17	1.1
17	0.146	0.176	3.0
18	0.099	0.181	8.2
19	0.141	0.184	4.3
		Mean width difference(cm)	1.85

Table 6 shows how the channel width changed at 19 transects along the flume every 50 centimetres, before and after a flood. On average, the channel widened by 1.85 cm, indicating that the flood caused significant erosion of the banks on most of the channel.
Among the 19 locations, 13 experienced widening and 6 became narrower. This suggests that erosion was the dominant process during the flood, although some areas also underwent deposition.
The most significant widening occurred at points 18, 1, and 7, with increases of 8.2 cm, 7.6 cm, and 6.7 cm respectively. The upstream, the second meander and the downstream of the flume are the location where the channel widened the most.
In contrast, points 13 and 5 showed the largest narrowing, by 5.0 cm and 4.5 cm, which corresponds to the upstream of the second meander and the downstream of the third meander.
Overall, the results show that the flood restructured the channel, widening it in most places but also depositing material in others.

River elevation

The riverbed elevation was measured at the same place on the flume for each storm. To simplify the analysis, only the last measure of each experiment will be shown and compared to each other.

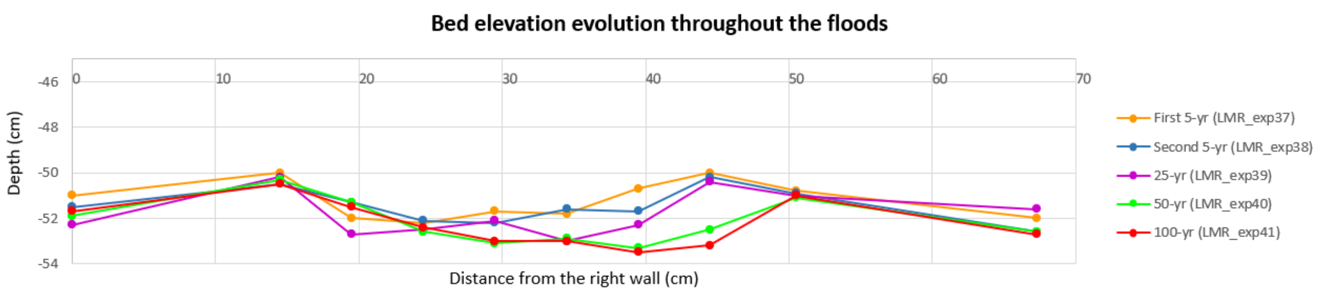

Figure 14: Bed elevation evolution throughout the sequence of flood

The point located at the walls goes deeper throughout the experiments. At the beginning, the elevation near the right wall was -51 cm and the left wall was -52 cm. At the end of all the floods, the right wall elevation is -51.7 cm and the left wall one is -52.7 cm. The elevations near both walls eroded by 0.7cm. The right and left bank elevations are for both -50 cm after the first flood. After the last flood, the banks are slightly lower: -50.5 cm for the right bank and -51 cm for the left bank.

After the first flood, the bottom of the channel has approximately an elevation of -52 cm. The elevation after the last storm is on the order of -53 cm towards the left bank. On average, between the two 5-year storm simulations, the riverbed eroded by 0.5cm. After the 25-years flood, between the banks, the riverbed has eroded by about 0.3 to 1.5 centimetres. The erosion of the riverbed continued through the other floods. The bed elevation of the last experiment shows that the area next to the left bank is deeper than the right bank. Whereas, at the end of the first flood, it is the opposite case. The left bank eroded more than the right bank. The channel looks like it is migrating to the left side of the river.

Overall, the location looked at to analyse more precisely the depth shows an incision of the bed.

Morphology evolution analysis

Despite the removal of the photographs of the upstream and downstream flume to improve the precision and lower the Z error, this technique did not work for all the sets of pictures taken after each flood. The second 5-years, the 25-years, and the 100-years flood still had a 2-centimetres Z error. This value was too high to have usable DEMs and DODs. These latter were incoherent with an erosion that was too important in comparison to the observation of the flume. Thus, further analysis is difficult regarding these specifics storms. However, the result of the 50-years flood was still interesting, and we were able to properly see the morphological evolution of the flume.

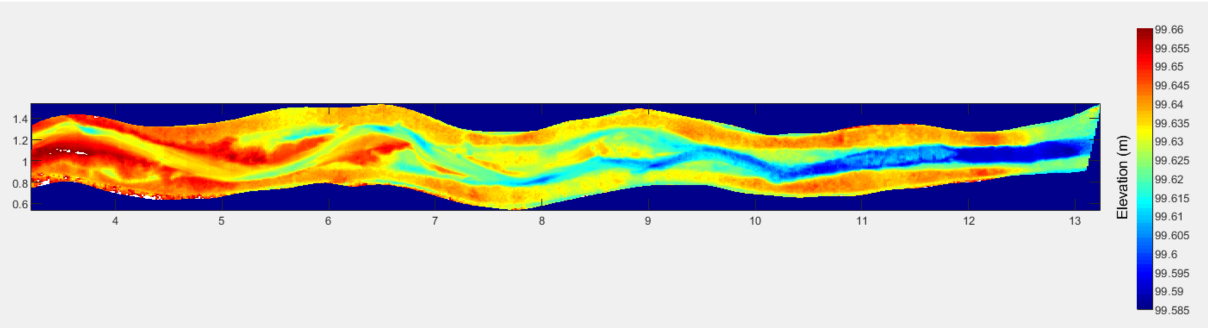

Figure 15: Detrended elevation of vegetation-less flume before the run of floods

Figure 15 above shows the detrended picture of the flume without the vegetation, before the experiments of floods started. Initially, the bends are subtle and not very pronounced as mentionned earlier with the sinuosity being of 1.05. There are three meander bends, and the third one located downstream is a little special because there is an island in its center. The upstream and downstream banks have an elevation of about 99.64 metres whereas the banks located in the middle of the flume are slightly lower, with an elevation of about 99.63 to 99.635 metres. The channel becomes straight from 10.3 metres until the end of the flume. It can be noted that elevation has a discrepancy up to the end of the flume, the value is about 99.585 m, which is considered low(). Indeed, there is a lack of sediment in this area that is not intentional. During the time of the last experiment ran on this flume until the beginning of the new series of experiments, the flume has been slightly disturbed, sediment was missing from 11.8 metres to the end of the flume.

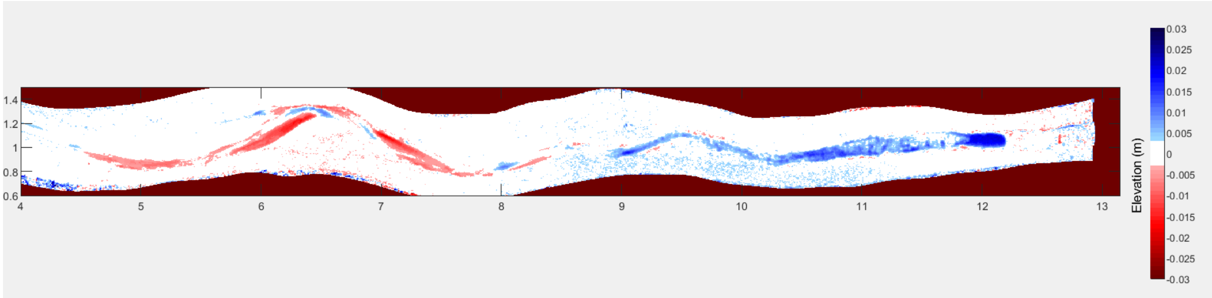

Figure 16: Difference of DEMs of the flume before and after the first 5-year flood

After the 5-years flood, according to the DOD (Figure 16), the sediment located from upstream has moved along to the downstream area. The erosion is minimal, between 0.5 cm to 2 cm on the inner bend of the second meander. There is a light deposition of around 0.5 centimetre on the outer bend on this same meander.

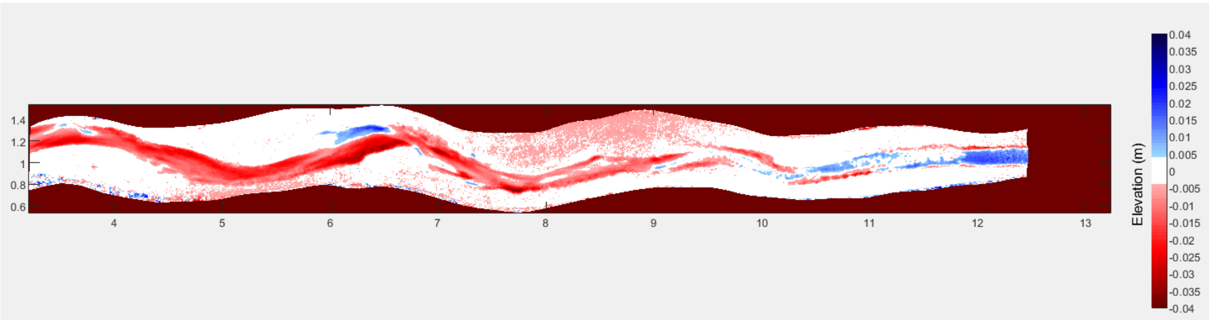

Figure 17: Difference of DEMs of the flume before and after the first 50-year flood

After all the floods up until the 50-years flood, the majority of the channel has eroded. There are forms of alternation between deep and less deep areas. This all along the flume up to 10 metres where the river is rather straight and the morphological behavior is slightly different from the meandering dynamic upstream of this area. Indeed, on this part, there is a lateral erosion of the channel of a few centimetres, approximately 2-3 centimetres based on the DOD. It can still be noticed that the largest movements occurred from downstream to the middle of the canal, downstream of the second meander.Afterwards,we will take a look more closely at these areas.

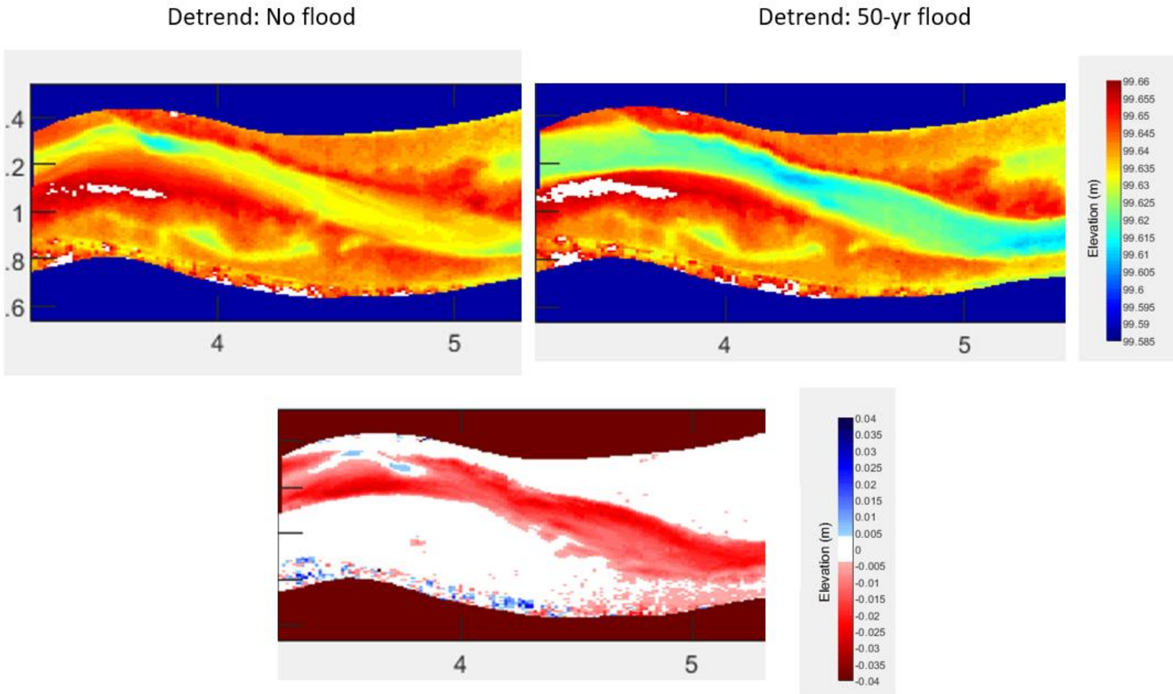

Figure 18: Zoom of the detrended pictures before and after the 50-year flood on the upstream flume

The zooms on the detrended pictures of the flume before and after the 50-years flood show clearly the enlargement. The right bank has eroded by about 10 centimetres at the most curved point of the bend. On the DOD, the elevation shows an incision of the channel of about 2 centimetres up to 4 centimetres on the inner bend of the meander.

Overall, the upstream meander looks slightly less curved, and the channel is incised and enlarged.

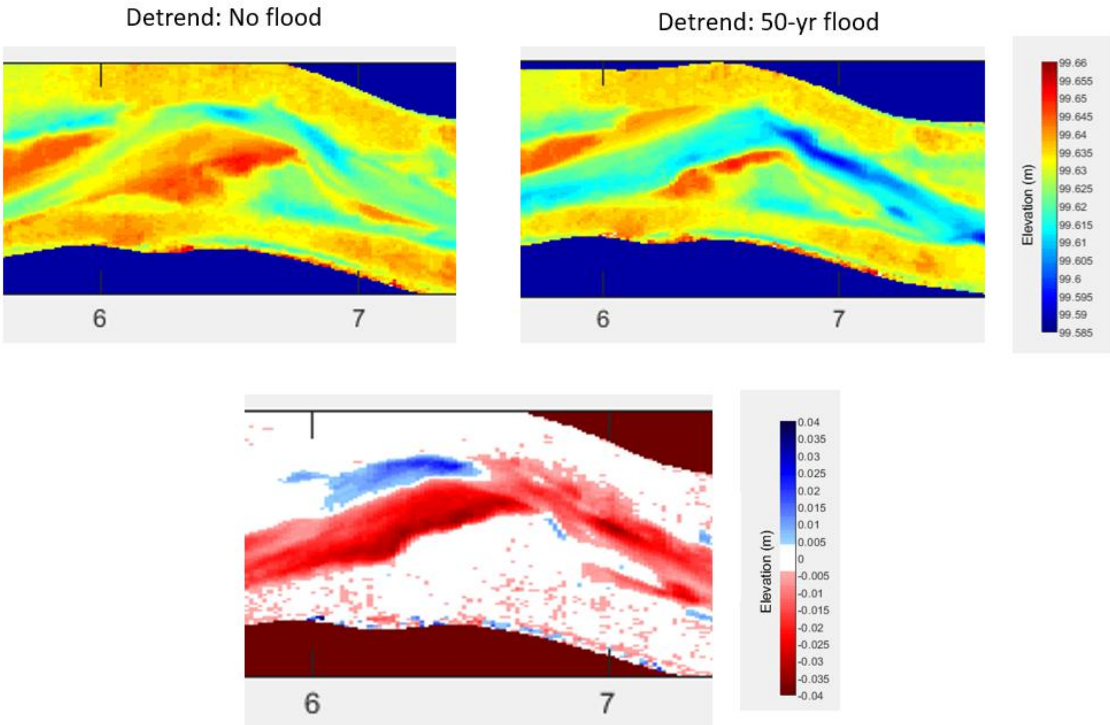

Figure 19: Zoom of the detrended pictures before and after the 50-year flood on the second meander of the flume

Figure 19 focuses on the second meander of the flume. This area has evolved quite a bit throughout the sequence of floods. Initially , there are two bars that can be seen on the detrended picture. As the other area we focused on before, the channel has incised by about 2-centimetres. The erosion of the bed is the most important, the “exit” of the meander where the bed has eroded by 4 centimetres. In this area, it is the bars that moved. The first bar located on the left bank has grown in length and is less large. The DOD shows a deposition up to 2 centimetres. The other bar located on the right bank, has by approximately 15 centimetres laterally.

There was no DEMs or DOD of the downstream flume, due the the issues with the pictures and their analysis. Figure 20 shows zoomed pictures of this same area. This way, there can be a visual analysis of the evolution there.

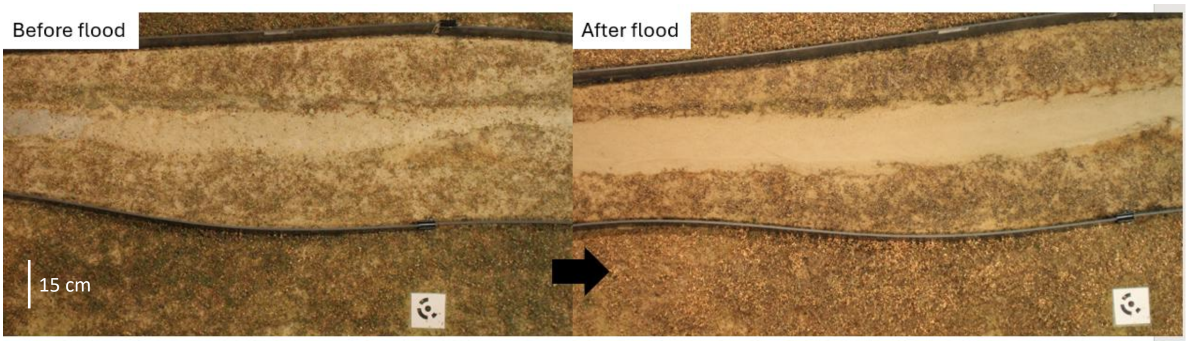

Figure 20: Zoomed photo of the downstream before and after the series of floods

Before the floods, the channel width was about 15 centimetres whereas after the all the storm the width is wider, about 18 centimetres. The downstream of the flume was narrower before the flood than after. It means that the storms eroded the banks which led to an enlargement of the downstream channel.

Figure 21: Photograph of the left bank of the flume after the running of the sequence of floods

Figure 21 shows a close-up of the left bank erosion observed after the floods.

IV. CONCLUSION

During this study, a sequence of flood was run in a flume where a vegetation-less constricted meander river is modelled. The objectives of the experiments were to see the effects of the removal of the vegetation on the floodplain constrained Jumping Pound Creek flume model. The results of this series of flood were a general incision of the riverbed and a channel enlargement almost all along the flume. The meander bends didn't move too much, so the sinuosity didn't change. The inner banks however eroded all along the flume which resulted in the channel widening. The hypothesis for the flume general morphology staying similar, can be that the removal of the vegetation was only partial and a lot of the root system of the Alfalfa was still strong and deeply implemented in the sand. Taking this into account, the banks of the flume were still stabilized by the dense ancient vegetation. The water flow energy was mostly on the minor bed and eroded the banks where the banks were weaker without the vegetation.

Looking back on the of aerial photography and the non-consistent results with the Agisoft processing, improvement can be made on the methodology that were used in these experiments. One thing that could be done is to change the camera placement on the movable camera cage. The vibration caused by moving the cage could have also been an issue. Despite the attempt to try to stabilize the camera cage and the cameras, there could still have been a small movement residue. That might have caused issues on the photographs taken and so problems on the Agisoft process.

Looking forward, the pursue of this flume study is planned, staring a PhD for the next few years to come. The research will consist in trying to find an ideal buffer zone around the river to reduce maximally the constriction effects on the river morphology. Also the ecological impacts that a floodplain constriction has.

This kind of research is important for the knowledge learned about rivers but also for the cities. It is a proof of the importance of preserving rivers' space, ecosystems, and floodplain ecosystems that can push away the urban development near rivers.

BIBLIOGRAPHY

Guo, X.; Chen, D.; Parker, G. *Flow directionality of pristine meandering rivers is embedded in the skewing of high-amplitude bends and neck cutoffs*. Proc. Natl. Acad. Sci. USA **2019**, 116, 23448-23454.
https://doi.org/10.1073/pnas.191087411

Lelpi A., Lapôtre M. G. A., Giblings M. R. and Boyce C. K. *The impact of vegetation on meandering rivers* (2022). Nature Reviews Earth & Environment, volume 3 p.165-178.
https://doi.org/10.1038/s43017-021-00249-6

Li B., Liang Y., Yan X., Yang S., Li X. and Lu J. *Morphological Characteristics of Constrained Meandering Rivers in the Loess Plateau.* Water 2024, 16(19), 2848.

https://doi.org/10.3390/w16192848

Meyer-Peter, E. and Muller, R. (1948*) Formulas for Bed Load Transport. Proceedings of 2nd meeting of the International Association for Hydraulic Structures Research*, Delft, 7 June 1948, 39-64.

Nicoll, T.J.; Hickin, E.J. *Planform geometry and channel migration of confined meandering rivers on the Canadian prairies.* Geomorphology 2010, 116, 37–47
https://doi.org/10.1016/j.geomorph.2009.10.005

Parsapour-Moghaddam P, Rennie CD. *Influence of Meander Confinement on Hydromorphodynamics of a Cohesive Meandering Channe*l. *Water*. 2018; 10(4):354.
https://doi.org/10.3390/w10040354

Rood S. and Kaluthoba S. Riparian. *Woodlands along the middle Bow River through Calgary: Patterns and Processes, including Plant Colonization and Succession*.
https://doi.org/10.13140/RG.2.2.23077.93924

Appendix 1: Interface of MatLAB used for the topography analysis