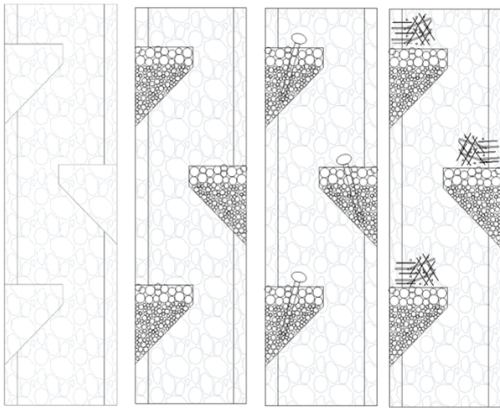


Ensuring Stream Stability with the use of Organic Material in a Flume-based Design Recommendation

WA-RD 939.1

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December 2023



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WA-RD 939.1

**Ensuring stream stability with the use of organic material
in a flume-based design recommendation**

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16. Abstract Fish populations in the Pacific Northwest have declined as spawning grounds disappear due to barriers, most commonly culverts. To reduce the number of culverts acting as fish barriers, in 1999 Washington State implemented new design policies. Accordingly, "stream simulation culverts" include a sediment lining, allowing for more movement of fish in the culvert. To better simulate the stream, more information is needed on maintaining a target channel shape while allowing fish passage during low flows. This research investigated how to incorporate organic material (deformable grade control, meander bars with wood, root wad-lined channel, and organic streambed mixture) into a simulated streambed inside of a flume. The first objective of this research was to investigate the use of deformable grade control and examine the relationship among dowel size, distribution of dowel size, ratio of dowels to sediment, and sediment transport. The second objective was to investigate the effect of meander bars made of coarse material and the addition of organic material in slash and root wads on channel stabilization. The third objective was to investigate using a root wad-lined meandering channel, and it examined the relationship between root wad spacing and channel stabilization. This research's fourth and final objective was to investigate the use of an organic streambed mixture and its effects on channel stabilization. Streambed designs were tested using 10-, 25-, and 50-yr flood events. Sediment transport was recorded after each flood event using a handheld 3D scanner. Sediment transport data was then analyzed to determine elevation changes, elevation differences, and net area change between flood events. Excluding baselines, 15 deformable grade control, 11 meander bars, 3 root wad-lined, and 9 organic streambed mixture channels were tested. The research shows that for deformable grade control, a wood-sediment ratio of 75:25 made from a mix of sizes reduces the overall sediment transport best at both 2% and 3% slopes for a straight U-shape channel. For meander bars, meander bars constructed from coarse material and slash with the cone constructed of D-100 material best maintained the target channel shape at 3% and 4% slopes. For a root wad-lined channel, a spacing of one root wad was the best, maintaining the target channel shape at a 0.7% slope for a meandering channel. For an organic streambed mixture, a wood-sediment ratio of 3:1 was best at retaining the target channel shape at a 2% slope for meandering and straight channels. This research indicates that adding organic material to a streambed reduces sediment transport and maintains the target channel shape.			
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Executive Summary

Fish movement in Pacific Northwest (PNW) streams has been affected by fish barriers. Fish barriers prevent fish from reaching their spawning grounds, which has led to a decline in fish populations. In 1999, Washington State implemented “stream simulation design” (SSD) guidelines to replace the most common barrier, culverts. The SSD is a sediment-lined culvert that should replicate the adjacent channel while maintaining a desired channel shape.

There is little to no guidance on stream designs that implement organic material inside a culvert. This research investigated how adding organic materials to stream features affects channel stability. The organic material was added to four stream features: meander bars (slash located on the upstream side of the feature and a root wad built into the feature), deformable grade control (grade control constructed of organic material), root wad-lined channel, and organic streambed mixture (organic material mixed into the streambed material). The simulated streambed was in a laboratory flume scaled to Asotin Creek (for meander bars, deformable grade controls, and organic streambed mixture) and Panther Creek (for root wad-lined channel).

The first objective of this research was to investigate the use of deformable grade controls specifically to examine different construction configurations (size of the dowels, ratio of dowels to sediment, and distribution of dowel sizes) and their impact on sediment transport. The second objective was to investigate the effects of meander bars constructed with coarse material, the addition of slash on the upstream side, and a built-in root wad on channel stability. The third objective was to investigate how root wad spacing in a meandering channel lined with root wads impacted channel stability. The final objective was to examine the effects of three organic

material to sediment ratios on channel stability. In total, 38 designs were tested: 15 deformable grade controls, 11 meander bars, 3 root wad-lined channels, and 9 organic streambed mixtures. Designs were tested using 10-, 25-, and 50-yr flood events. The transport was recorded after each flood event by scanning the streambed morphology with a handheld 3D scanner after construction and after each flood event. The scans determined elevation and net-area changes between each flood event.

The research shows several effects: 1) Deformable grade controls with a mixture of different diameters and a wood-sediment ratio of 50:50 or 75:25 had the highest reduction of sediment transport. The feature started to deform at higher flood events, and the deformation increased with slope (3-4%); 2) Meander bars constructed with coarse material increased stream stability by 15-21% (one culvert-width spacing) at 2 % slope, 25-36% (three culvert-width spacing) at 2 % slope, and 52-63% (one culvert-width) at 3 % slope. Adding organic material increased the stability at one culvert-width to 10-34% and three culvert-widths to 28-38% for a 2% slope. Adding organic material to the meander bars at a 3% slope increased stability 54-67%; 3) Root wad-lined channels with a spacing of one root wad-diameter increased channel stability by 39-66% and maintained the channel shape. Increasing the spacing between root wads decreased the channel stability; 4) Organic streambed mixture at a sediment-organic material ratio of 3:1 increased channel stability by 23-47% for one culvert-width and 45-56% for three culvert-widths, and the channel shape was maintained. The ratio of material can be raised to 1:1 and still increase channel stability.

The limitations of this work are the size of the flume, smooth dowels for simulating sticks/branches, and the root wads used in the meander bar design. Further research needs to be

done in a wider flume to allow variable sinuosity and woody material that can capture the complexity of root wads and sticks/branches. This research introduces new questions about the use of organic material in SSD: How does channel stability change if meander bars constructed from coarse material are added to an organic streambed mixture, and what is the longevity of organic debris in stream channels?

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CHAPTER ONE: INTRODUCTION

1.1 Culverts

Human-made barriers in streams restrict the movement paths of fish (Nehlsen et al. 1991; Bottom et al. 2005). Dams present the most evident barriers, but road crossings and culverts, which pass water under roads and railways, are formidable barriers as well. The state of Washington has 3,931 culverts statewide, and 2,057 of them are documented as fish barriers (Engdahl et al. 2020; Kanzler et al. 2020). Over the past three decades, Washington has been removing these barriers (Engdahl et al. 2020). Nevertheless, the restricted movement of fish and water have greatly reduced spawning habitat for regionally important fish. According to a 2014 study, salmon spawning habitat has declined by 33% (Roni et al. 2014). Fish passage and populations are closely related to the structures that humans place in streams.

Culverts are designed to ensure that a stream's annual bank full discharge is supported. But using pipe flow hydraulics, doesn't account for the stream process, including floods. Thus, culverts can become barriers with potentially shallow flow depths: channels flatten due to bank erosion, the channel fills with sediment or washes completely out of the culverts, leaving the culvert bare. The sediment washout has led culverts to be well above the water surface on the downstream side (Behlke et al. 1991; Olsen and Tullis 2013). Fish are made to jump into the culvert to move upstream, but in some cases, the height between the culvert and the water surface is too large for fish to jump. Additionally, using yearly discharge leaves the culvert undersized for a significant flood event. Yet the effects of climate change, including increased air temperature and snowmelt occurring earlier (Stewart et al. 2004; Siegel and Crozier 2019), have increased the frequency of significant weather events. The decline of annual snowpack and faster melting mean the early spring months are experiencing more significant peak flow events (Miles

et al. 2000; Praskievicz 2016; Wilhere et al. 2017). Rain, now the most common form of precipitation in late winter and early spring, adds to the runoff in the streams and leads to rain-on-snow flood events (Praskievicz 2016). Using climate data to determine a 100-yr flood and the bankful width for 2040 and 2080, the Washington Department of Fish and Wildlife (WDFW) developed a modeling tool to help design fish passage structures (Wilhere et al. 2017).

The hydraulics of culverts are well understood, which allows for interested parties to focus on the management of flow via stream characteristics. Until recently, there was little guidance on the placement of sediment material to achieve the desired hydraulic and sediment mobility characteristics. Research shows that organic material can increase aquatic habitat and stabilization of the bed and banks (Douglas Shields Jr et al. 2003; Roni et al. 2015; Addy and Wilkinson 2016). However, little research looked at using organic material to build in-stream structures, and what did exist investigated the use in unconfined channels. No work has looked at the use in confined channels (i.e., culverts). While Engdahl et al. (2020) looked at the effect of coarse bands and boulder bars on sediment transport and channel stability inside a culvert, to date no substantial research exists on using organic material within culverts to create habitat and stabilize the channel.

1.2 Stream simulation design

Stream channels subjected to flow through a stream crossing (culvert) differ from unconfined channels in many ways; the swift change in velocity with the discharge limit the cross-section of the channel. This change affects all aspects of sediment transport.

Stream simulation design (SSD) aims to represent an unimpaired reach within the culvert by maintaining a desired channel shape and a low-flow channel for fish movement. Constructing

a simulated stream channel is a costly and labor-intensive process; therefore, low-maintenance designs could provide significant benefits to organizations, like WSDOT, tasked with channel maintenance. The SSD process is outlined in WDFW's Water Crossing Design Guidelines (WCDG) in five steps: 1) watershed review, 2) site assessment, 3) structure selection/channel design, 4) design finalization, and 5) construction of stream simulation design (Barnard et al. 2013). Other than a recent study by Engdahl et al. (2020), which offers guidance for the third step (i.e., the construction of coarse bands to maintain a channel shape for streams at a slope of 2-4%), the process is essentially trial and error in the field, which is a costly and risky approach.

Culvert water crossing installation involves several considerations. The gaps in the WCDG were addressed in the hydraulic manual developed by WSDOT, which details working with fish passages in the manual's chapter 7. The chapter has seven sections: existing conditions, hydraulic analysis, design, other design methods, temporary stream diversions, monitoring, and additional resources. Existing condition, which involves site assessment, outlines the information (sediment distribution curve, slope, discharge, etc.) that is collected from the site (WSDOT Engineers 2019). An unimpaired section of the stream is used as a reference reach for geomorphology features. The assessment also provides stream classification type (step-pool, plane-bed, etc.), bank full width, longitudinal profile, and sediment distribution, among other factors, for the new crossing (Barnard et al. 2013; WSDOT Engineers 2019; Montgomery and Buffington 1998; Barnard et al. 2015). Stream classification types are separated into two scenarios in WCDG. Scenario 1 reads: slope less than 4%, stream classification of plane-bed, step-pool, and dune-ripple. Scenario 2 reads: step-pool, or cascade-type channel, slope greater than 4% (Maxwell and Papanicolaou 2001; Barnard et al. 2013). For more detailed information, refer to the WSDOT hydraulic manual chapter 7.

This research investigated streams that fall within the scenario 1 definition (the slope of the channel is less than 4%). Water crossings under scenario 1 are subject to organic material use to control the channel's structure and cross-section shape. Organic material has been used in stream restoration for decades to improve channel stability and increase aquatic habitat (Roni et al. 2015; Addy and Wilkinson 2016; Dixon 2016) but has not been applied inside stream crossings. The organic material used in stream restoration has been in the form of large woody debris (LWD). Examples of LWD are root wads and logs used to build log jams, which increase bank stability by reducing erosion along the channel banks. In the unconfined channel, the size of the LWD material can be tens of feet long and over a foot in diameter. This LWD is excellent for building massive structures outside a culvert, but it will be too large inside a culvert. Determining the proper sizing of organic material and geometry of features are essential for the long-term durability of a stream simulation culvert.

1.3 Research objective

The use of organic material in streambed designs has been established. Organic stream material provides fish habitat, increases bank stability, and creates stream features. However, there are no clear guidelines on how organic material can be used inside a culvert and no systematic research on the most effective methods to stabilize channels within culverts. Without scientifically based guidelines, designs tested in the field are an expensive trial and error process and culverts are more likely to become fish barriers.

To provide more detailed and scientifically based design guidance, this project aimed to evaluate the efficiency of different channel designs containing organic material on sediment transport, streambed stability, and culvert hydraulics for different flood events. The key research

questions were divided into four cases: deformable grade controls, meander bars, root wad-lined channels, and organic streambed mixture channels.

The first set of hypotheses (H1) were for deformable grade controls: H1.1) a deformable grade control made of a single diameter dowel will maintain the target channel shape downstream while containing sediment upstream; H1.2) increasing the ratio of wood to sediment in the design will decrease the amount of sediment moved over the flow events; H1.3) the distribution of diameter size used in the deformable grade control will decrease sediment transport.

The second set of hypotheses (H2) were for meander bars: H2.1) the construction of a meander bar with coarse material will increase channel stability and maintain the desired channel shape; H2.2) the addition of organic material, in the form of root wads or sticks, to the design will further decrease sediment transport over the flow events.

The third set of hypotheses (H3) were for a root wad-lined channel: H3.1) the addition of root wads is sufficient to maintain a meandering channel shape throughout the structure; H3.2) increasing the spacing between root wads will increase sediment in the channel while also maintaining the desired channel shape.

The fourth set of hypotheses (H4) were for organic streambed mixture channels: H4.1) mixing organic material into the streambed material will decrease sediment transport in the lowest flow event.

These hypotheses were evaluated by constructing physical, scaled experiments in a laboratory flume. The desired channel was constructed and exposed to a range of flood events. The primary datum was the streambed elevation, which was used to determine the change of

elevation in the channel over time as a measure of overall sediment transport. Various channel designs with organic material were constructed in the flume, and the elevation change of each (surface) was compared to determine which channel designs were the most effective at maintaining the channel shape.

CHAPTER TWO: METHODOLOGY

2.1 Albrook Hydraulics Laboratory

This research was conducted at the R. L. Albrook Hydraulics Laboratory on the Washington State University campus in Pullman, Washington. A tilting flume 75 ft long, 2.9 ft wide, and 1.75 ft deep located in the central lab was the primary research tool (Engdahl et al. 2020).

The lab is supplied by a 28,000-gal water supply sump beneath the flume's end. Water is pulled from the sump using a 40 HP pump that delivers water to a distribution manifold, where valves are used to control the direction of the water. The tilting flume has two main configurations to obtain water. Configuration 1: water is pumped from the sump into the central manifold. It flows through a large gate valve into a holding tank, where water fills an equalizing reservoir of 120 ft³ before spilling over a 5-ft-tall sharp-crested weir. Water from the holding tank is removed by a 25 HP pump and sent to the flume. The pump has a gate valve attached to the outflow and has two butterfly valves, one located 5 ft past the gate valve that regulates the flow out of the pump and the other located off a tee about 3 ft past the gate valve to be used as a bleed-off to lower the flow in the flume. A velocity meter is 6 ft past the gate valve and 1 ft past the last butterfly valve to discern the flow in the flume. This configuration provides discharges from 0.02-1.5 ft³/s. Configuration 2: water is pumped from the sump into the central manifold. The large gate valve leading to the holding tank is closed. A 3-in diameter pipe that runs to the top of the flume is connected to the central manifold. A gate valve about 3 ft from the main manifold directly controls the flume's flow. A third configuration combines both systems with the large gate valve opened 12 revolutions, and the bleed-off valve located on the 40 HP pump supply line before the manifold, half-open. This configuration supplies a flow of 2.9 ft³/s through the flume. A fourth configuration is the same, except the 40 HP pump supply line bleed-off is closed. This configuration delivers 4.2 ft³/s to the flume, the maximum for the current plumbing. See Table 1 for the flow of each pipe configuration.

Table 1 Flow in each pipe configuration

Pipe Configuration	Q (cfs)
1	0.02-1.5
2	0.2-1.4
3	2.9
4	4.2

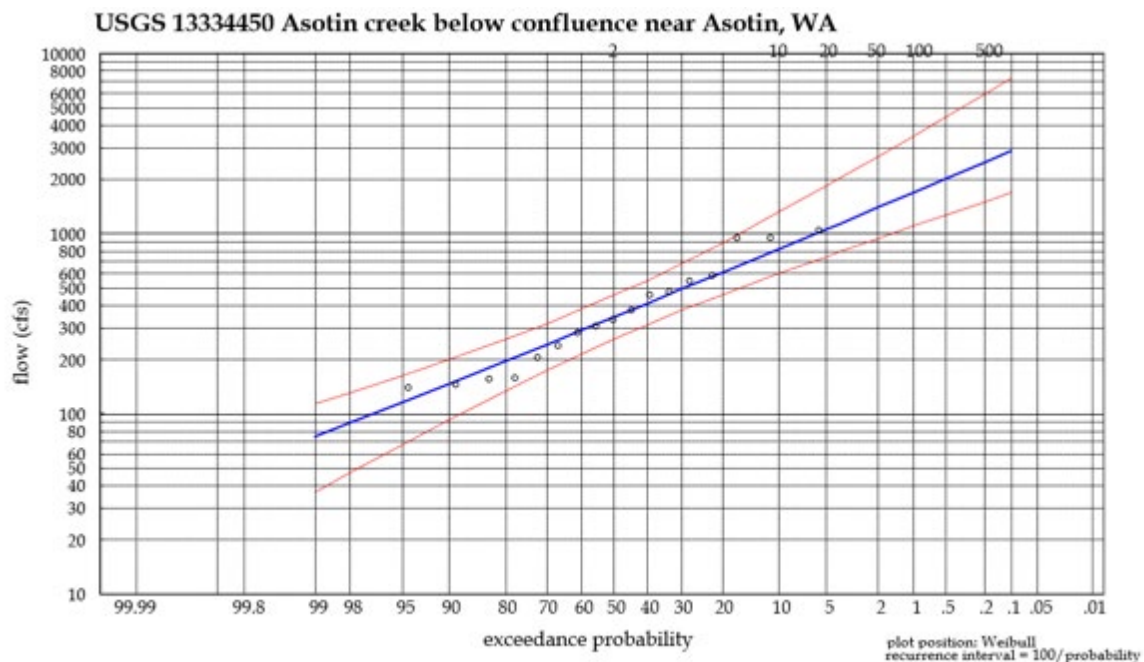
2.2 Asotin Creek

The reference stream for our study is Asotin Creek, located in the southeast corner of Washington State. For detailed information about Asotin Creek, refer to our previous study, “Flume-Based Design Recommendations for Coarse Bands and Boulder Bars to Improve Retention of Channel Shape in Stream Simulation Culverts” (Engdahl et al. 2020). Grain size distribution and flow statistics from the reference stream were used to scale the laboratory simulations. The mean substrates (D50) for the South Fork and North Fork of Asotin Creek were calculated using Wollman pebble count, which obtained 2.5 in and 2.9 in (Bennett et al. 2018). A 7.6:1 scale of the field to the lab was applied to the length units for the deformable grade control, meander bars, and organic streambed mixture.

Flood intervals were determined using the USGS gage station 13334450 on Asotin Creek below the confluence of the North and South Forks. The average flow of water in 2017 was 76 ft³/s; flows had a high of 692 ft³/s and a low of 21 ft³/s (USGS Gage). A frequency Curves Analyzer version 306 used the record of peak discharge at this gage station to provide the flow discharge for flood events required for our simulation testing (Table 2b). The discharge is shown in a logarithmic function graph, the flow duration curve. The flow duration curve graph has three lines representing the best fit (blue line), the Q5 percentile, and the Q95 percentile. Lab-scaled flows were kept between the Q5 and Q95 lines.

Table 2 Flood frequency values for Asotin Creek and the flows in the lab.

Recurrence	Q	Q5	Q95	Lab flow
	(cfs)	(cfs)	(cfs)	(cfs)
1.01	75	114	37	0.08
2	345	456	261	0.59
5	609	894	460	1.04
10	822	1,317	602	1.36
25	1,135	2,024	792	1.79
50	1,400	2,689	943	2.13



2.3 Laboratory methods

This study created streambeds within the flume and subjected them to various flows based on the reference stream. The streambeds were initially simulated without organic features to establish their baseline performance; then, different streambed configurations were tested to evaluate the effects of organic features on channel stability. Detailed scenario descriptions are included in the following sections, and results are provided in chapter 3.

A short overview of the experimental process is as follows: 1) a flat, uniform streambed was initially constructed in the flume, 2) the desired channel shape was excavated, 3) if required for the layout, coarse material and organic features were added by excavating streambed material in the location they were to be placed, placing the organic material, then carefully backfilling around the feature to ensure a continuous streambed. After these setup steps, sediment transport was quantified using a streambed profile scan, and the flume was run at each discharge for 20 min. To prevent shifts in the channel's surface, the flows gradually increased and decreased. After the final scan for a particular streambed configuration, the organic material was removed, the streambed design was re-created, and two replicates of the experiment were conducted before moving on to the following layout. Data from all three trials were averaged to estimate sediment transport. Sediment transport was calculated as the area difference between the initial measurements of the streambed elevation and the streambed elevation after each flow event.

The streambed was constructed with a flat sediment bed. The desired channel shape was constructed by removing material from the flume or placing the material next to the walls of the flume to raise the banks of the channel. The channel used for the deformable grade control was a straight U-notch channel for which the material removed in the center of the flume was placed on the sides of the channel.

The study's focus area was the middle 10 ft of the 18 ft length of the experimental streambed to avoid boundary effects at the upstream and downstream end of the streambed. To account for water forces entering/exiting the streambed that could lead to increased erosion or deposition, the study section was closer to either end of the streambed. Vertical metal bars were placed at the downstream end of the streambed to create an upstream force to keep the overall streambed in place. The space between the bars was wide enough to pass the D100 of the stream material, thus sediment mobility was not inhibited. Design features were added after the desired channel shape was constructed and their locations determined by the particular scenario being considered.

Three flows were used: baseflow-10-yr flood event, a 25-yr flood event, and a 50-yr flood event. Each of the 3 flow conditions was executed for 20 min for a total flow event of 1 hr. Twenty minutes was used because our initial observation of the streambed changes in the flume indicated that maximum movement happened during this timeframe; a longer interval did not demonstrate significant changes in bed material movement rates. Streambed profile scans were collected using an Einscan H 3D handheld scanner before the first run and after each run. Each set of scans took about 3-5 min. After the final scan, the experimental streambed was reset following the procedure described above. Each trial took approximately 3 hr to complete.

2.4 3D scanner methodology

The 3D scanner used in the study was the EinScan-H, a 3D handheld scanner that must be connected to a computer during scans. This 3D scanner has an overall accuracy of up to 0.05 mm, a resolution of 0.25-3 mm, and a scanning speed of 1,200,000 points/second. There are 2 scan modes (White Light (LED) or Invisible Infrared) and 4 alignment modes (features, texture alignment, hybrid alignment, and global markers). The EinScan software has instrument setup, object scanning, and post-processing steps. The next paragraph describes the object scanning and post-processing steps.

When setting up the scanner, the user must connect the scanner to the computer; create a new project; and select the scan mode, alignment mode, resolution settings, and whether texture is turned on or off. During scanning, a light on top of the scanner will indicate the correct distance from the scanner to the feature being scanned. Blue means the scanner is too far from the feature, green is the optimal distance, and red is too close. The brightness of the scanner can be adjusted to ensure as many points as possible are included in the scan. During post-processing, the user may edit the scan (delete points or scan), create a point cloud, build a mesh (watertight or unwatertight), and edit the mesh (fill holes, etc.). Once the mesh is completed, the scan coordinates can be changed to a known orientation. The data from the scan can then be exported as asc, obj, stl, ply, p3, and 3mf files. For a more in-depth description of the scanner and software, refer to the Shining3D EinScan H user manual.

For this research, we used the White Light (LED) scan mode, texture alignment mode, and resolution at 1 mm. The streambed was scanned 1 ft before and after the study section to ensure the whole study section was captured. Post-processing of the scan included creating a point cloud from the scan data, then creating an unwatertight mesh from the point cloud with the fill small holes option of curvature at a perimeter of 100mm was used. selected. Three reference points on the flume were used to change the mesh coordinates. The data was then exported as an asc file. Further analysis of the data was performed in MATLAB.

2.5 Deformable grade control

A deformable grade control (DGC) design is a trench of organic material (logs, branches, and sticks) perpendicular to the flow that acts as a typical grade control but can deform over time. The material used in the construction of DGC was wood dowels with a diameter of 1/8 in, 3/8 in, and 7/8 in, and the lengths of the dowels are, in terms of the flume width, 3/4 , 1/2 , 1/4 , and 1/6 . This design was tested at 2%, 3%, and 4% slopes. The following sections will discuss the configurations of DGC at each slope.

At the 2% slope, we tested 14 configurations of DGC (Table 3). Four categories make up most of the layouts that were tested: 1/8 in diameter, 3/8 in diameter, 7/8 in diameter, and a distribution of the 3 diameters. In each category, the ratio of wood to sediment was tested at 75:25, 50:50, and 25:75. The design with the lowest sediment transport was used to test the width and depth of the trench. The design with the lowest sediment transport was then also constructed at a 3% and 4% percent slope.

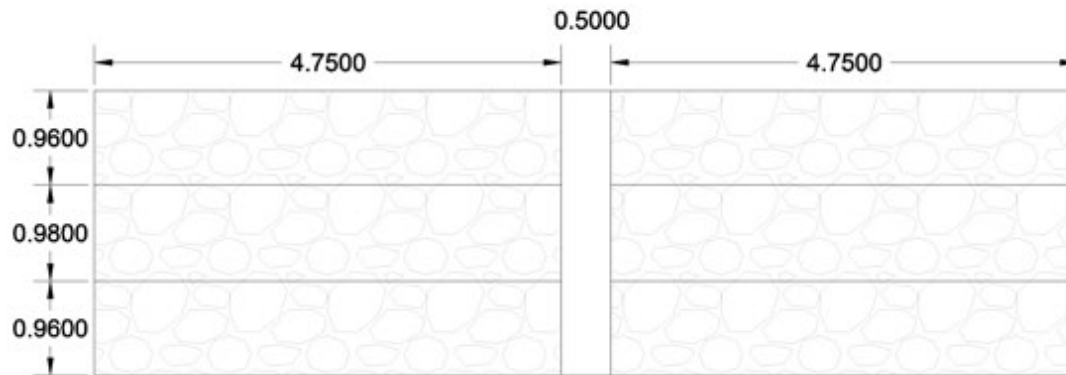


Figure 1 Plan view of the location of the trench for DGC in the channel.



Figure 2 Cross section of a trench dug for DGC.

Table 3 Inventory of the experimental runs (layouts) tested in this study for Deformable Grade Controls.

Layout Number	Description.	Ratio (sediment-wood)
0	Baseline – no DGC	
1	DGC constructed with 7/8" dowel at a ratio of 50:50. The trench width was 6" and extends to the bottom of the flume.	
2	DGC constructed with 7/8" dowel at a ratio of 75:25. The trench width was 6" and extends to the bottom of the flume.	
3	DGC constructed with 7/8" dowel at a ratio of 25:75. The trench width was 6" and extends to the bottom of the flume.	
4	DGC constructed with 3/8" dowel at a ratio of 25:75. The trench width was 6" and extends to the bottom of the flume.	

5	DGC constructed with 3/8" dowel at a ratio of 50:50. The trench width was 6" and extends to the bottom of the flume.
6	DGC constructed with 3/8" dowel at a ratio of 75:25. The trench width was 6" and extends to the bottom of the flume.
7	DGC constructed with 1/8" dowel at a ratio of 25:75. The trench width was 6" and extends to the bottom of the flume.
8	DGC constructed with 1/8" dowel at a ratio of 50:50. The trench width was 6" and extends to the bottom of the flume.
9	DGC constructed with 1/8" dowel at a ratio of 75:25. The trench width was 6" and extends to the bottom of the flume.
10	DGC constructed with mixture (1/8-7/8") dowel at a ratio of 25:75. The trench width was 6" and extends to the bottom of the flume.
11	DGC constructed with mixture (1/8-7/8") dowel at a ratio of 50:50. The trench width was 6" and extends to the bottom of the flume.
12	DGC constructed with mixture (1/8-7/8") dowel at a ratio of 50:50. The trench width was 6" and extends half the depth of to the bottom of the flume.
13	DGC constructed with mixture (1/8-7/8") dowel at a ratio of 50:50. The trench width was 3" and extends to the bottom of the flume.

2.6 Meander bars with wood

The meander bars (MBs) design is a trapezoidal channel with point bars (meander bars) extending into the center of the channel. The trapezoidal channel parameters are a bottom width of 1.6 ft, a height of 0.41 ft, and a top width of 2.24 ft (Figs. 3 and 4). The meander bars look like an ice cream cone split in half (Fig. 3), with the head of the cone made up of sizeable coarse material (D200-300 of the streambed material) and the cone made of material larger than D100. The head of the MBs cone is 2 particle-diameters wide, extends just under halfway across the channel, and has a depth to the bottom of the culvert (flume). The cone extends in the downstream direction and has a length of two-thirds of culvert-width for one culvert-width spacing between features and one culvert-width for three culvert-widths between features.

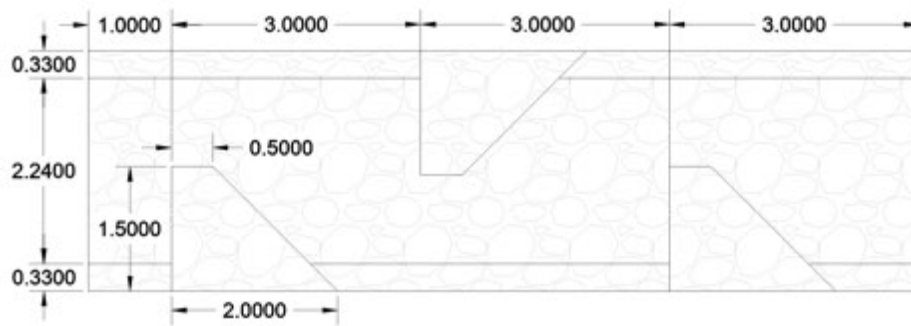


Figure 3 Plan view of meander bar channel at one culvert width spacing.

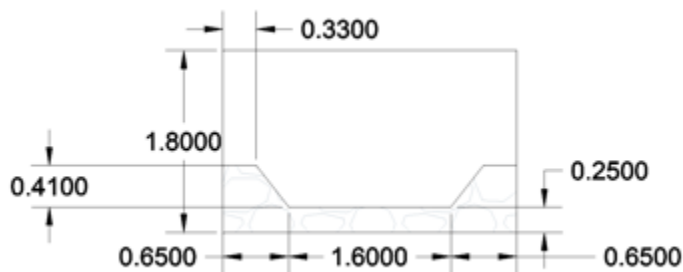


Figure 4 Cross section of meander bar channel.

Meander bars have 4 configurations: streambed material (MB-SBM), coarse material (MB-CM), coarse material with root wad (MB-CMR), and coarse material with slash (MB-CMS). MB-SBM (Fig.5, left panel) is built with streambed material, while the other 3 are made with coarse material D200-300 for the head and greater than D100 for the cone. MB-CMR (Fig. 5, second panel from right) has a root wad built into the feature, with the root wad facing upstream. The root wad has a maximum diameter of 3 in and is attached to a 1 1/2-in diameter log that is half a culvert-width long. MB-CMS (Fig. 5, right panel) has 18 dowels placed into the streambed just upstream of the head of the MBs. Five of the dowels are 3/8 in diameter; two of these are 1/4 culvert-width in length and three are 1/6 culvert-width length. The remaining eleven dowels have a 1/8 in diameter and a length of 1/6 culvert-width.

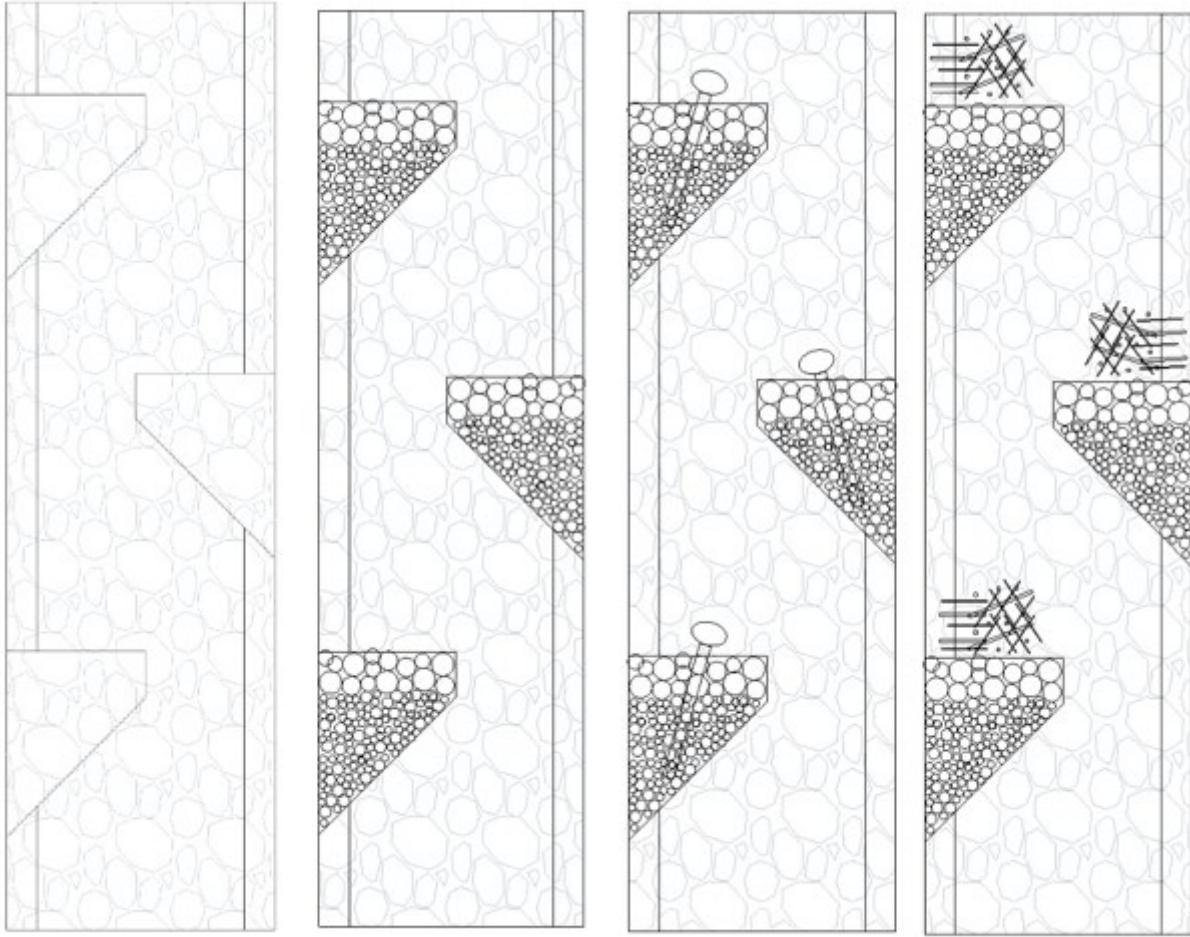


Figure 5 Plan view of meander bar layouts tested at one channel width spacing. From left to right, the first figure is MB-SBM. The second figure is MB-CM. The third figure is MB-CMR. The final figure is MB-CMS.

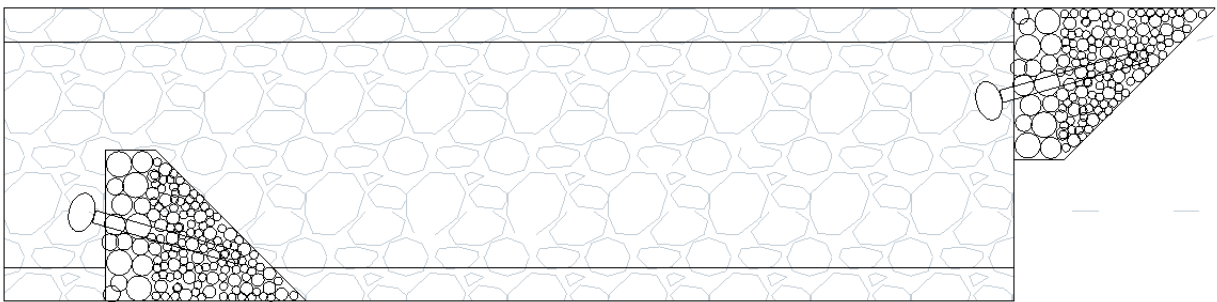


Figure 6 Plan view of MB-CMR at three channel-width spacing.

2.7 Root wad-lined channel

Root wads used in this study were simulated by screwing 2 plywood disks with a diameter of approximately 2 1/2 in and 1 in to a 7/8-in-diameter dowel. The plywood was wrapped in burlap, and finishing nails were used to represent the roots coming from the root wad. Figure 9 shows the construction of a root wad.

The root wad-lined channel design represents a floodplain with a low gradient stream. To illustrate this type of channel, the flume is lowered to a slope of 0.7%, and the streambed material was sieved to have a D50 of 4.25 mm (see appendix B for sediment distribution curve). This design uses the reference stream of Panther Creek, the outlet of Panther Lake, located in Kent, WA. The flume has a scale of 4.8 to Panther Creek, and the new flow value adjusted accordingly (Table 4). With the larger material removed, the streambed length is shortened to 13 ft, which leads to the study section being shortened to 7 ft. This distance allows spacing between the inlet and outlet, reducing the boundary effect.

Table 4 Flow values used for the root wad-lined channel.

Recurrence (yr)	Q (cfs)
2	0.14
10	0.27
25	0.34
50	0.40

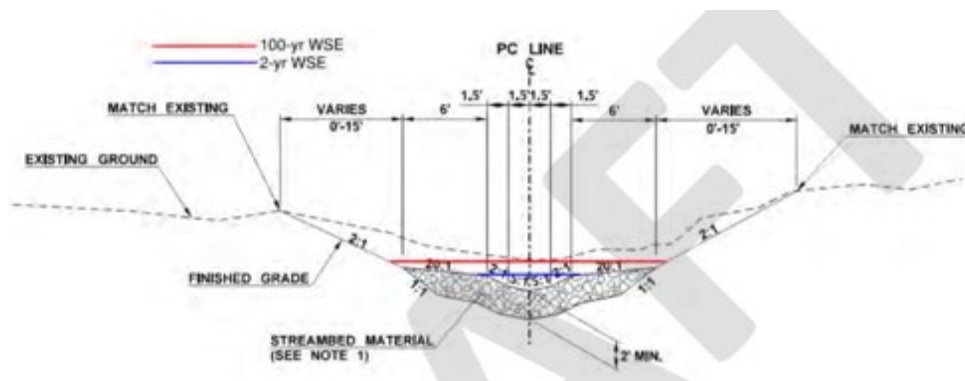


Figure 7 designed cross-section for root wad-lined channel.

For the root wad-lined design, the desired shape is a meandering trapezoid channel. The cross-section shape was provided by WSDOT engineers from the design report for Panther Creek. Figure 7 shows the design of the cross-section, scaled down to fit the flume using the scale size given above. The meandering channel point bars are 4 ft apart (Fig. 8).

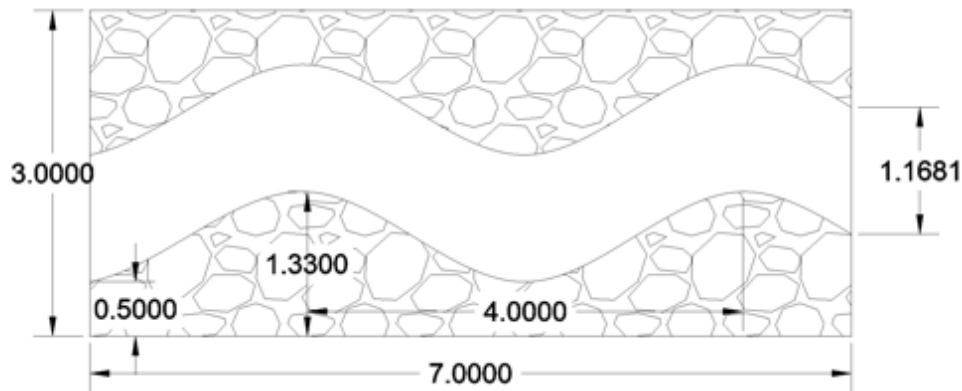


Figure 8 Plain view of the meandering channel for root wad-lined channel.



Figure 9 A constructed root wad used in the root wad-lined channel designs.

The objective of this design is to test the spacing between root wads. The spacing between root wads was scaled to the diameter of the root wad width (root wad diameter is approximately 3 in). The

spacing was tested at one root wad-width (1-RW) or 3 in, two root wad-widths (2-RW) or 6 in and four root wad-widths (4-RW) or 1 ft.

2.8 Organic streambed mixture

This design adds a ratio of organic material (OM) to the streambed material at sediment to organic material volume ratios of 3:1, 1:1, and 1:3. The total volume of the study section is 208.26 gal, therefore the volume of OM will be 52.06 gal for 3:1, 104.13 gal for a 1:1, and 156.19 gal for 1:3.

The OM used the study was broomcorn, 1/8-in dowel, and 1/4-in dowel. The material was chosen to ensure a distribution of diameters under 2 in when scaled to the field. The length of the material is less than half a culvert-width, as follows: 1/4-in diameter dowels will have lengths of 1/2, 1/4, and 1/6 culvert-width (18 in, 9 in, and 6 in, respectively); 1/8-in diameter dowels will have lengths of 1/6, 1/12 culvert-widths (6 in and 3 in, respectively); and broomcorn will have length of less than 1/18 culvert-width (less than 2 in). Broomcorn is 60% of OM, 1/8-in dowels are 18% of OM, and 1/4-in dowels are 22% of OM.

This design was tested at the Asotin Creek scales with a 2% channel slope. The channel shapes tested are straight U-notch channels used for the deformable grade control and meander bar design (one culvert-width and three culvert-widths). Each channel design was tested with ratios of 3:1, 1:1, and 1:3 OM mixed into the streambed material.

2.9 Sediment transport estimation

The scan data were analyzed with the assistance of MATLAB programming. Channel stability and sediment transport data of the streambed without features (i.e., deformable grade controls, meander bars, root wads, and organic streambed mixture) provided baseline data for evaluating streambed area changes and sediment transport. Change in area was calculated by subtracting the initial streambed scan from streambed scans after flow events. Change in area for

each scan was integrated to obtain the area changed in numbers and percentage for the total streambed. Figure 10 is a flow chart showing how the difference in area was calculated.

Channel migration during flood events details deposition and erosion. The volume and channel shape are compared with baseline data, such that all transport data are expressed relative to the no-features scenario. Positive percent reductions mean the features give a performance advantage, with greater percentages providing increasingly better stability; a 100% reduction would indicate no sediment movement. Interpolated color plot maps were constructed to demonstrate where the changes in streambed surface were taking place (Fig. 11).

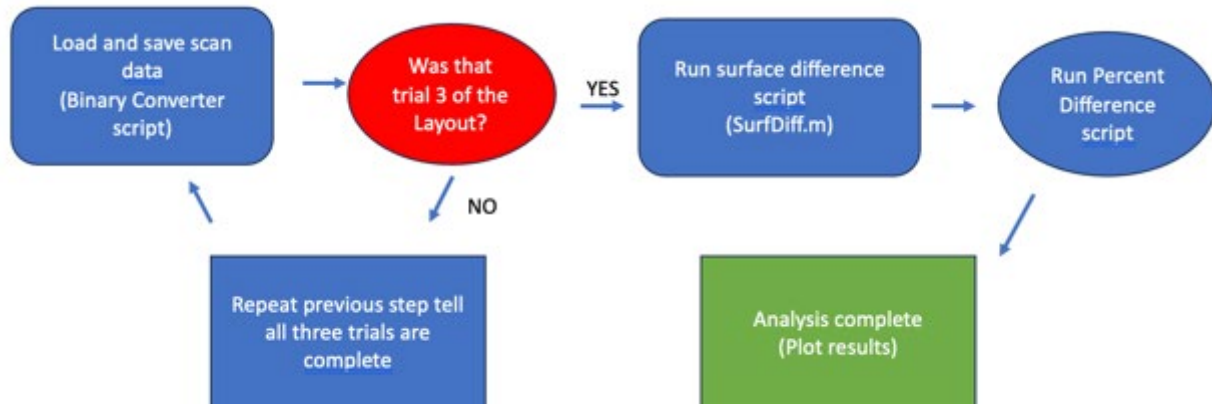


Figure 10. A flow chart of the calculations for the cross-sectional area difference for each flood event.

CHAPTER THREE: RESULTS

This chapter describes the results of each design separately, following the order in Chapter 2.3. After the results for all slopes of the deformable grade control, the sections will cover the results for the meander bar, root wad lined channel, and organic streambed mixture. Results represent the average of three experimental trials for each design.

3.1 Deformable Grade Control

The results for deformable grade control (DGC) in a straight channel are organized by the slope of the tested flume. These were 2%, 3%, and 4% slopes.

3.1.1 2% Slope results

The addition of DGC in a straight U-notch channel at 2% slope captured sediment transport upstream of the feature and maintained the channel shape downstream. Figure 11 shows the difference in streambed elevation between the initial streambed and the 25-yr flood event. Erosion is represented by negative numbers and blue color, deposition by positive numbers and yellow color. After a 25-yr flood, layout 0 (baseline, i.e., no features) had erosion

on the channel's banks. In contrast, deposition occurred in the center of the channel.

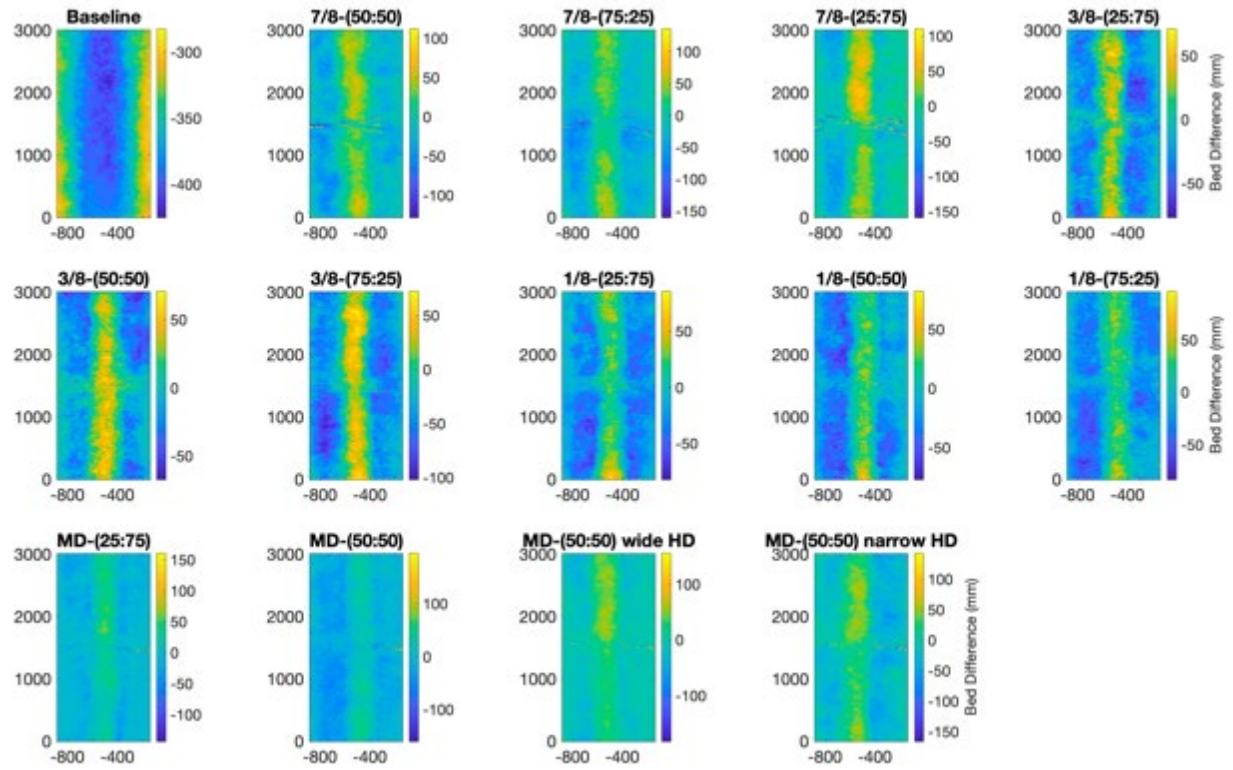


Figure 11 The elevation difference between the original streambed and after a 25-yr flood for a straight U-shaped channel at a 2% slope. DGC is placed in the center. Yellow represents deposition, while blue represents erosion.

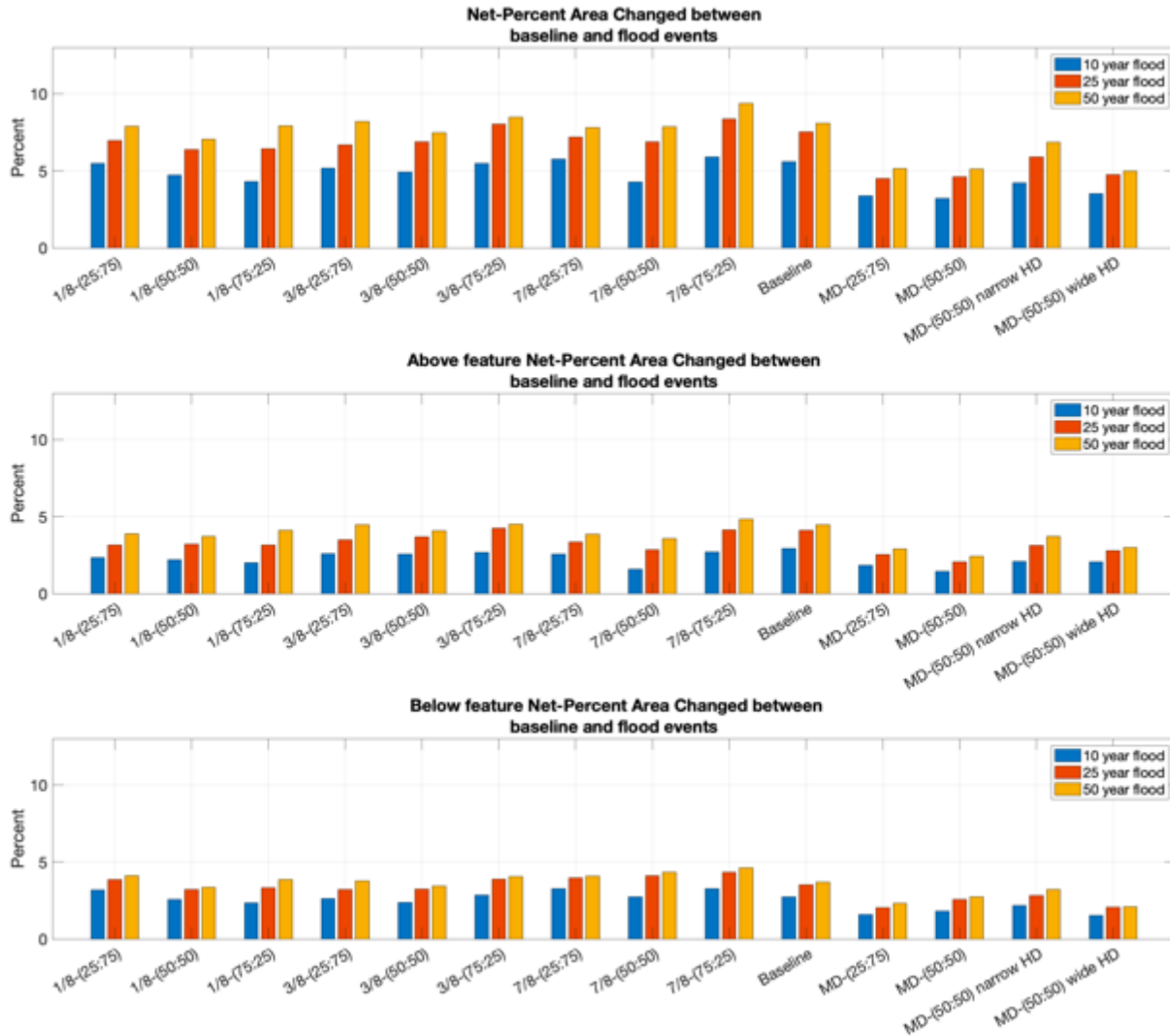


Figure 12 The percent difference between the original elevation and after every flood event of cross-sectional area changes for a straight U-shaped channel at a 2% slope.

3.1.2 3% percent slope results

DGC at a 3% slope was constructed with a mixture of dowel diameters and a wood-sediment ratio of 75:25 (also written as 75-25). The net percent area changed between the baseline and flood events is shown in Figure 12. At a 10-yr flood event, the DGC had 1.1% less area change than the baseline, while at a 25-yr flood event, the DGC had 0.19% more than the

baseline, and at the 50-yr flood event, the DGC had 0.18% fewer changes than the baseline. The majority of the area changes occurred above the DGC location (middle graph in Fig. 12). DGC had more movement below the DGC location at a 10-yr flood event and less during the 25- and 50-yr flood events.

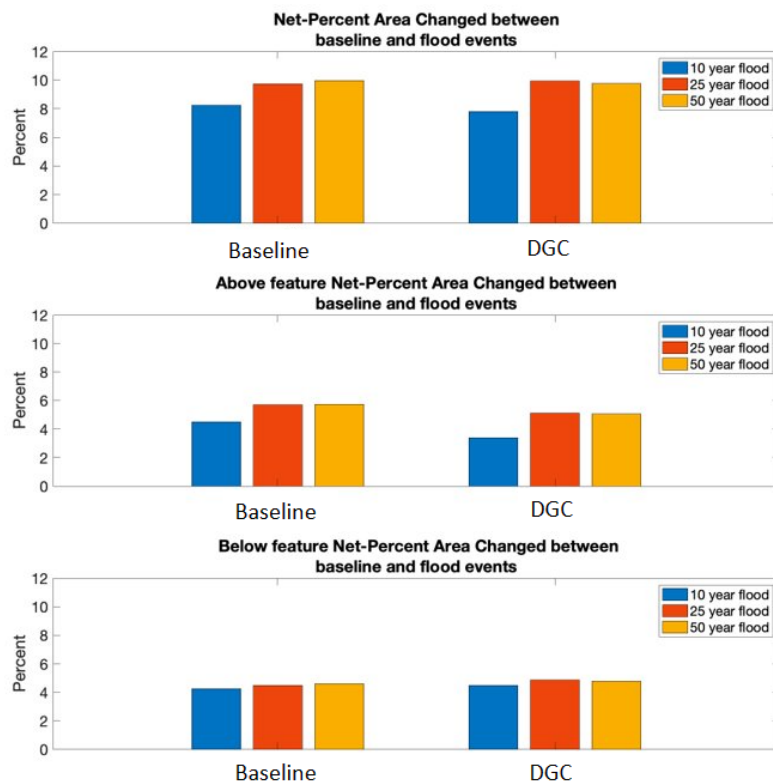


Figure 13 Shows the net-percent area changed between the baseline and the flood event for DGC at a 3% slope.

Figure 14 shows a color plot of the difference in the streambed elevation between the baseline and 25-yr flood events. The color yellow represents deposition, and the color blue represents erosion. In the baseline channel, deposition has taken place in the center of the channel, and erosion occurred on the sides of the channel. Erosion is predominant on the left bank of the channel. In the DGC (7/8-1/8 (72-25)) plot, erosion in the center of the channel is

reduced, and little change has occurred on the right side. The most erosion occurred on the left bank of the channel, as seen in the baseline design.

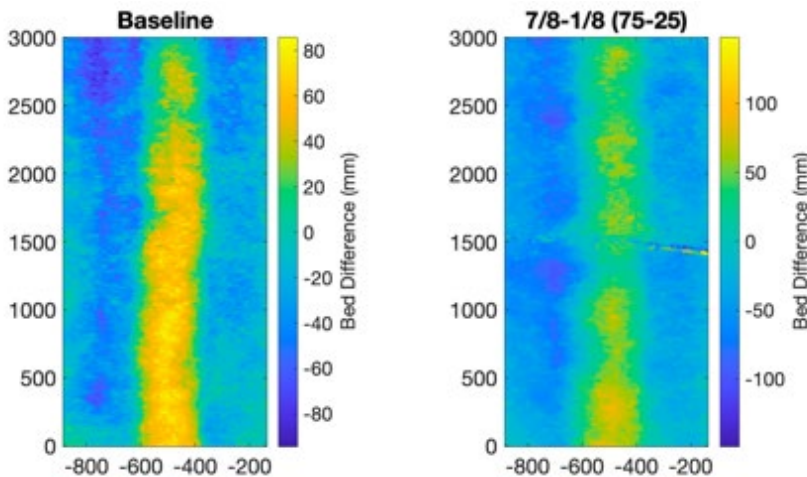


Figure 14 The elevation difference between the original streambed and after a 25-yr flood event for a straight U-shaped channel at a 3% slope. DGC is placed in the center. Yellow represents deposition, while blue represents erosion. The figure shows the DGC significantly reduces erosion of the edges of the channel and deposition in the center of the channel compared to the baseline channel.

3.1.3 4% percent slope results

DGC at a 4% slope was constructed using a mixture of diameter dowels at a wood-sediment ratio of 75:25. Figure 15 shows the net-percent area change between the initial streambed and flood events and confirms that the DGC reduced sediment transport for each flood event, but the reduction is minimal. The middle and bottom graphs in Figure 15 show the area

changed above and below the DGC. Sediment transport occurred more upstream of the DGC location than downstream for both the baseline and the DGC scenarios.

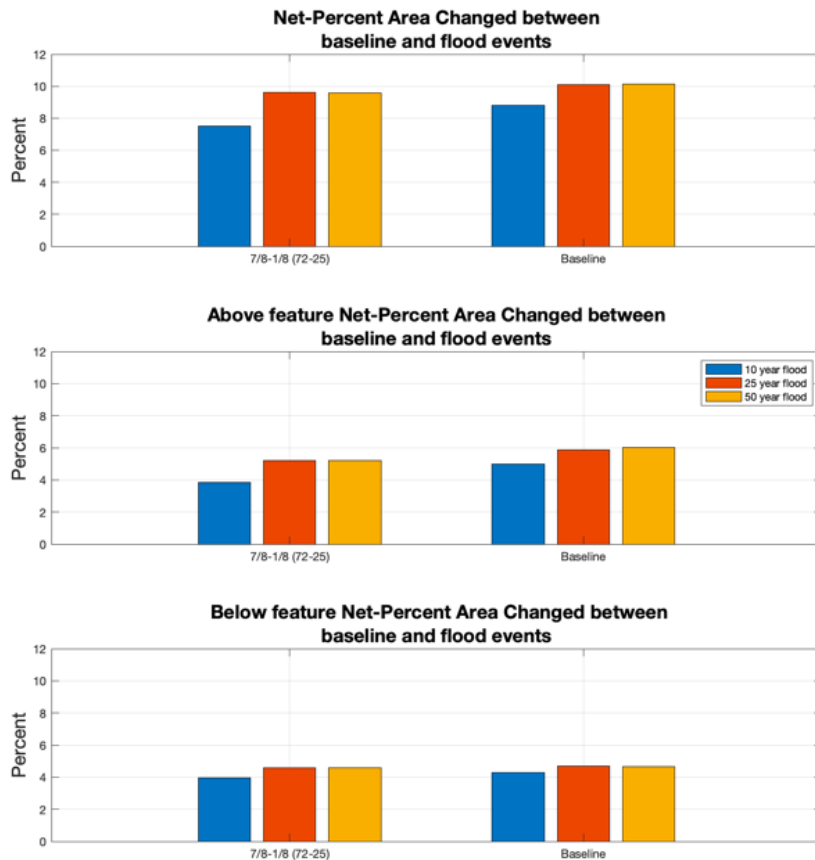


Figure 15 The percent difference between the original elevation and after every flood event of cross-sectional area changes for a straight U-shaped channel at a 4% slope. The top figure is the area changed for the whole channel. The middle figure is the area changed upstream from the DGC. The bottom figure is the area changed downstream from the DGC.

Figure 16 shows where erosion and deposition occurred in the channel after a 25-yr flood event. The baseline channel had deposition in the center of the channel and erosion on the channel's banks. The DGC (7/8-1/8 (75-25)) reduced the deposition in the center of the channel both upstream and downstream of the feature compared to baseline. A 25-yr flood event resulted in

more erosion on the left bank at the DGC location than on the opposite bank, which experienced little change.

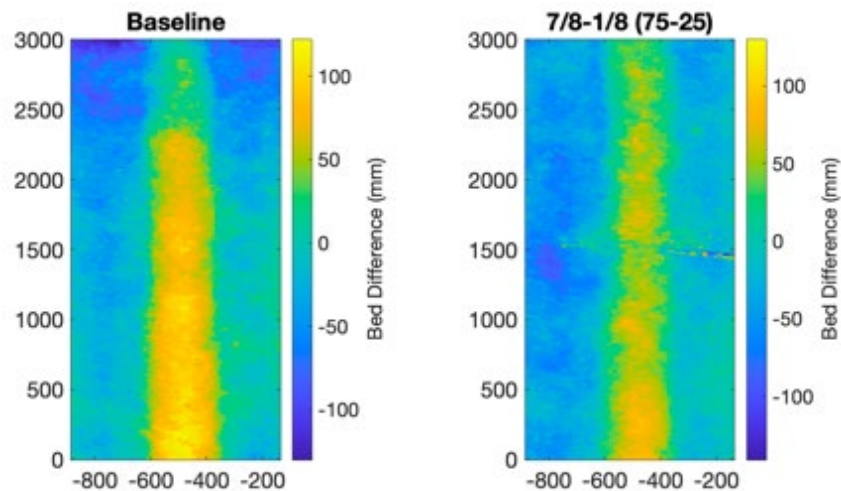


Figure 16 The elevation difference between the original streambed and after a 25-yr flood event for a straight U-shaped channel at a 4% slope. DGC is placed in the center. Yellow represents deposition, while blue represents erosion. The figure shows the reduced deposition in the channel's center compared to the baseline channel.

3.2 Meander bars

The results for meandering channels made of streambed material (MB-SBM), coarse material (MB-CM), coarse material with root wad (MB-CMR), and coarse material with slash (MB-CMS) are organized by the slope of the flume used for the test. Slopes tested are 2%, 3%, and 4% slopes.

3.2.1 2% slope results

Meander bar channels at a 2% slope were tested at one- and three-channel-width (1 CW, 3 CW) spacings between the meander bars. In all scenarios, meander bars at a 1 CW spacing had

less erosion of the edges of the channel and less deposition in the center of the channel than meander bars at 3 CW spacing as difference plots in Figure 17 show. Blue represents a decrease in elevation, while yellow represents an increase in elevation. Meander bar channels made of streambed material for 1 CW- and 3 CW- spacing had erosion of its edges (blue) and deposition in the center of the channel (yellow). The erosion and deposition patterns caused these channels to flatten out after a 50-yr flood event.

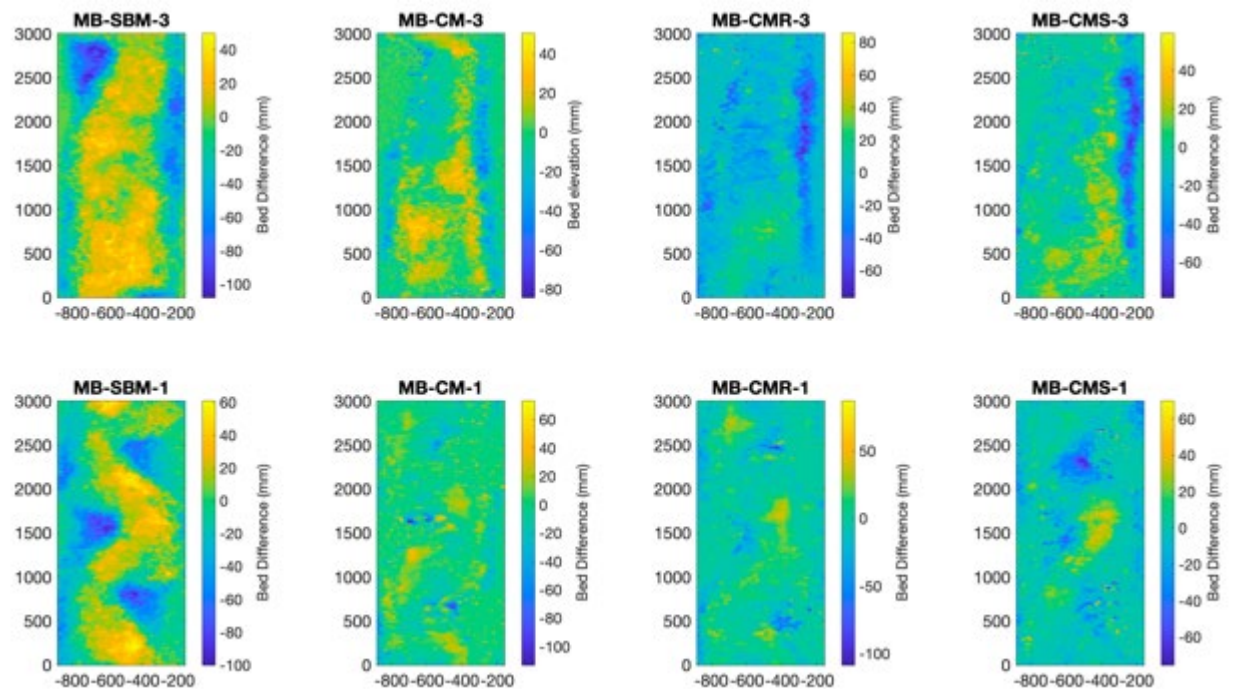


Figure 17 The elevation difference between the original streambed and after a 25-yr flood event for a meandering channel at a 2% slope. Yellow represents deposition, while blue represents erosion.

For 1 CW spacing, meander bars made of coarse material with slash experienced the smallest net percent area changed; however, meander bars made out of coarse material and meander bars made of coarse material and root wads had a net percent change within 0.5% of each other after a 50-yr flood event (Fig. 18). Meander bars made of coarse material and slash had little erosion of

edges, represented by green in Figure 16, and erosion at the midpoint of the channel in its center, represented by yellow. For 3 CW spacing, meander bar channels with had more erosion of the edges on the right side of the channel than the left side, represented by dark blue in figure (18) on the right side of the channels.

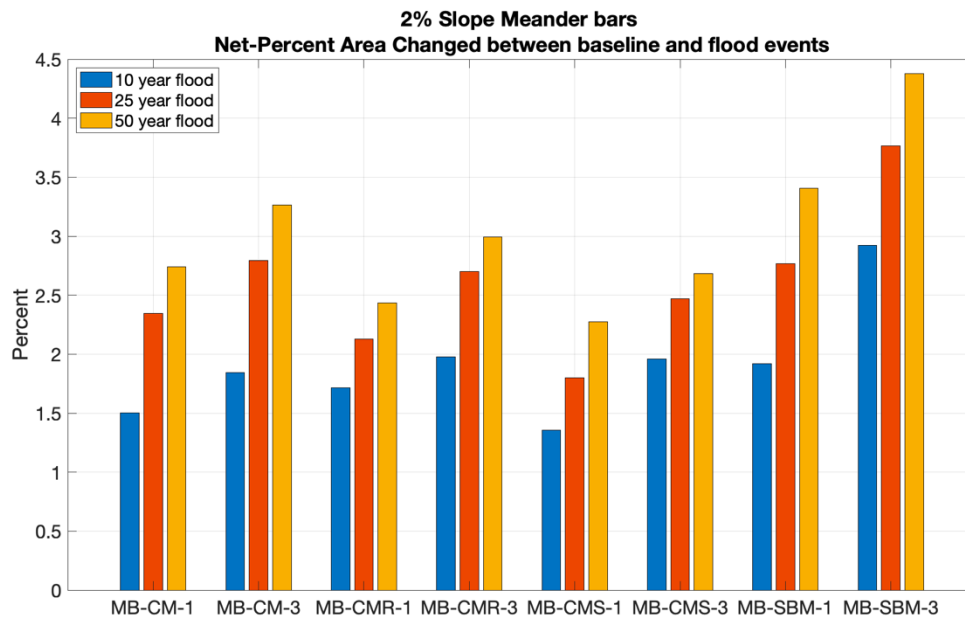


Figure 18 The percent difference between the original elevation and after every flood event of cross-sectional area changes for a meandering channel at a 2% slope.

3.2.2 3% slope results

Meander bar channels at a 3% slope were tested at 1 CW spacing between meander bars. Meander bars made from streambed material had the most significant net percent area changed, as seen in Figure 19. Meander bars made of streambed material were flattened out by the end of a 10-yr flood event and had the most erosion of edges and deposition in the center of the channel as seen in Figure 20. Yellow represents deposition, and blue represents erosion. Meander bars made of coarse material, coarse material with root wads, and coarse material with slash all had similar net percent area changed within 0.5% of each other after a 50-yr flood event (Fig. 19). Meander bars made with coarse material and slash had the least amount of deposition in the

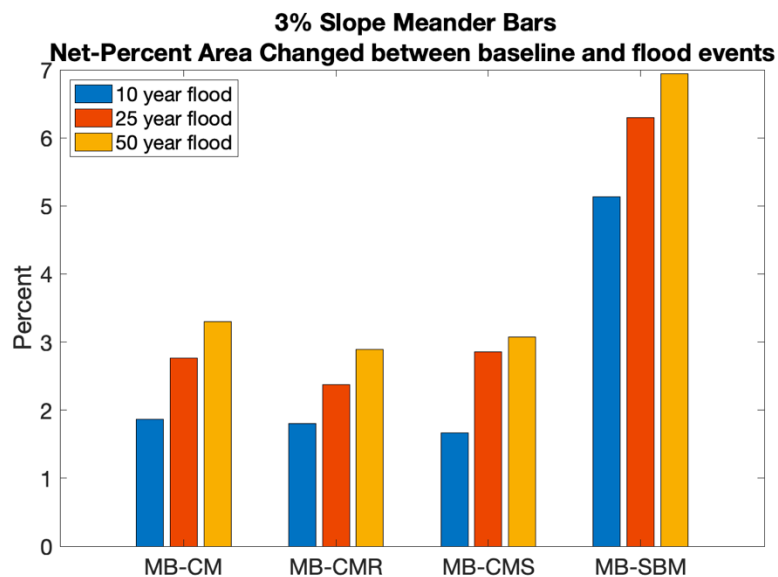


Figure 19 The percent difference between original elevation and after every flood event of cross-sectional area changes for a meandering channel at a 3% slope.

center of the channel compared to meander bars made with coarse material and root wads and meander bars made with streambed material; deposition is represented by yellow in Figure 20. Meander bars made of coarse material had some boulders come loose from the meander bar that deposited in the center of the channel starting at a 10-yr flood event, causing deposition of

streambed material to occur at the base of these boulders in the center of the channel; there is also some erosion in the center of the channel at the tips of the meander bars, creating puddles. Meander bars made of root wads also had boulders come loose from the boulder bars and deposit in the center of the channel starting at a 10-yr flood event. Root wads also started to come loose after a 25-yr flood event. There was also erosion of the channel under the root wads, creating low spots. Meander bars made of coarse material and slash also had boulders come loose and deposit into the center of the channel after a 10-yr flood event.

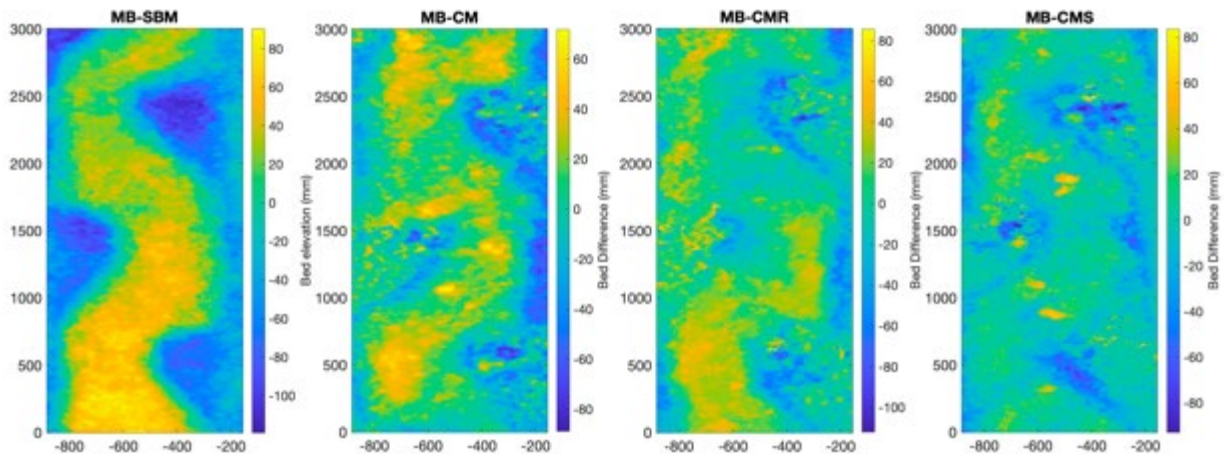


Figure 20 The elevation difference between the original streambed and after a 25-yr flood event for a Meandering channel at a 3% slope. Yellow represents deposition, while blue represents erosion.

3.2.3 4% slope results

Meander bar channels at a 4% slope were tested at a 1 CW spacing. Meander bars made of streambed material became flat after a 10-yr flood event. Also, at a 10-yr flood event, meander bars made of slash and D100 or D200 material experienced deposition at the base of the slash. Both D100 and D200 layouts also experienced erosion of the meander bars, causing rocks

to deposit in the center of the channel. After a 25-yr flood event, the most downstream boulder bar and slash for both D100 and D200 layouts became nearly buried. These layouts also experienced erosion in the center of the channels at the tips of the meander bars, creating low spots in the channel. After a 50-yr flood event, meander bars made of streambed material had the largest net percent area changed of all flood events compared to baseline, whereas meander bars made of slash with D100 material had the lowest net percent area changed of all flood events compared to baseline (Fig. 21). Meander bars made of slash and D200 material had about a 1.5% increase in area changed over meander bars made of slash and D100 material after a 50-yr flood event. After a 50-yr flood event, meander bars made of D100 and slash had the least amount of erosion of their edges and deposition in the center of the channel of all materials, whereas meander bars made of slash and D200 material had more erosion of their edges and deposition in the center of the channel of all materials, as seen in Figure 22, where yellow represents an increase in elevation or deposition, blue represents a decrease in elevation or erosion, and green represents no change.

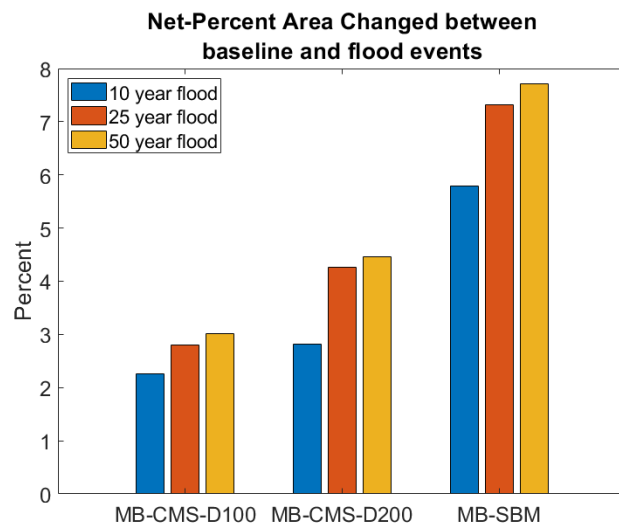


Figure 21 Shows the net-area changed for all flood events for meander bars at a 4% slope.

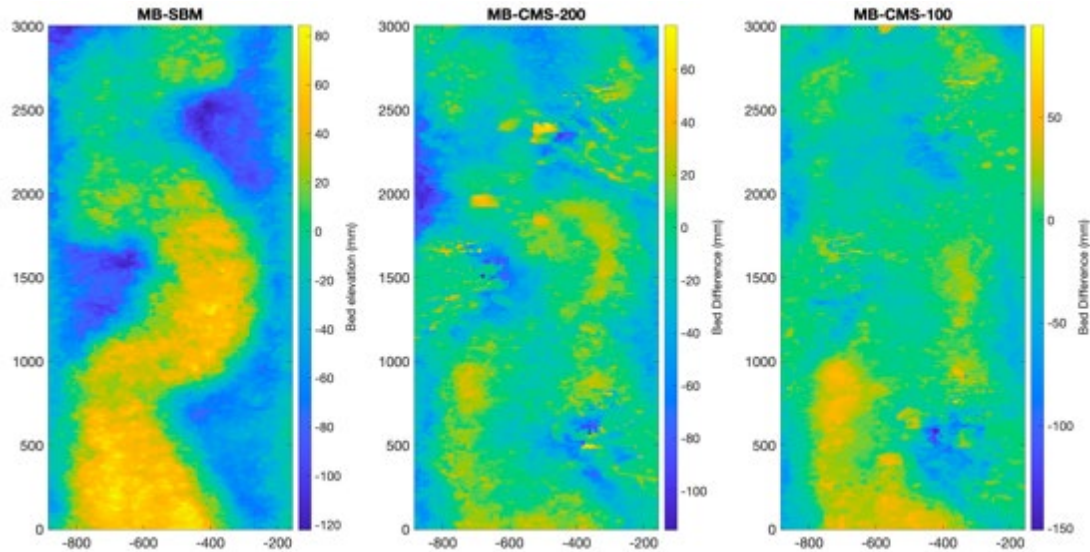


Figure 22 The elevation difference between the original streambed and after a 25-yr flood event for a meandering channel at a 4% slope. Yellow represents deposition, while blue represents erosion.

3.3 Root wad-lined channel

The root wad-lined channel (RC) was tested at a slope of 0.7% and at one root wad-diameter spacing (RC-1RW), two root wad-diameter spacing (RC-2RW), four root wad-diameter spacing (RC-4RW), and baseline, which had no features (RC-Baseline). . The RC-Baseline had erosion occur on the right bank of the meandering channel and deposition on the left bank of the channel (shown in Fig. 23, where erosion is blue, and deposition is yellow). The floodplain of the

channel saw erosion and deposition on both sides of the channel.

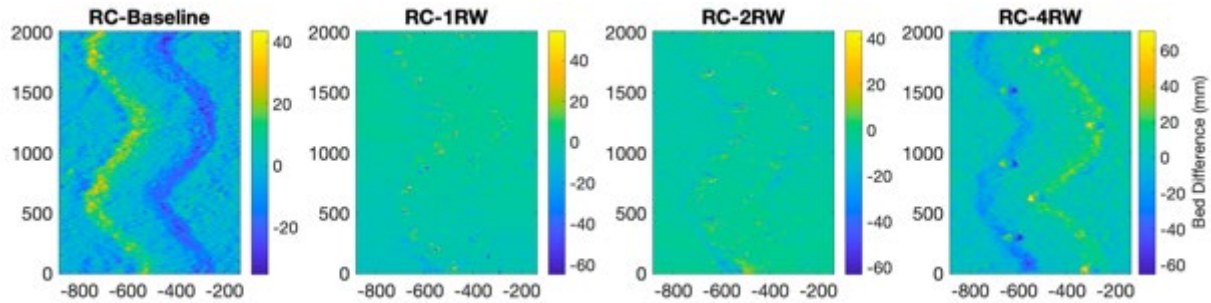


Figure 23 The elevation difference between the original streambed and after a 25-yr flood event for a root wad-lined meandering channel at a 0.7% slope. Yellow represents deposition, while blue represents erosion.

A channel with root wads spaced one root wad-width (RC-1RW) saw decreased sediment transport. Figure 23 shows a color plot of the difference between the initial streambed elevation and after a 25-yr flood event. The figure shows little change (erosion or deposition) occurs on the floodplain for RC-1RW and RC-2RW. Erosion and deposition along the banks for RC-4RW increased while little change occurred on the floodplain. Figure 24 shows the net percent area changed between the baseline and flood events. The graphs also show, at a 25-yr flood event,

RC-2RW and RC-4RW had a more extensive sediment transport than the baseline event. All root wad spacing designs reduce sediment transport for a 50-yr flood event compared to the baseline.

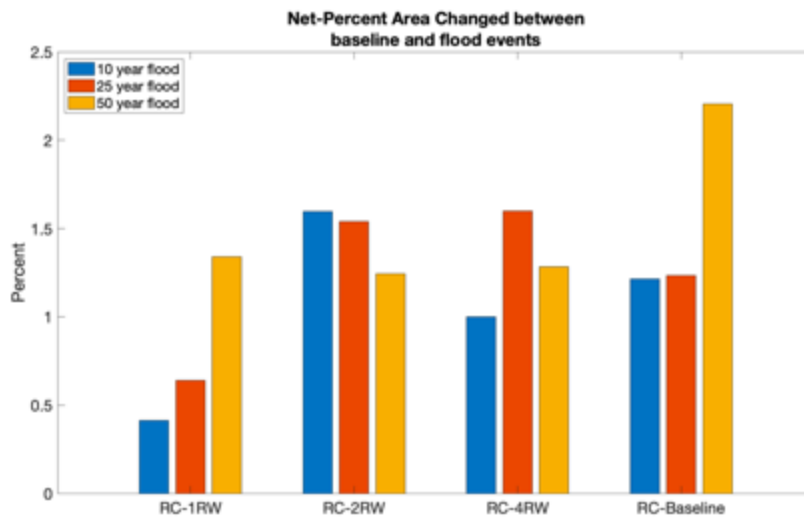


Figure 24 The percent difference between the original elevation and after every flood event of cross-sectional area changes for a root wad-lined meandering channel at a 0.7% slope.

Figure 25 shows the elevation of the baseline and RC-1RW channels at cross sections 1500 and 750 after each flood event. The figure shows the RC-1RW channel had much less elevation change than the baseline channel after the flood events.

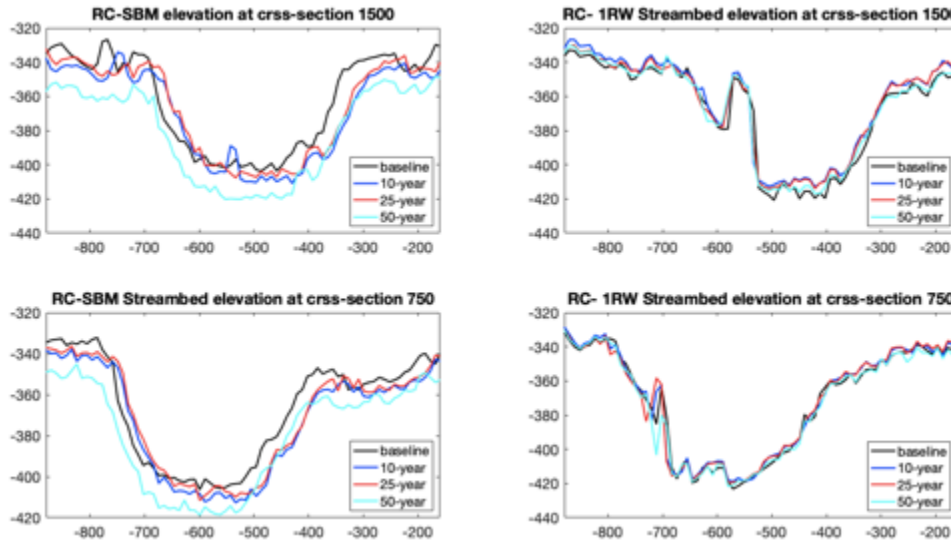


Figure 25 The channel elevation at cross sections 750 and 1500 for the baseline channel (RC-SBM) and RC-1RW. The two figures on the right are the RC-1RW channel, while the left is the baseline channel. The top 2 figures are the elevation at cross-section 1500, while the bottom figures are at cross-section 750.

3.4 Organic streambed mixture

The results for organic streambed mixture channels with sediment-organic material (OM) ratios of 1:0 (Baseline), 3:1, 1:1, and 1:3 are organized by channel shape. Channel shapes tested are straight U-shape channels, meander bars with one channel-width (MB-1CW), and meander bars with two channel-width (MB-2CW).

3.4.1 Straight channel

The organic streambed mixture was tested in a U-shape channel with sediment-OM ratios of 1:0 (Baseline), 3:1, 1:1, 1:3. Organic mixtures of 3:1, 1:1, and 1:3 all reduced erosion of the channel edges and deposition into the center of the channel compared to the baseline channel; 1:3 had the most compared to other mixtures (Fig. 26, where yellow represents deposition and

blue represents erosion). At 1:3, loose organic material at the surface of the streambed was washed away and accumulated at different locations in the streambed (seen in Fig. 26, where yellow represents deposition and blue represents erosion). Figure 27 shows the net percent area changed after each flood event. At the end of a 50-yr flood event, a channel made of a 1:1 ratio had the lowest net percent area changed of all mixtures; however, after a 25-yr event, a channel made of 3:1 had the lowest net percent area changed. The difference is due to less loose organic material at the surface of the streambed with 1:1 and 3:1 mixtures than a 1:3 mixture.

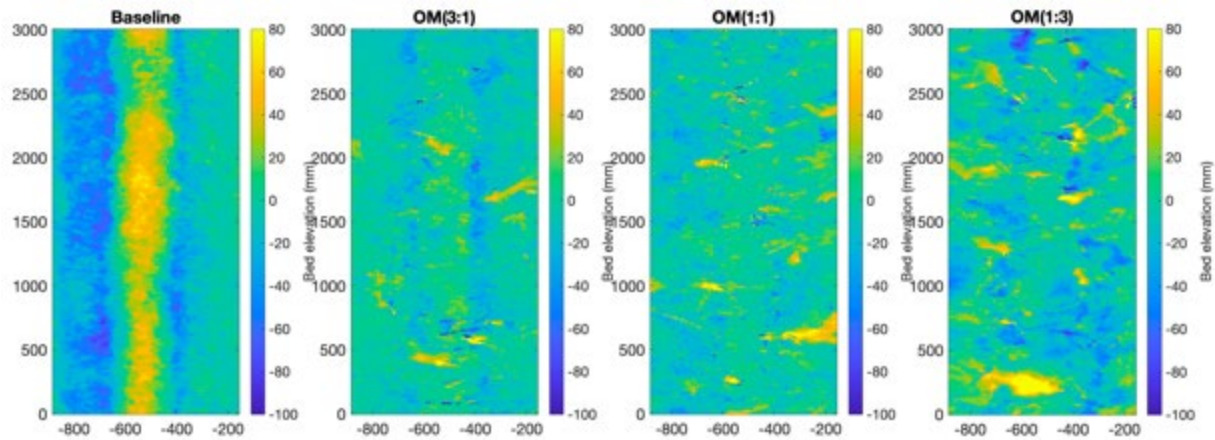


Figure 26 The elevation difference between the original streambed and after a 25-yr flood event for a straight U-shape organic mixture channel with sediment to organics ratio of 1:0 (Baseline), 3:1, 1:1, and 1:3.

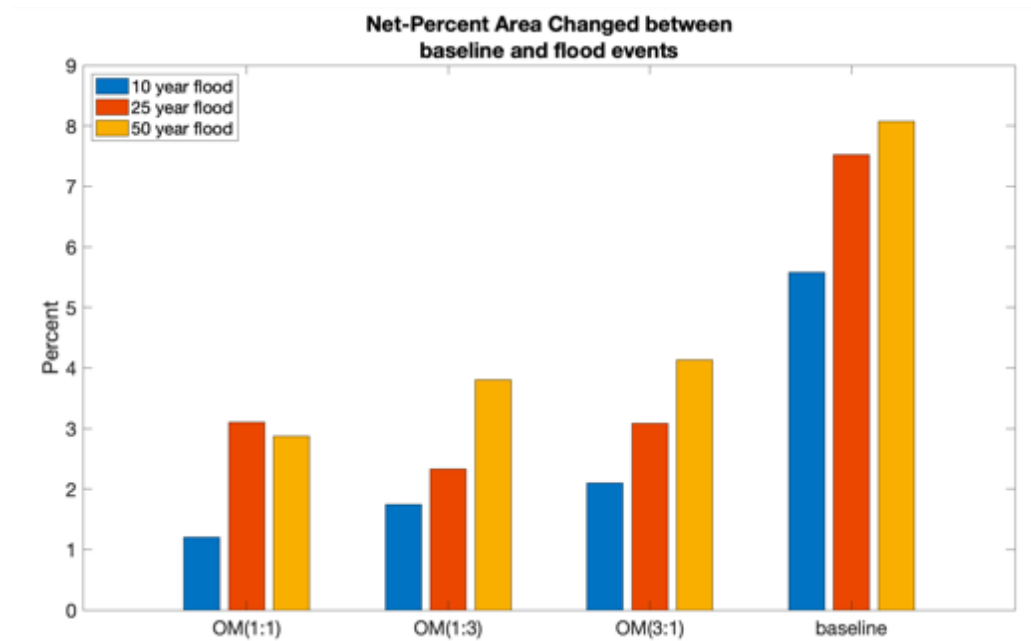


Figure 27 The percent difference of cross-sectional area changes between the original streambed elevation and the elevation after each flood event for a straight U-shaped channel with sediment to organics ratio of 1:0 (Baseline), 3:1, 1:1, and 1:3.

3.4.2 Meander bars one culvert-width

The organic streambed mixture was tested in a meandering channel with one culvert-width spacing. Sediment-organic mixture (OM) ratios tested were 1:0 (baseline) (MB -SBM-1CW), 3:1 (MB-OM(3:1)-1CW) and 1:3 (MB-OM(1:3)-1CW). OM mixtures at a ratio of 1:1 and 3:1 reduced the amount of erosion of the channel edges and deposition into the center of the channel compared to the baseline channel. A channel with a 3:1 mixture had the least erosion and deposition of the ratio mixtures; this can be seen in Figure 27, where yellow represents deposition and blue represents erosion. A channel with 1:3 mixture had the most erosion and deposition of the ratio mixtures (Fig. 28). Loose organic material was washed away and accumulated in different locations on the streambed. A channel with a 1:3 mixture became flattened out after a 50-yr flood event and experienced a greater net percent area changed after each flood event compared to the baseline channel (Fig. 29). Figure 29 shows the net percent

area changed after each flood event. An OM mixture with a ratio of 3:1 had the lowest total area changed after each flood event due to less loose organic material on the surface of the streambed being washed away, compared to the other mixtures tested.

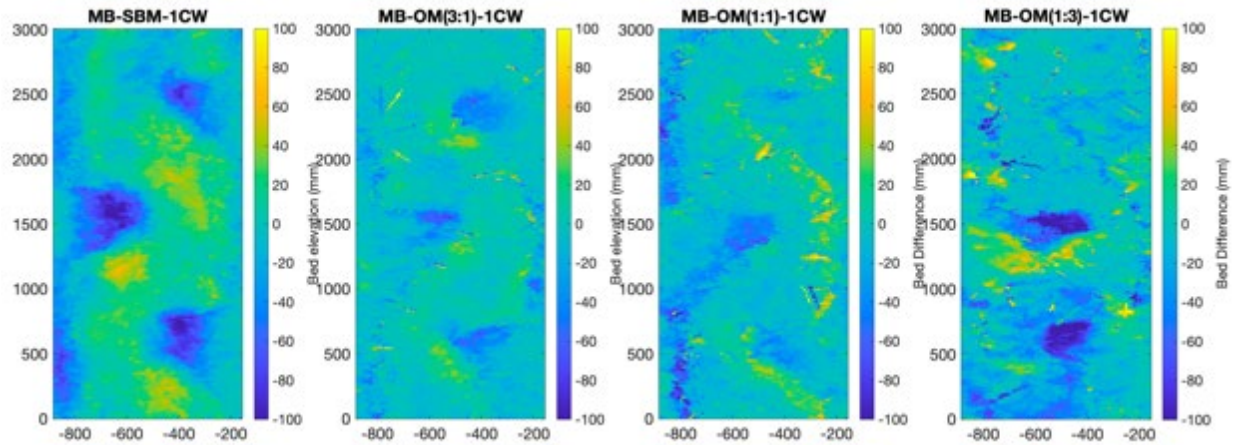


Figure 28 The elevation difference between the original streambed and after a 25-yr flood event for a one channel-width spacing meandering organic mixture channel with sediment to organics ratio of 1:0 (Baseline), 3:1, 1:1, and 1:3.

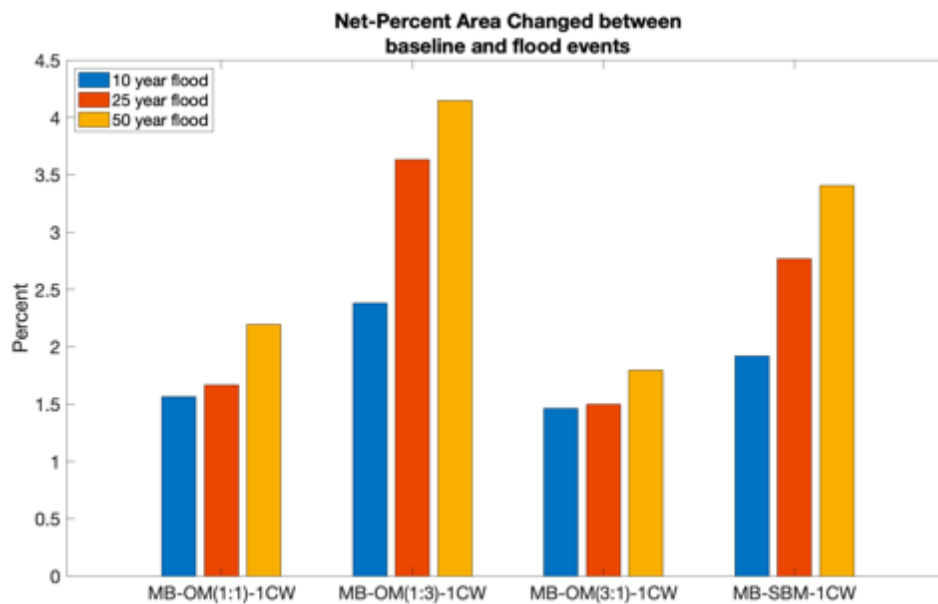


Figure 29 The percent difference of cross-sectional area changes between the original streambed elevation and the elevation after each flood event for a one channel-width channel with sediment to organics ratio of 1:0 (Baseline), 3:1, 1:1, and 1:3.

3.4.3 Meander bars three culvert-width

The organic streambed mixture was tested in a meandering channel with three culvert-width spacing. Sediment-organic material (OM) ratios tested were 1:0 (baseline) (MB-SBM-3CW), 3:1 (MB-OM(3:1)-3CW) and 1:3 (MB-OM(1:3)-3CW). All layouts with an organic streambed mixture had a lower net percent area changed than the baseline streambed for each flood event (Fig. 31). At the end of a 10-yr flood event, the 1:3 mixture had the lowest net percent area changed of mixtures; however, after 25 and 50-yr flood events, it had a greater net percent area changed yr when compared to organic streambeds with 1:1 and 3:1 mixtures (Fig. 32). This result is due to there being more loose organics in the 1:3 mixture compared to the 1:1 and 3:1 mixtures, which caused more organic material to wash away, catch, and build up in the channel. Figure 30 shows the elevation change for each layout after a 50-yr flood event, where yellow represents deposition and blue represents erosion. Both 1:1 and 3:1 channels have small amounts of erosion at the meander bars and channel walls, along with deposition in the center of the channel; some loose organic material was washed away and built up at different locations in the channel. In contrast, channels with 3:1 and 1:1 mixtures could retain the channel shape.

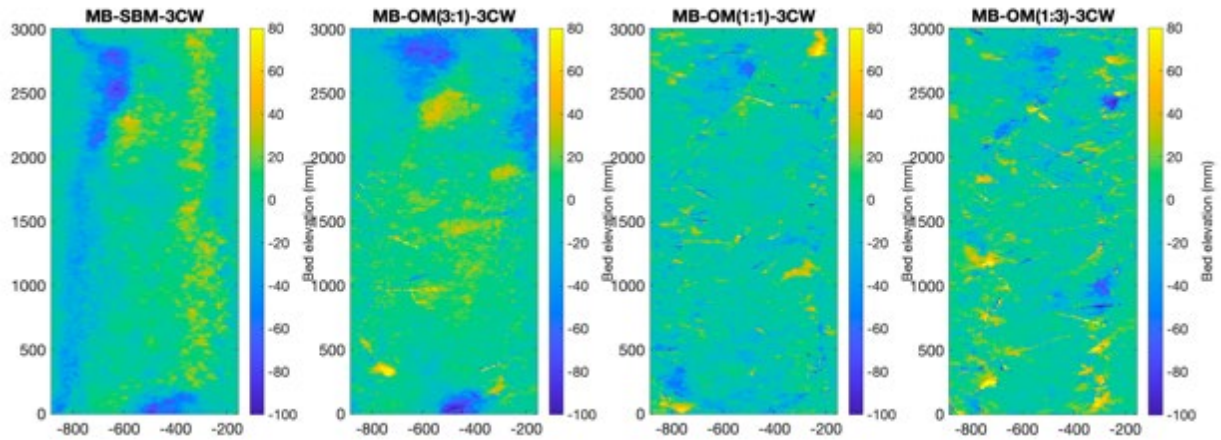


Figure 30 The elevation difference between the original streambed and after a 25-yr flood event for a three channel-width spacing meandering organic mixture channel with sediment to organics ratio of 1:0 (Baseline), 3:1, 1:1, and 1:3.

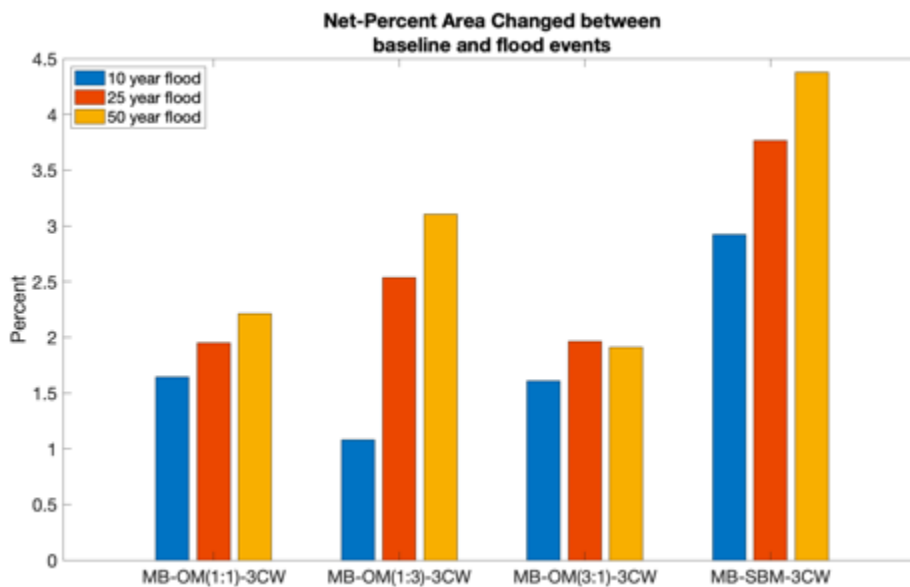


Figure 31 The percent difference of cross-sectional area changes between the original streambed elevation and the elevation after each flood event for a three channel-width channel with sediment to organics ratio of 1:0 (Baseline), 3:1, 1:1, and 1:3.

CHAPTER FOUR: DISCUSSION

4.1 Deformable grade control

This research set forth 3 hypotheses for deformable grade control (DGC), all of which were confirmed, as follows.

H1.1: a deformable grade control made of a single diameter dowel will maintain the target channel shape downstream while containing sediment upstream. This hypothesis was confirmed with the first test of a DGC made of 7/8-in diameter dowels at a wood-sediment ratio of 50:50 (Fig. 11). DGC made of 7/8-in diameter dowels reduced erosion of the channel edges and deposition in the center of the channel, causing less sediment transport from upstream of the feature compared to a channel without DGC. This allowed the channel to maintain its shape downstream of the feature.

H1.2: increasing the ratio of wood used to design will decrease the amount of sediment moved over the flow events. This hypothesis was confirmed with the tests of DGC made of 7/8-in diameter dowels at wood-sediment ratios of 25:75, 50:50, and 75:25 at a 2% slope. Figure 11 shows that as the ratio of wood to sediment increased, erosion of the edges of the channel and deposition in the channel decreased. Erosion is represented by blue, and deposition is yellow in Figure 11.

H1.3: the diameter size distribution used in the deformable grade control will decrease sediment transport. This hypothesis was confirmed with the test of DGC made of a mix of 7/8-, 3/8-, and 1/8-in diameter dowels at wood-sediment ratios of 25:50, 50:50, and 75:25. Each ratio of DGC made of a mix of different diameter dowels performed better at maintaining the target

channel shape and reducing the sediment transport compared to DGC made of a single dowel size.

4.2 Meander bars

The second hypothesis (H2) examined meander bars at a channel slope of 2%, 3%, and 4% for 3 meandering channel designs; H2.2) the addition of organic material in the form of root wads or sticks to the design will further decrease sediment transport over the flow events. These channel designs were tested at two different spacings, a one culvert-width (1 CW) and three culvert-widths (3 CW), at a 2% slope. A spacing of 1 CW was investigated at 3% and 4% slopes. A spacing of 3 CW was not considered because our previous study on coarse bands found that a slope over 2% cannot support a channel with a spacing greater than 1 CW.

4.2.1 Coarse material

H2.1: the construction of a meander bar with coarse material will increase channel stability and maintain the desired channel shape. This sub-hypothesis was confirmed in all tested conditions. H2.1 examined the meander bar design constructed with streambed material (MB-SBM). At the 2% slope, both the MB-SBM at 3 CW and the MB-SBM at 1 CW spacing had erosion of the meander bars and deposition in the center of the channel (Fig. 17). This led to a plane bed by a 50-yr flood event.

Modifications were also tested: meander bars with coarse material and sticks (cone material D100-D200 (MB-CMS-100) and cone material D200 (MB-CMS-200)). The modification of building the meander bars with coarse material (head (D200-D300) and cone (D100-D200)) (MB-CM) reduced the erosion of the meander bars for both channel spacings at 2% slope (Fig. 17). Little change in the channel occurred at the meander bars, but bank erosion

took place across from the meander bars. A channel with a spacing of 3 CW had more deposition in the center of the channel and bank erosion than a channel with a spacing of 1 CW. In fact, 1 CW spacing for the MB-SBM and MB-CM channels had less sediment transport than a channel with a 3 CW spacing.

At a 3% slope, meander bars made of streambed material (MB-SBM) became flat after a 25-yr flood event. The meander bars were eroded away, and the center of the channel was filled with material (Fig. 20). According to our previous study Engdahl et al 2020 spacing over 1 CW shall not be used., Meander bars with coarse material and sticks (MB-CMS) were tested for lowest sediment transport of all designs after a 10-yr flood event.

The erosion seen in Figure 20 on the meander bars is a couple of D200-D300 particles rolling off and landing in the center of the channel. The movement of these particles is due to unstable construction. The particles are not locked in. Instead, they are placed on other, larger particles. The absence of smaller particles did not allow the larger particles to be locked in to keep them from moving. The larger particles roll into the channel and rest within a few particle-diameters of the meander bars. The particles will stay in the channel throughout the flood events. Other than the large particles showing deposition in the center of the channel, there are two plums of deposition just upstream of the middle meander bar and a smaller plum above the upstream meander bar (Fig. 20).

At a 4% slope, a channel with streambed material had deposition in the center of the channel and erosion on the banks (Fig. 22). Figure 21 shows the net percent area changed for three channel designs: MB-SBM, MB-CMS-100 and MB-CMS-200. Larger materials had a higher sediment transport than smaller material. The increase in sediment transport of MB-CMS-200 may be due to the larger particles being unstable during construction. Figure 22 shows

higher erosion can occur in the location of the meander bars than in other locations in the channel.

4.2.2 The addition of organic material

H2.2: adding organic material to MB-CM in the form of root wads and sticks will increase channel stability. This hypothesis was confirmed by a meandering channel with coarse material and root wad (MB-CMR) at a 2% slope. Figure 18 shows that channels with meander bars with coarse material and root wads at one root wad spacing (MB-CMR-1) and three root wad spacing (MB-CMR-3) have a smaller net percent change than channels with meander bars with coarse material without root wads at both MB-CM-1 and MB-CM-3 for all three flood events. This indicates the root wads have increased channel stability.

The color plot of the channel difference in Figure 17 shows that MB-CMR-3 reduced deposition in the center of the channel between the meander bars compared to MB-CM-1. Still, the erosion of the right bank opposite the meander bar increased compared to MB-CM-1. Decreasing the channel spacing to 1 CW reduced the bank erosion across from the meandering.

At a 2% slope, channel stability increased further in the design of meander bars with coarse material and sticks (MB-CMS) 2%. This design had the lowest sediment transport of all designs for both channel spacing at all 3 flood events (Fig. 18). A channel spacing of 1 CW had the lowest sediment transport. Figure 17 shows the erosion on the right bank between the meander bars is reduced at smaller channel spacing. Deposition in the center of the channel is reduced due to the stability of the right bank.

At a 3% slope, the addition of organic material reduced sediment transport. At a 10-yr flood, MB-CMS had the lowest net percent area changed of all designs. At more than a 10-yr

flood, MB-CMR had reduced sediment transport and reduced net percent area changed compared to other materials (Fig. 19). The organic material reduced the erosion along the banks and deposited in the center of the channel. Large material from the meander bar head rolled off and rested in the channel's center during testing of the MB-CMS design (Fig. 20). The MB-CMR had less erosion than MB-CMS but a little more deposition throughout the channel.

At a 4% slope, the size of the meander bar cone material was modified and tested. The MB-CMS design was tested with the D100-D200 (MB-CMS-100) cone material and D200 (MB-CMS-200). Both designs reduced sediment transport compared to MB-SBM, but MB-CMS-200 had a higher net percent area changed than MB-CMS-100 (Fig. 21). MB-CMS-200 had erosion along the banks and at the meander bars (Fig. 22). Material from the head and cone was being eroded and moved into the center of the channel. The particles moved due to unstable stacking. The larger head material rolled off the meander bars and came to rest a 1-3 particle-diameters downstream. These particles stayed in place through a 50-yr flood.

4.3 Root wad-lined channel

To test the third set of hypotheses, three channel designs were constructed: root wad channel with root wads spaced one root wad-diameter (RC-1RW), root wads spaced two root wad-diameters (RC-2RW), and root wads spaced four root wad-diameters (RC-4RW).

H3.1: the addition of root wads is sufficient to maintain a meandering channel shape throughout the structure. This sub-hypothesis was confirmed for root wads at 1 RW spacing. The meandering channel with no features (RC-baseline) had erosion along the right channel bank and deposition on the left channel bank (Fig. 23). Erosion and deposition occurred in the center of the channel and on the floodplain. Adding RC-1RW throughout the channel reduced sediment

transport over all three flood events (Fig. 23). Most of the changes in the channel that occurred around the root wads at 1 RW spacing were deposition on the upstream side and erosion on the downstream side of the root wads.

Figure 25 shows the channel's two cross sections; the graphs on the top are located in the upstream section of the channel, and the graphs on the bottom are located in the downstream section. The graphs on the left are from the RC-Baseline channel and show bank erosion on the right side of the channel and deposition on the left side for the 10- and 25-yr flood events. After a 50-yr flood event, the channel had erosion on the floodplain and in the center of the channel. In contrast, the channel with RC-1RW saw very little change in overall flood events at both cross sections. Root wads spaced one root wad-width will maintain a desired channel shape.

H3.2: increasing the spacing between root wads will increase sediment in the channel but will still maintain the desired channel. This sub-hypothesis was confirmed. RC-2RW and RC-4RW were tested. RC-2RW increased the amount of sediment transport at a 10- and 25-yr flood but had a decrease at a 50-yr flood. For RC-4RW, the 10- and 50-yr floods had a decrease in sediment transport and a 25-yr flood had an increase (Fig. 24). The erosion and disposition process in the RC-Baseline also occurs in the RC-4RW, where erosion occurs on one bank and deposition on the other (Fig. 23). Increasing the spacing between root wads will increase sediment transport.

4.4 Organic streambed mixture

The fourth set of hypotheses (H4) concerned sediment to organic material mixture at ratios of 3:1, 1:1, and 1:3 tested in a straight channel, a meandering channel with one culvert-width (1 CW) spacing, and a meandering channel with three culvert-width (3 CW) spacing.

H4.1: the addition of organic material mixed into the streambed material will decrease sediment transport in the lowest flow event. This sub-hypothesis was confirmed. All ratios for a straight and meandering channel with 3 CW spacing reduced sediment transport (Fig. 27 and Fig. 31). A 1:1 mixture had the smallest net percent area changed of all mixtures at 10- and 50-yr floods but the largest change at a 25-yr flood event. A 1:3 mixture had the lowest net percent area changed at a 25-yr flood event. Erosion and deposition increased with larger flood events. In the color plots (Figs. 26, 28, and 30), the spikes of deposition are where organic material collected. The collection of organic material increased as the ratio of organic material to sediment increased.

Meandering channels with 1 CW spacing had a decrease in sediment transport in 3:1 and 1:1 mixtures (Fig. 29). The ratio with the lowest net percent area changed was 3:1, and the change between each flood event was minimal (Fig. 29). In the 1:3 mixture, with the increase in organic material, sediment transport increased compared to other mixtures, which led to decreased streambed stability. The middle and lower meander bars had high erosion toward the middle of the channel and deposition around the middle meander bar (Fig. 28).

CHAPTER FIVE: CONCLUSIONS

5.1 Assessment of hypotheses

This report's research investigated the ability of organic material designs to support channel stability and maintain a low-flow channel in stream simulation culverts.

Hypotheses H1.1-H1.3 addressed the use of wood to construct a deformable grade control. Our research indicates: i.) adding a DGC reduces the movement of material downstream and the sediment transport from upstream of the feature. ii.) As the wood-sediment ratio increases, the sediment movement decreases. iii.) DGC made of a mix of diameters reduced the amount of sediment movement compared to DGC made from one diameter, iv.) DGC deformed above a 2% slope.

Hypotheses H2.1 addressed the use of coarse material in constructing meander bars. Our research indicates: i.) Building the meander bars with coarse material (D200-D300 for the head and D100-D200 for the cone) reduced sediment movement in one and three culvert-width spacing meander bars. ii.) A channel with a spacing of one culvert-width reduces the amount of sediment movement compared to a channel with three culvert-width spacing. iii.) Increasing the size of the material in the cone of the meander bar from D100 to D200 increases the movement of sediment.

Hypotheses 2.2 addressed adding organic material such as root wads or sticks/slash to the design of the meander bars. Our research indicates: i.) Adding root wads to meander bars at a 2% slope increases channel stability. ii.) Adding sticks to meander bars at a 2% slope further increases channel stability compared to root wads. iii.) Adding sticks to meander bars at a 3% slope further increases channel stability compared to root wads at a 10-yr flood event. But at a

flood event more significant than a 10-yr flood, the addition of root wads to meander bars further increases channel stability compared to sticks.

Hypotheses 3.1-3.2 addressed the addition of a root wad-lined channel to a meandering channel. Our research indicates i.) The addition of root wads spaced one root wad width apart throughout the channel reduced sediment transport compared to no root wads for all three flood events and will maintain a target channel shape. ii.) Increasing the spacing between root wads increases sediment movement.

Hypothesis 4 addressed adding organic material mixed into the streambed of a straight channel and meandering channels with both one culvert-width spacing and three culvert-width spacing. Our research indicates: i.) Adding organic material reduces sediment transport for straight and meandering channels with three culvert-width spacing. A 1:1 ratio has the smallest net percent area changed at 10 and 50-yr flood events; however, a 1:3 ratio had the smallest area changed at a 25-yr flood event. ii.) Adding organic material with ratios of 3:1 and 1:1 reduces sediment transport for a meandering channel with one culvert-width spacing compared to no organic material. A ratio of 3:1 had the lowest net percent area changed for all flood events. An increase in organic material increases sediment transport. iii.) The collection of organic material increases with higher ratios of organic material.

5.2 Potential limitations

Experimental work has limitations that should be addressed before extrapolating the findings to the field. The main limitation of this research is the size of the flume. The flume's size limits sediment depth, flow depth, and sinuosity of the stream. The flume has a height of

1.83 ft and a maximum depth of streambed material of 0.75 ft on the sides and 0.33 ft in the center of the channel. The flume width is also a limitation because it does not allow much lateral migration of the channel.

Potential limitations can be found in the reference site. Asotin Creek was selected because it matched the lab's flow regimes and sediment. Calculating the flood frequency used the annual peak flows, but the number was less than 30, leading to the statistical analysis not being robust. The annual peak flow period of record was not long, which makes the flood frequency biased.

Whereas natural streams have replenishing sediment supply, our study was limited by having no sediment supply added to the upstream section of the flume. In our previous study Engdahl et al 2020, we added sediment to the upper section of the streambed, but the transport rates were not high enough to move the added material through the flume. The study section in the middle of the streambed had material from upstream enter the study section.

Another limitation is using dowels to simulate sticks, branches, and small logs (organic debris). Dowels provided the correct shape for organic debris, but the smooth dowels did not capture the complexity of organic debris. Natural organic debris could interlock due to the knobs/branches extending from the main stem of the organic debris. Interlocking could improve the ability to gather sediment on the upstream side of the features, reduce the erosion of organic debris during floods, and increase channel stability further.

The final limitation is the construction of root wads. The root wads used in the meander bar section of this report did not capture the complexity of root wads because they lacked root fingers extending from the root wad. The objective was to capture the weight of the root wad to

see if the root wad acts as a lever and can be pushed out of the meander bar. Natural root wads with root fingers could increase streambed stability by collecting sediment and transporting it downstream. Though the root wads used in the root wad channel did simulate the complexity by using framing nails to represent root fingers, this feature did not capture complexity to a realistic degree or magnitude. Natural root wads could increase deposition on the upstream side and erosion downstream. Their complexity could also reduce the erosion of the bank on the inside of the root wad at larger flood events.

5.3 General recommendations for SSC design

The following sections will discuss the recommendations for deformable grade control meander bars, root wad-lined channels, and organic streambed mixture for each tested slope.

5.3.1 Deformable grade control at 2% slope - channel recommendations

Deformable grade control at a wood-sediment ratio of 75:25 was the best at maintaining the original channel shape at a 2% slope. The DGC was made of a mix of dowels with diameters of 1/8 in, 3/8 in and 7/8 in and lengths of 3/4, 1/2, 1/4, and 1/6 of the width of the flume. Decreasing the ratio of wood to sediment increases the overall sediment transport. Reducing the dowel size also increases the general sediment transport in the channel.

5.3.2 Deformable grade control at more significant than 2% slope channel recommendations

Deformable grade control constructed with a mix of diameter dowels with a wood-sediment ratio of 75:25 performed the best above a 2% slope. The DGC was made from dowels with diameters of 1/8, 3/8 and 7/8 in and lengths of 3/4, 1/2, 1/4, and 1/6 of the width of the flume. The DGC reduced the deposition in the center of the channel and overall sediment

transport compared to the baseline design. Most sediment transport occurred upstream of the DGC. It is not recommended to use DGC in a channel above a 4% slope due to the DGC making only a slight difference at a 4% slope.

5.3.3 2% Meander bars at 2% slope channel recommendations

The best design for meander bars at a 2% slope to stabilize the channel was meander bars at a one channel-width spacing. Adding organic material further increased the stability of the channel. Meander bars made of coarse material with slash at one channel-width spacing had the lowest overall sediment transport. The meander bars are made of coarse material, which is D200-D300 of the streambed material at the head and material D100-200 at the cone. The slash is constructed from 18 dowels in the streambed just upstream of each meander bar. Five dowels are 3/8-in diameter, with two dowels having a length of 1/4 culvert-width and three dowels having a length of 1/6 culvert-width. Eleven dowels are 1/8-in diameter with a length of 1/6 culvert-width. Meander bars made of coarse material at one channel-width spacing and meander bars made of coarse material with root wads at one channel-width spacing had a net percent area changed within 0.5% of meander bars made of coarse material with slash after a 50-yr flood event. Thus, the meandering channel at a 2% slope can be stabilized with meander bars at a one channel-width spacing.

5.3.4 Meander bars at 3% slope channel recommendations

At a 3% slope, meander bars at a one channel-width spacing with slash and meander bars at a one channel-width spacing with root wads performed the best. Both designs are meander bars made of coarse material with organic material added. After a 10-yr flood event, meander bars made of coarse material with slash had the lowest sediment transport, while after 25 and 50-

yr flood events meander bars made with coarse material and root wads had the lowest sediment transport. These designs reduced the erosion of the edges and deposition in the center of the channel. MB-CMS had more erosion of the edges but less deposition in the center of the channel than MB-CMR.

5.3.5 Meander bars at 4% slope channel recommendations

Meander bars made of D100 material at the cone with slash performed the best at a 4% slope. The slash is just upstream of each meander bar. The slash is constructed from 18 dowels in the streambed. Five dowels are 3/8-in diameter, two have a length of 1/4culvert-width, and three have a length of 1/6 culvert-width. Eleven dowels are 1/8-in diameter with a length of 1/6 culvert-width. Meander bars made of D100 material and slash reduced the erosion of the edges and deposition in the center of the channel. It is not recommended to increase the size of the material in the cone due to the increase in sediment transport when increasing the size of the cone material to D200.

5.3.6 Root wad-lined channel recommendations

Root wads spaced at one root wad-diameter did the best at maintaining the original channel shape for a root wad-lined channel. The root wads are about 3-in diameter. Very little sediment transport occurred in the channel with one root wad spacing, and it was able to keep its channel shape through the flood events. Increasing the spacing between the root wads also increased the overall sediment transport in the channel.

5.3.7 Organic streambed mixture channel recommendations

Organic streambed mixtures with a sediment to organic material ratio of 3:1 did the best at maintaining the target channel shape while also not being too difficult to construct. For

meander bars at one channel-width and three channel-width spacing, a 3:1 mixture had the lowest net percent area changed after a 50-yr flood event. For a straight channel, although a 1:1 ratio had a slightly lower net percent area changed, the 3:1 mixture still maintained the target channel shape and was much easier to construct. At both 1:1 and 1:3 ratios, it became difficult to mix the organic and sediment evenly . These mixtures also require a large amount of organic material to reach the proper ratio. A sediment-organic material ratio of 3:1 will maintain the target channel shape without becoming too difficult to construct.

5.3.8 Recommendations for further research

Questions that were uncovered during this work are:

- How would channel stability change if meander bars constructed from coarse material were added to an organic streambed mixture?
- What is the longevity of organic debris in stream channels?
- Would erosion in the channel bottom increase if only the banks were made from an organic streambed mixture?
- Would changing the size of the root wad in the root wad-lined channel design affect the stream processes found in this study?
- Can small log jams be placed in a meandering channel instead of lining the whole channel with root wads?

Investigating these questions will provide further insight into the function of organic material in culverts.

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APPENDICES

Appendix A – Sediment distribution curve

Appendix B – Streambed height and surface difference for each flood event.

Appendix A– Sediment distribution curve

The distribution curves below show the grain class of sediment used in the study.

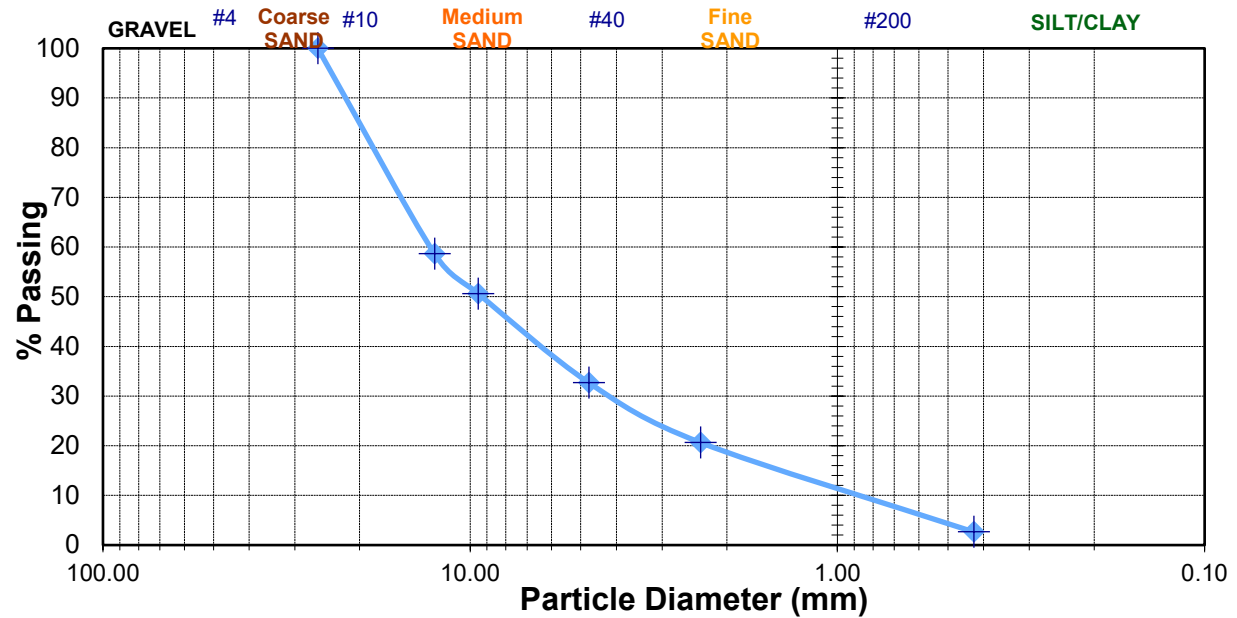


Figure 32 Sediment distribution curve of material used for Asotin Creek designs.

The distribution curve above is for the sediment used for the Asotin Creek designs (deformable grade control, meander bar, and organic streambed mixture (1-3% slope)). The curve below was the sediment used for the Panther Creek designs (root wad-lined channel and organic streambed mixture (0.7% slope)).

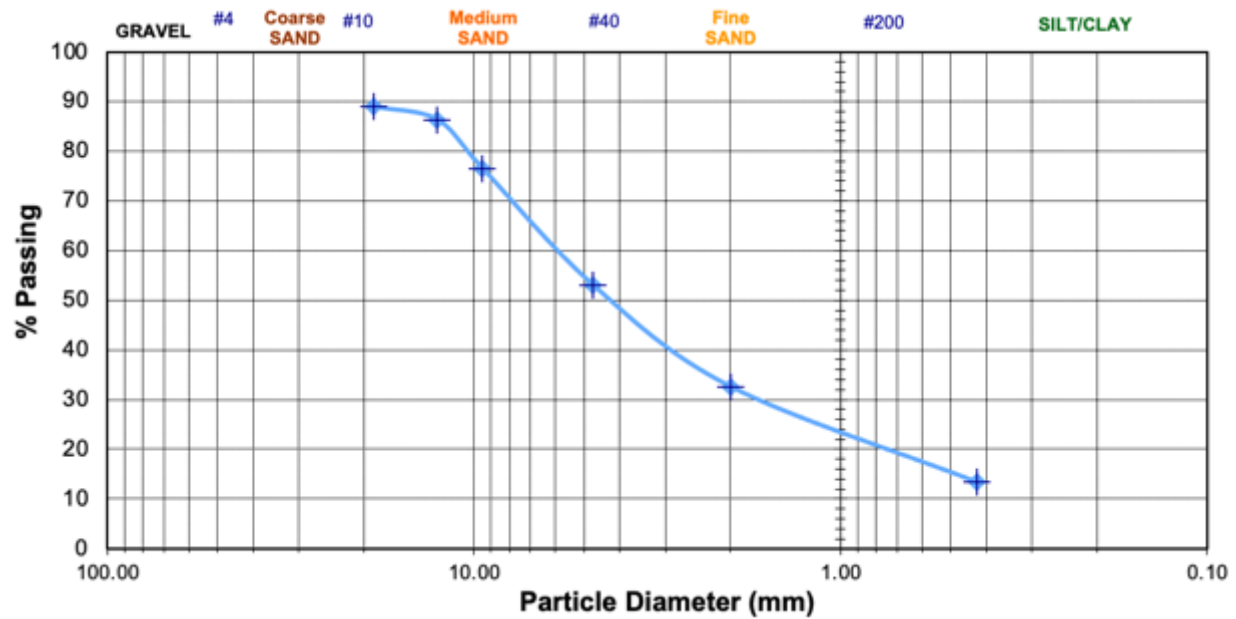


Figure 33 Sediment distribution curve of the material used for Panther Creek designs.

Appendix B— Streambed height and surface difference for each flood event.

In all cases, a description of the layout of the height of the streambed gives an understanding of the contour of the streambed, and the surface difference shows where the stream channel is changing, the amount of change, and the direction.

Layout 0 is a straight U-notch channel at a 2%2% slope. This layout does not have any features in the channel. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

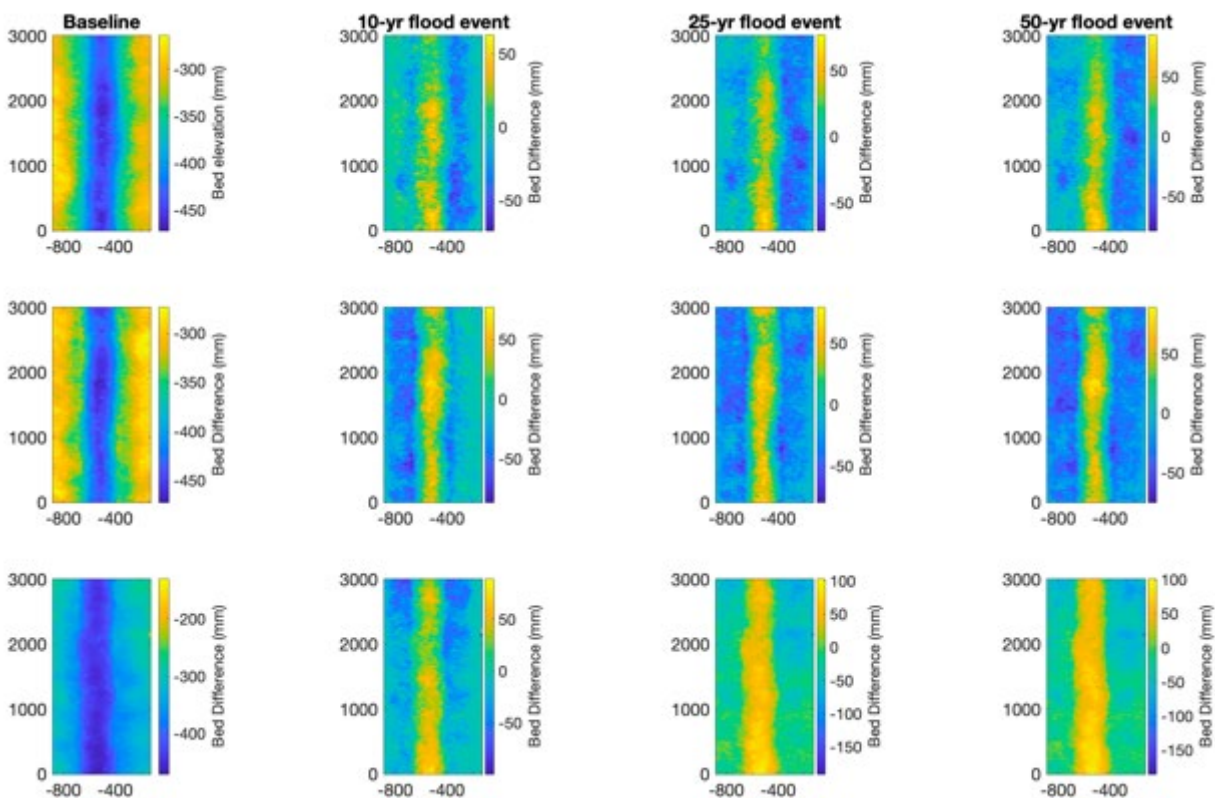


Figure 34 Difference of streambed elevation of layout 0 after each flood event.

After the 10-yr flood events, we saw minor erosion of the channel edges depositing into the center of the channel. The channel has more erosion at the beginning of the channel than the baseline. The right edge of the channel also has more erosion. After the 25-yr flood, we saw that the channel edges continued to erode and deposit into the center of the channel, causing it to become flatter. There is

more erosion at the start of the channel and more erosion on the right side than after the 10-yr flood events. After the 50-yr flood event, we saw the channel edges continue to erode and deposit material into the center of the channel, causing the channel to become nearly flattened.

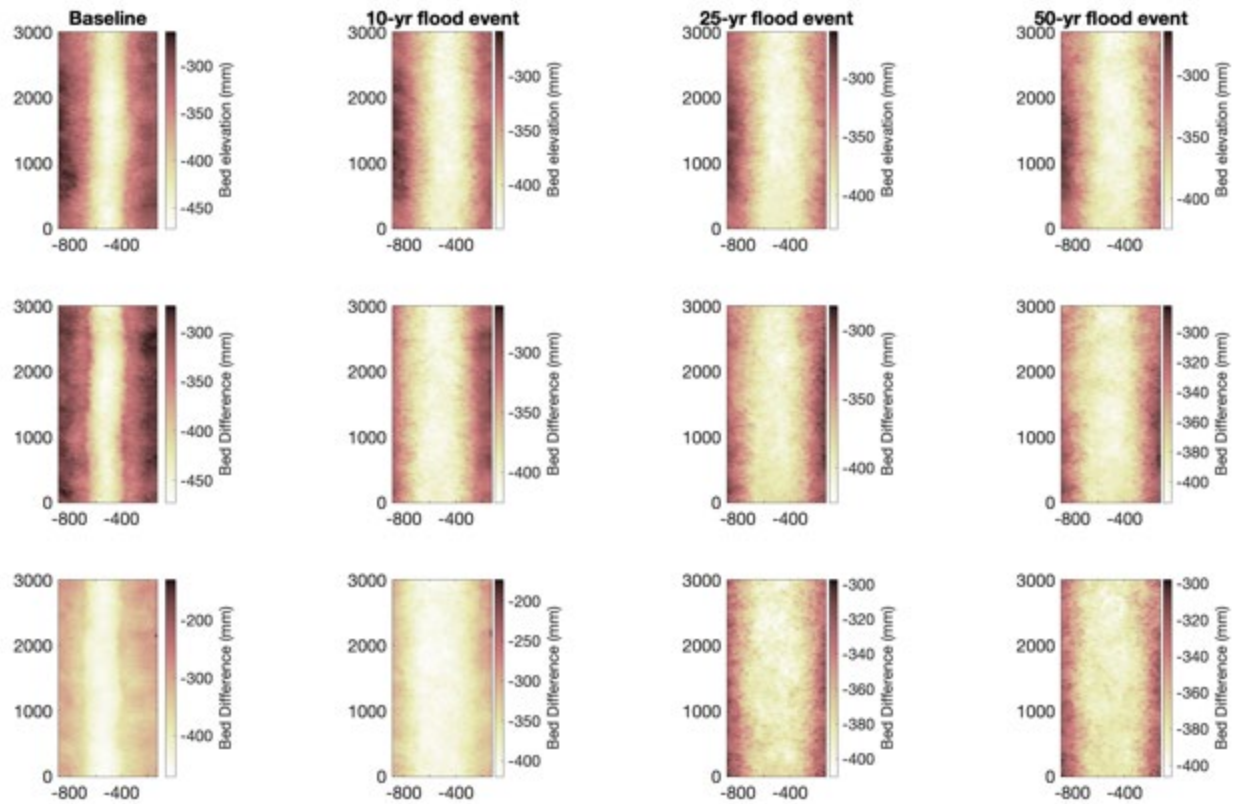


Figure 35 Streambed elevation for layout 0 after each flood event.

Layout 2

Layout 2 is a straight U-notch channel at a 2%2% slope. This layout has a deformable grade control (DGC) design in the middle of the study section. The DGC is made up of 7/8-in diameter dowels that have lengths of 3/4 and 1/2 channel-width. The feature is constructed in a trench with a width of 1/6 channel and a depth to the bottom of the flume. The feature has a wood-sediment ratio of 50:50. DGC was built with two 27-in, five 18-in and four 9-in dowels. See the figure below for layout construction. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

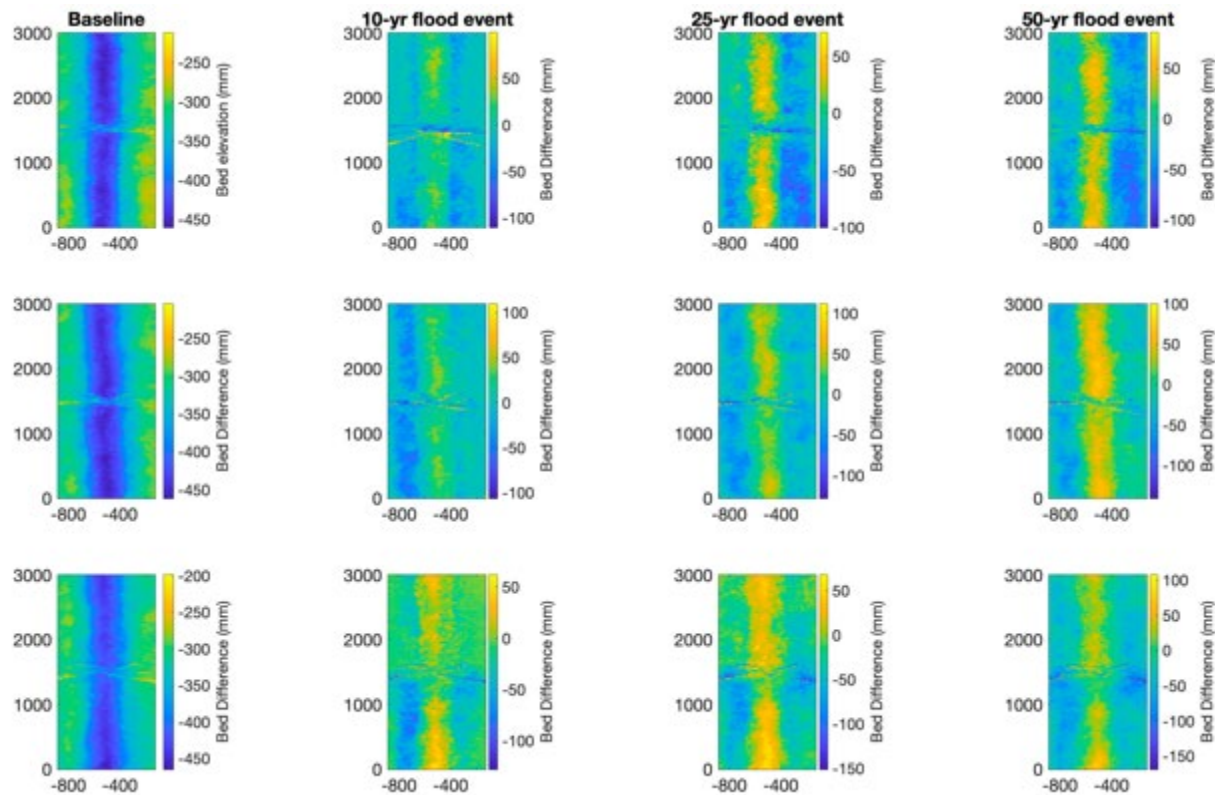


Figure 36 Difference of streambed elevation for layout two after each flood event.

After the 10-yr flood event, we saw minor erosion of the edges depositing into the center of the channel downstream of the feature, but the channel still had its U shape. There is more erosion on the section of the channel upstream of the feature than the baseline. There is also more erosion on the right side of the channel. After the 25-yr flood event, we saw more erosion of the channel edges depositing into the center of the channel than after the 10-yr flood event. The section of the channel upstream of the feature has more erosion than the downstream, causing it to become flattened. The section of the channel upstream of the feature still has its U shape. Some material is deposited at the base of the feature on its upstream side in the center of the channel. Material has also eroded at the base of the feature on its downstream side, creating a low spot in the center of the channel. After the 50-yr flood

event, we saw more erosion of the channel edges depositing into the center of the channel than after the 25-yr flood. The section of the channel upstream of the feature has more erosion than the downstream, causing it to become nearly flattened. The section of the channel upstream of the feature still has its U shape. More material is deposited at the base of the feature on its upstream side in the center of the channel than after the 25-yr flood event. More material has also eroded at the base of the feature on its downstream side than after the 25-yr flood event.

At the beginning of the 10-yr flood event for trial 1, three 18-in dowels and two 9-in dowels came loose and flowed downstream. During the 10-yr flood event for trial one, another 18-in dowel came loose and floated downstream. During the 10-yr flood for trial 2, one 18-in dowel came loose and flowed downstream.

During the 25-yr flood for trial 1, two 27-in dowels, one 18-in dowel, and one 9-in dowel came loose and flowed downstream.

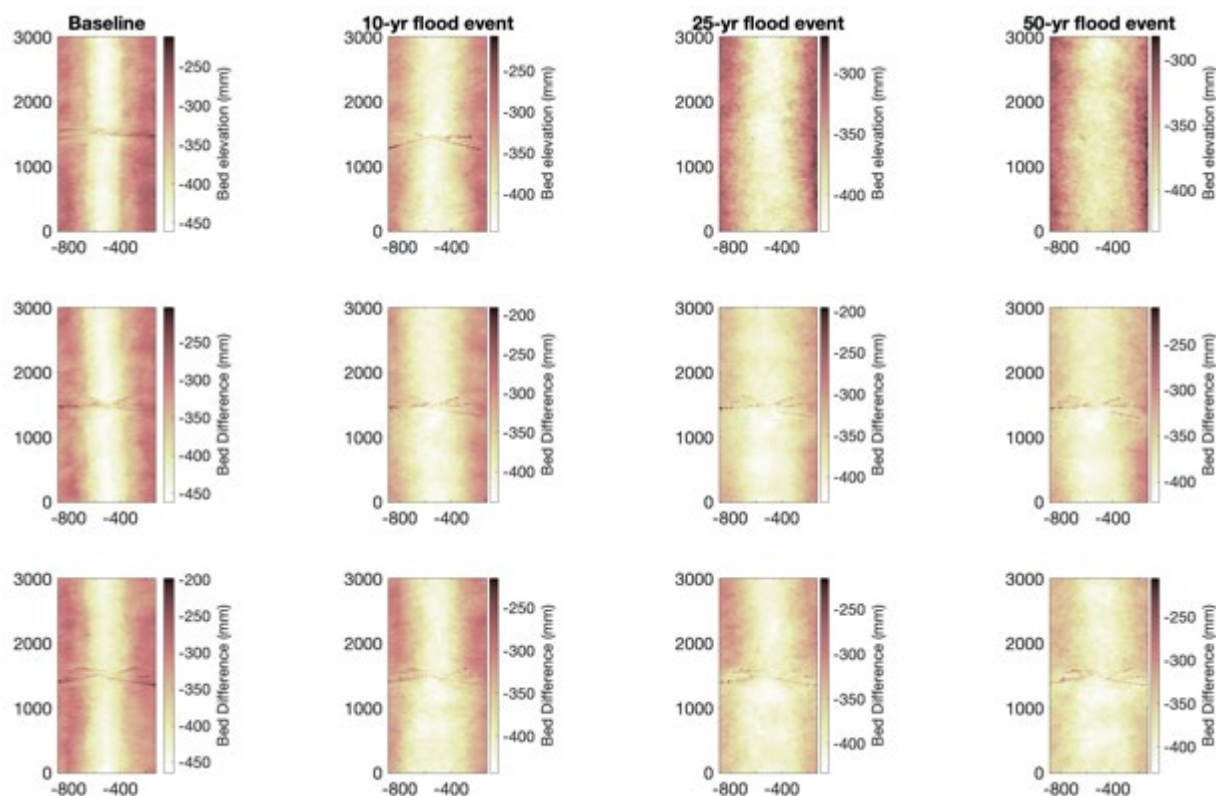


Figure 37 Streambed elevation for layout two after each flood event.

Layout 3

Layout 3 is a straight U-notch channel at a 2%2% slope. This layout has a deformable grade control (DGC) design in the middle of the study section. The DGC is made up of 7/8-in diameter dowels that have lengths of 3/4 and 1/2 channel-width. The feature is constructed in a trench with a 1/6 channel-width and a depth to the bottom of the flume. The feature has a wood-sediment ratio of 25;75. DGC was built with two 27-in, two 18in, and two 9-in dowels. See the figure below for layout construction. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

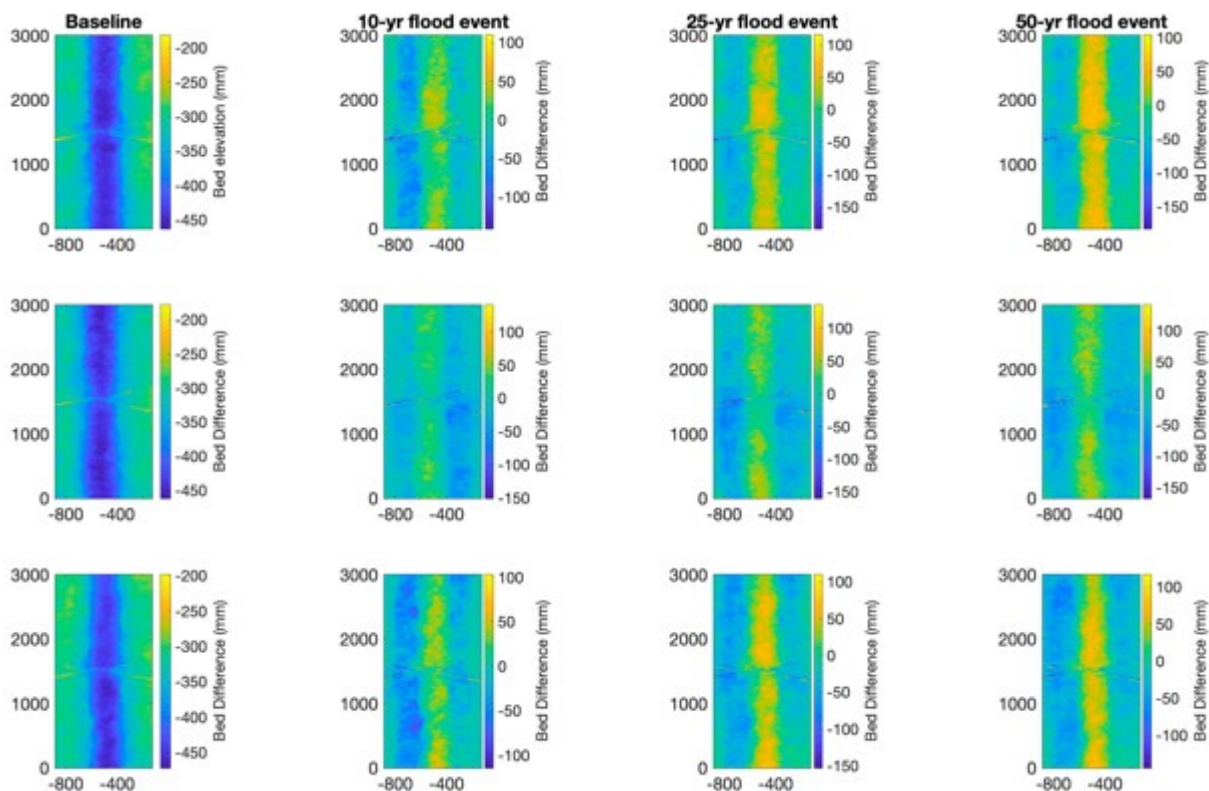


Figure 38 Difference of streambed elevation for layout three after each flood event.

After the 10-yr flood event, we saw erosion of the channel edges into the center of the channel, but the channel still has its U shape. There is a small sediment buildup at the base of the feature on its upstream side in the center of the channel. After the 25-yr flood event, we saw more erosion of the channel edges depositing into the center of the channel than after the 10-yr flood event, causing it to become flatter. More material has been deposited at the base of the feature on its upstream side in the center of the channel than after the 10-yr flood event. After the 50-yr flood event, we saw more erosion of the channel edges depositing into the center of the channel than after the 25-yr flood event, causing the channel to become additionally flattened.

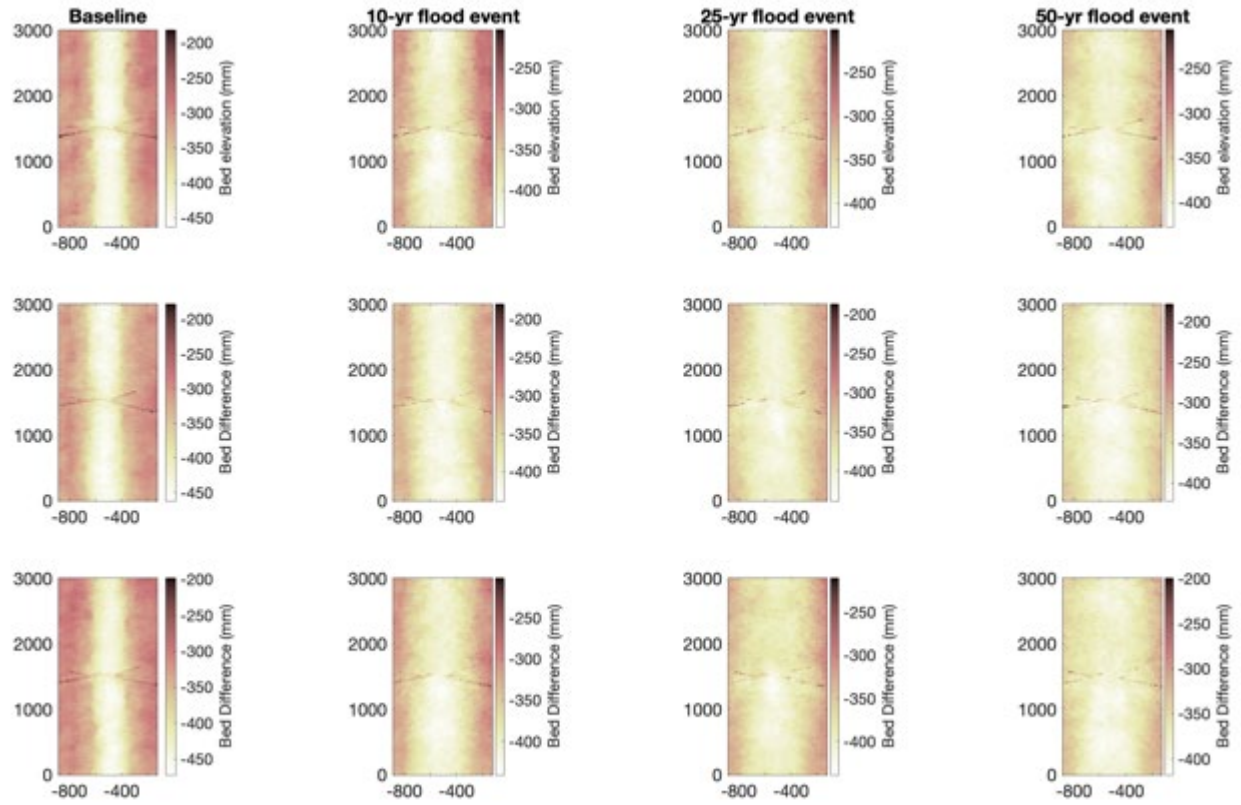


Figure 39 Streambed elevation for layout three after each flood event.

Layout 4

Layout 4 is a straight U-notch channel at a 2%2% slope. This layout has a deformable grade control (DGC) design in the middle of the study section. The DGC is made up of 7/8-in diameter dowels that have lengths of 3/4 and 1/2 channel-width. The feature is constructed in a trench with a 1/6 channel-width and a depth to the bottom of the flume. The feature has a wood-sediment ratio of 75:25. DGC was built with two 27-in, five 18-in, and four 9-in dowels. See the figure below for layout construction. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

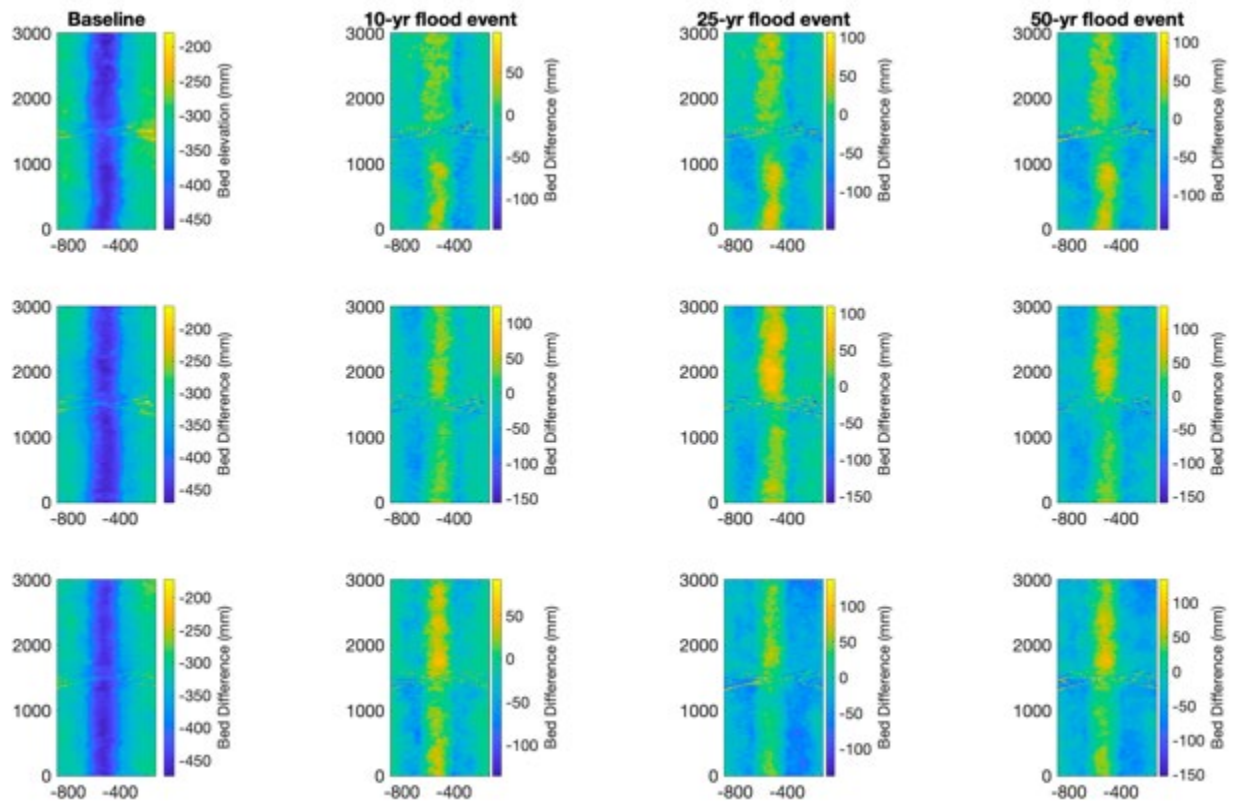


Figure 40 Difference of streambed elevation for layout four after each flood event.

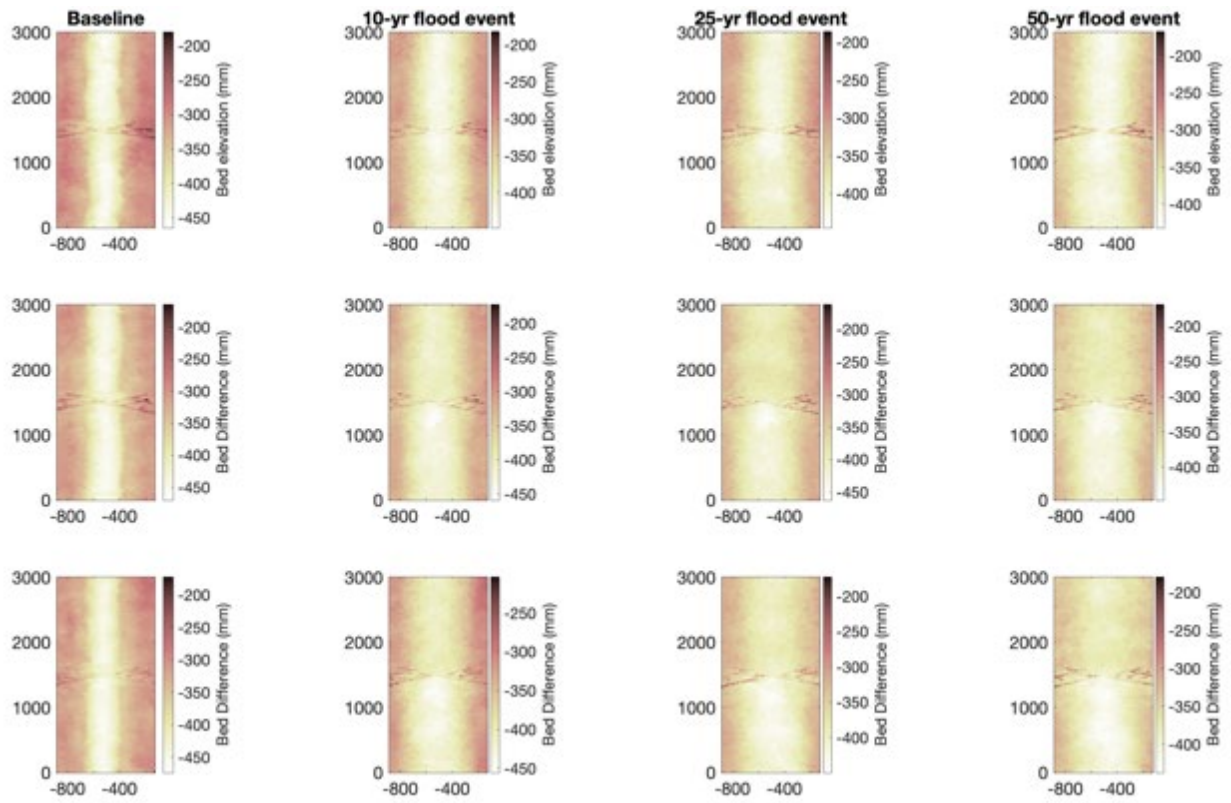


Figure 41 Streambed elevation for layout four after each flood event.

Layout 5

Layout 5 is a straight U-notch channel at a 2%2% slope. This layout has a deformable grade control (DGC) design in the middle of the study section. The DGC is made up of 3/8-in diameter dowels that have lengths of 3/4 and 1/2 channel-width. The feature is constructed in a trench with a 1/6 channel-width and a depth to the bottom of the flume. The feature has a wood-sediment ratio of 75:25. DGC was built with four 18-in, twelve 9-in, and twelve 6-in dowels. See the figure below for layout construction. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

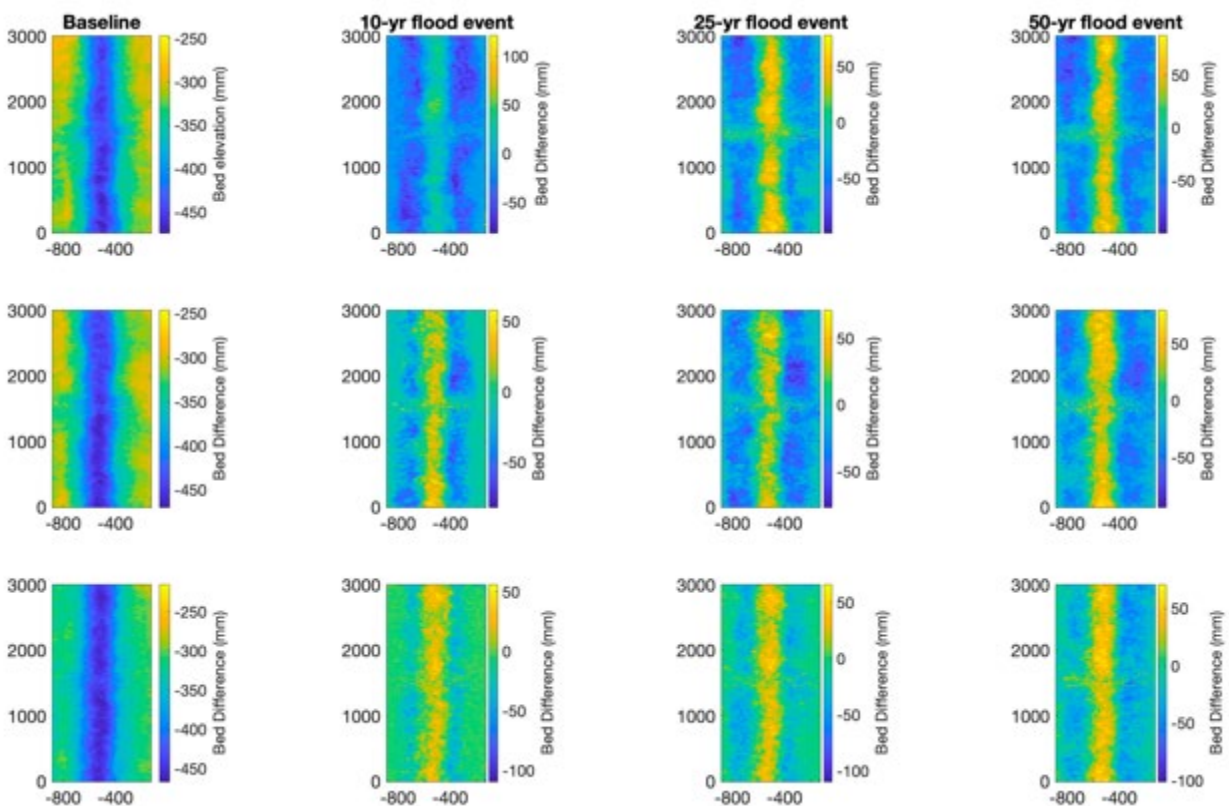


Figure 42 Difference of streambed elevation for layout five after each flood event.

After the 10-yr flood event, we saw erosion of the channel edges depositing into the center of the channel, but the channel kept its U shape. Material is deposited at the base of the feature on its upstream side in the center of the channel. Material is also eroded at the base of the feature on its downstream side in the center of the channel, creating a low spot. After the 25-yr flood event, we saw more erosion of the channel edges depositing into the center of the channel than after the 10-yr flood event, causing it to become flatter. More material is deposited at the base of the feature on its upstream side in the center of the channel than after the 10-yr flood event. Similarly, more material is also eroded at the base of the feature on its downstream side in the center of the channel. After the 50-yr flood event, we saw more erosion of the channel edges depositing into the center of the channel than after the 25-yr flood event, causing it to become additionally flattened. More material is deposited at the base of the feature on its upstream side in the center of the channel than after the 25-yr flood event. Similarly, more material is also eroded at the base of the feature on its downstream side in the center of the channel.

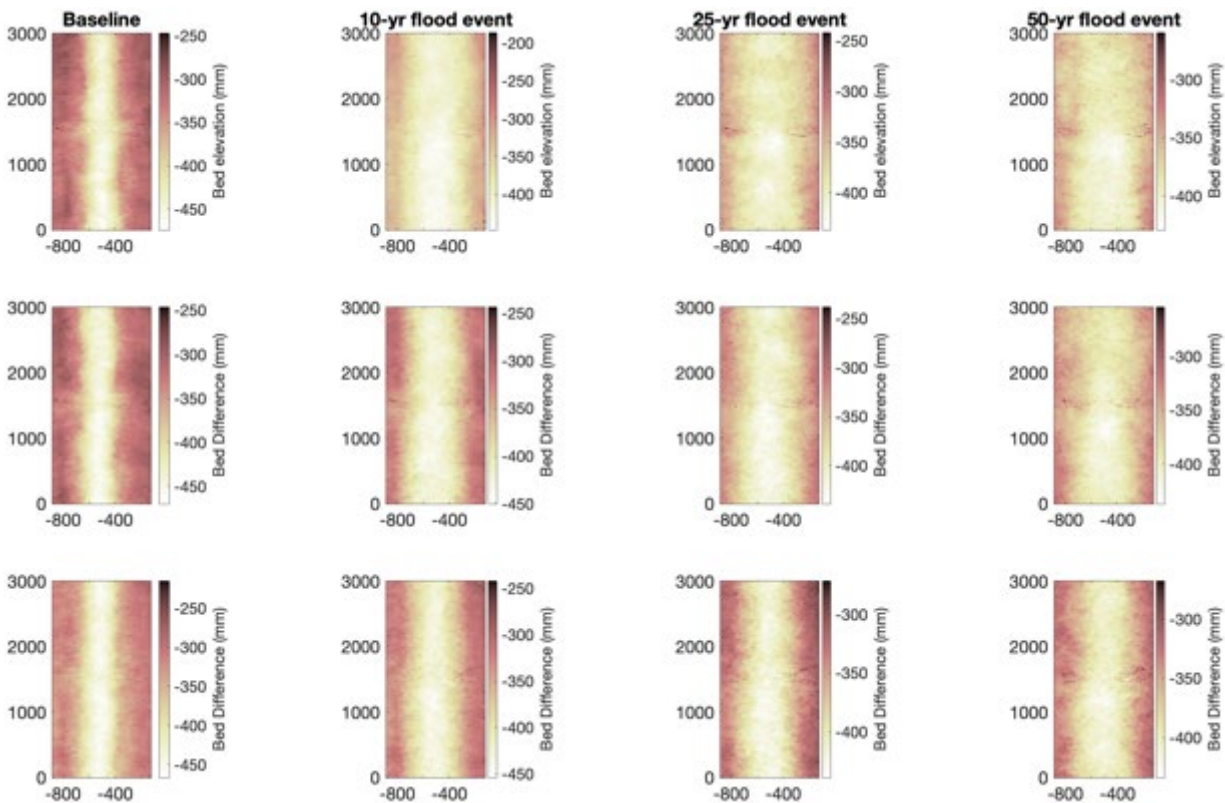


Figure 43 Streambed elevation for layout five after each flood event.

Layout 6

Layout 6 is a straight U-notch channel at a 2% slope. This layout has a deformable grade control (DGC) design in the middle of the study section. The DGC is made up of 3/8-in diameter dowels that have lengths of 3/4 and 1/2 channel width. The feature is constructed in a trench with a 1/6 channel width and a depth to the bottom of the flume. The feature has a wood-sediment ratio of 50:50. DGC was built with three 18-in, eight 9-in and eight 6-in dowels. See the figure below for layout construction. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

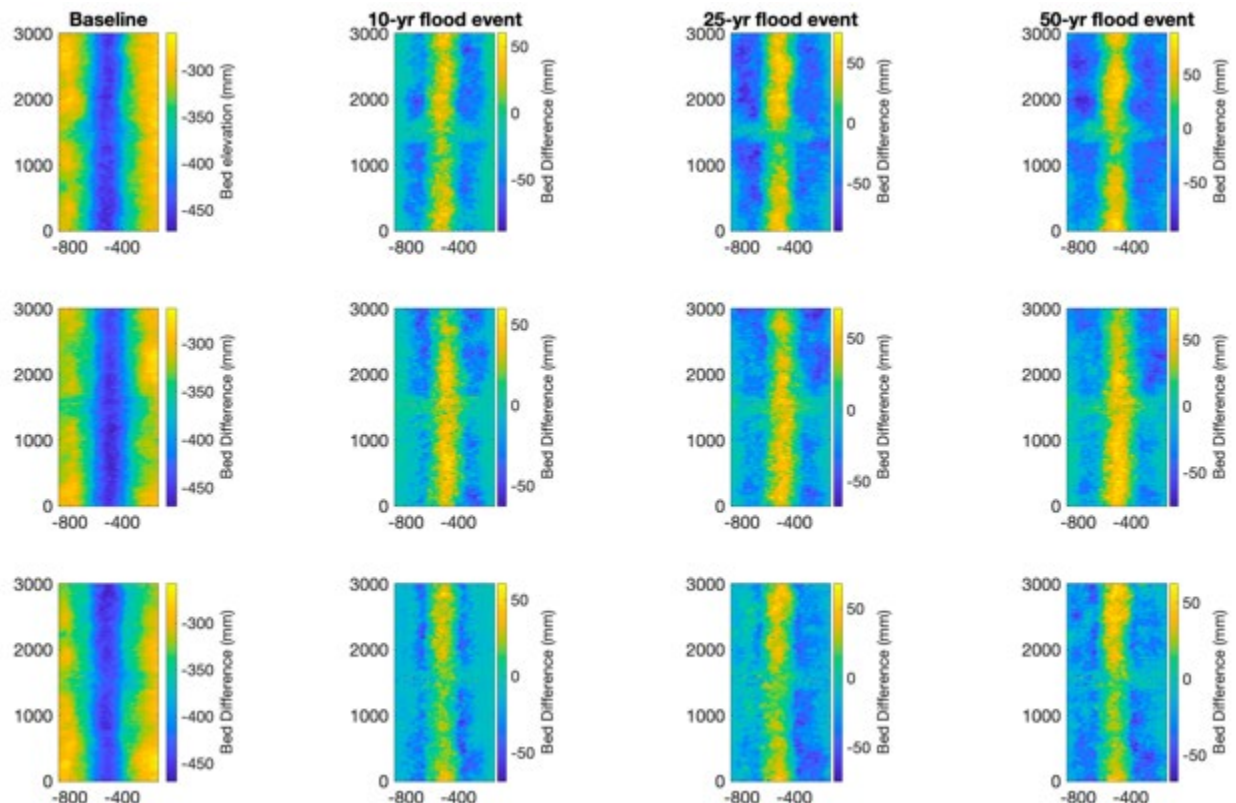


Figure 44 Difference of streambed elevation for layout six after each flood event.

After the 10-yr flood event, we saw erosion of the channel edges into the center of the channel, causing it to become more flattened than the baseline. Similarly, there is more erosion upstream of the feature. Some material is deposited at the base of the feature on its upstream side in the center of the channel; this causes dowels in the center of the channel to become more buried compared to baseline. After the 25-yr flood event, we saw more erosion of the edges into the center of the channel than the 10-yr flood event. Similarly, more erosion on the upstream side causes it to become more flattened out on the upstream side. More material is deposited at the base of the feature on its upstream side. Material is also eroding at the base of the feature on its downstream side in the center of the channel, creating a low spot in the channel. After the 50-yr flood, we saw more erosion of the edges depositing into the center of the channel than after the 25-yr flood event, causing the channel to become

additionally flattened. More erosion on the upstream side causes it to become more flattened out on the upstream side than after the 25-yr flood event. Similarly, more material is deposited at the base of the feature on its upstream side. More material is also eroding at the base of the feature on its downstream side in the center of the channel, creating a low spot in the channel.

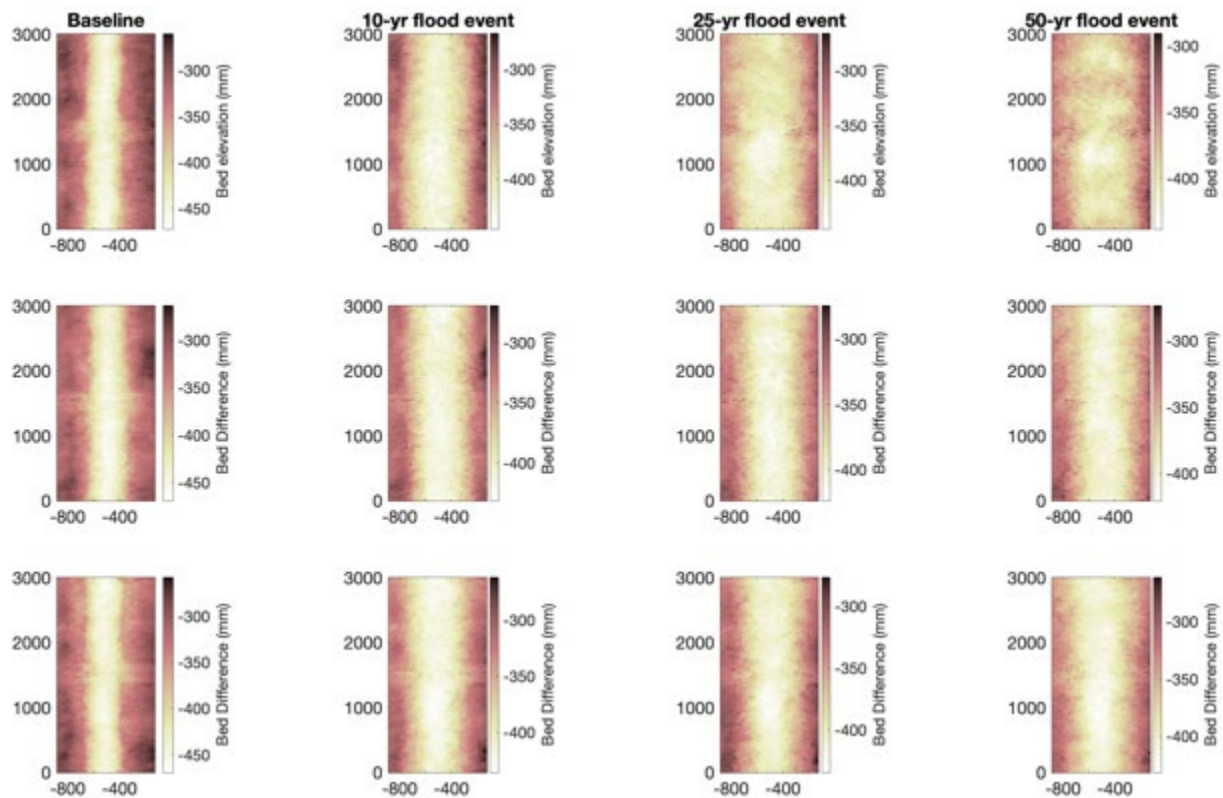


Figure 45 Streambed elevation for layout six after each flood event.

Layout 7

Layout 7 is a straight U-notch channel at a 2%2% slope. This layout has a deformable grade control (DGC) design in the middle of the study section. The DGC is made up of 3/8-in diameter dowels that have lengths of 3/4 and 1/2 channel-width. The feature is constructed in a trench with a width of 1/6 channel-width and a depth to the bottom of the flume. The feature has a wood-sediment ratio of 25:75. DGC was built with two 18-in, four 9-in, and four 6-in dowels. See the figure below for layout construction. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

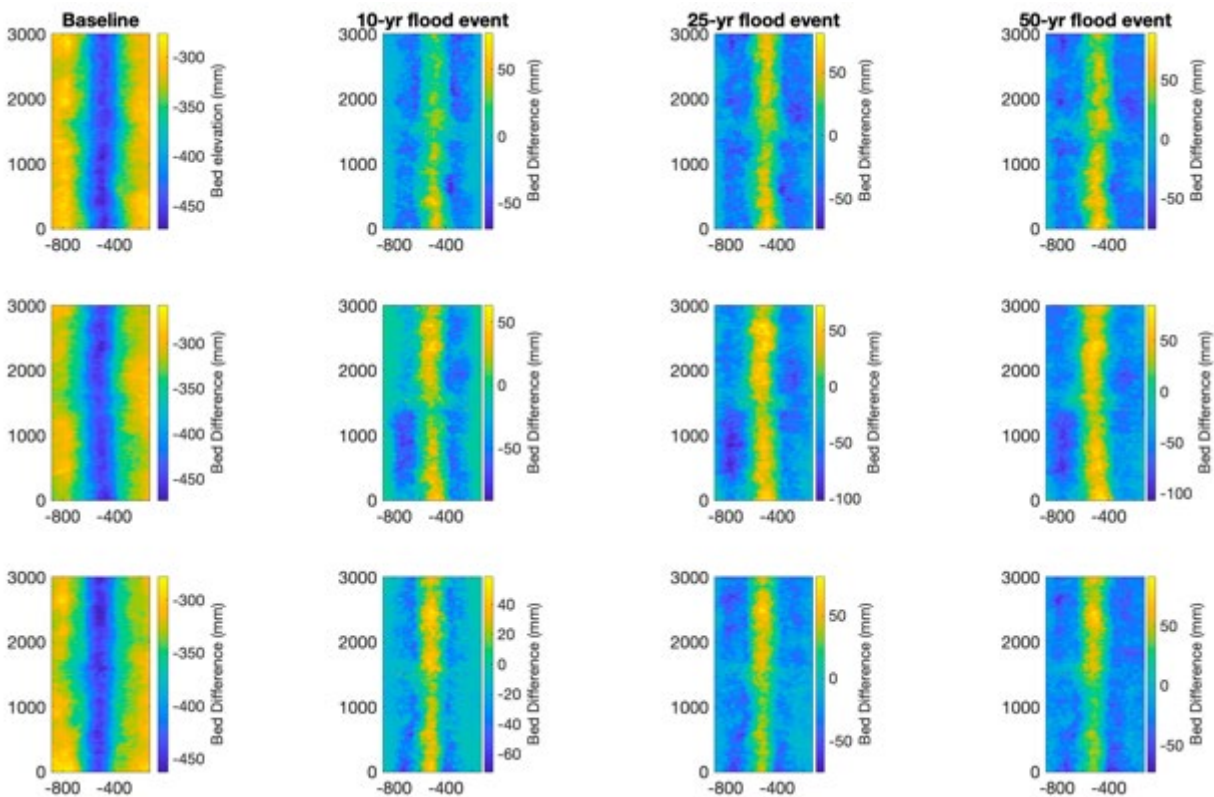


Figure 46 11 Difference of streambed elevation for layout seven after each flood event.

After the 10-yr flood event, we saw erosion of the channel edges depositing into the center of the channel, causing it to become flatter than the baseline, but the channel still has its U shape. The right side of the channel is more eroded. After the 25-yr flood, we saw more erosion of the channel edges depositing into the center of the channel than after the 10-yr flood event, causing it to further flatten. Some material is deposited at the base of the feature on its upstream side in the center of the channel. The right side of the channel appears to be more eroded. After the 50-yr flood event, we saw more erosion of the edges depositing into the center of the channel than after the 25-yr flood event, causing the channel to be nearly flattened out. The channel is slightly more eroded upstream of the feature than downstream. More material is deposited at the base of the feature than after the 25-yr flood event. Some erosion at the base of the dowels on its downstream side in the center of the channel creates a low spot.

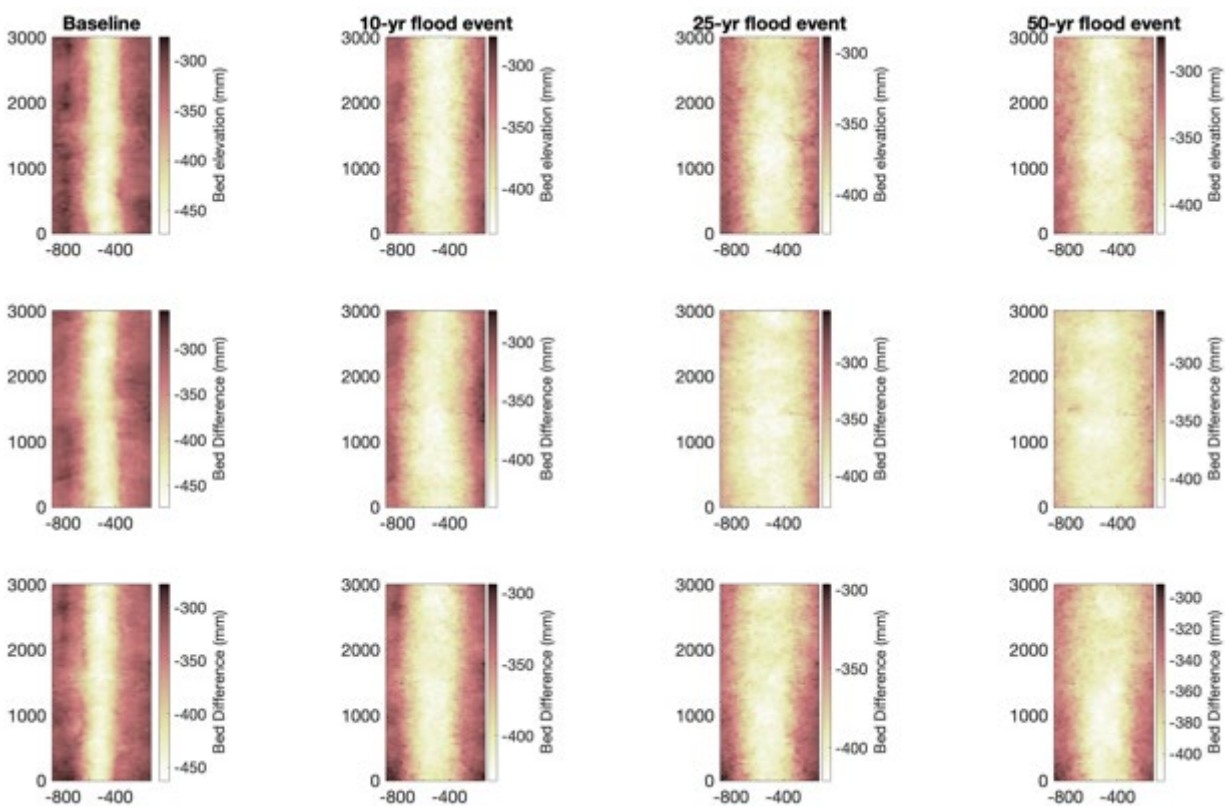


Figure 47 10 Streambed elevation for layout seven after each flood event.

Layout 8

Layout 8 is a straight U-notch channel at a 2%2% slope. This layout has a deformable grade control (DGC) design in the middle of the study section. The DGC is made up of 1/8-in diameter dowels that have lengths of 3/4 and 1/2 channel-width. The feature is constructed in a trench with a width of 1/6 channel-width and a depth to the bottom of the flume. The feature has a wood-sediment ratio of 75:25. DGC was built with four 9-in and four 6-in dowels. See the figure below for layout construction. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

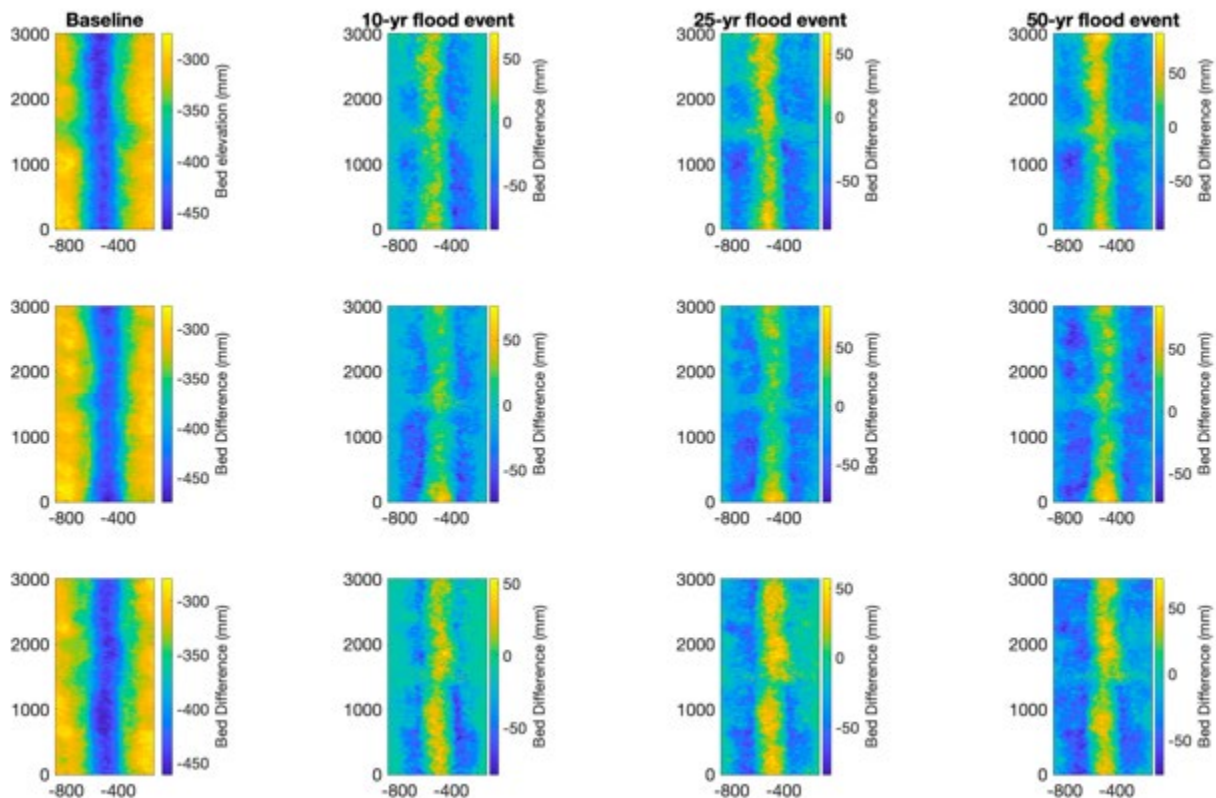


Figure 48 11 Difference of elevation for layout eight after each flood event.

After the 10-yr flood event, we saw some erosion of the edges depositing into the center of the channel, but the channel still has its U-shaped. Some material is being deposited at the base of the feature on its upstream side. After the 25-yr flood event, we saw more erosion of the edges into the center of the channel and slightly more material deposited at the base of the feature than after the 10-yr flood event. The dowels in the center of the channel are mostly covered with material. After the 50-yr flood event, we saw more erosion of the channel edges depositing into the center of the channel than after the 25-yr event. The channel is nearly flattened out due to the channel walls eroding and depositing into the center of the channel; there is less channel erosion on the downstream side than the upstream side. More material has been deposited at the base of the feature in the center of the channel.

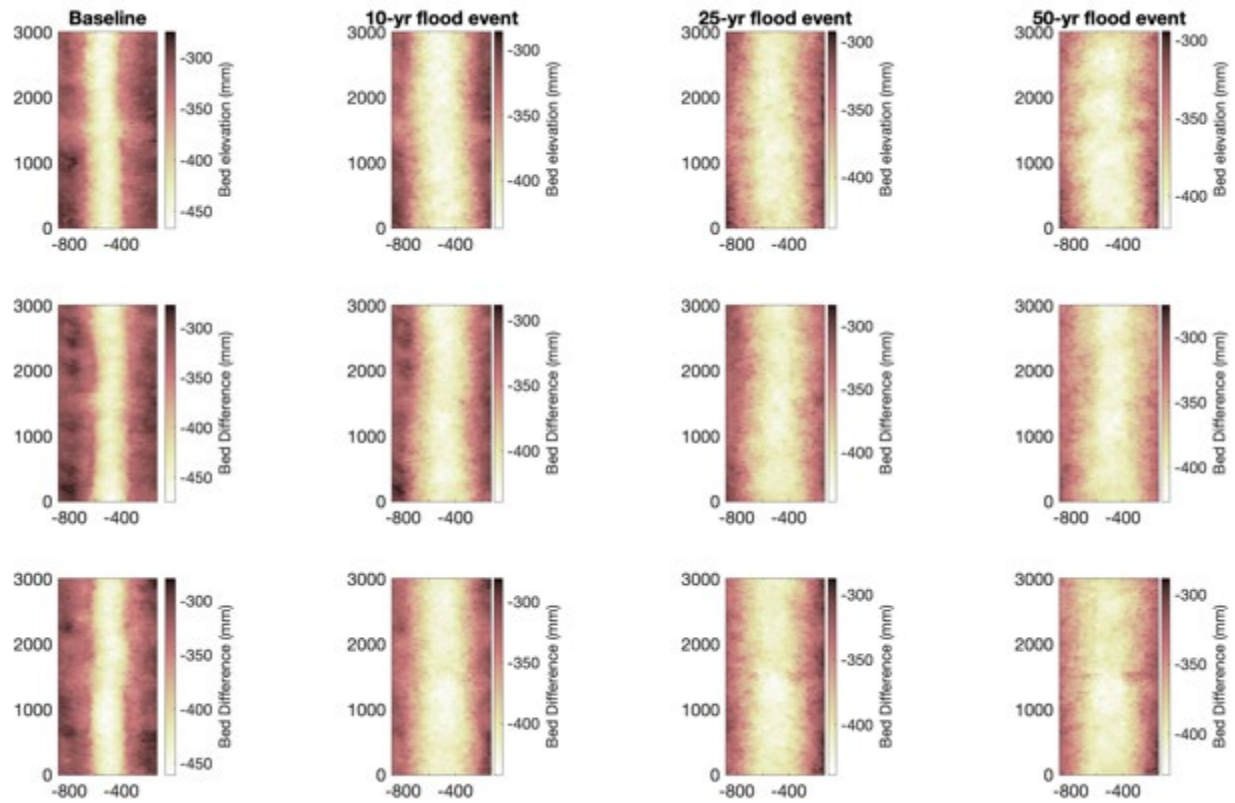


Figure 49 12 Streambed elevation for layout eight after each flood event.

Layout 9

Layout 9 is a straight U-notch channel at a 2%2% slope. This layout has a deformable grade control (DGC) design in the middle of the study section. The DGC is made up of 3/8-in diameter dowels that have lengths of 3/4 and 1/2 channel-width. The feature is constructed in a trench with a width of 1/6 channel-width and a depth to the bottom of the flume. The feature has a wood-sediment ratio of 50:50. DGC was built with fourteen 9-in and twenty-four 6-in dowels. See the figure below for layout construction. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

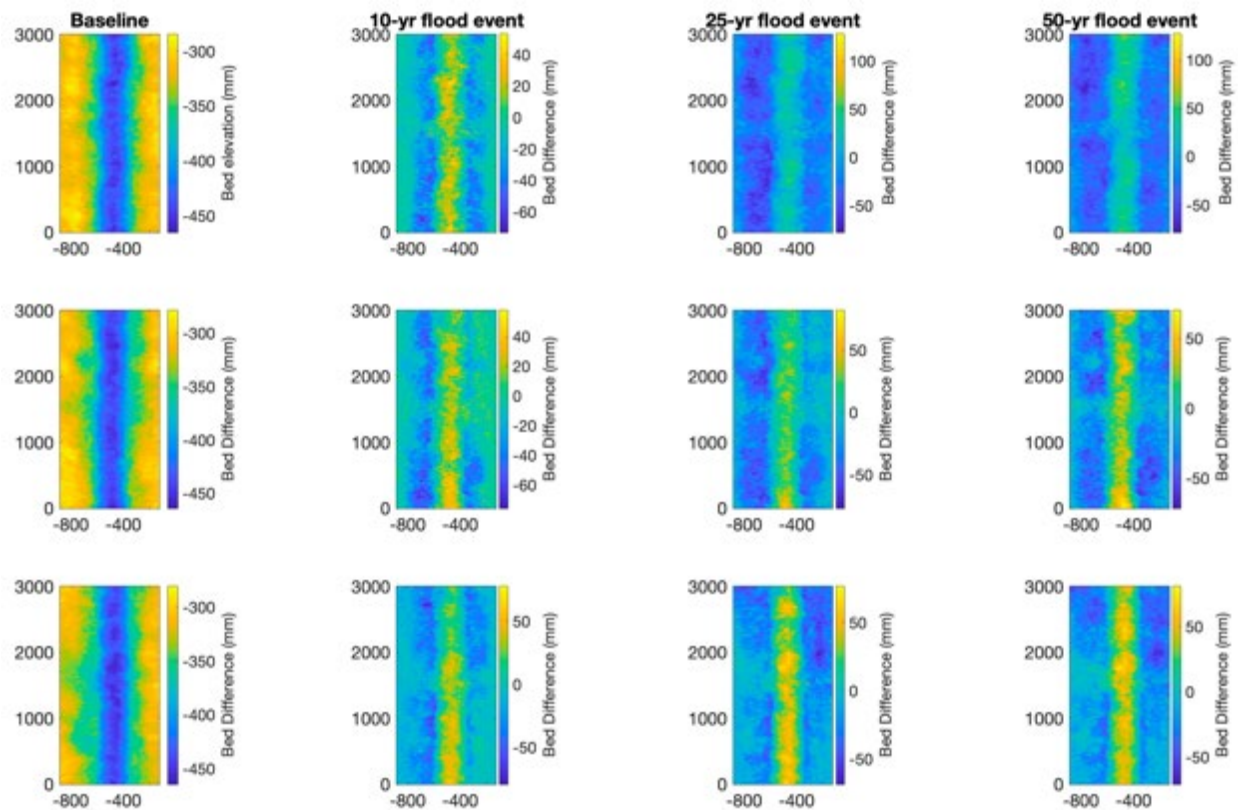


Figure 50 13 Difference in streambed elevation for layout nine after each flood event.

After the 10-yr flood event, we saw some erosion of the edges depositing into the center of the channel, but the channel still has its U-shaped. Some material is being deposited at the base of the feature on its upstream side. After the 25-yr flood event, we saw more erosion of the edges into the center of the channel than after the 10-yr flood event, causing it to become flatter. Slightly more material is deposited at the base of the feature. Light erosion at the base of the feature on its downstream side creates a low spot in the center of the channel.

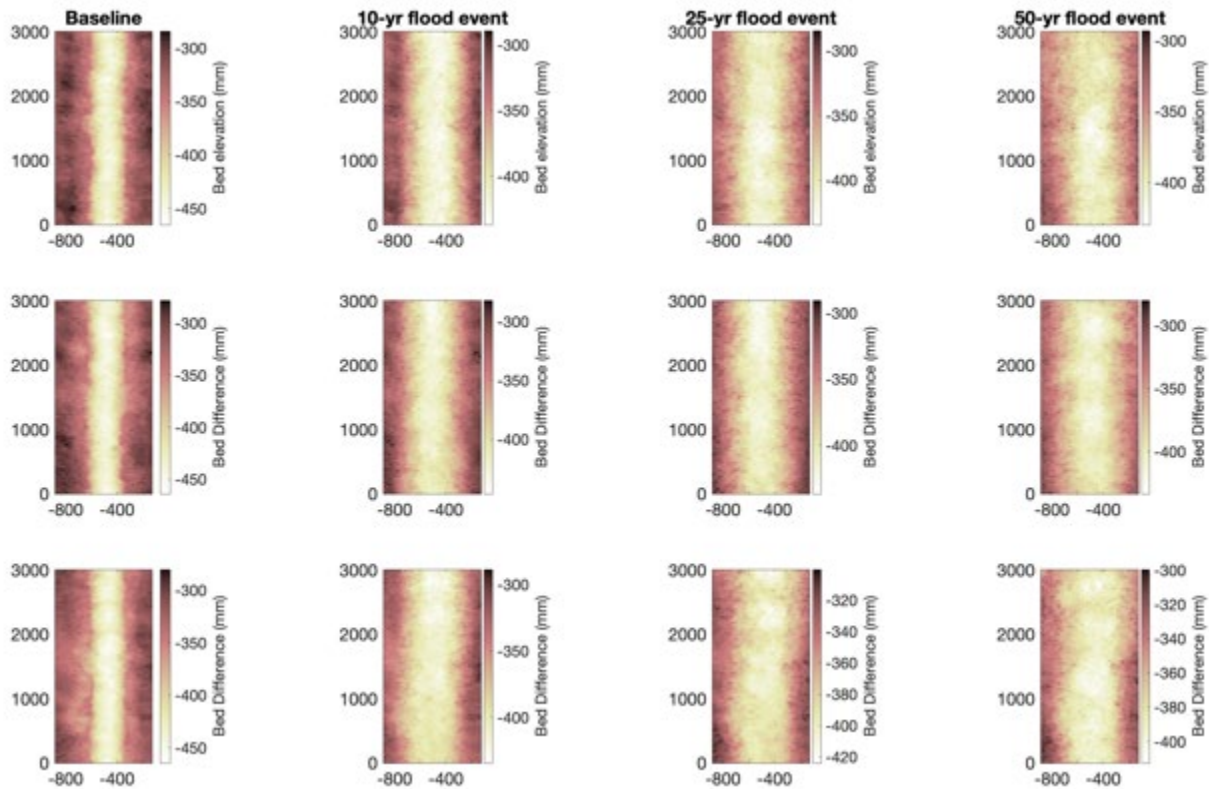


Figure 51 14 Streambed elevation for layout nine after each flood event.

Layout 10

Layout 10 is a straight U-notch channel at a 2% slope. This layout has a deformable grade control (DGC) design in the middle of the study section. The DGC is made up of 3/8-in diameter dowels that have lengths of 3/4 and 1/2 channel-width. The feature is constructed in a trench with a width of 1/6 channel-width and a depth to the bottom of the flume. The feature has a wood-sediment ratio of 25:75. DGC was built with six 9-in and fourteen 6-in dowels. See the figure below for layout construction. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

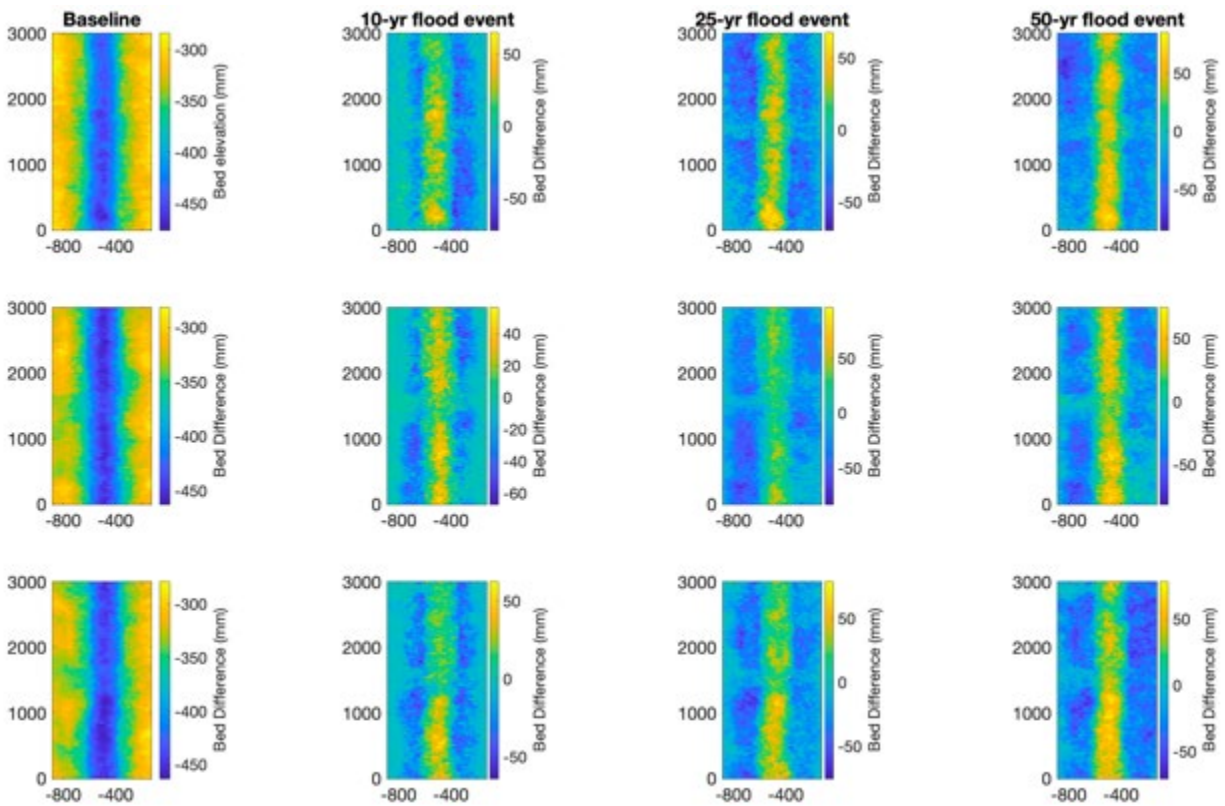


Figure 15 52 Difference of streambed elevation for layout ten after each flood event.

After the 10-yr flood event, we saw some erosion of the edges depositing into the center of the channel, but the channel still has its U-shaped. Some material is being deposited at the base of the feature on its upstream side in the center of the channel. After the 25-yr flood event, we saw more erosion of the edges into the center of the channel than after the 10-yr flood event, causing it to become more flattened. Slightly more material is deposited at the base of the feature. After the 50-yr flood event, we saw more erosion of the channel edges depositing into the center of the channel than after the 25-yr flood event, causing it to become additionally flattened. More material is also being deposited at the base of the feature on its upstream side in the center of the channel.

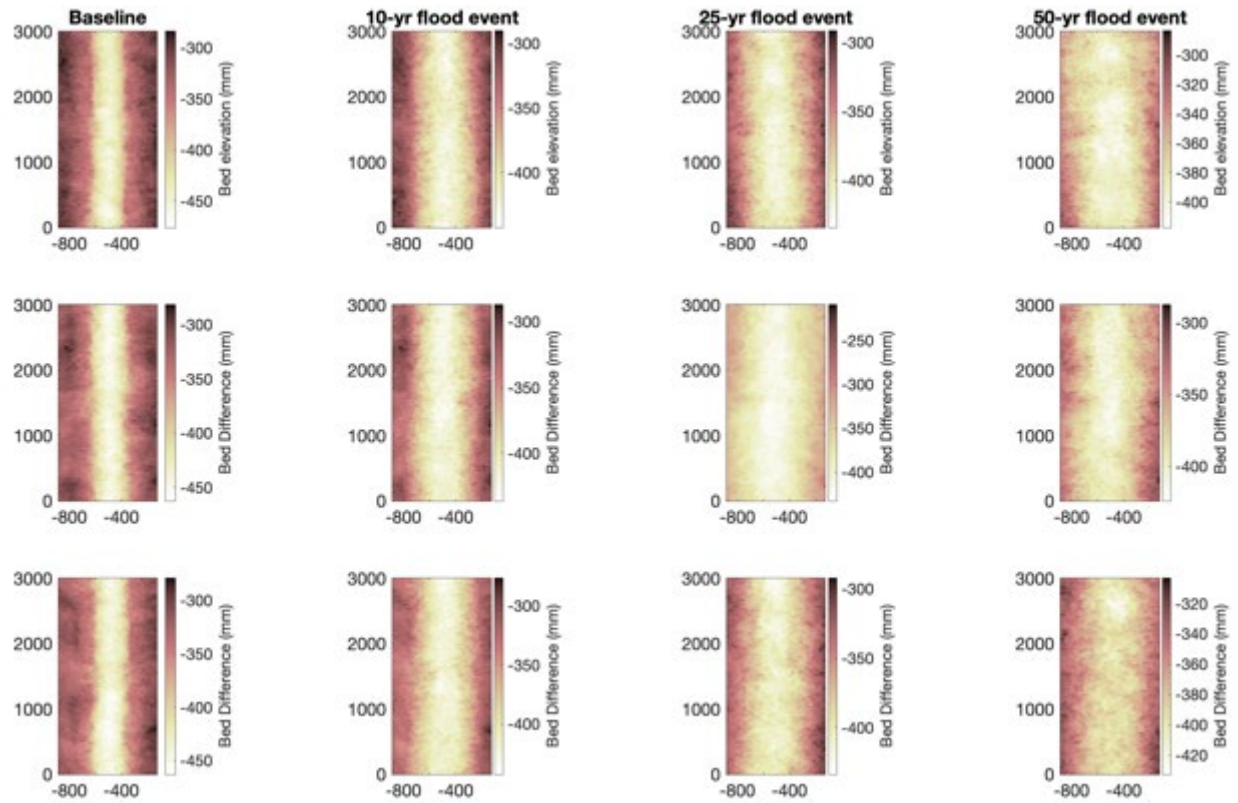


Figure 53 16 Streambed elevation for layout ten after each flood event.

Layout 11

Layout 11 is a straight U-notch channel at a 2% slope. This layout has a deformable grade control (DGC) design in the middle of the study section. The DGC comprises a distribution of 7/8-, 3/8-, and 1/8-in diameter dowels with lengths of 3/4, 1/2, 1/4, and 1/6 channel-width. The dowel sizes are distributed at a ratio of 15:50:35. The feature is constructed in a trench with a width of 1/6 channel-width and a depth to the bottom of the flume. The feature has a wood-sediment ratio of 75:25. DGC was built with one 27-in and one 18-in long 7/8^t-in diameter dowels, twelve 9-in and twelve 6-in long 3/8-in diameter dowels, and four 9-in and thirty-one 6-in long 1/8-in diameter dowels. See the figure below for layout construction. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

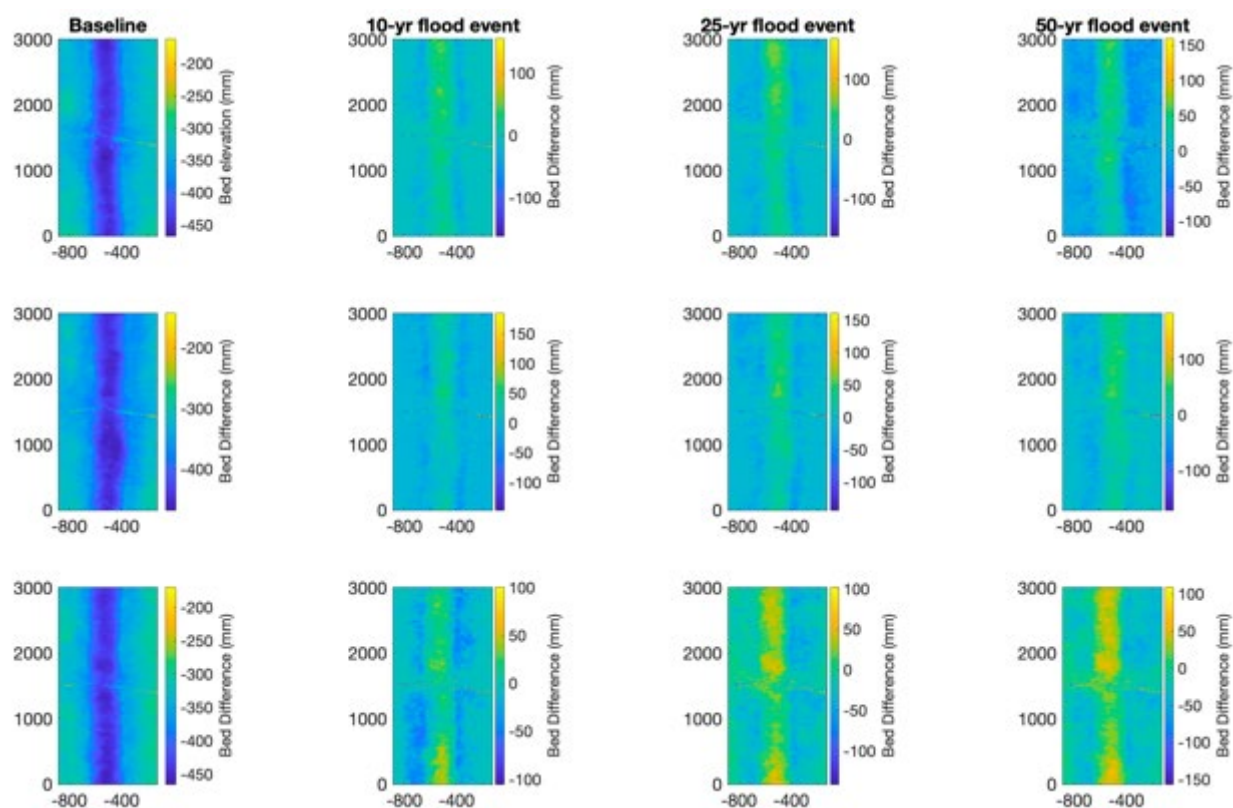


Figure 54 17 Difference of streambed elevation for layout 11 after each flood event.

After the 10-yr flood event, we saw some erosion of the edges depositing into the center of the channel, but the channel still has its U-shaped. Some material is being deposited at the base of the feature on its upstream side in the center of the channel. There is also some material erosion at the base of the feature in the center of the channel on its downstream side, creating a low spot in the channel. After the 25-yr flood event, we saw more erosion of the edges into the center of the channel than after the 10-yr flood event, causing it to become flatter. Slightly more material was deposited at the base of the feature on its upstream side, and more erosion of the center of the channel on its downstream side. There is more erosion of the channel edges into the center of the channel upstream of the feature than downstream, causing the channel to be more flattened out upstream. After the 50-yr flood event, we saw more erosion of the channel edges depositing into the center of the channel upstream of the feature than after the 25-yr flood event, causing it to become additionally flattened out. The channel has kept its U shape much better downstream of the feature. More material is also being deposited at the base of the feature on its upstream side in the center of the channel than after the 25-yr flood event, as well as more erosion of the center of the channel on its downstream side.

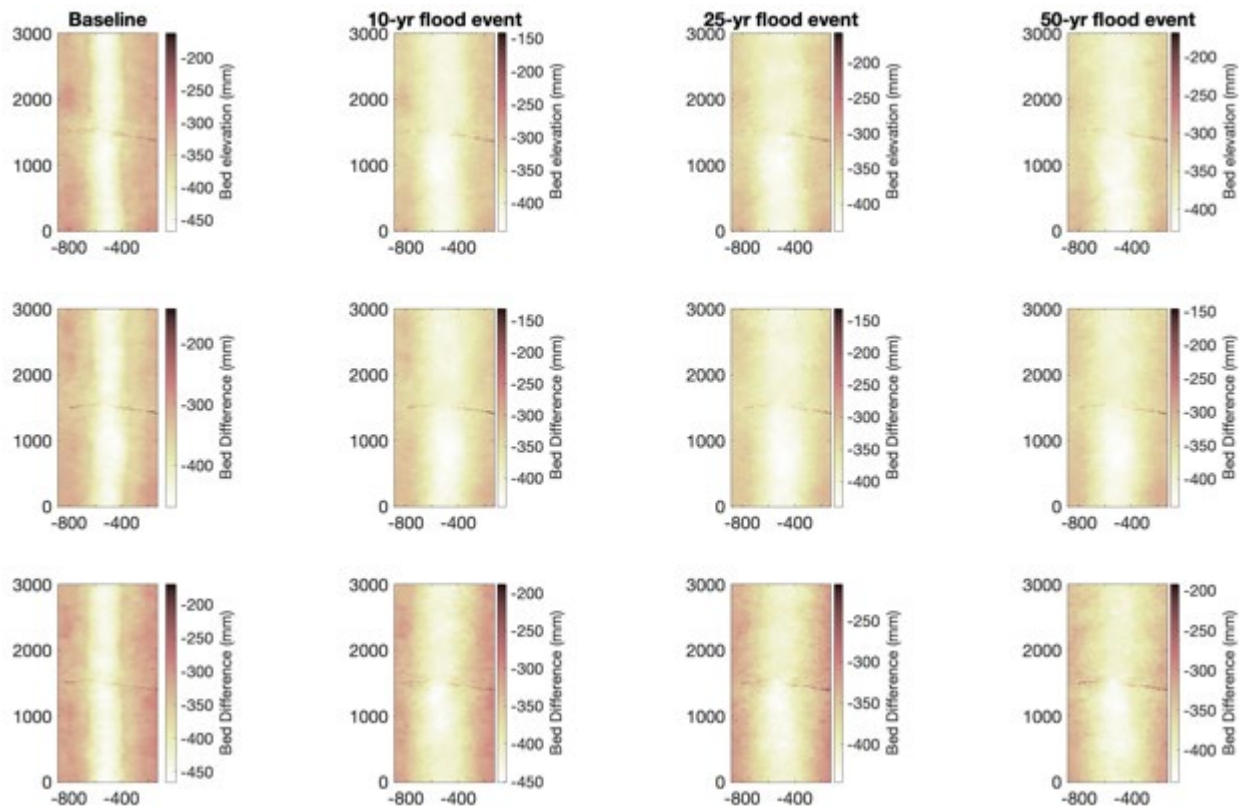


Figure 55 18 Streambed elevation for layout 11 after each flood event.

Layout 12

Layout 12 is a straight U-notch channel at a 2% slope. This layout has a deformable grade control (DGC) design in the middle of the study section. The DGC comprises a distribution of 7/8-, 3/8-, and 1/8-inch diameter dowels with lengths of 3/4, 1/2, 1/4, and 1/6 channel-width. The dowel sizes are distributed at a ratio of 15:50:35. The feature is constructed in a trench with a width of 1/6 channel-width and a depth to the bottom of the flume. The feature has a wood-sediment ratio of 50:50. DGC was built with one 27-in and one 18-in long 7/8-in diameter dowels, six 9-in and six 6-in long 3/8-in diameter dowels, and two 9-in and seventeen-one 6" long 1/8th diameter dowels. See the figure below for layout construction. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

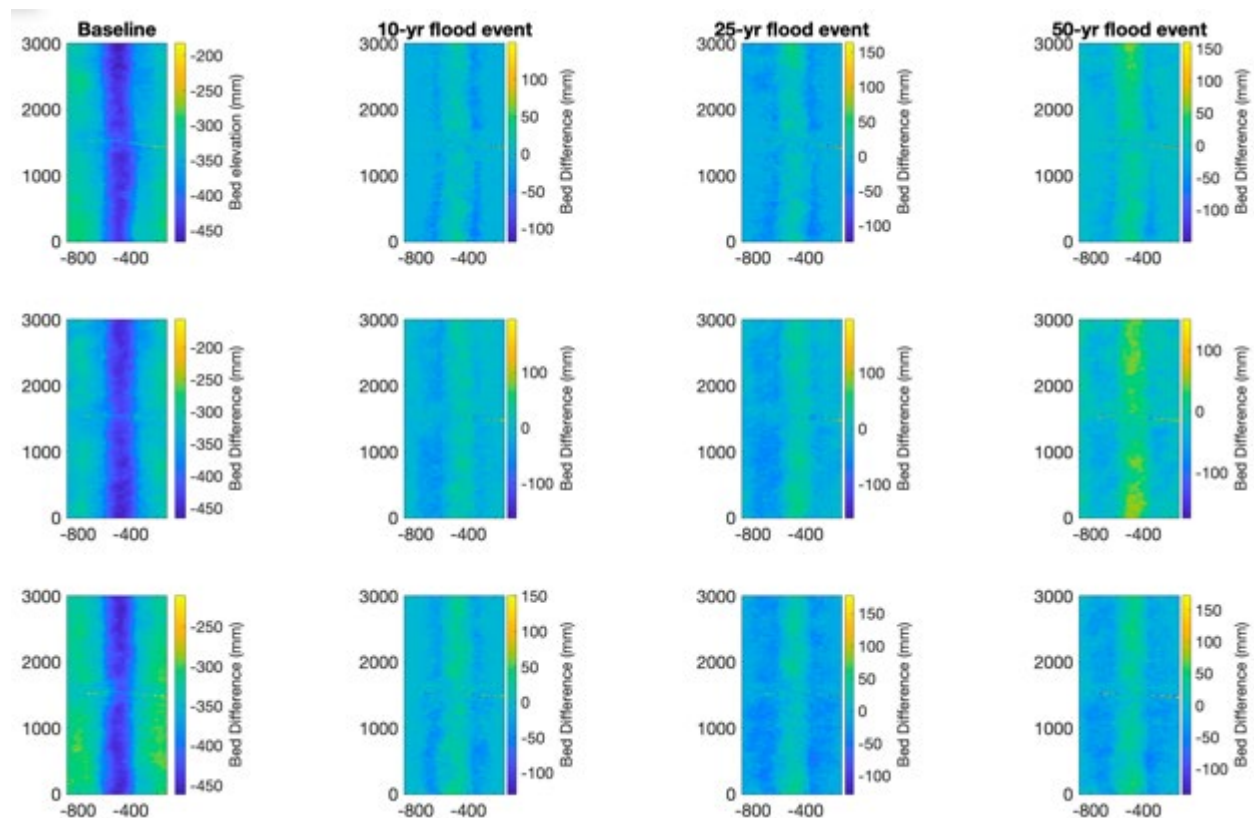


Figure 19 56 Difference in streambed elevation for layout 12 after each flood event.

After the 10-yr flood event we saw some erosion of the edges depositing into the center of the channel, but the channel still has its U-shaped. There is some material being deposited at the base of the feature on its upstream side in the center of the channel. There is also some erosion of material at the base of the feature in the center of the channel on its downstream side, creating a low spot in the channel. After the 25-yr flood event we saw more erosion of the edges into the center of the channel than after the 10-yr flood event. More material is deposited at the base of the feature on its upstream side, and more

erosion of the center of the channel on its downstream side than after the 10-yr flood event. After the 50-yr flood event we saw more erosion of the channel edges depositing into the center of the channel than after the 25-yr flood event. The channel has kept its U shape much better downstream of the feature and is much more flattened out upstream of the feature. There is also more material being deposited at the base of the feature on its upstream side in the center of the channel, and more erosion of the center of the channel at the base of the feature on its downstream side.

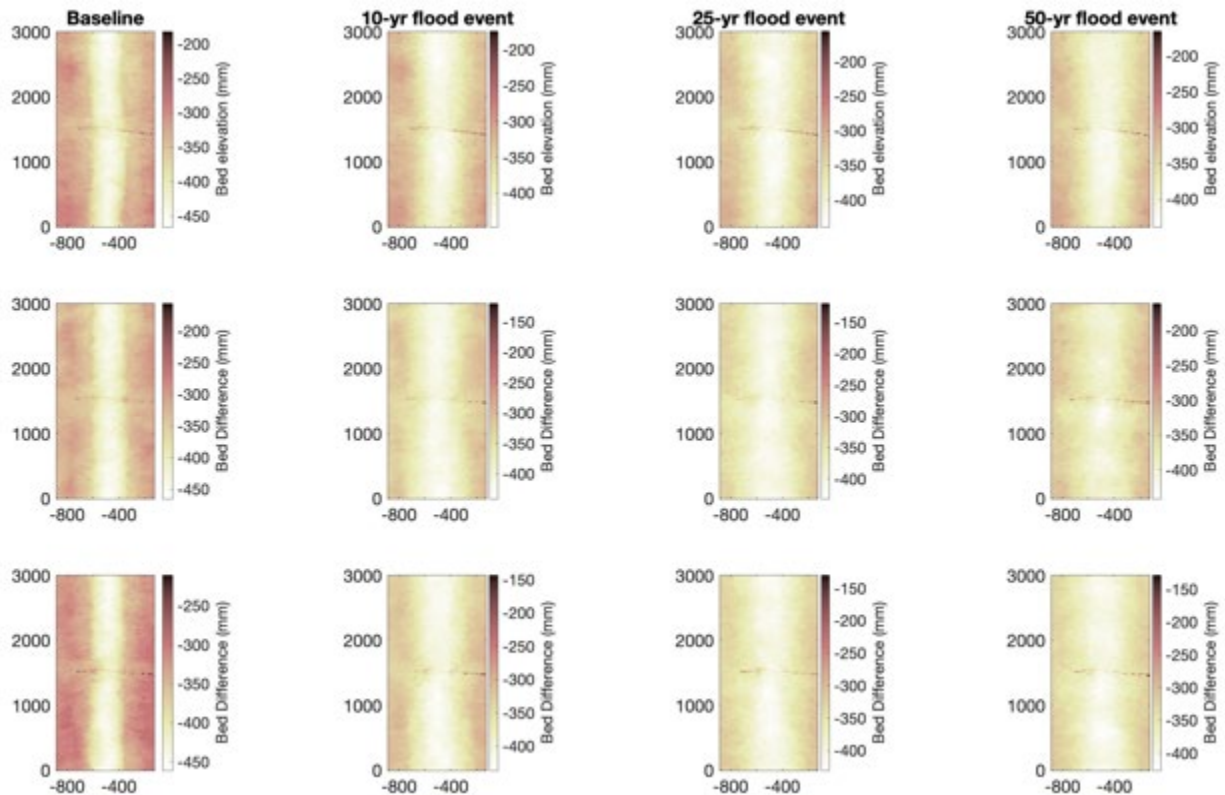


Figure 57 20 Streambed elevation for layout 12 after each flood event.

Layout 13 is a straight U-notch channel at a 2% slope. This layout has a deformable grade control (DGC) design in the middle of the study section. The DGC is made up of a distribution of 7/8-, 3/8- and 1/8-in diameter dowels that have lengths of 3/4, 1/2, 1/4 and 1/6 channel-width. The dowel sizes are distributed at a ratio of 15:50:35. The feature is constructed in a trench that is has a width of 1/6 channel-width and a depth half the distance to the bottom of the flume. The feature has a wood-sediment ratio of 50:50. DGC was built with one 27-in and one 18-in long 7/8-in diameter dowels, six 9-in and six 6-in long 3/8-in diameter dowels, and two 9-in and seventeen-one 6" long 1/8-in diameter dowels. See figure below for layout construction. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

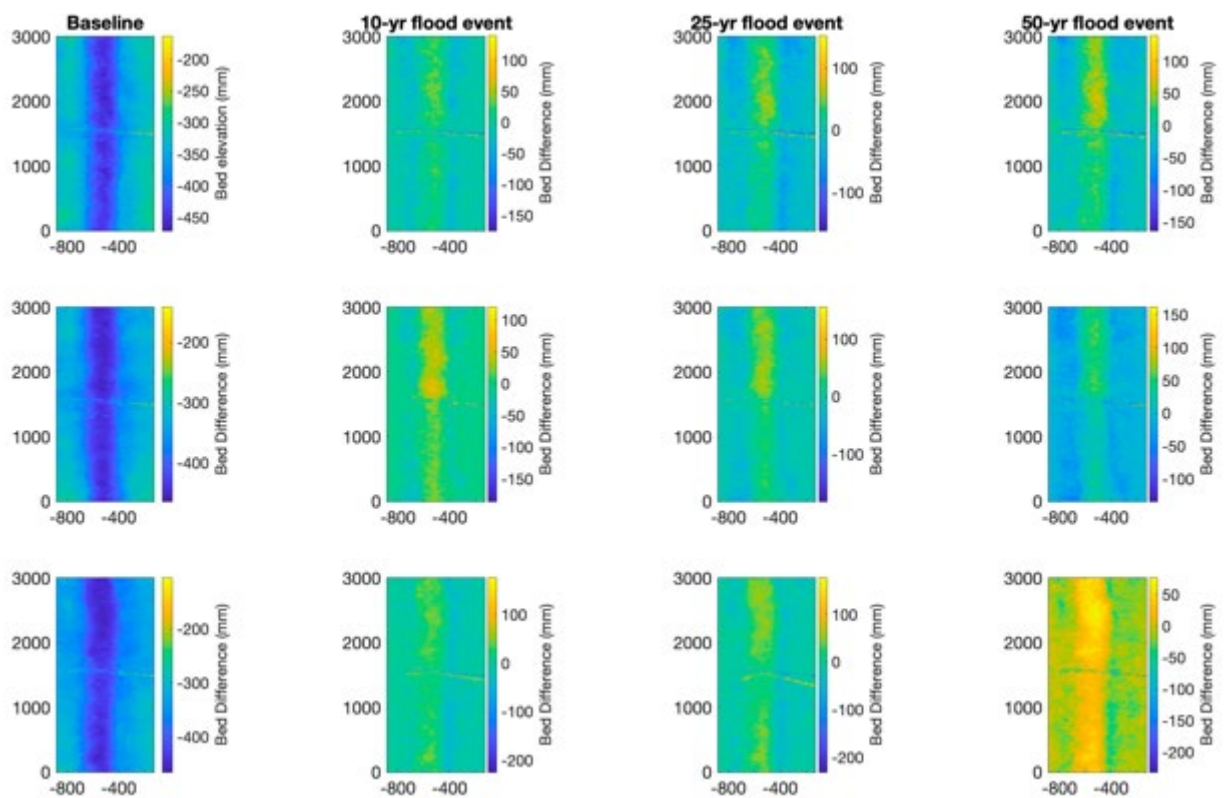


Figure 58 21 Difference of streambed elevation for layout 13 after each flood event.

Layout 13 Trial 2 had to be redone after Flow 2 because the scanner messed up. During Trial 2 attempt 1 2 7/8th in, 2 1/8th, came loose from the feature.

After the 10-yr flood event we saw all dowels are still in place. Some erosion of channel edges into the center, there is more erosion of the channel edges on the upstream side of the feature than on the downstream side of the feature. A small amount of deposition shows at the base of the feature/dowels on its upstream side. Slight erosion shows at the base of the feature on the downstream side, creating an indentation in the center of the channel. After the 25-yr flood event we saw all dowels still in place. We saw more erosion of channel edges into the center than after the 10-yr flood event. There is more

erosion of the channel edges on the upstream side of the feature causing it to be nearly flattened out. The downstream side of the feature still has its U shape. More deposition shows at base of feature/dowels on its upstream side than after the 10-yr flood event. More erosion shows at the base of the feature on the downstream side than after the 10-yr flood event, creating an indentation in the center of the channel. After the 50-yr flood event we saw all dowels still in place. We saw more erosion of the channel edges into the center of the channel than after the 25-yr flood event. Similarly, there is more erosion on the upstream side of the channel of the feature, causing it to become additionally flattened out. The channel still has its U shape on the downstream side of the feature. There is more deposition at the base of the feature/dowels on its upstream side. There is more erosion at the base of the feature on its downstream side, creating an indentation in the center of the channel.

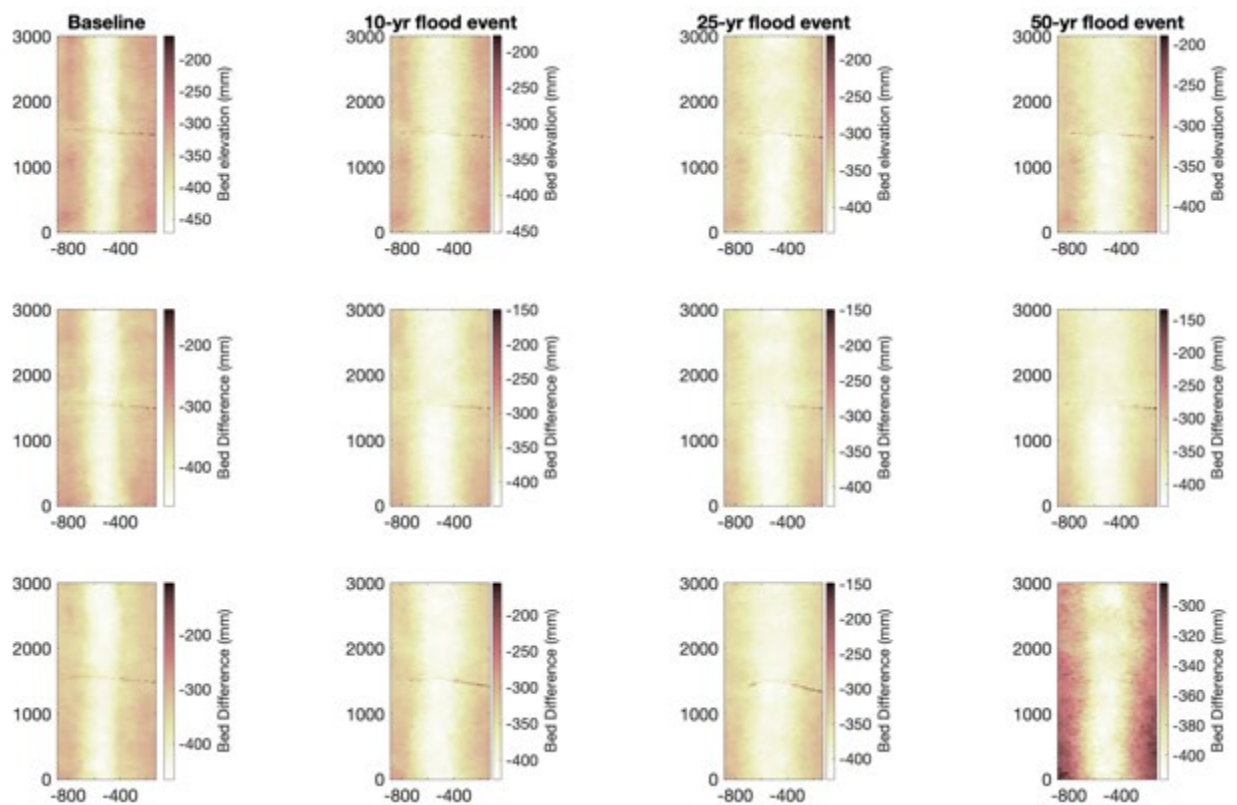


Figure 59 22 Streambed elevation for layout 13 after each flood event.

Layout 14

Layout 14 is a straight U-notch channel at a 2% slope. This layout has a deformable grade control (DGC) design in the middle of the study section. The DGC is made up of a distribution of 7/8-, 3/8-, and 1/8-in diameter dowels that have lengths of $\frac{3}{4}$, $\frac{1}{2}$, $\frac{1}{4}$ and $\frac{1}{6}$ channel width. The dowel sizes are distributed at a ratio of 15:50:35. The feature is constructed in a trench that has a width of $\frac{1}{10}$ channel-width and a depth to the bottom of the flume. The feature has a wood-sediment ratio of 50:50. DGC was built with one 27-in and one 180-in long 7/8-in diameter dowels, six 9-in and six 6-in long 3/8-in diameter dowels, and two 9-in and seventeen-one 6" long 1/8-in diameter dowels. See figure below for layout construction. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

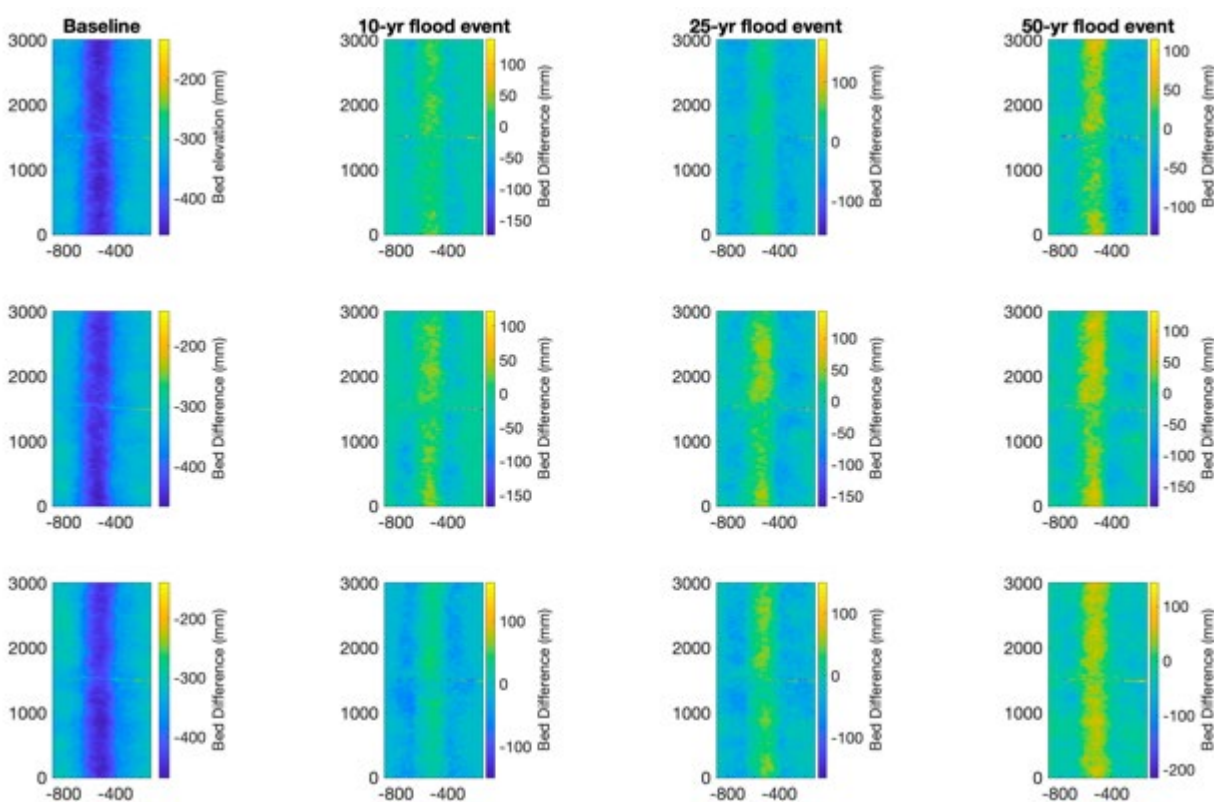


Figure 60 23 Difference of streambed elevation for layout 14 after each flood event.

After the 10-yr flood event we saw some erosion of the edges depositing into the center of the channel. There is less erosion of the channel downstream of the feature. There is some material being deposited at the base of the feature on its upstream side in the center of the channel. There is also some erosion of material at the base of the feature in the center of the channel on its downstream side, creating a low spot in the channel. After the 25-yr flood event we saw more erosion of the edges into the center of the channel than after the 10-yr flood event. Similarly, more material is deposited at the base of the feature on its upstream side, and more erosion of the center of the channel on its downstream side. Downstream of the feature the channel still has its U shape but is becoming much more flattened out.

upstream of the feature. After the 50-yr flood event we saw more erosion of the channel edges depositing into the center of the channel than after the 25-yr flood event. The channel has kept its U shape much better downstream of the feature and is much more flattened out upstream of the feature. There is also more material being deposited at the base of the feature on its upstream side in the center of the channel, and more erosion of the center of the channel at the base of the feature on its downstream side.

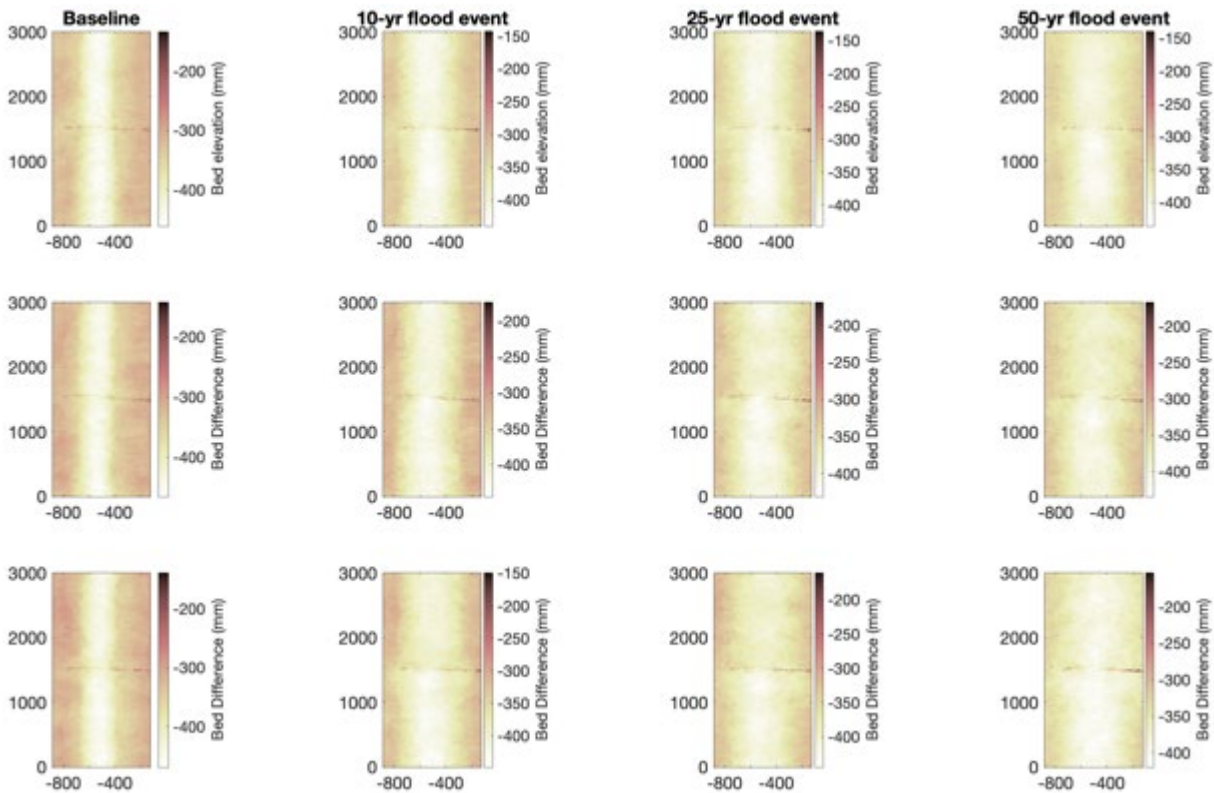


Figure 61 24 Streambed elevation for layout 14 after each flood event.

Layout 19 (MB-CM 3CW 2% slope)

Layout 19 is a meandering channel with a three culvert-width spacing at a 2% slope. The meander bars are made of D200-300 for the head and D100 for the cone, which extends to the bottom of the streambed. The head of the meander bars is two particle-diameters wide and extends just under halfway across the channel. The cone has a length of one culvert-width. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

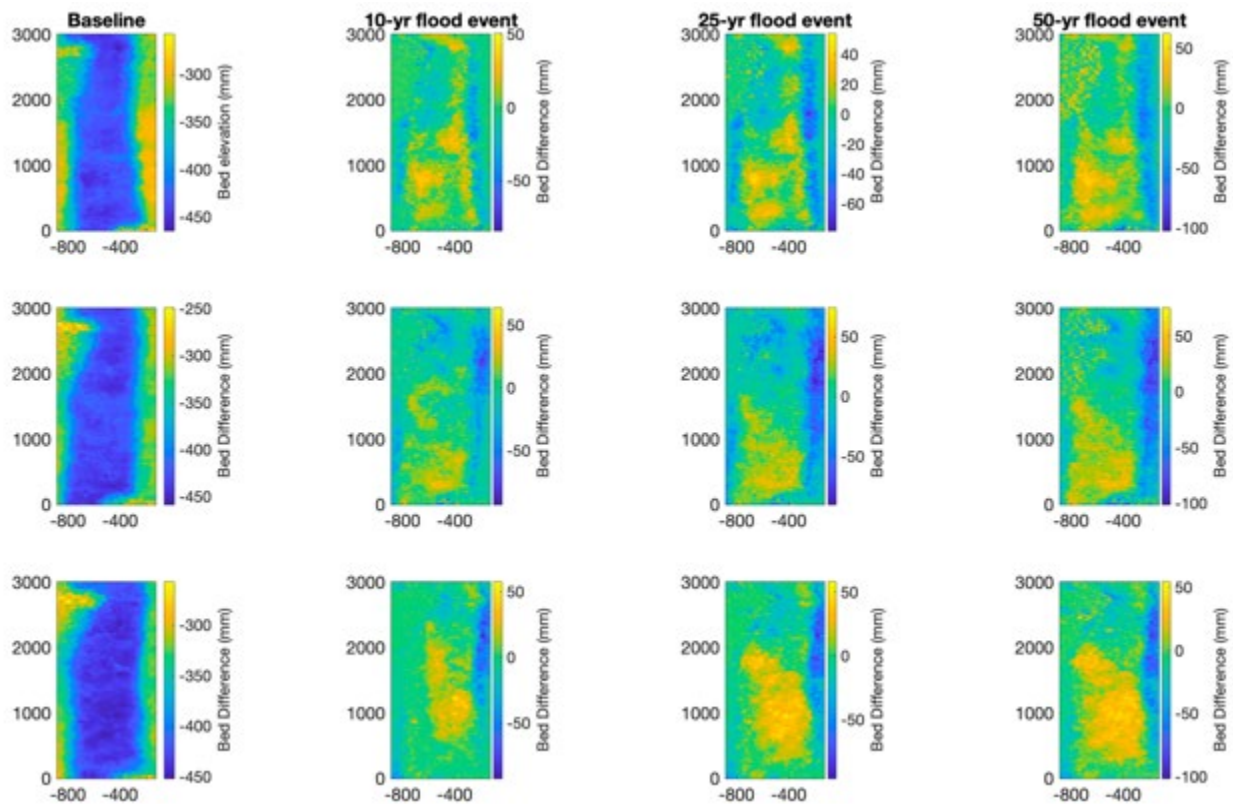


Figure 62 25 Difference of streambed elevation for layout 19 after each flood event.

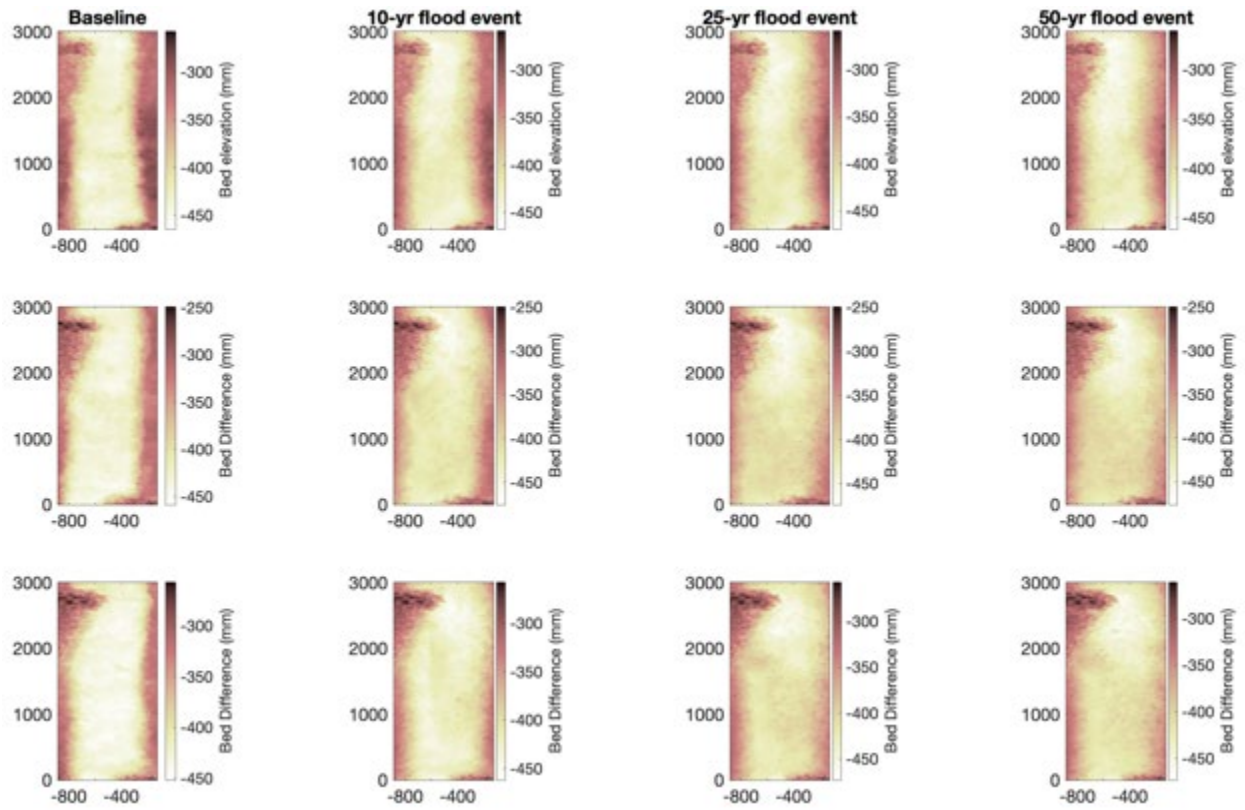


Figure 63 28 Streambed elevation for layout 19 after each flood event.

Layout 20 (MB-SBM 3CW 2% slope)

Layout 20 is a meandering channel with a three culvert-width spacing at a 2% slope. The meander bars are made of streambed material for the head and cone. The head of the meander bars is two particle-diameters wide and extends just under halfway across the channel. The cone has a length of one culvert-width. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

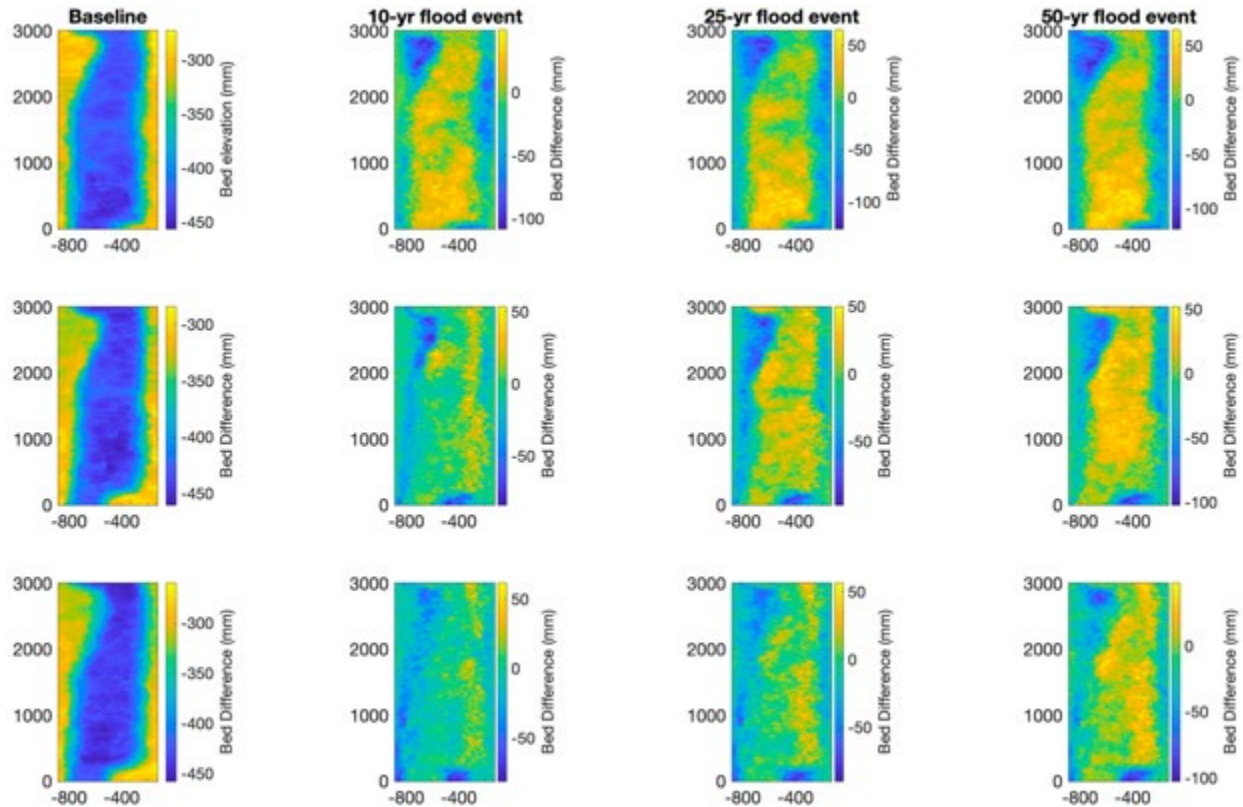


Figure 64 26 Difference of streambed elevation for layout 20 after each flood event.

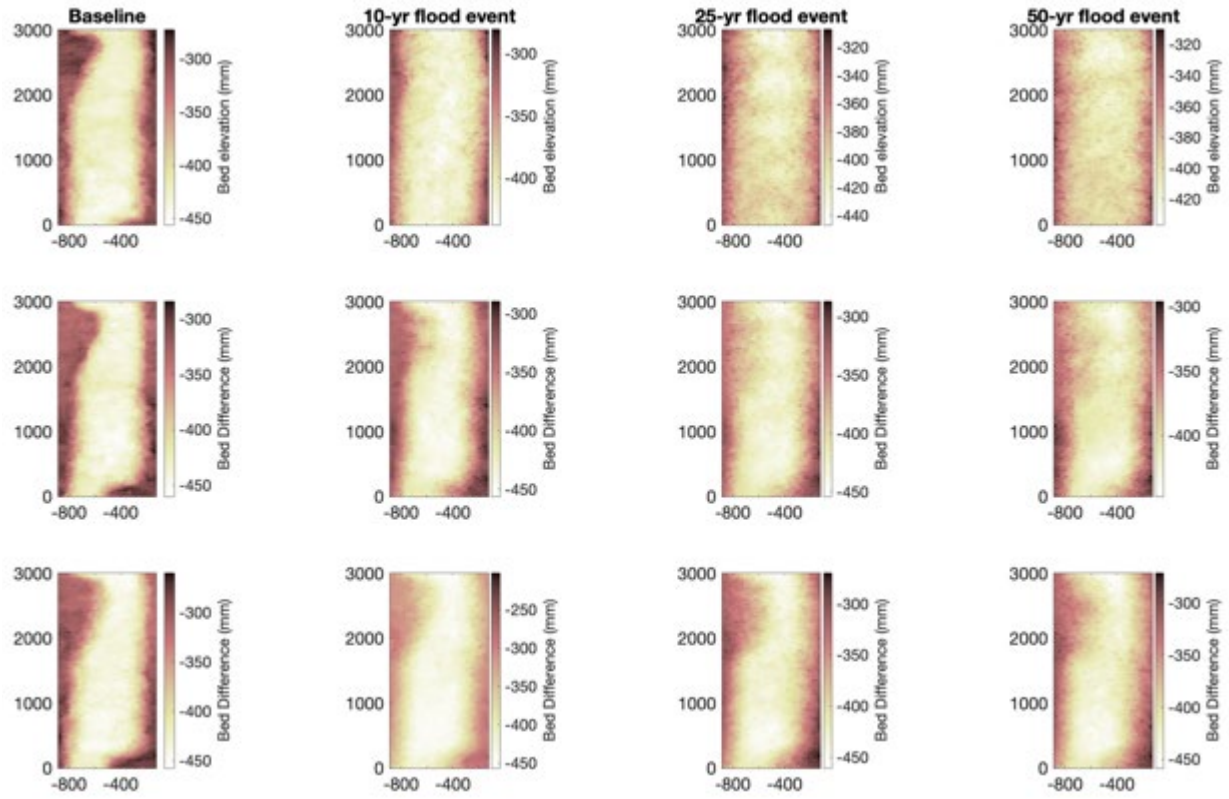


Figure 65 27 Elevation of streambed for layout 20 after each flood event.

Layout 21 (MB-CMR 3CW 2% slope)

Layout 21 is a meandering channel with a three culvert-width spacing at a 2% slope. The meander bars are made of D200-300 for the head and D100 for the cone, which extends to the bottom of the streambed. The head of the meander bars is two particle-diameters wide and extends just under halfway across the channel. The cone has a length of one culvert-width. There is a root wad built into the head of the meander bar facing upstream. The root wad has a max diameter of 3 in and is attached to a 1 1/2-in diameter dowel, which is 1/2 culvert-width in length. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

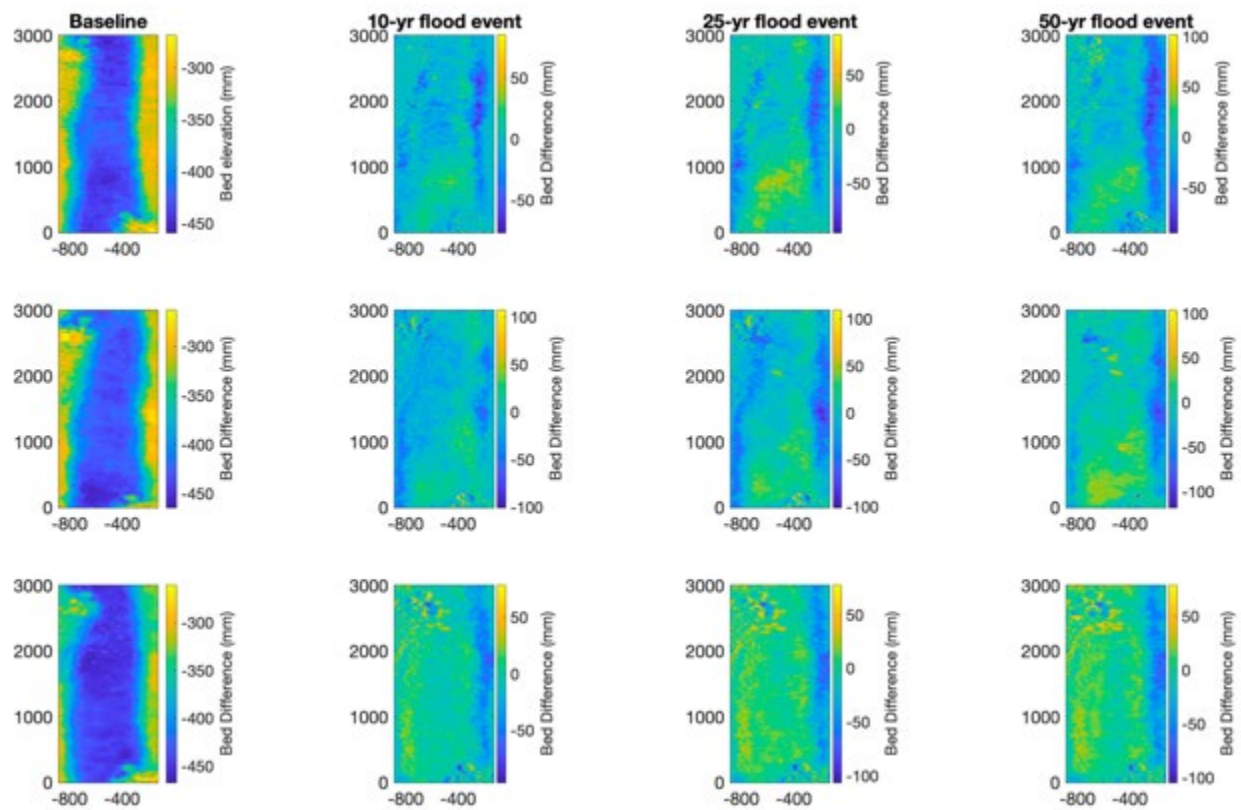


Figure 66 31 Difference of streambed elevation for layout 21 after each flood event.

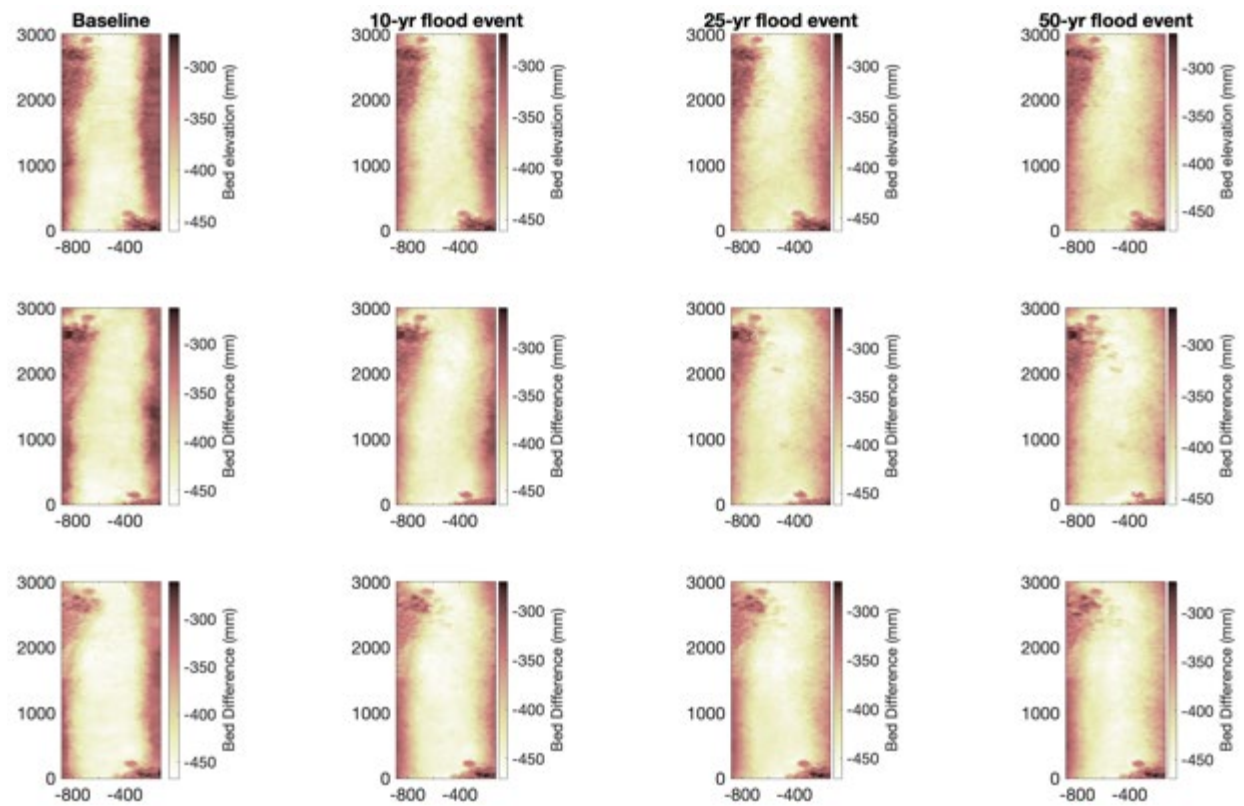


Figure 67 32 Streambed elevation for layout 21 after each flood event.

Layout 22 (MB-CMS 3CW 2% slope)

Layout 22 is a meandering channel with a three culvert-width spacing at a 2% slope. The meander bars are made of D200-300 for the head and D100 for the cone, which extends to the bottom of the streambed. The head of the meander bars is two particle-diameters wide and extends just under halfway across the channel. The cone has a length of one culvert-width. There are 18 dowels placed into the streambed just upstream of the head of the meander bars. Five dowels are 3/8-in diameter with two being 1/4culvert-width in length and three being 1/6 culvert-width in length. Eleven dowels are 1/8 -in diameter at a length of 1/6 culvert-width. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

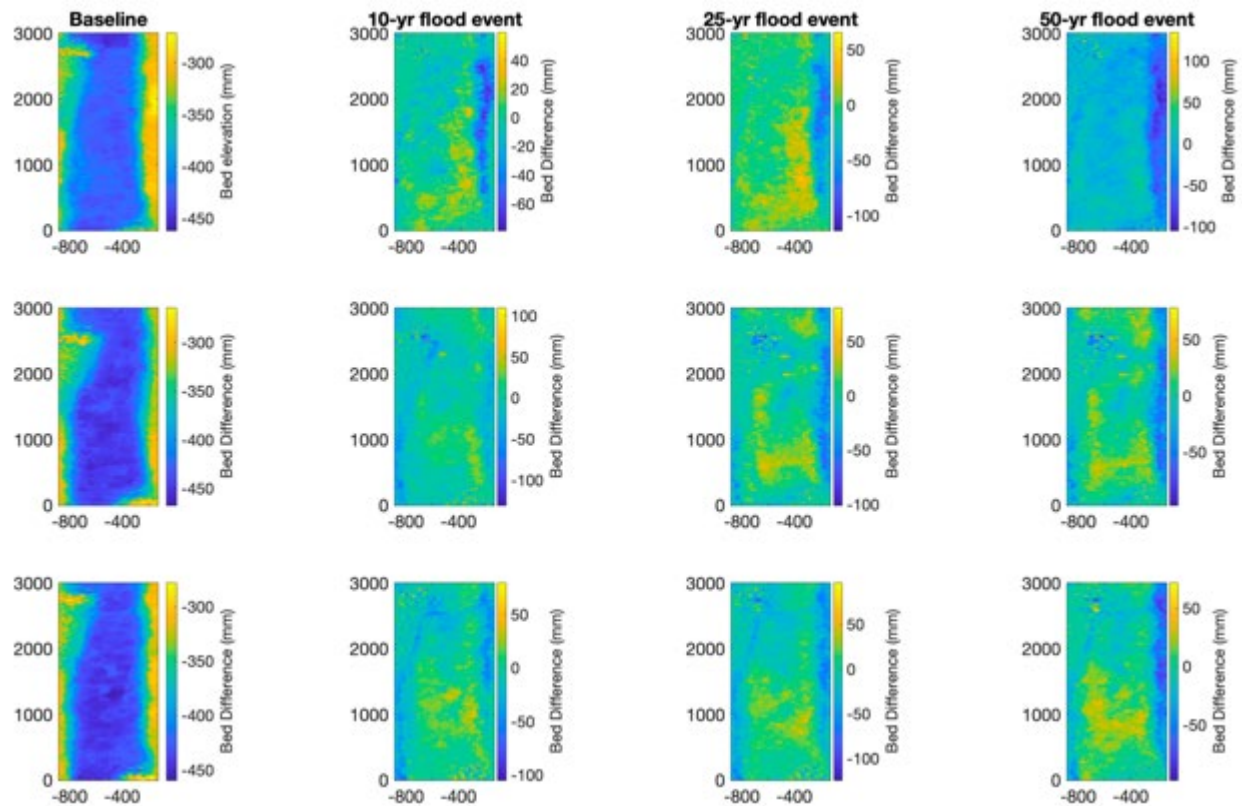


Figure 68 33 Difference of streambed elevation for layout 22 after each flood event.

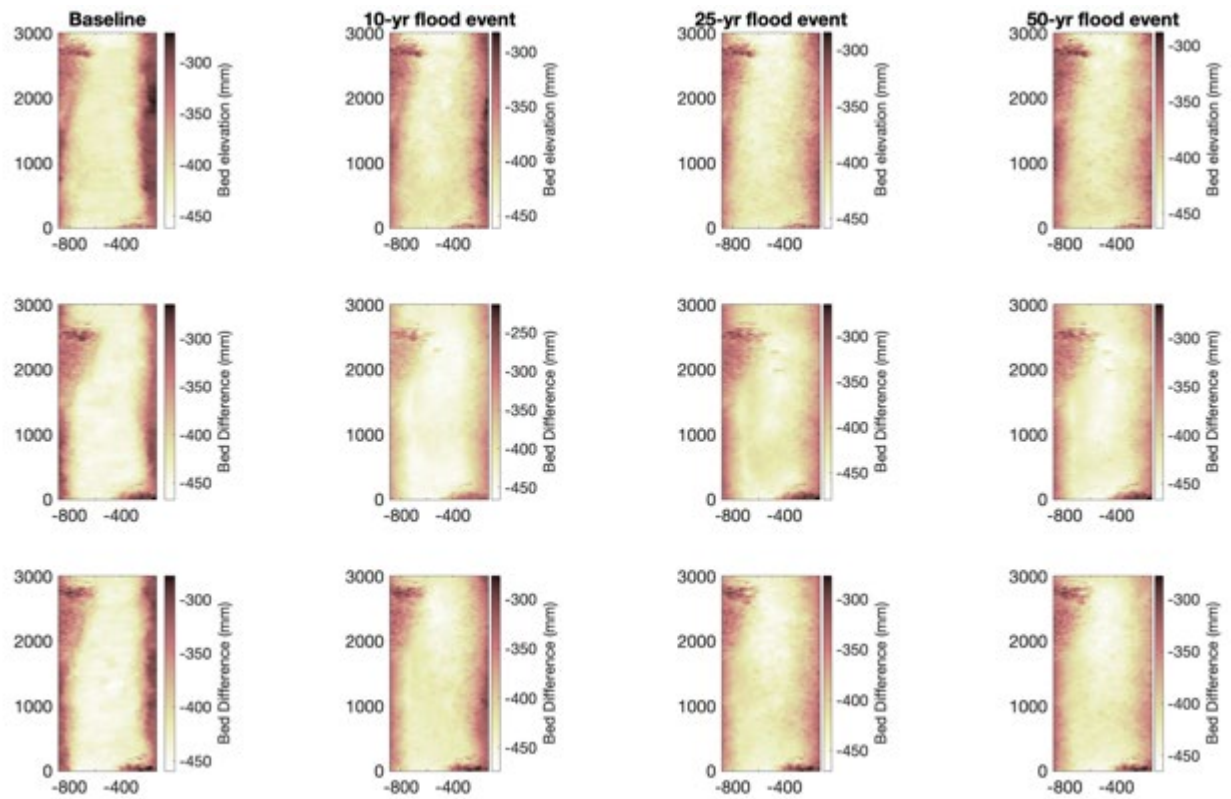


Figure 69 28 Streambed elevation for layout 22 after each flood event.

Layout 23 (MB-SBM 1CW 2% slope)

Layout 23 is a meandering channel with a one culvert-width spacing at a 2% slope. The meander bars are made of streambed material for the head and cone. The head of the meander bars is two particle-diameters wide and extends just under halfway across the channel. The cone has a length of 2/3 culvert-width. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

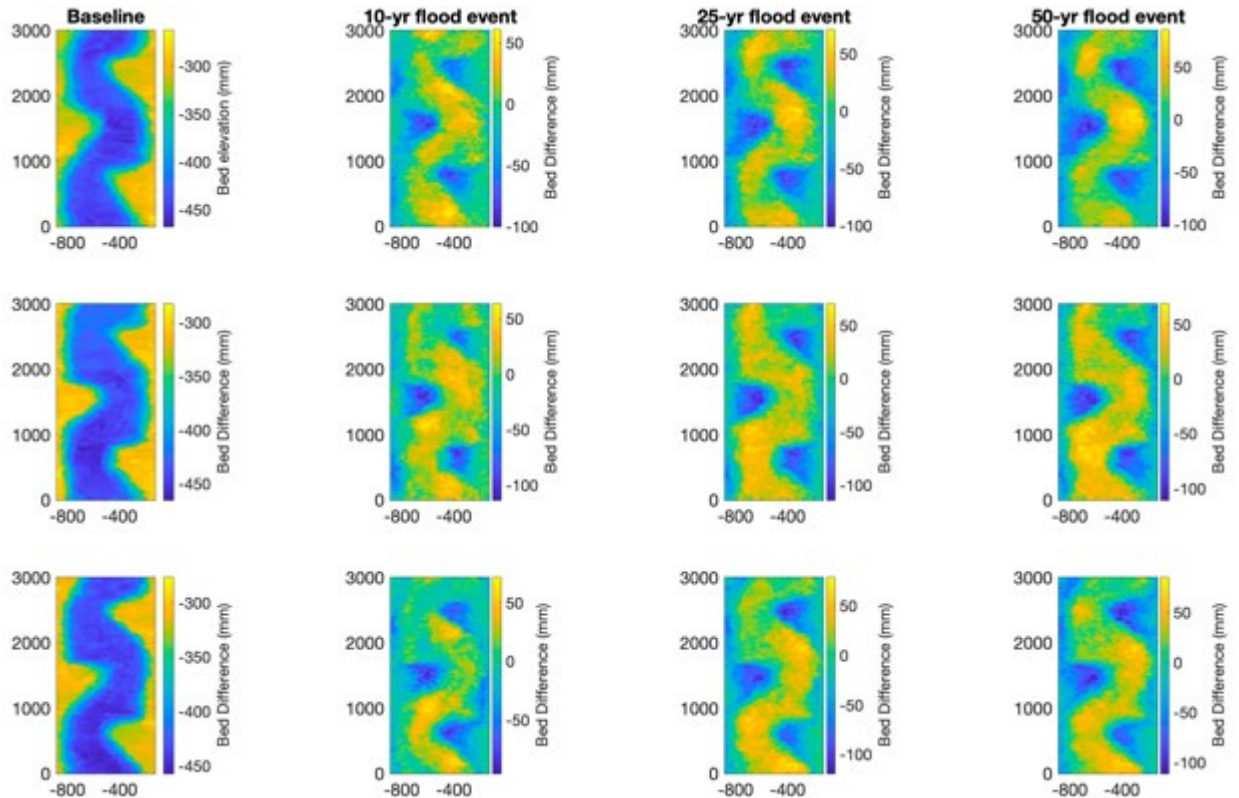


Figure 70 29 Difference of streambed elevation for layout 23 after each flood event.

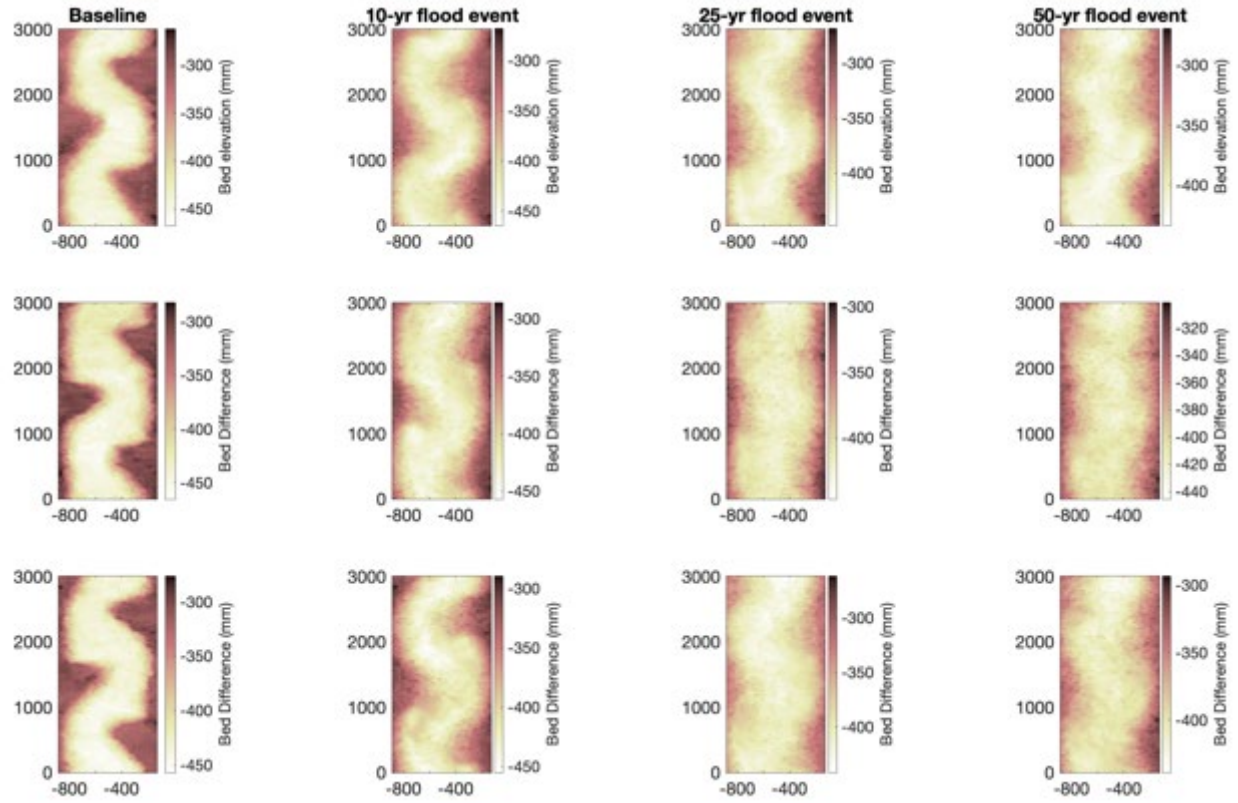


Figure 71 30 Surface elevation of layout 23 after each flood event.

Layout 24 (MB-CM 1CW 2% slope)

Layout 24 is a meandering channel with a one culvert-width spacing at a 2% slope. The meander bars are made of D200-300 for the head and D100 for the cone, which extends to the bottom of the streambed. The head of the meander bars is two particle-diameters wide and extends just under halfway across the channel. The cone has a length of $2/3$ culvert-width. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

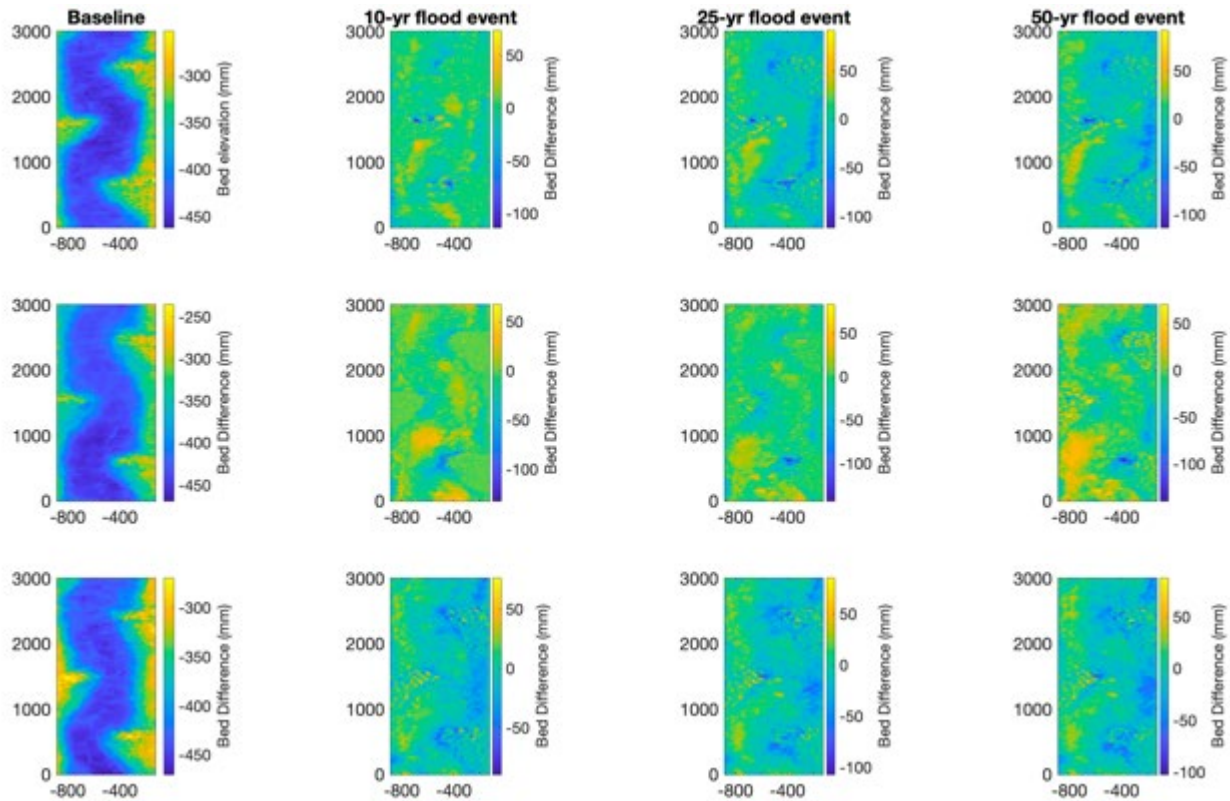


Figure 72 31 Difference of streambed elevation for layout 24 after each flood event.

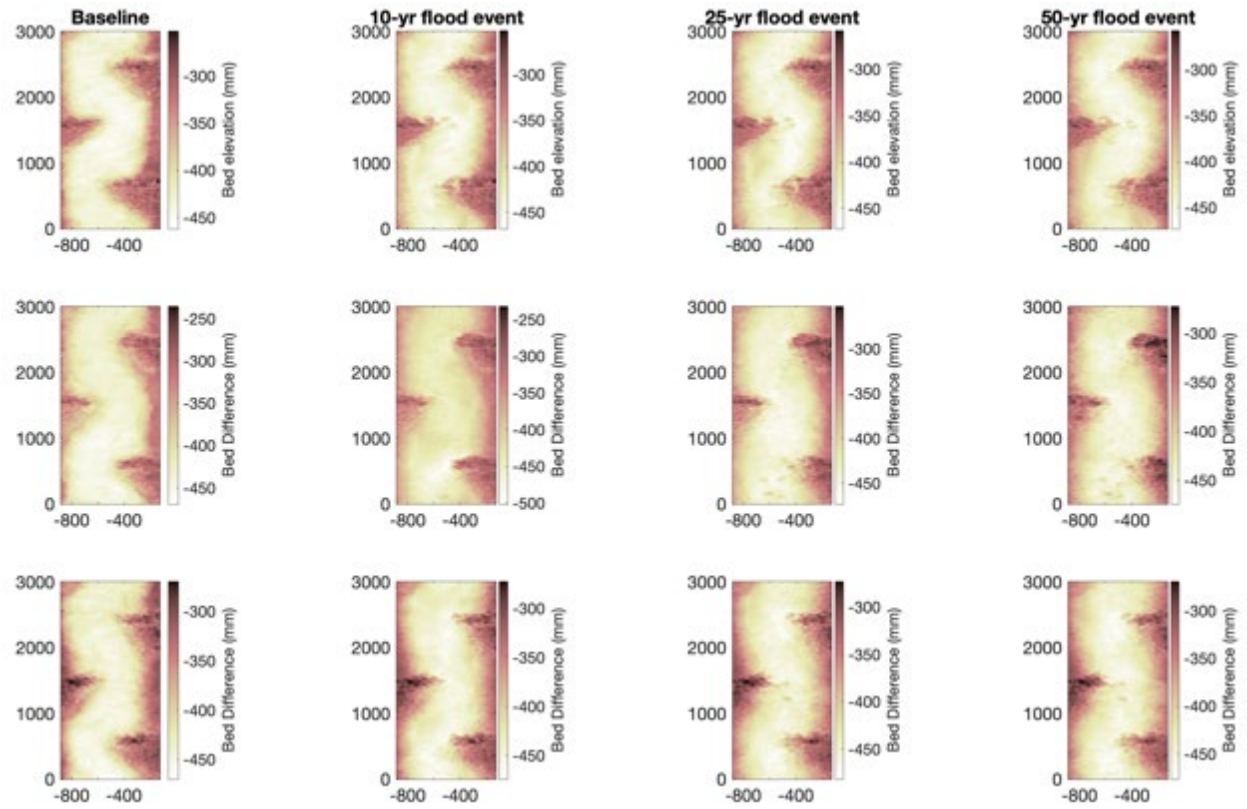


Figure 73 32 Streambed elevation for layout 24 after each flood event.

Layout 25 (MB-CMR 1CW 2% slope)

Layout 25 is a meandering channel with a one culvert-width spacing at a 2% slope. The meander bars are made of D200-300 for the head and D100 for the cone, which extends to the bottom of the streambed. The head of the meander bars is two particle-diameters wide and extends just under halfway across the channel. The cone has a length of $2/3$ culvert-width. There is a root wad built into the head of the meander bar facing upstream. The root wad has a max diameter of 3 in and is attached to a 1 1/2-in diameter dowel, which is $1/2$ culvert-width in length. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

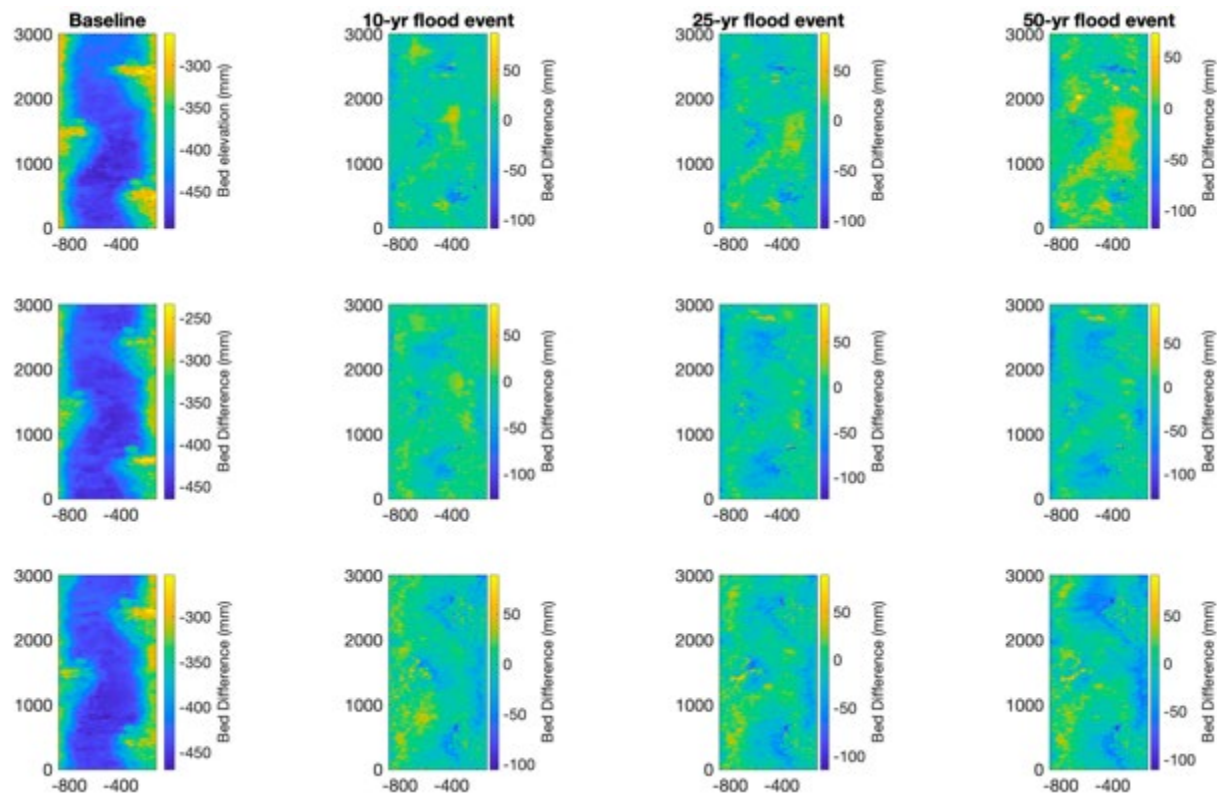


Figure 74 33 Difference of streambed elevation for layout 25 after each flood event.

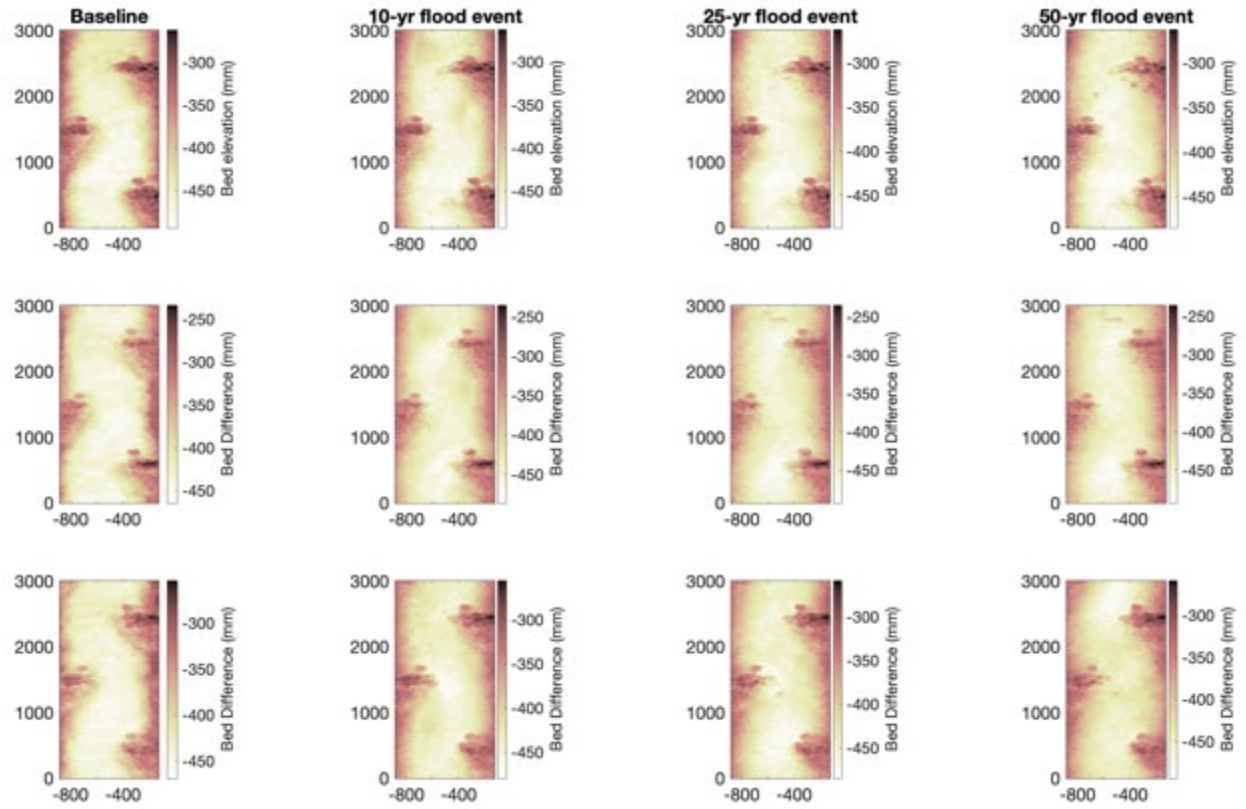


Figure 75 40 Surface elevation for layout 25 after each flood event.

Layout 26 (MB-CMS 1CW 2% slope)

Layout 26 is a meandering channel with a one culvert-width spacing at a 2% slope. The meander bars are made of D200-300 for the head and D100 for the cone, which extends to the bottom of the streambed. The head of the meander bars is two particle-diameters wide and extends just under halfway across the channel. The cone has a length of $2/3$ culvert-width. There are 18 dowels placed into the streambed just upstream of the head of the meander bars. Five dowels are $3/8$ -in diameter with two being $1/4$ culvert-width in length and three being $1/6$ culvert-width in length. Eleven dowels are $1/8$ -in diameter at a length of $1/6$ culvert-width. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

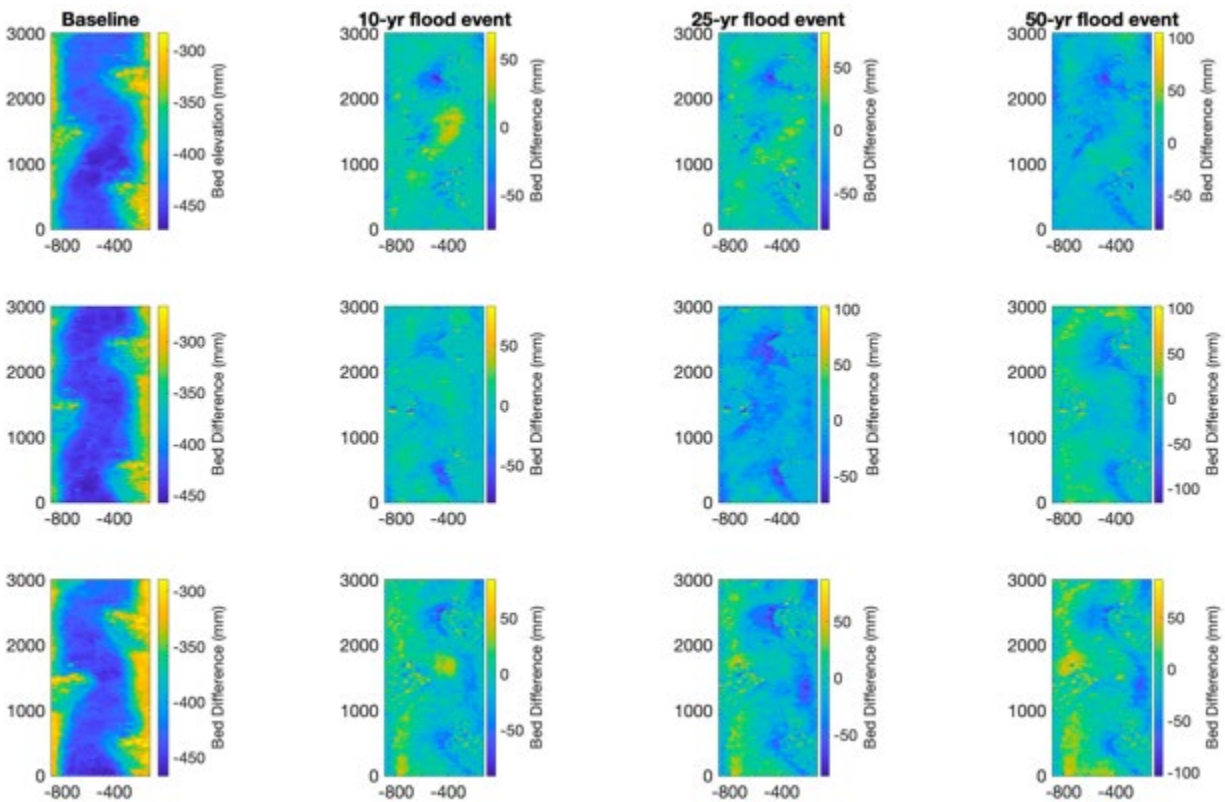


Figure 76 41 Difference of streambed elevation for layout 26 after each flood event.

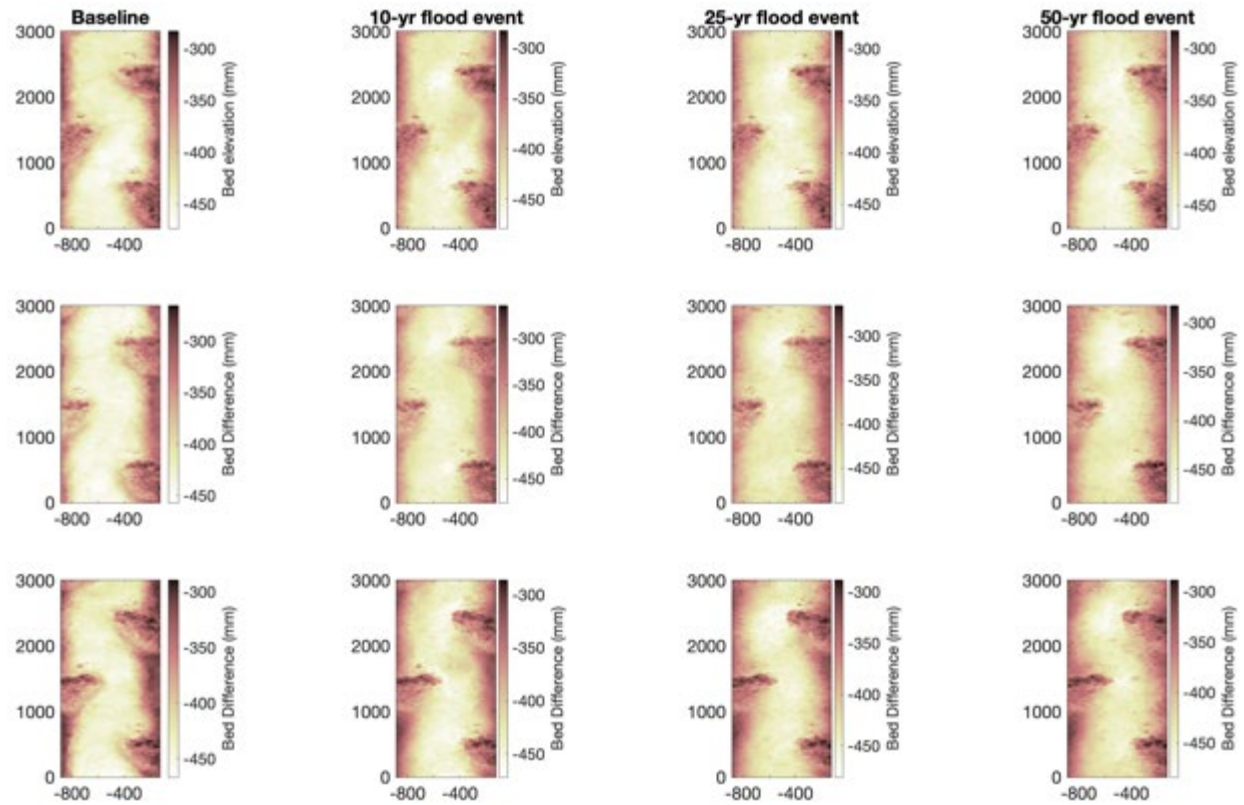


Figure 77 42 Streambed elevation for layout 25 after each flood event.

Layout 27 (MB-SBM 3% slope)

Layout 27 is a meandering channel with a one culvert-width spacing at a 3% slope. The meander bars are made of streambed material for the head and cone. The head of the meander bars is two particle-diameters wide and extends just under halfway across the channel. The cone has a length of 2/3 culvert-width. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

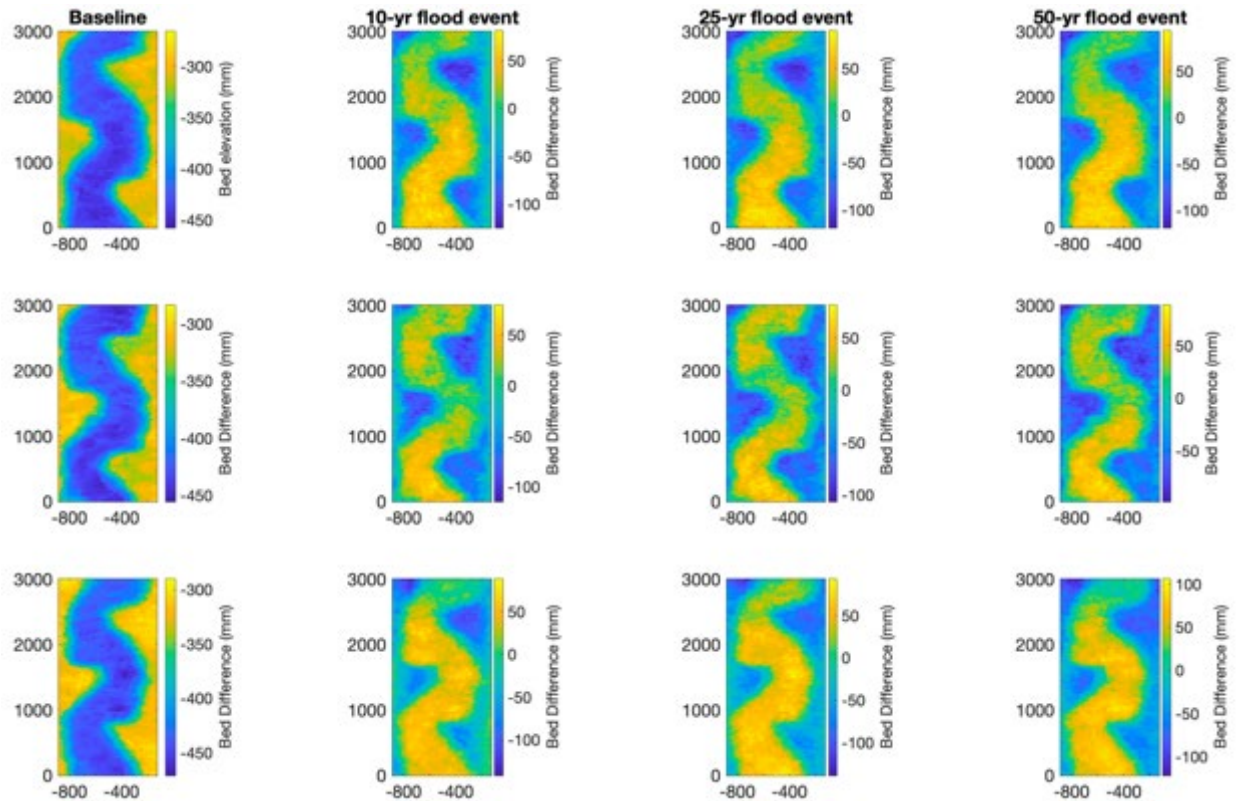


Figure 78 34 Difference of streambed elevation for layout 27 after each flood event.

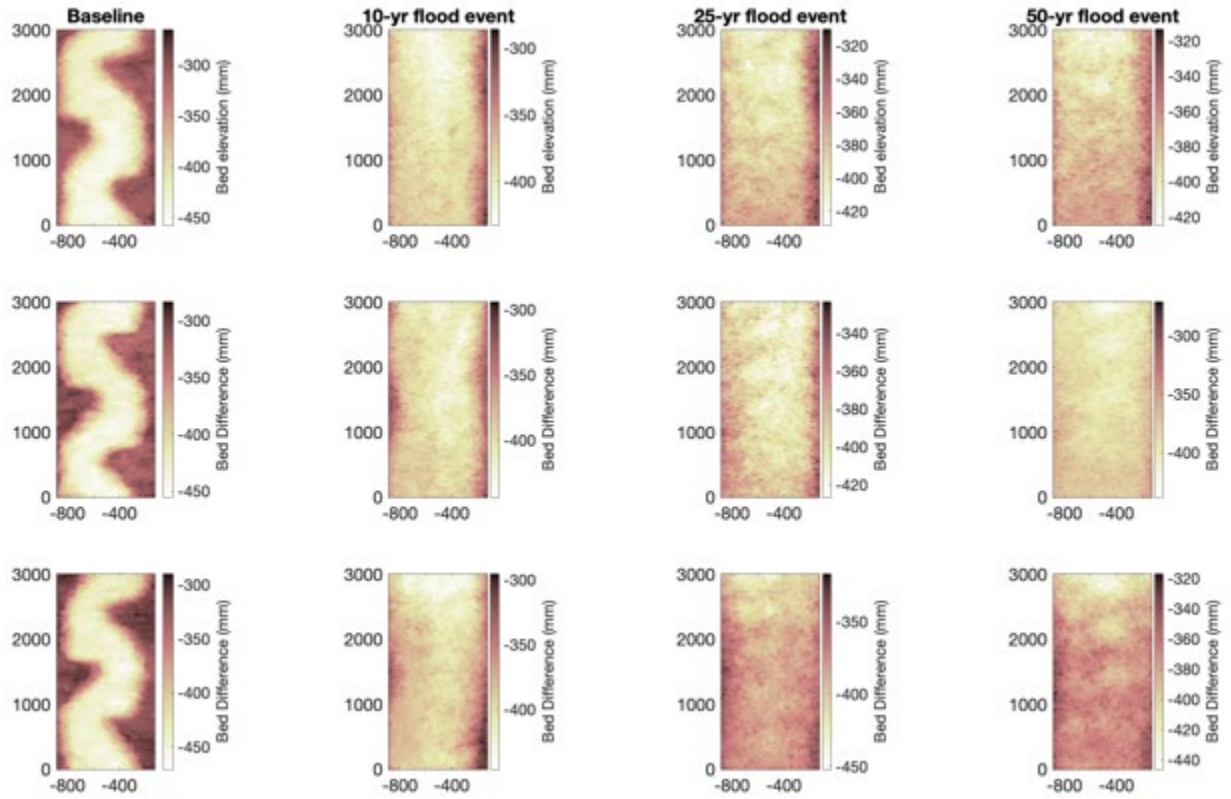


Figure 79 44 Streambed elevation for layout 27 after each flood event.

Layout 28 (MB-CM 3% slope)

Layout 28 is a meandering channel with a one culvert-width spacing at a 3% slope. The meander bars are made of D200-300 for the head and D100 for the cone, which extends to the bottom of the streambed. The head of the meander bars is two particle-diameters wide and extends just under halfway across the channel. The cone has a length of $2/3$ culvert-width. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

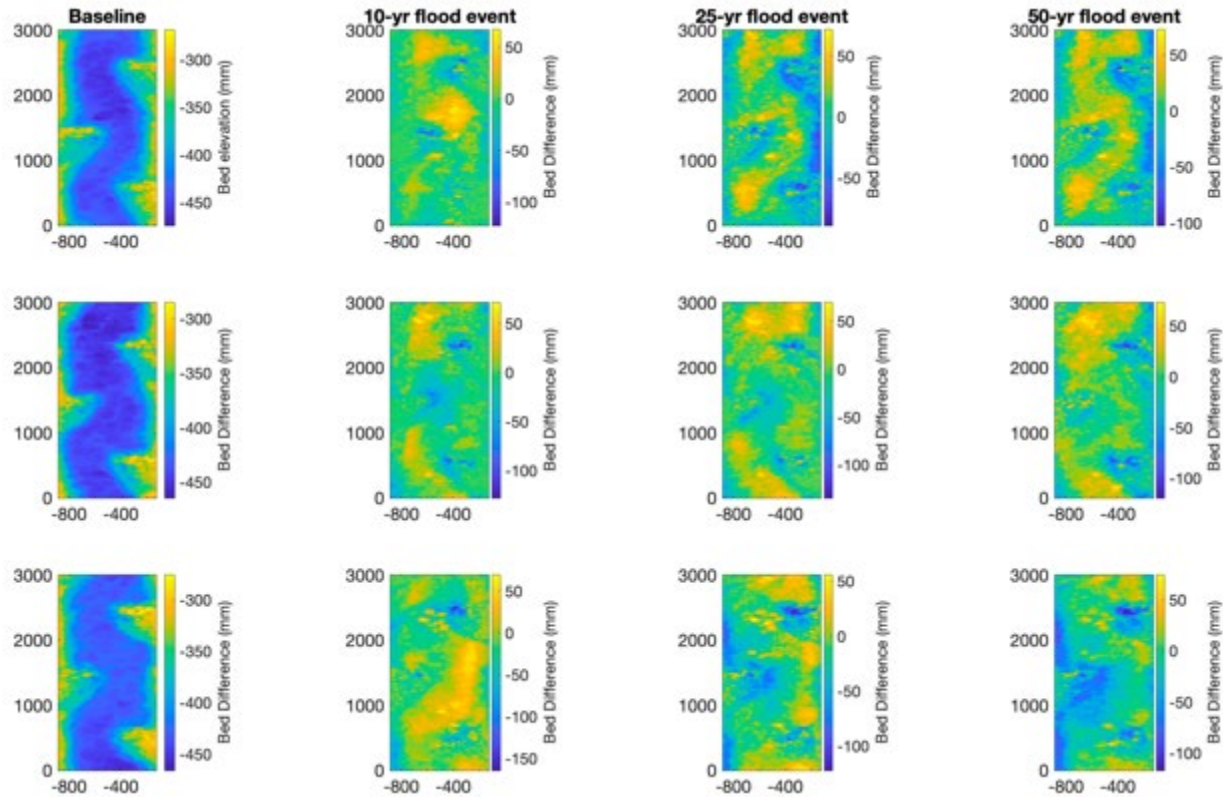


Figure 80 35 Difference of elevation for layout 28 after each flood event.

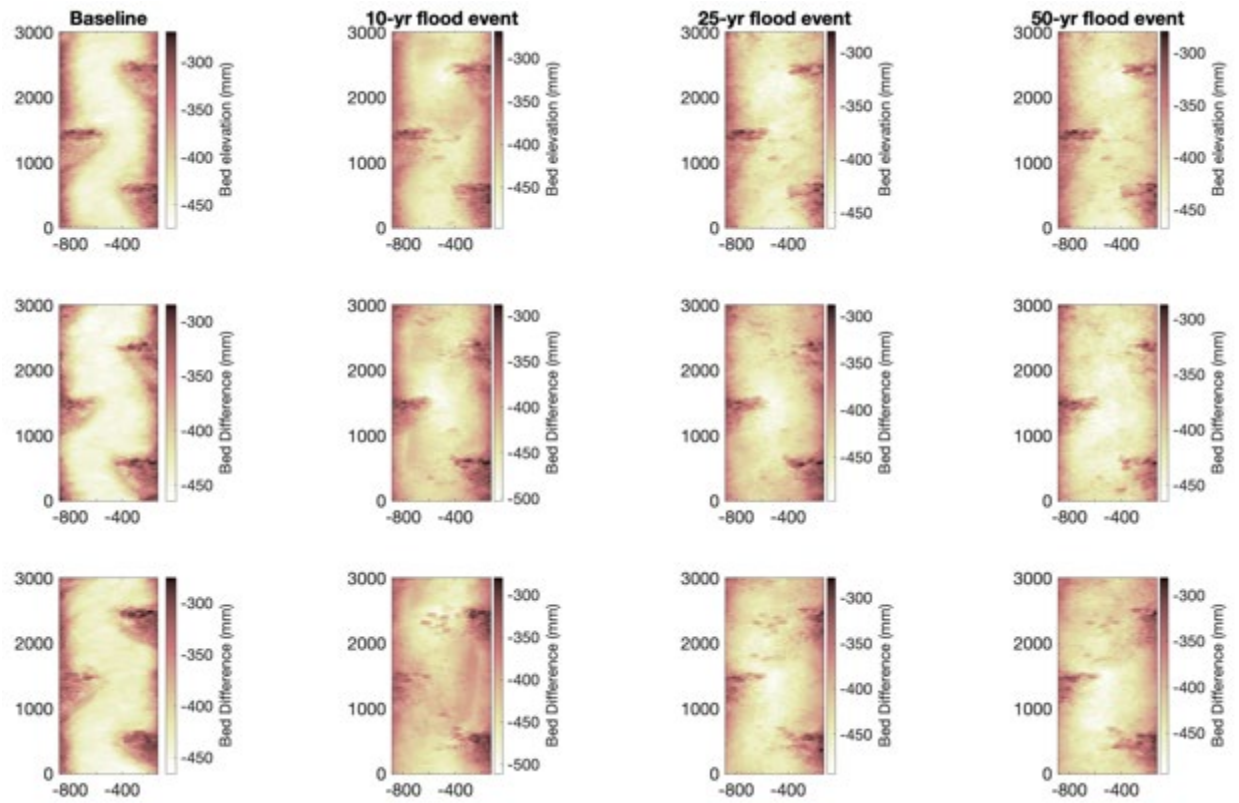


Figure 81 46 Surface elevation of layout 28 after each flood event.

Layout 29 (MB-CMR 3% slope)

Layout 29 is a meandering channel with a one culvert-width spacing at a 3% slope. The meander bars are made of D200-300 for the head and D100 for the cone, which extends to the bottom of the streambed. The head of the meander bars is two particle-diameters wide and extends just under halfway across the channel. The cone has a length of $2/3$ culvert-width. There is a root wad built into the head of the meander bar facing upstream. The root wad has a max diameter of 3 in and is attached to a 1 1/2-in diameter dowel, which is $1/2$ culvert-width in length. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

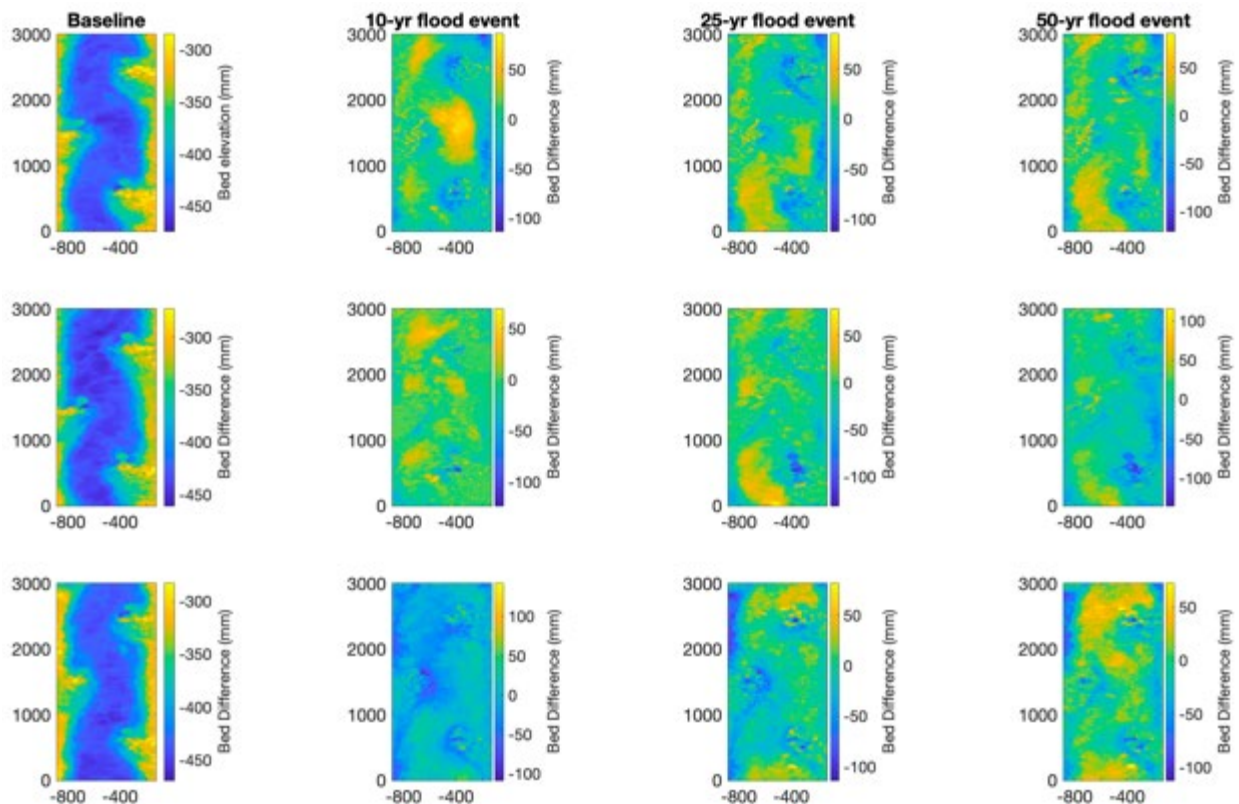


Figure 82 36 Difference of surface elevation for layout 29 after each flood event.

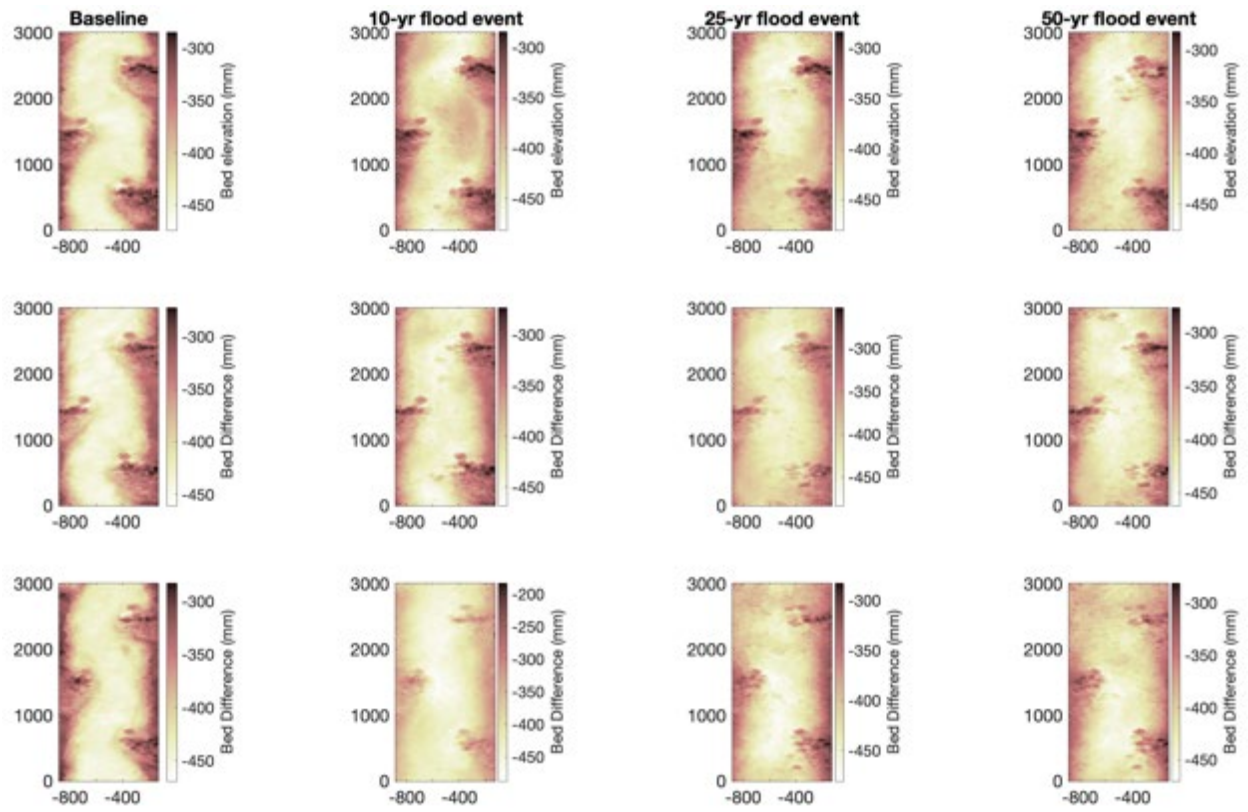


Figure 83 48 Surface elevation of layout 29 after each flood event.

Layout 30 (MB-CMS 3% slope)

Layout 30 is a meandering channel with a one culvert-width spacing at a 3% slope. The meander bars are made of D200-300 for the head and D100 for the cone, which extends to the bottom of the streambed. The head of the meander bars is two particle-diameters wide and extends just under halfway across the channel. The cone has a length of $2/3$ culvert-width. There are 18 dowels placed into the streambed just upstream of the head of the meander bars. Five dowels are $3/8$ -in diameter with two being $1/4$ culvert-width in length and three being $1/6$ culvert-width in length. Eleven dowels are $1/8$ -in diameter at a length of $1/6$ culvert-width. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

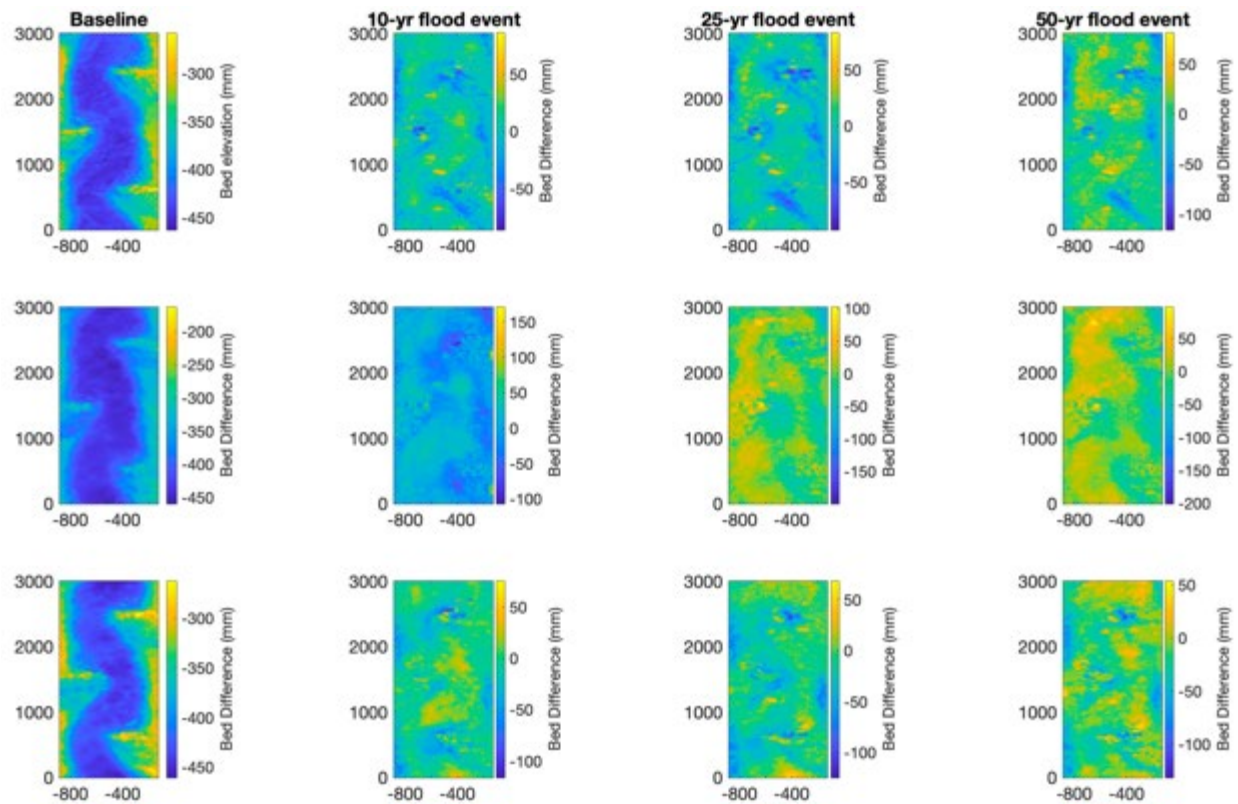


Figure 84 37 Difference of surface elevation for layout 30 after each flood event.

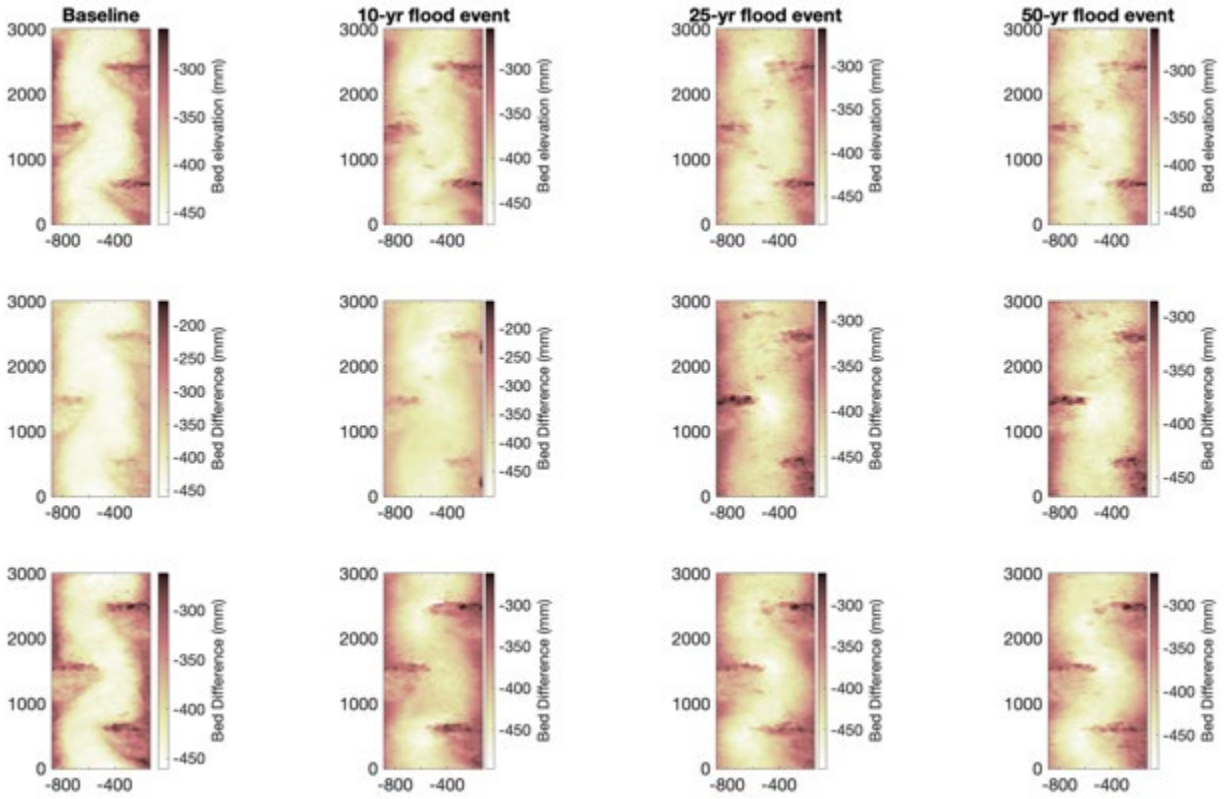


Figure 85 38 Surface elevation for layout 30 after each flood event.

Layout 31 (U-notch straight channel baseline 3% slope)

Layout 31 is a straight U-notch channel at a 3% slope. This layout does not have any features in the channel. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

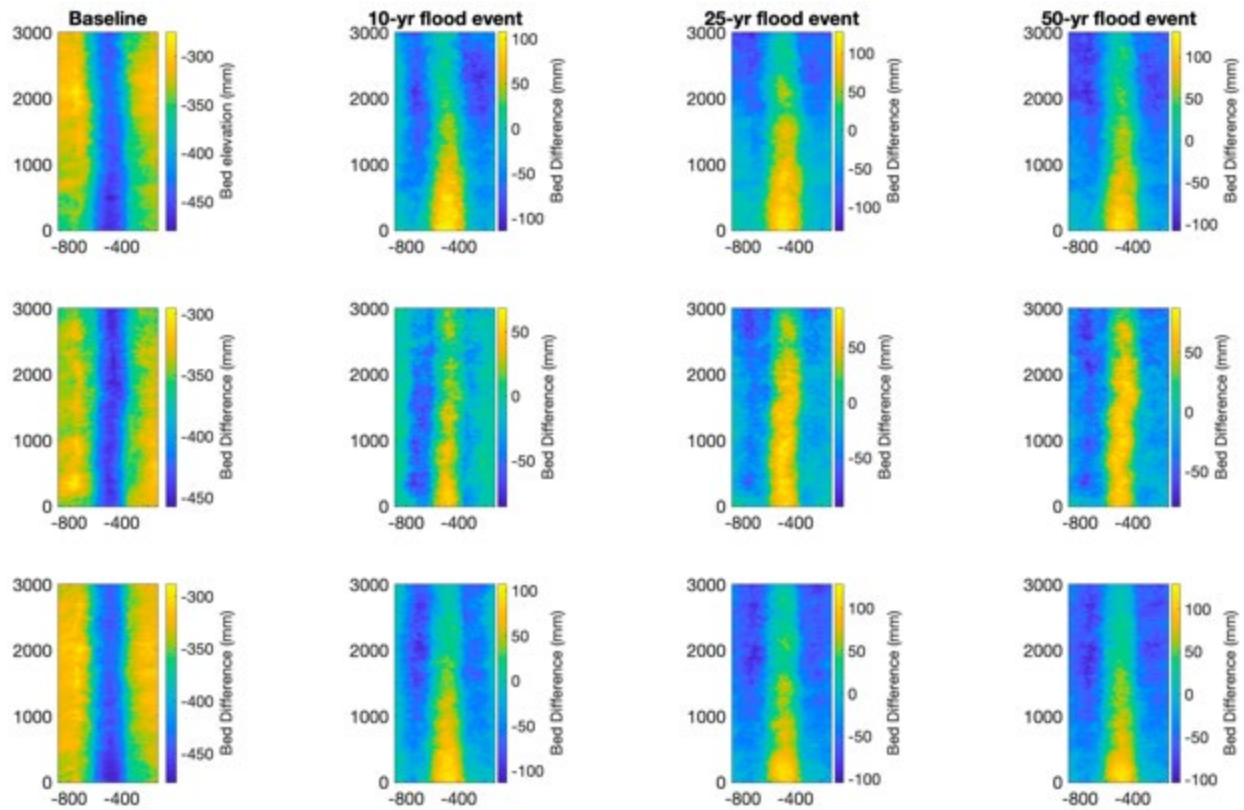


Figure 86 51 Difference of surface elevation for layout 31 after each flood event.

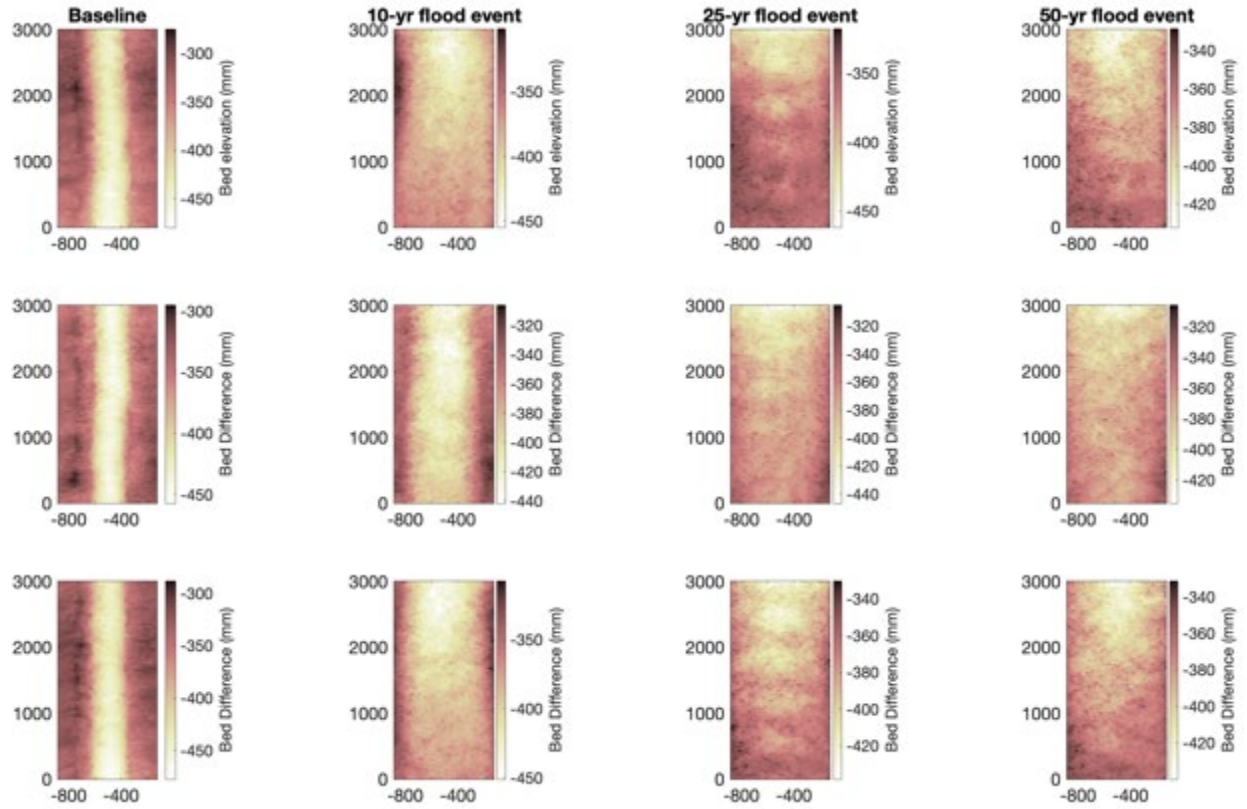


Figure 87 39 Surface elevation for layout 31 after each flood event.

Layout 32 (DGC diameter mixture 75:25 3% slope)

Layout 32 is a straight U-notch channel at a 3% slope. This layout has a deformable grade control (DGC) design in the middle of the study section. The DGC is made up of a distribution of 7/8-, 3/8-, and 1/8-inch diameter dowels that have lengths of 3/4, 1/2, 1/4 and 1/6 channel-width. The dowel sizes are distributed at a ratio of 15:50:35. The feature is constructed in a trench that has a width of 1/6 channel and a depth to the bottom of the flume. The feature has a wood-sediment ratio of 75:25. DGC was built with one 27-in and one 18-in long 7/8-in diameter dowels, twelve 9-in and twelve 6-in long 3/8-in diameter dowels, and four 9-in and thirty-one 6-in long 1/8-in diameter dowels. See figure below for layout construction. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

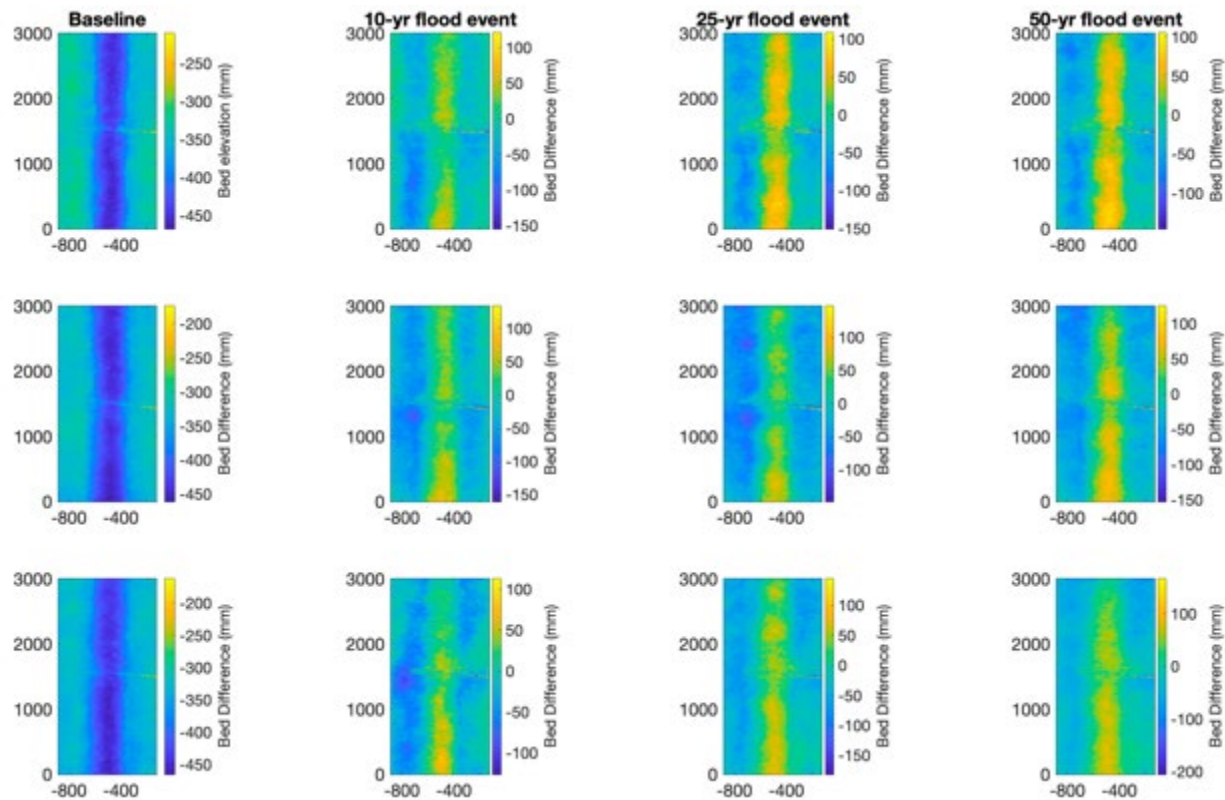


Figure 88 53 Difference of surface elevation for layout 32 after each flood event.

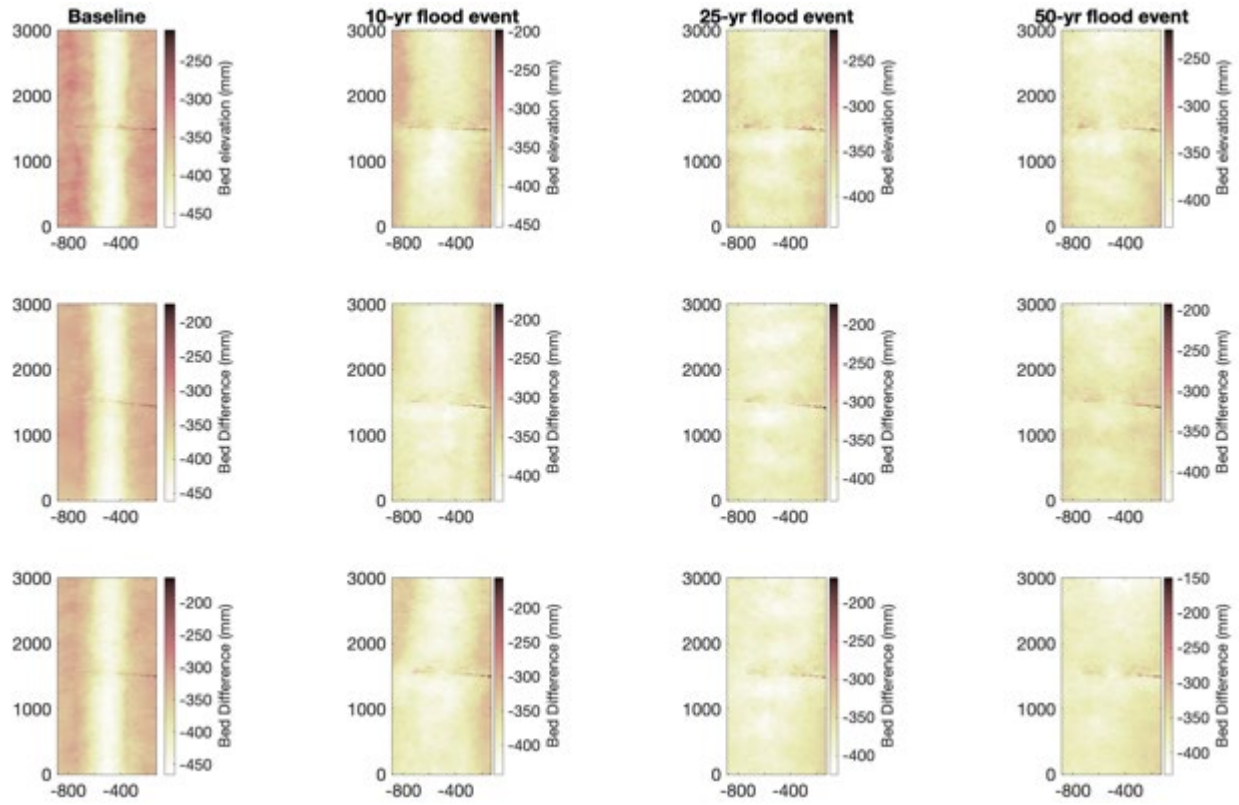


Figure 89 40 Surface elevation of layout 32 after each flood event.

Layout 33 (MB-SBM 4% slope)

Layout 33 is a meandering channel with a one culvert-width spacing at a 4% slope. The meander bars are made of streambed material for the head and cone. The head of the meander bars is two particle-diameters wide and extends just under halfway across the channel. The cone has a length of 2/3 culvert-width. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

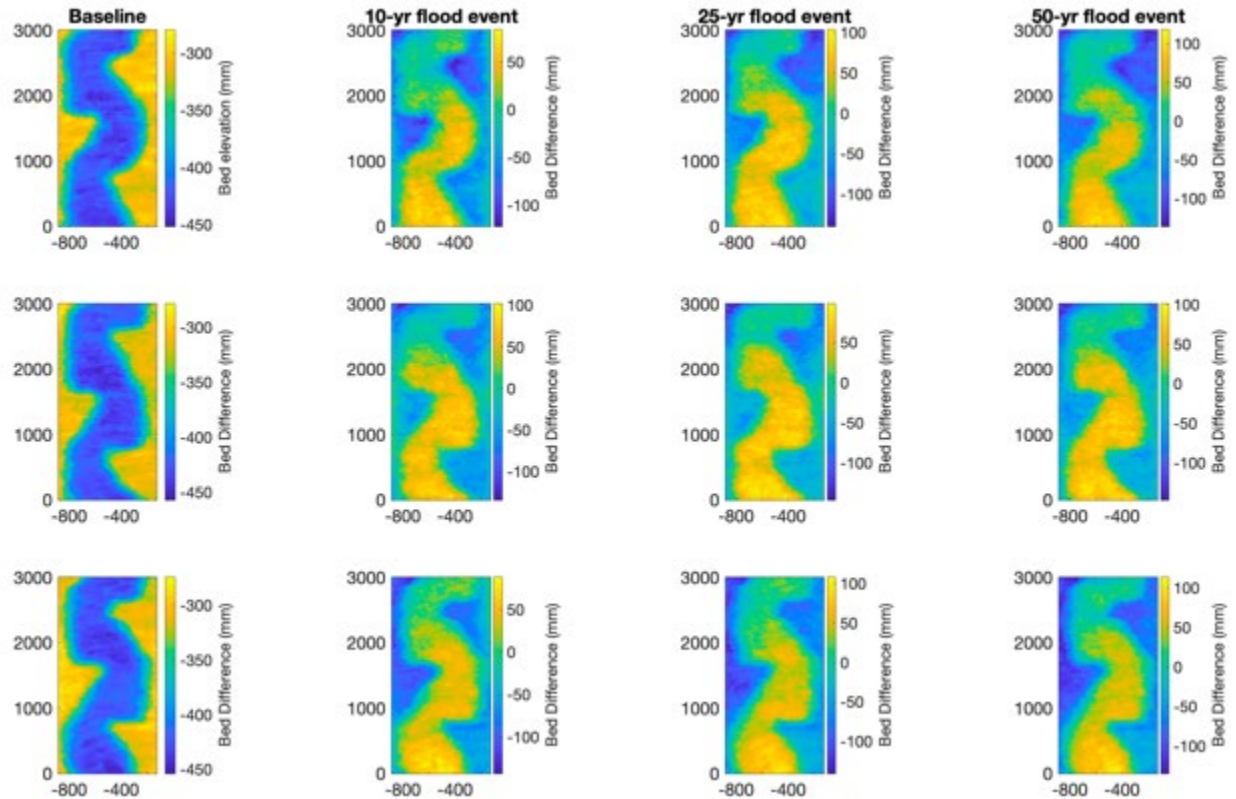


Figure 90 55 Difference of surface elevation for layout 33 after each flood event.

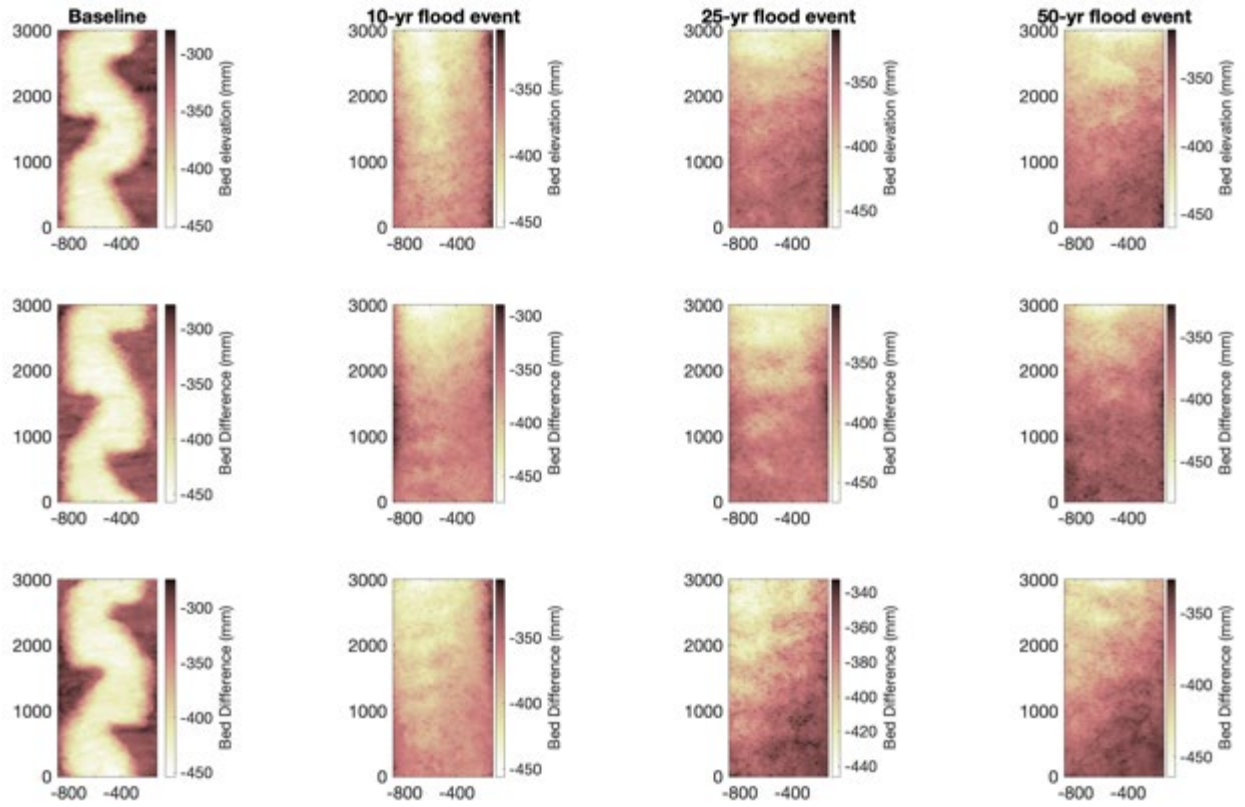


Figure 91 41 Surface elevation of layout 33 after each flood event.

Layout 34 (MB-CMS-200 4% slope)

Layout 34 is a meandering channel with a one culvert-width spacing at a 4% slope. The meander bars are made of D200-300 for the head and D200 for the cone, which extends to the bottom of the streambed. The head of the meander bars is two particle-diameters wide and extends just under halfway across the channel. The cone has a length of $2/3$ culvert-width. There are 18 dowels placed into the streambed just upstream of the head of the meander bars. Five dowels are $3/8$ -in diameter with two being $1/4$ culvert-width in length and three being $1/6$ culvert-width in length. Eleven dowels are $1/8$ -in diameter at a length of $1/6$ culvert-width. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

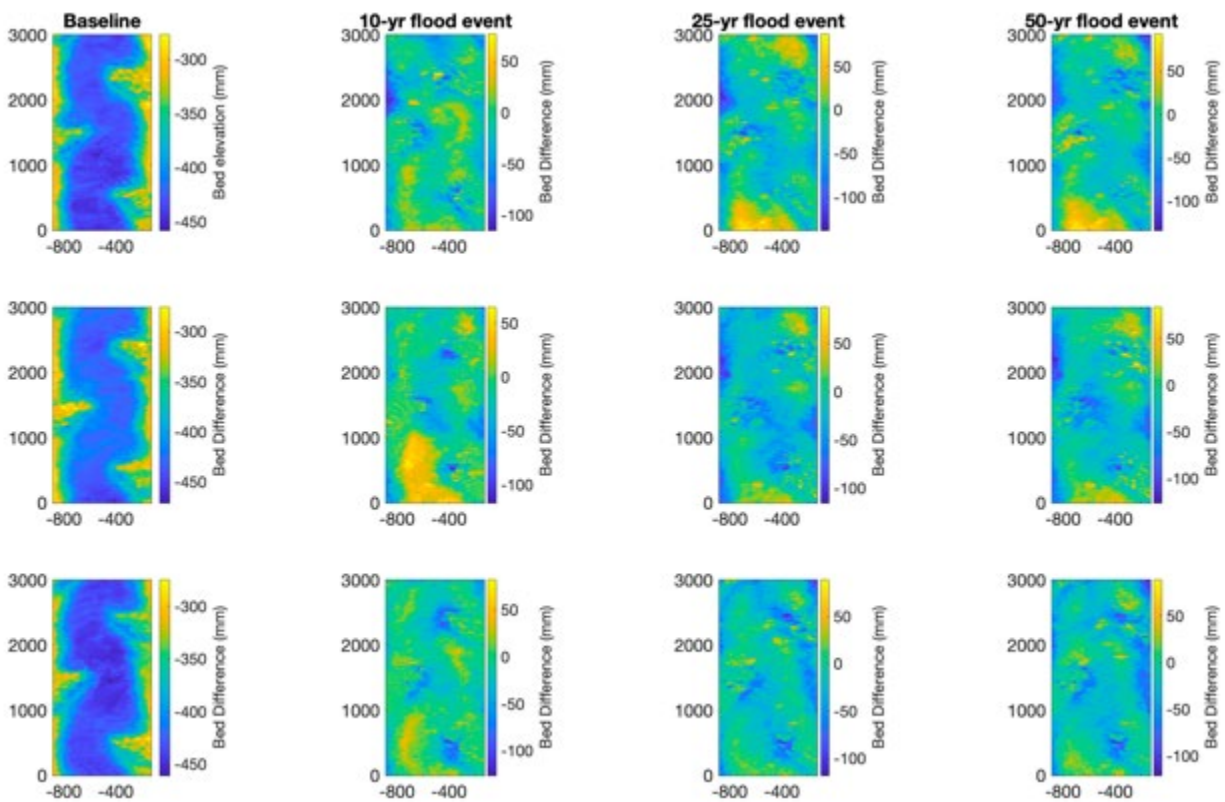


Figure 92 57 Difference of surface elevation of layout 34 after each flood event.

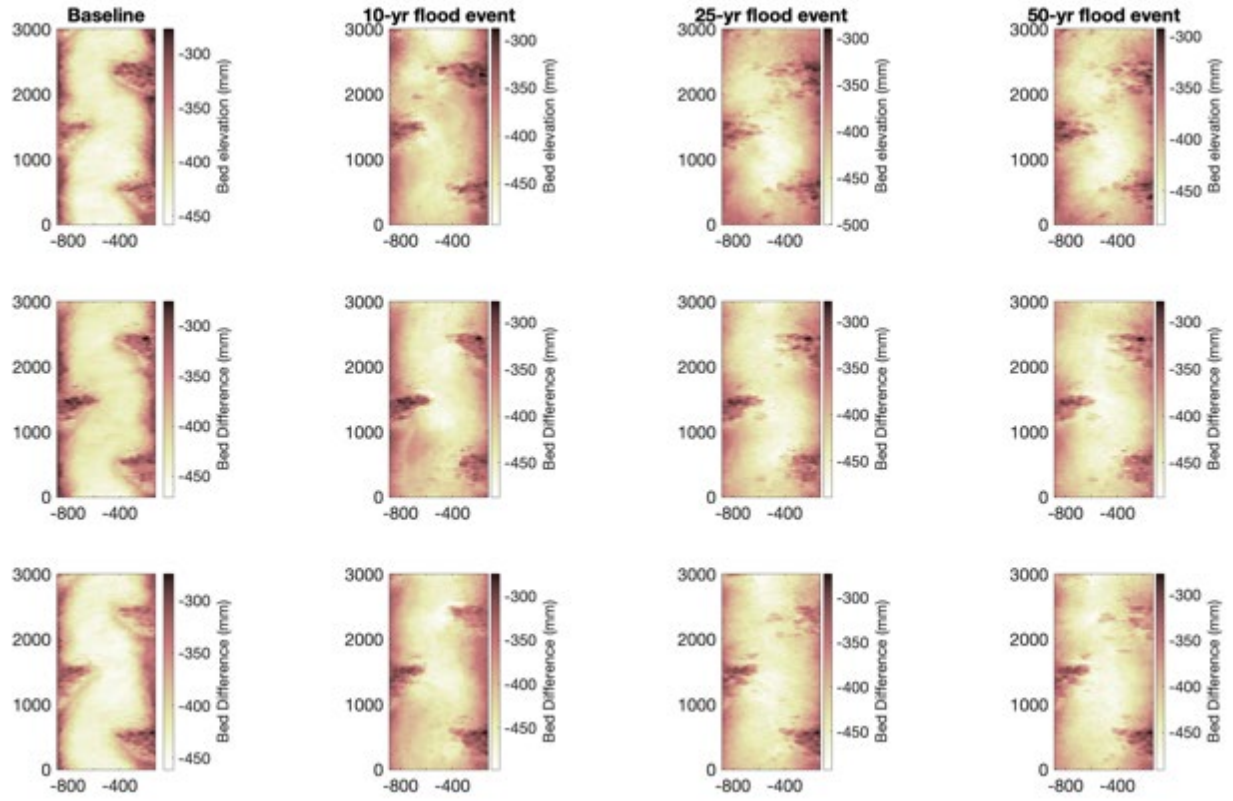


Figure 93 42 Surface elevation of layout 34 after each flood event.

Layout 35 (MB-CMS-100 4% slope)

Layout 35 is a meandering channel with a one culvert-width spacing at a 4% slope. The meander bars are made of D200-300 for the head and D100 for the cone, which extends to the bottom of the streambed. The head of the meander bars is two particle-diameters wide and extends just under halfway across the channel. The cone has a length of $2/3$ culvert-width. There are 18 dowels placed into the streambed just upstream of the head of the meander bars. Five dowels are $3/8$ -in diameter with two being $1/4$ culvert-width in length and three being $1/6$ culvert-width in length. Eleven dowels are $1/8$ -in diameter at a length of $1/6$ culvert-width. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

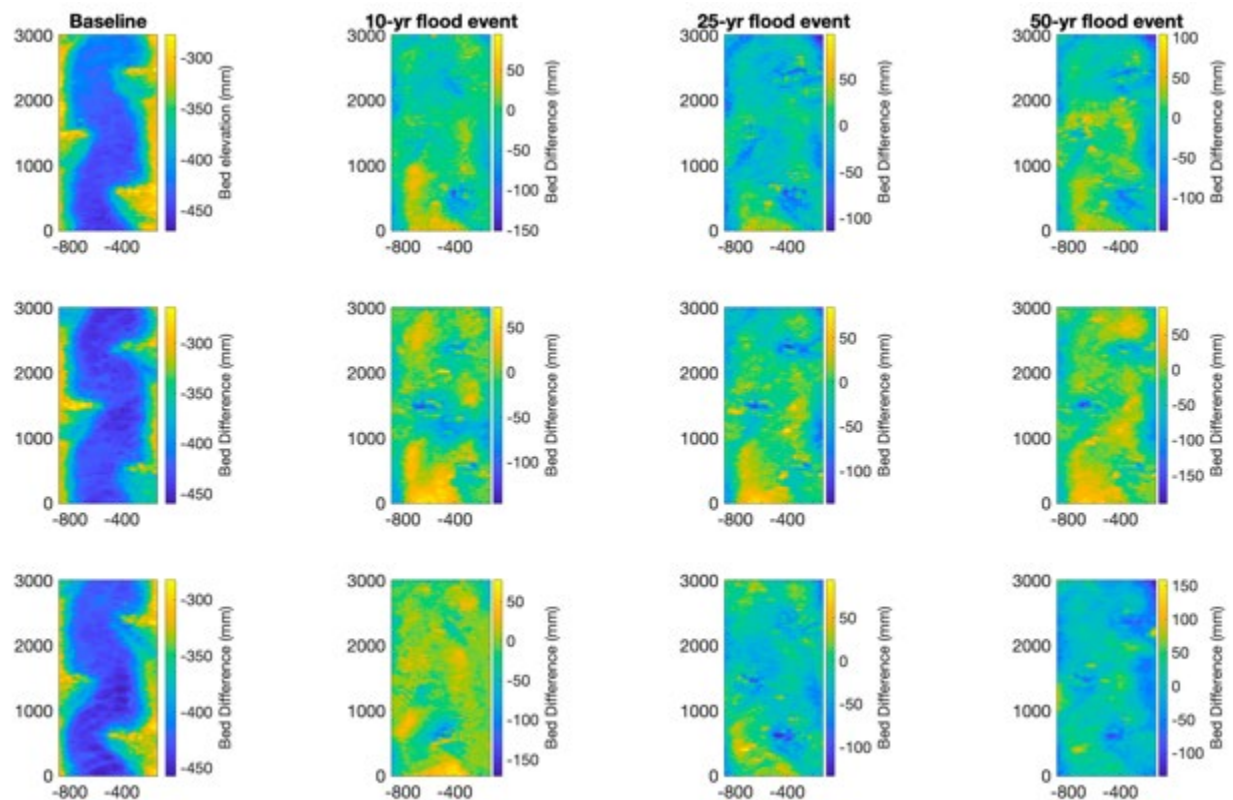


Figure 94 43 Difference of surface elevation of layout 35 after each flood event.

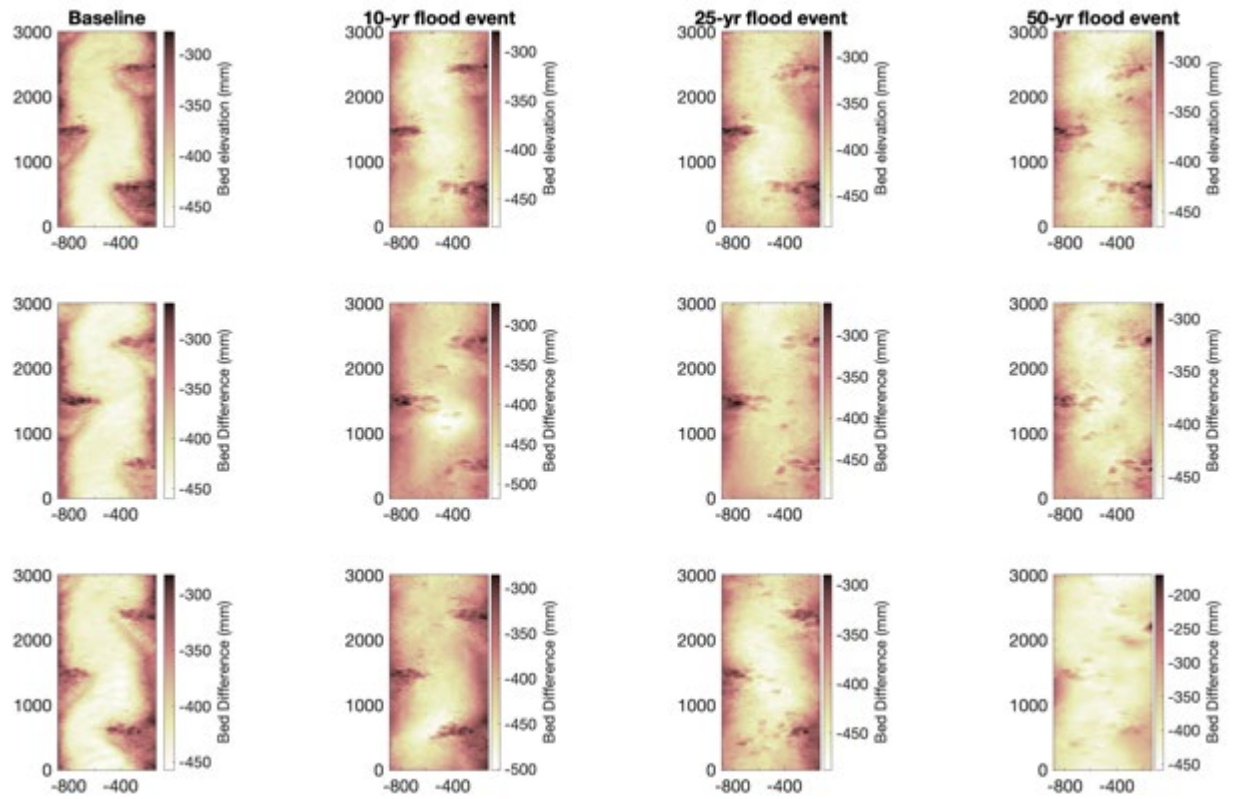


Figure 95 60 Surface elevation of layout 35 after each flood event.

Layout 36 (U-notch straight channel baseline 4% slope)

Layout 36 is a straight U-notch channel at a 4% slope. This layout does not have any features in the channel. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

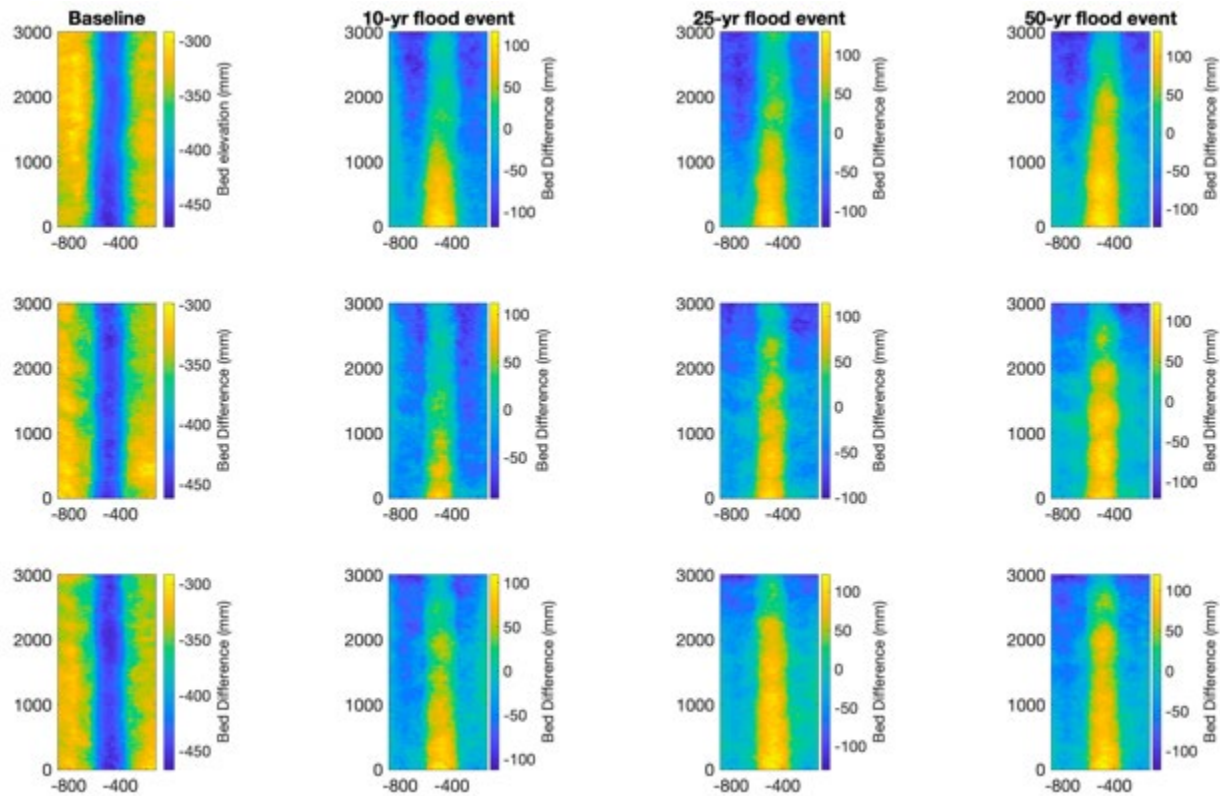


Figure 96 61 Difference of elevation for layout 36 after each flood event.

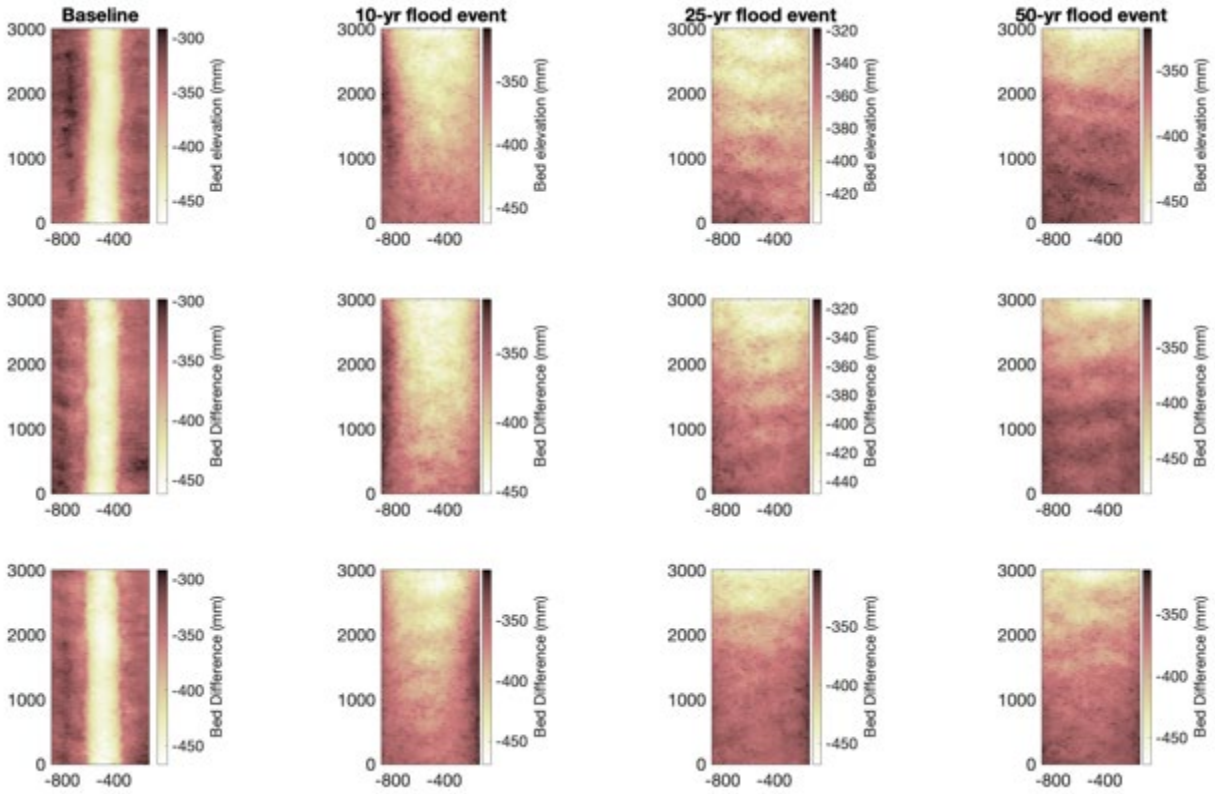


Figure 97 62 Surface elevation of layout 36 after each flood event.

Layout 37 (DGC-diameter mixture 75:25 4% slope)

Layout 37 is a straight U-notch channel at a 4% slope. This layout has a deformable grade control (DGC) design in the middle of the study section. The DGC is made up of a distribution of 7/8-, 3/8- and 1/8-in diameter dowels that have lengths of $\frac{3}{4}$, $\frac{1}{2}$, $\frac{1}{4}$ and $\frac{1}{6}$ channel width. The dowel sizes are distributed at a ratio of 15:50:35. The feature is constructed in a trench that has a width of $\frac{1}{6}$ channel-width and a depth to the bottom of the flume. The feature has a wood-sediment ratio of 75:25. DGC was built with one 27-in and one 18-in long 7/8-in diameter dowels, twelve 9-in and twelve 6-in long 3/8-in diameter dowels, and four 9-in and thirty-one 6-in long 1/8-in diameter dowels. See figure below for layout construction. These graphs show the streambed elevation and surface difference at each flood event for all three trials.

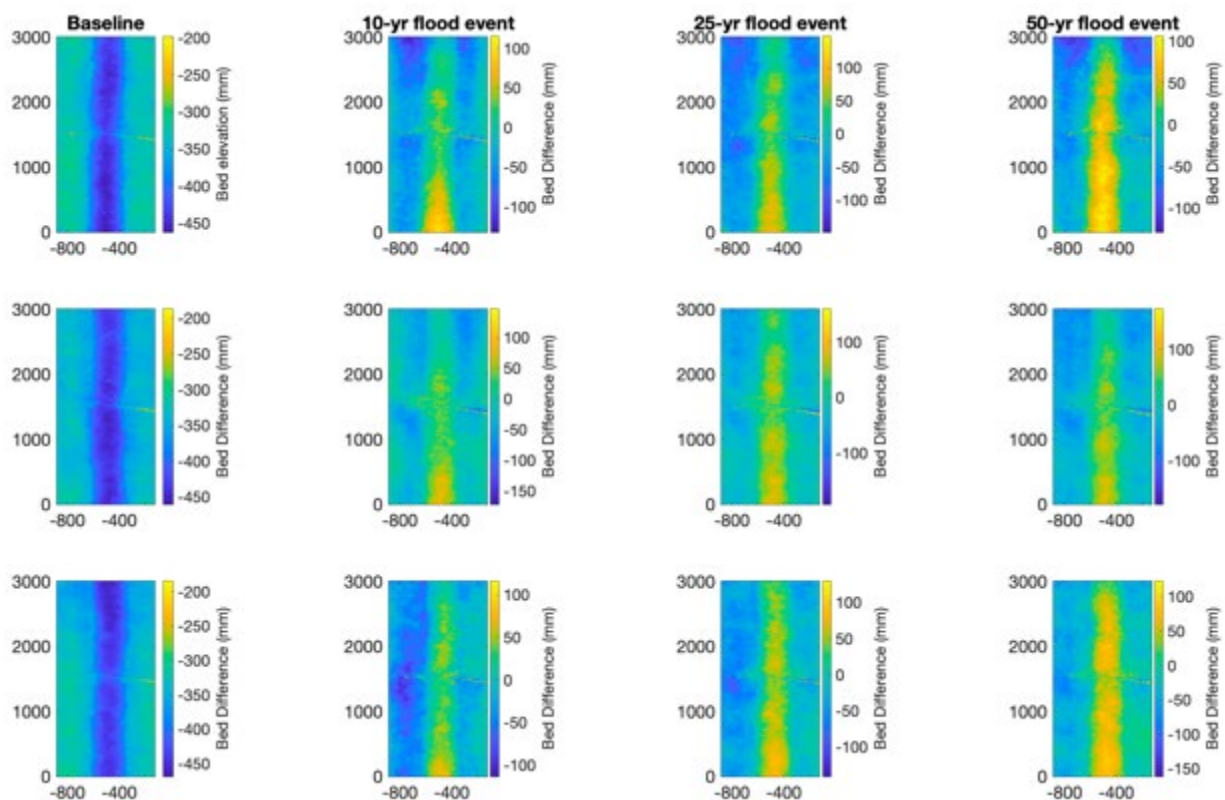


Figure 98 63 Difference of surface elevation of layout 37 after each flood event.

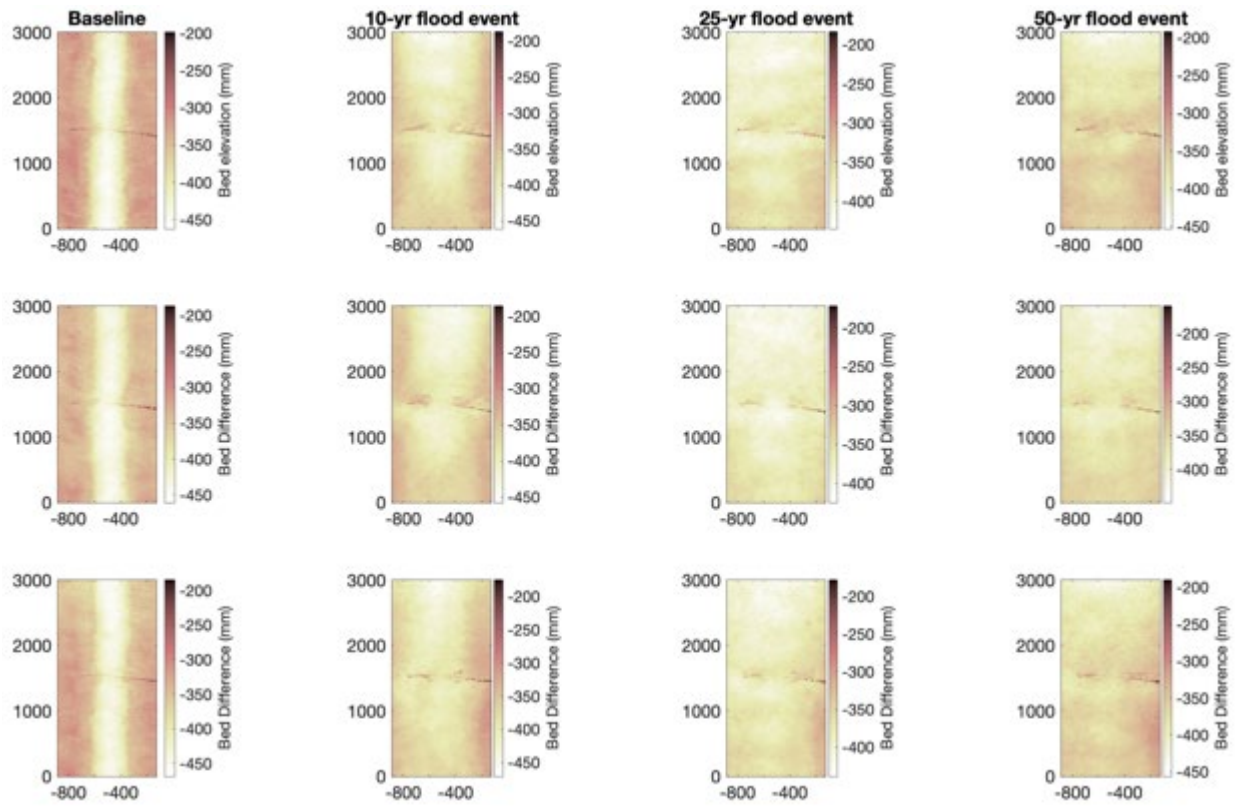


Figure 99 44 Surface elevation of layout 37 after each flood event.

Layout 38 (RC-Baseline)

This channel is a meandering channel with no root wads at a 0.7% slope.

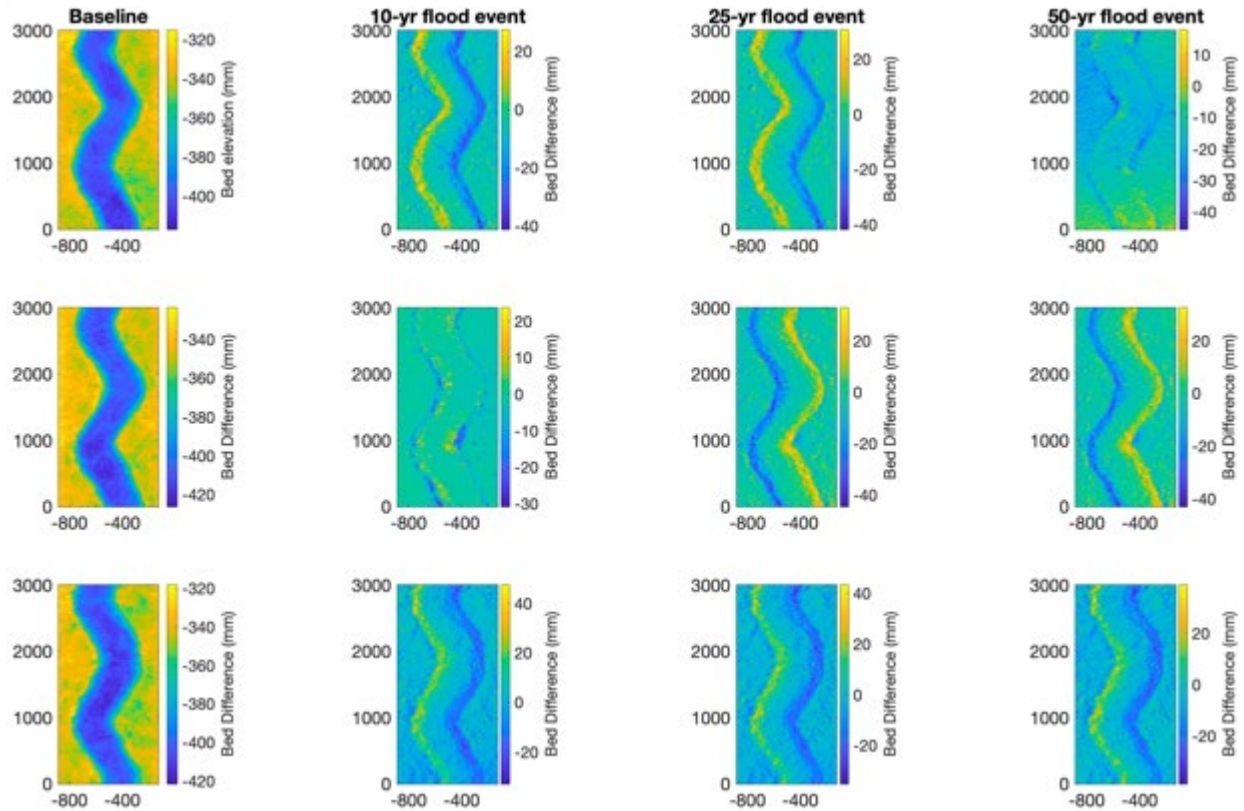


Figure 100 45 Difference of surface elevation of layout 38 after each flood event.

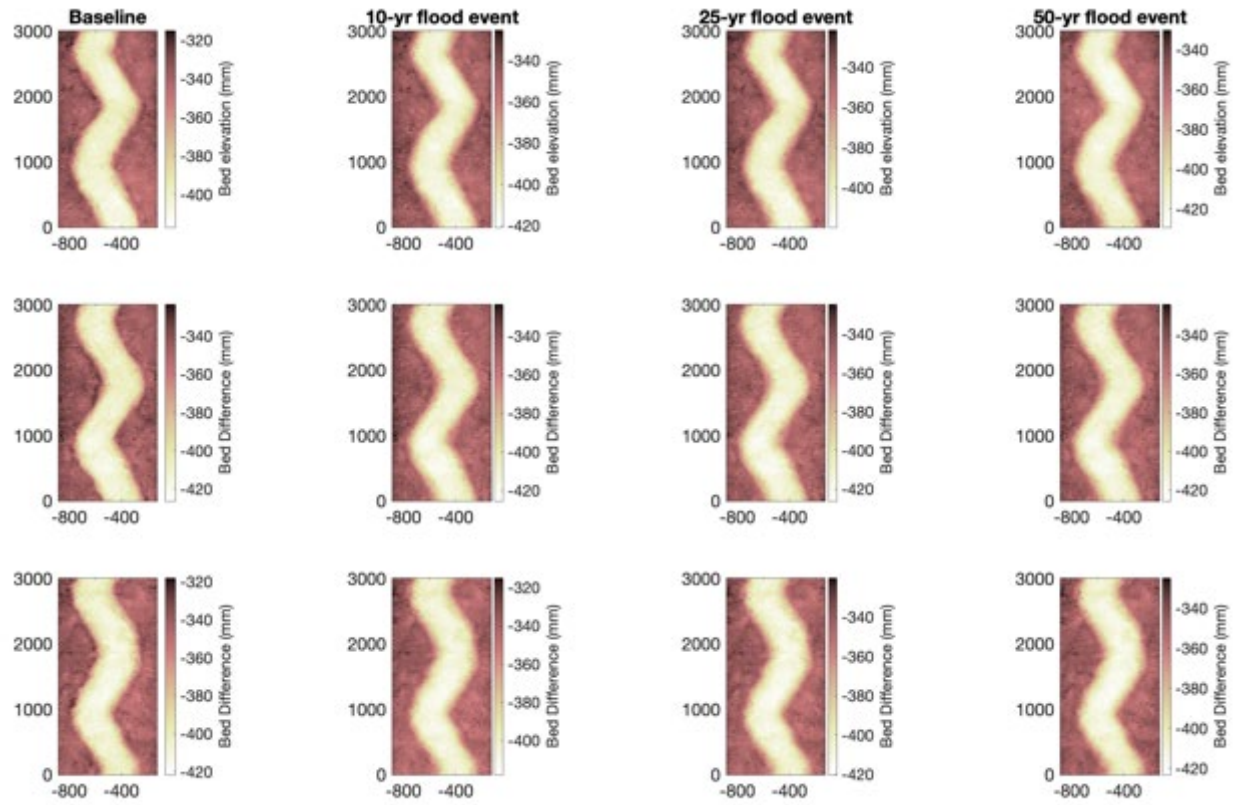


Figure 101 46 Surface elevation of layout 38 after each flood event.

Layout 39 (RC-1RW)

This channel is a meandering channel lined with root wads that are spaced one root wad-width apart. The channel is at a 0.7% slope.

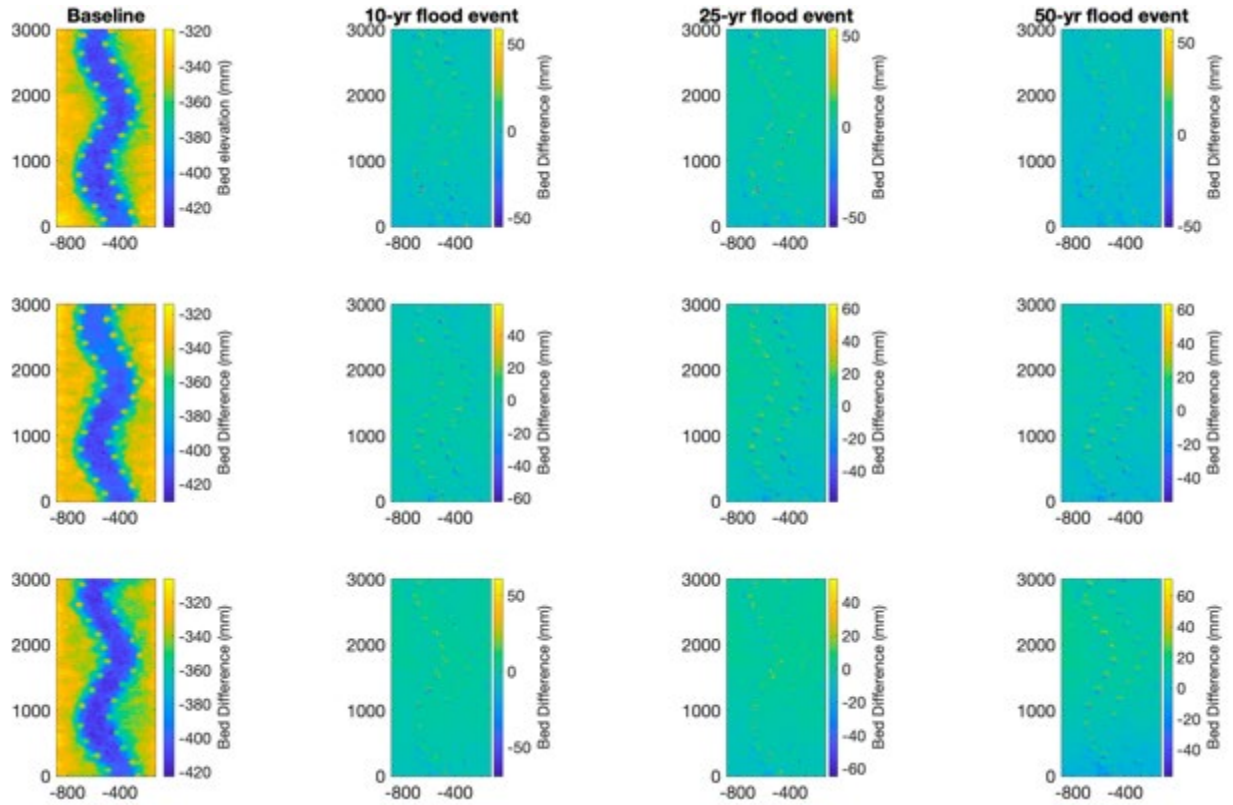


Figure 102 67 Difference of surface elevation of layout 39 after each flood event.

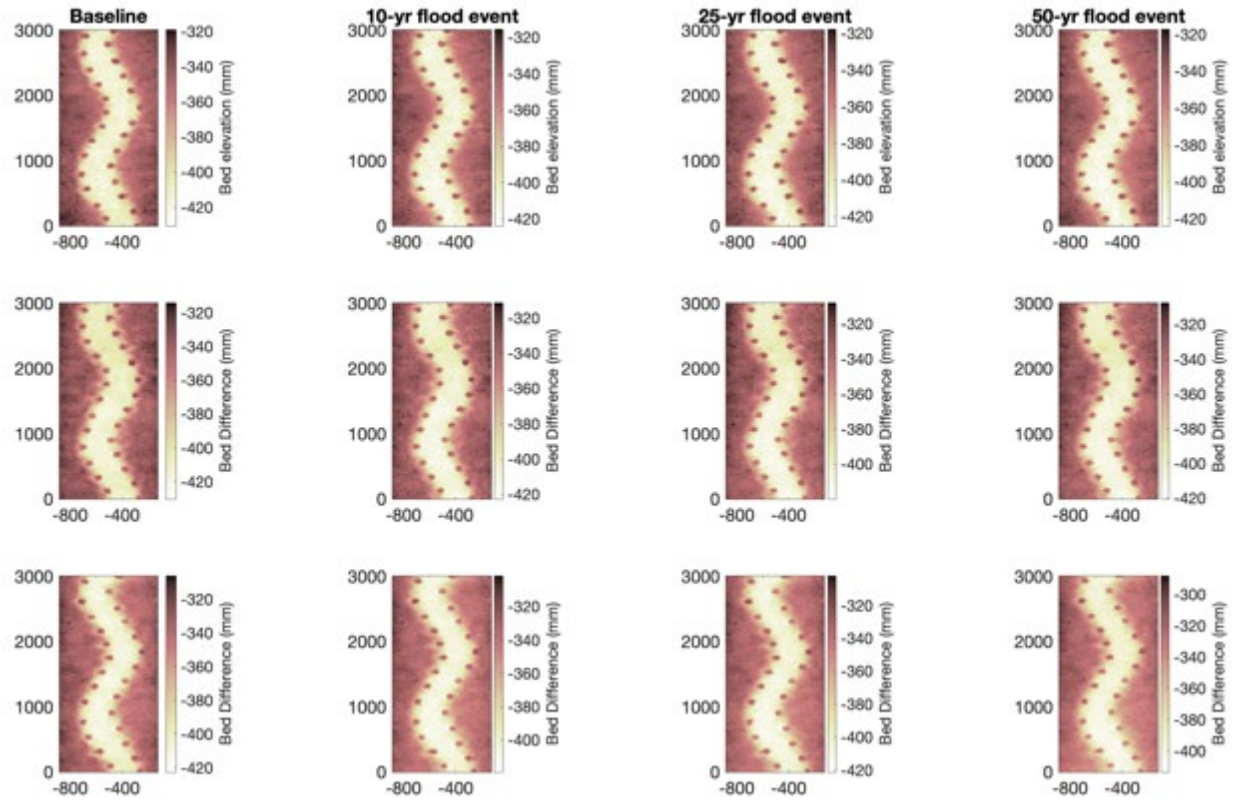


Figure 103 47 Surface elevation of layout 39 after each flood event.

Layout 40 (RC-2RW)

This channel is a meandering channel lined with root wads that are spaced two root wad-widths apart. The channel is at a 0.7% slope.

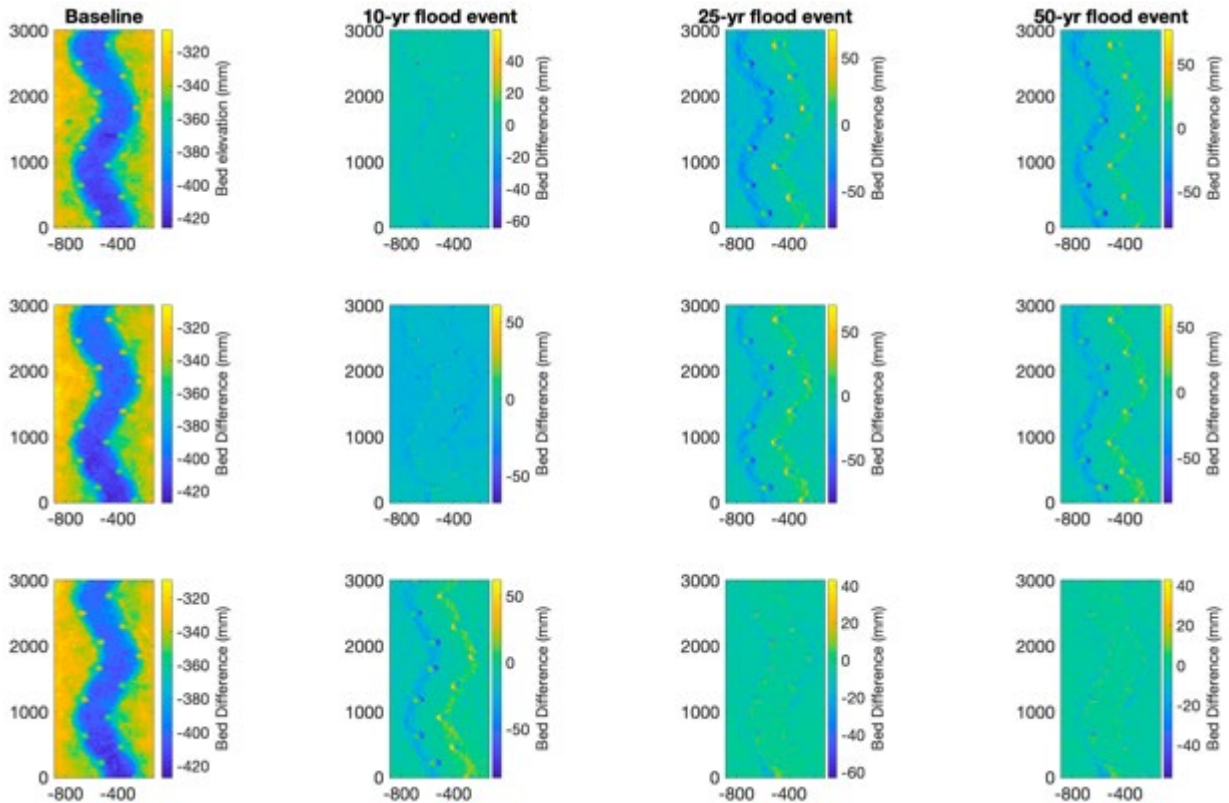


Figure 104 69 Difference of surface elevation of layout 40 after each flood event.

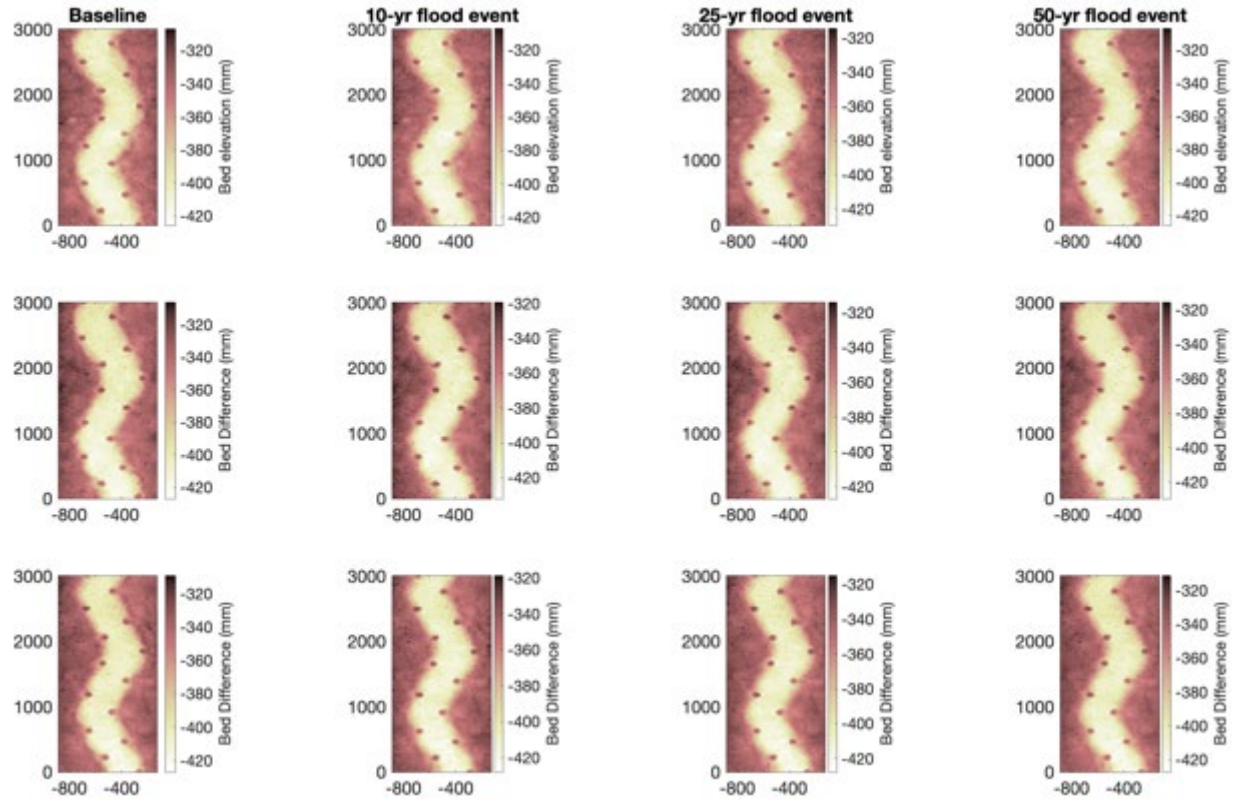


Figure 105 48 Surface elevation of layout 40 after each flood event.

Layout 41 (RC-4RW)

This channel is a meandering channel lined with root wads that are spaced four root wad-widths apart. The channel is at a 0.7% slope.

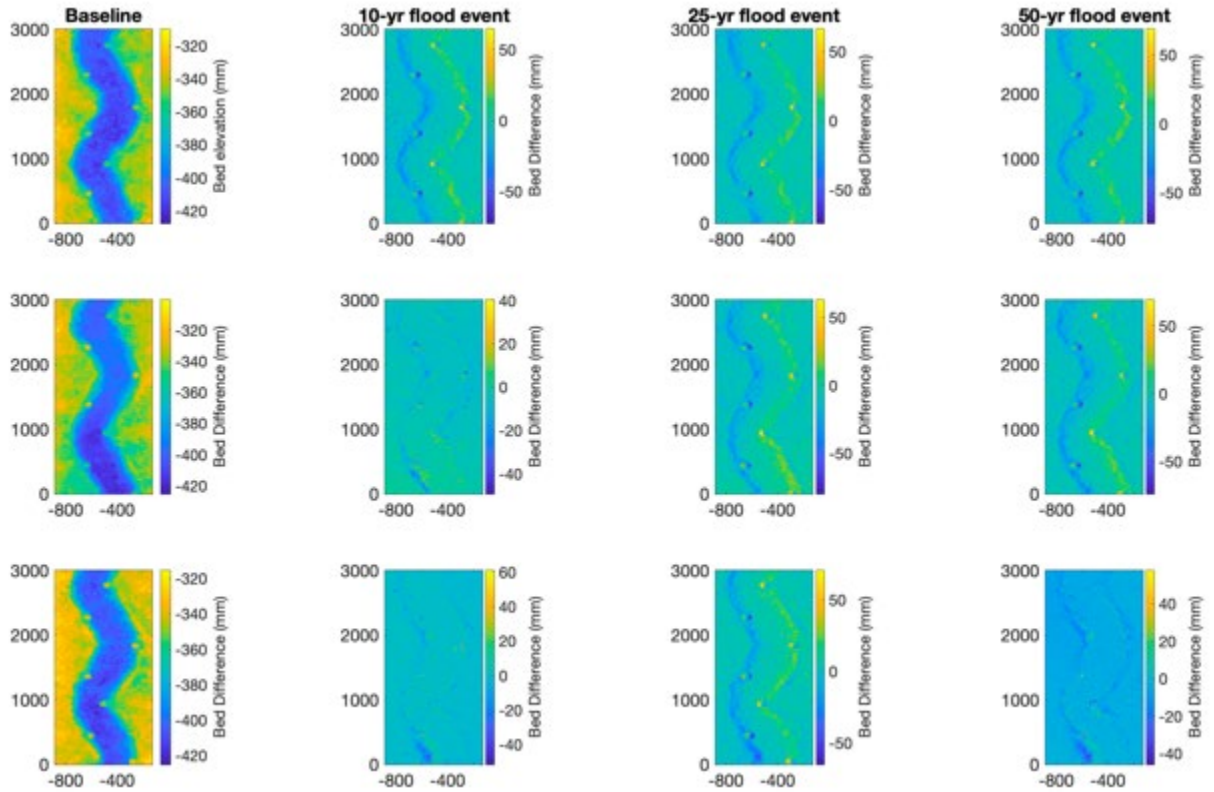


Figure 106 71 Difference of surface elevation of layout 41 after each flood event.

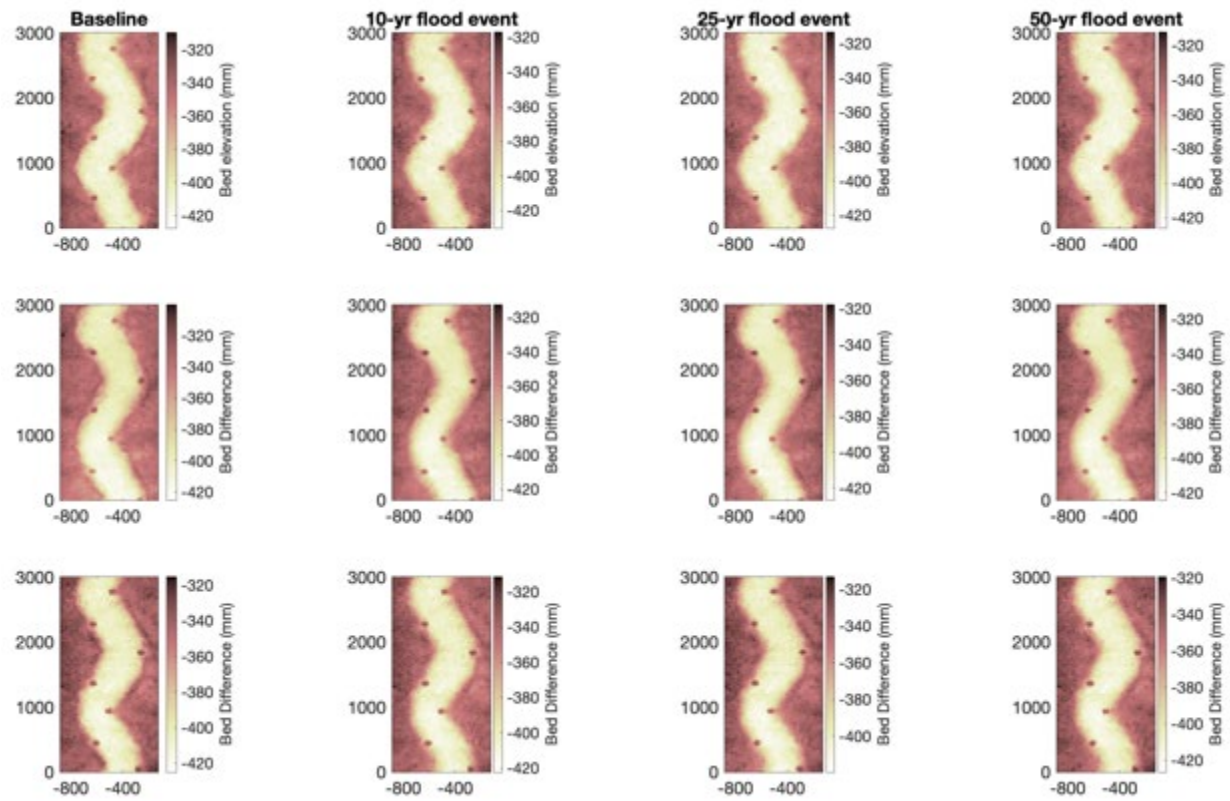


Figure 107 49 Surface elevation of layout 41 after each flood event.

Layout 42- 44

These layouts were looking at a channel at a 1% slope. The scope of the design was changed, and data collection was stopped.

Layout 45

This layout is a straight channel with a sediment-organic material ratio of 3:1. The channel is at a 2% slope.

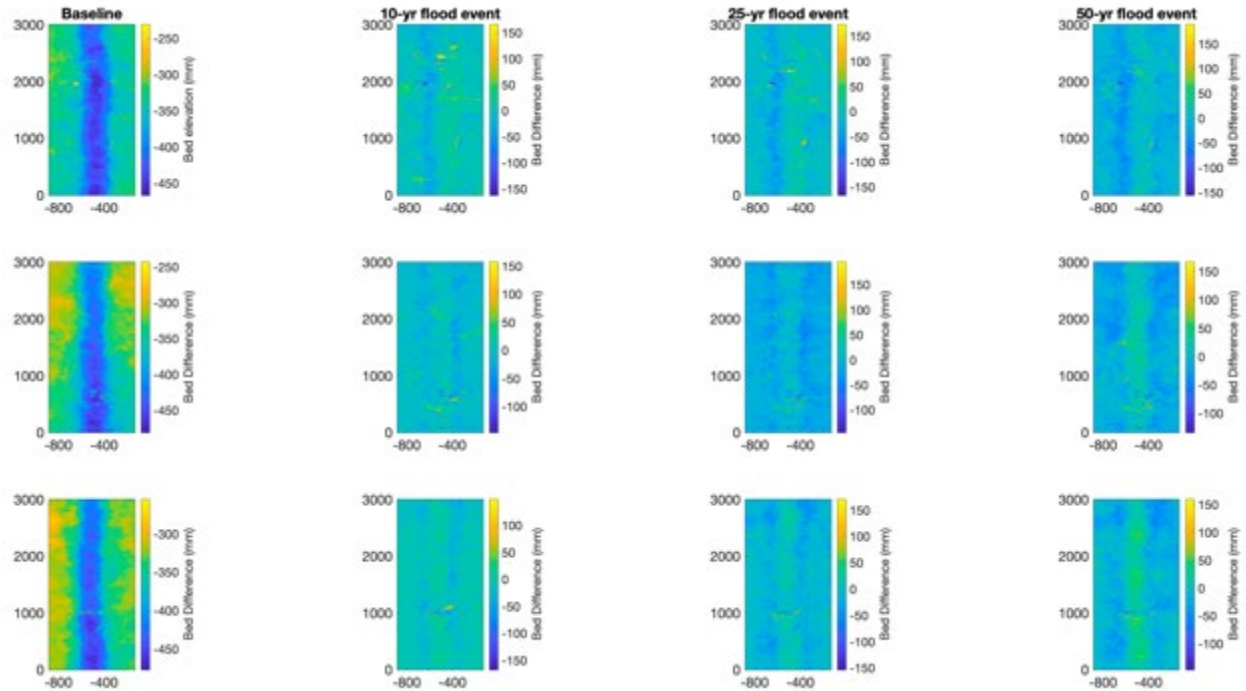


Figure 108 Surface difference between baseline and flood events. The banks of the channel had erosion and center of the channel had deposition at each flood event.

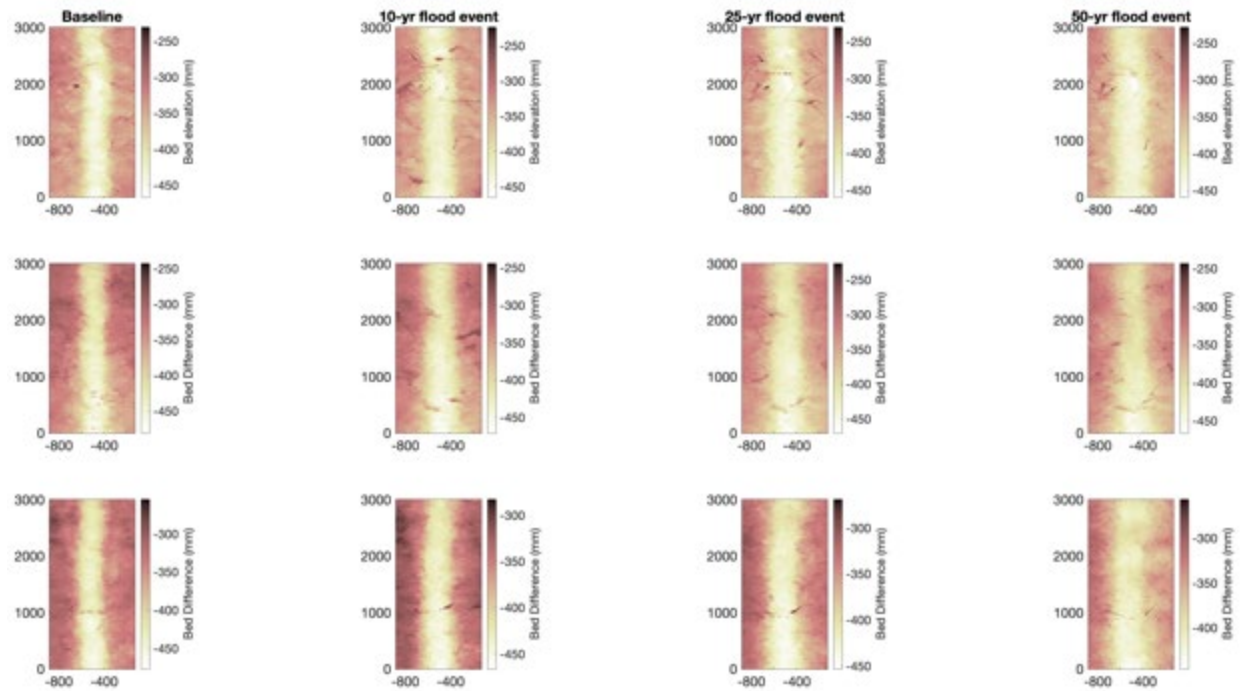


Figure 109 Surface elevation at each flood event. The elevation of the banks decreases at each flood event.

Layout 46

This layout is a meander bar design at three culvert-width with a sediment-organic material ratio of 3:1. The channel is at a 2% slope.

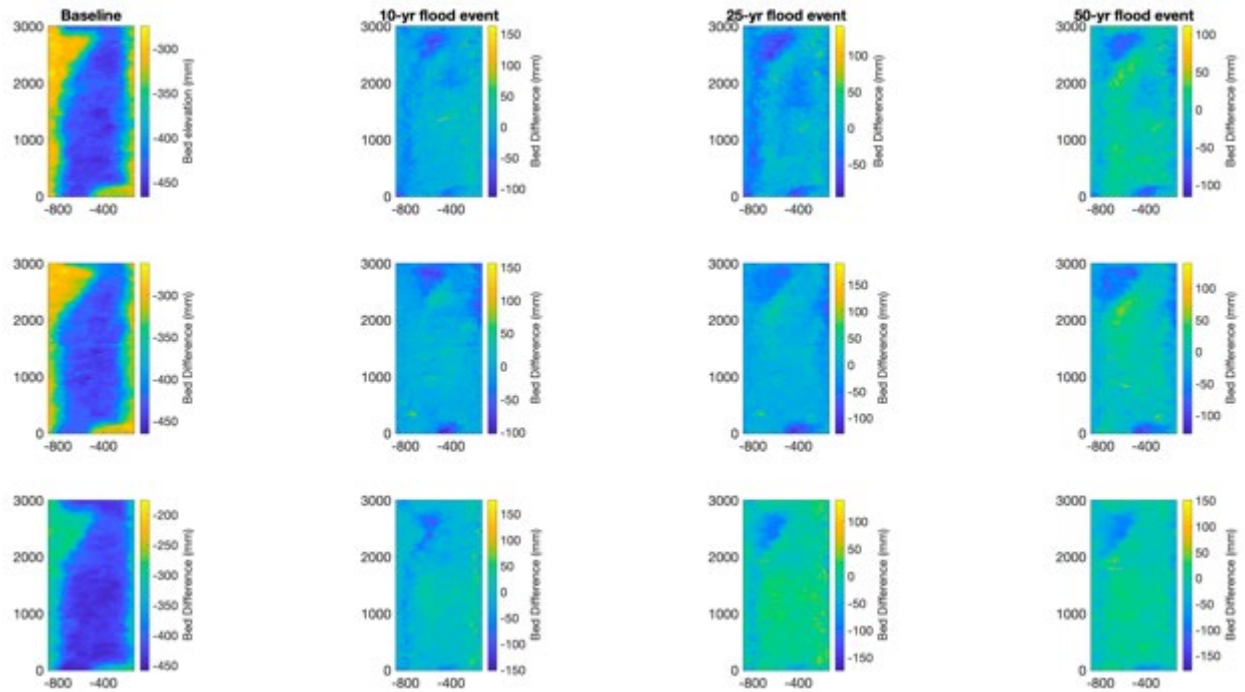


Figure 110 Surface difference between the baseline and flood events. The first two flood events had primary erosion for the trial one and two. Deposition in the center of the channel for 50-yr flood events at all three trials.

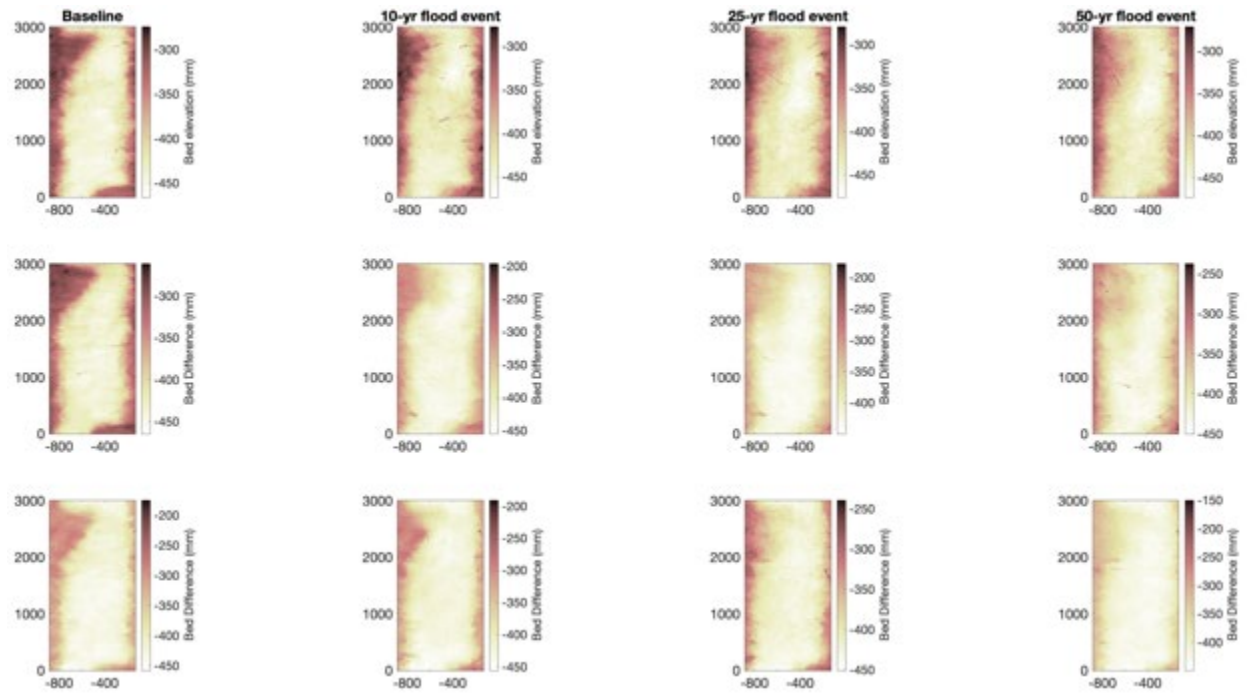


Figure 111 Surface elevation at each flood event. The center of the channel increased, and the banks decrease with the increase of flood events.

Layout 47

This layout is a meander bar design at one culvert-width with a sediment-organic material ratio of 3:1 . The channel is at a 2% slope.

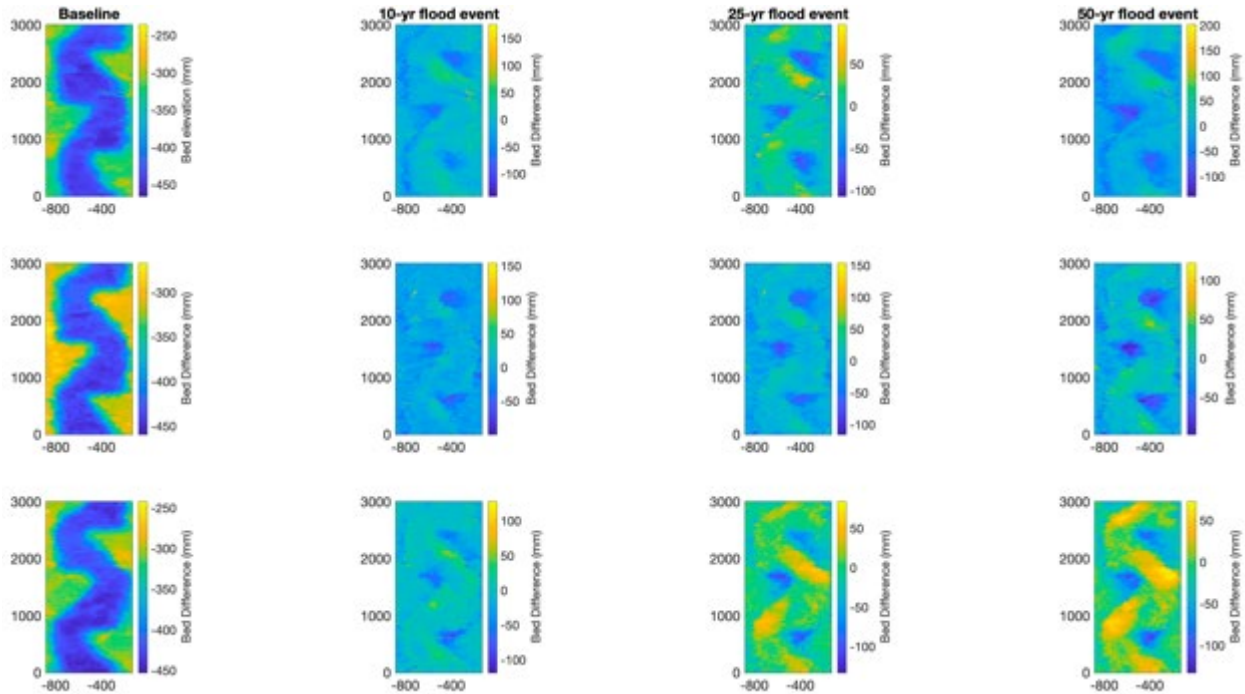


Figure 112 Surface difference between the baseline and flood events. For the first two trials little deposition occurred in the channel but for the third trial deposition increased greatly for the last two flood events.

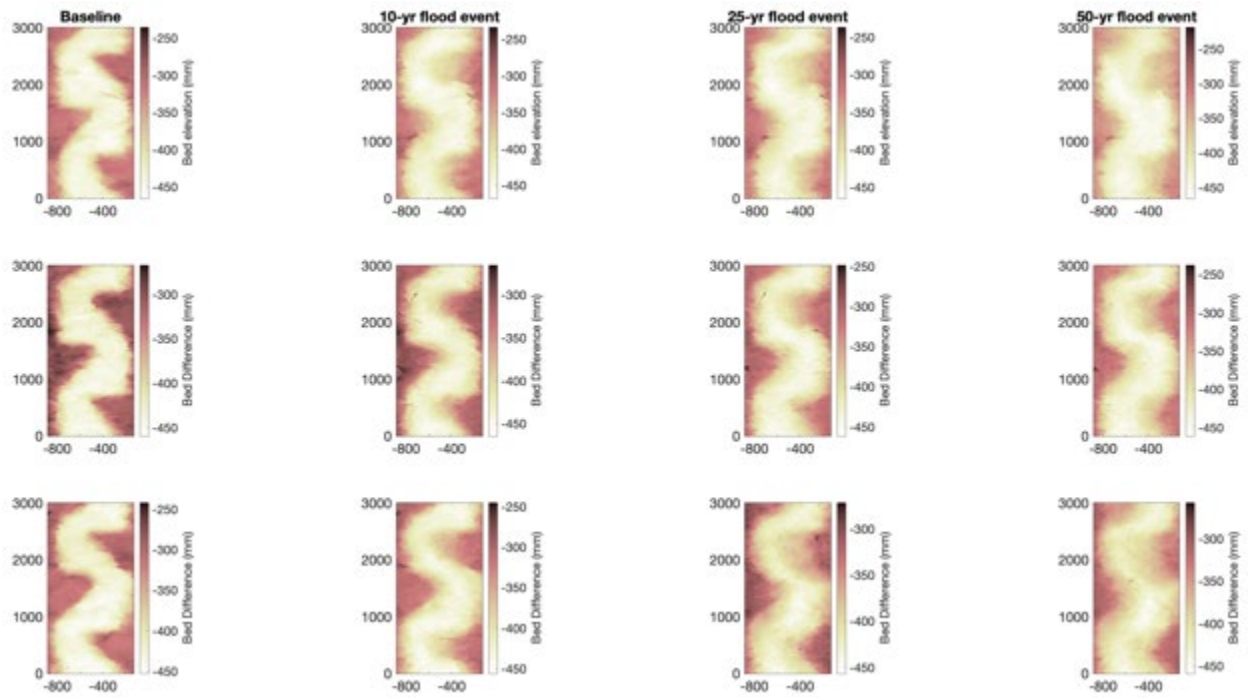


Figure 113 Surface elevation at each flood event. The center of the channel increased at each flood event.

Layout 48

This layout is a straight channel with a sediment-organic material ratio of 1:1. The channel is at a 2% slope.

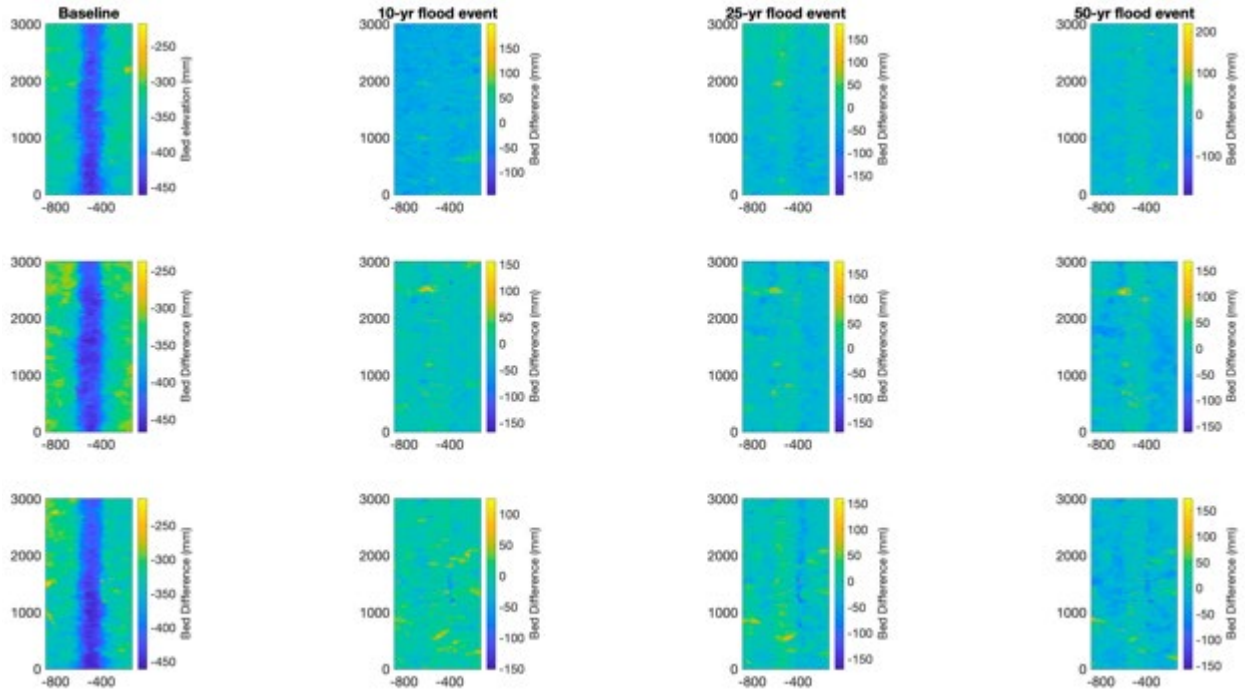


Figure 114 Surface difference between baseline and each flood event. Erosion is predominant in the last flood event while depositions were in the smaller floods.

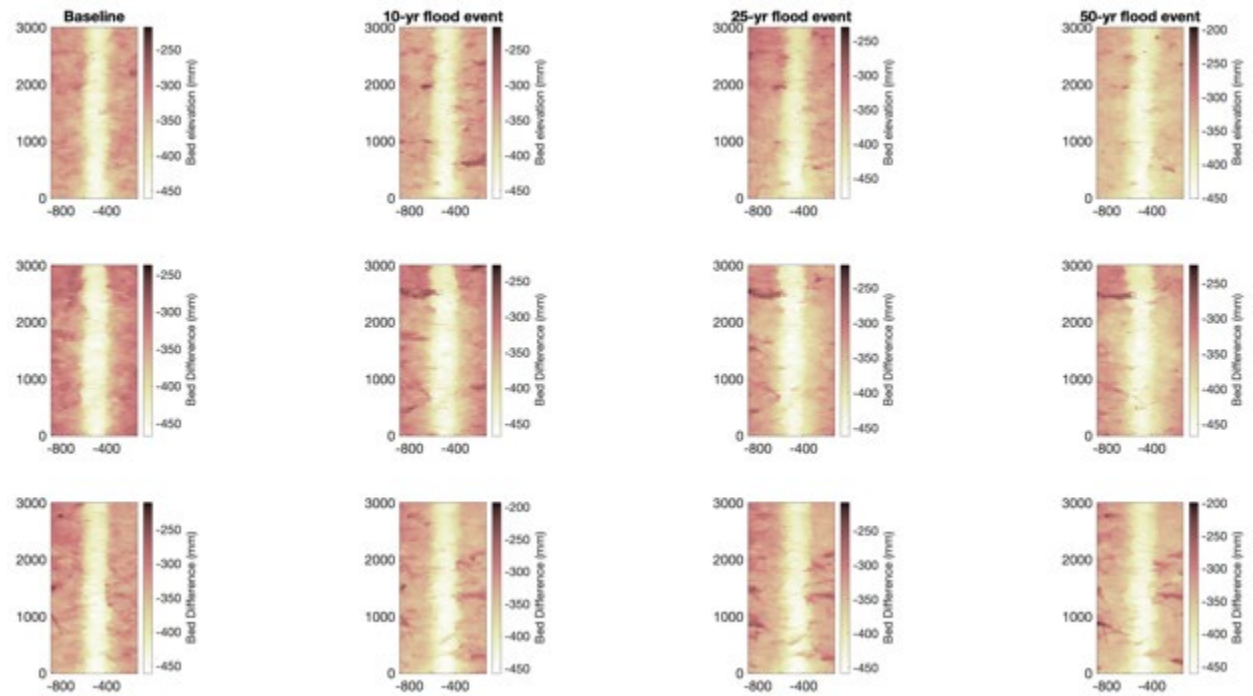


Figure 115 Surface elevation at each flood event. The bank elevation decreased a little over the flood events.

Layout 49

This layout is a meander bar design at three culvert-width with a sediment-organic material ratio of 1:1. The channel is at a 2% slope.

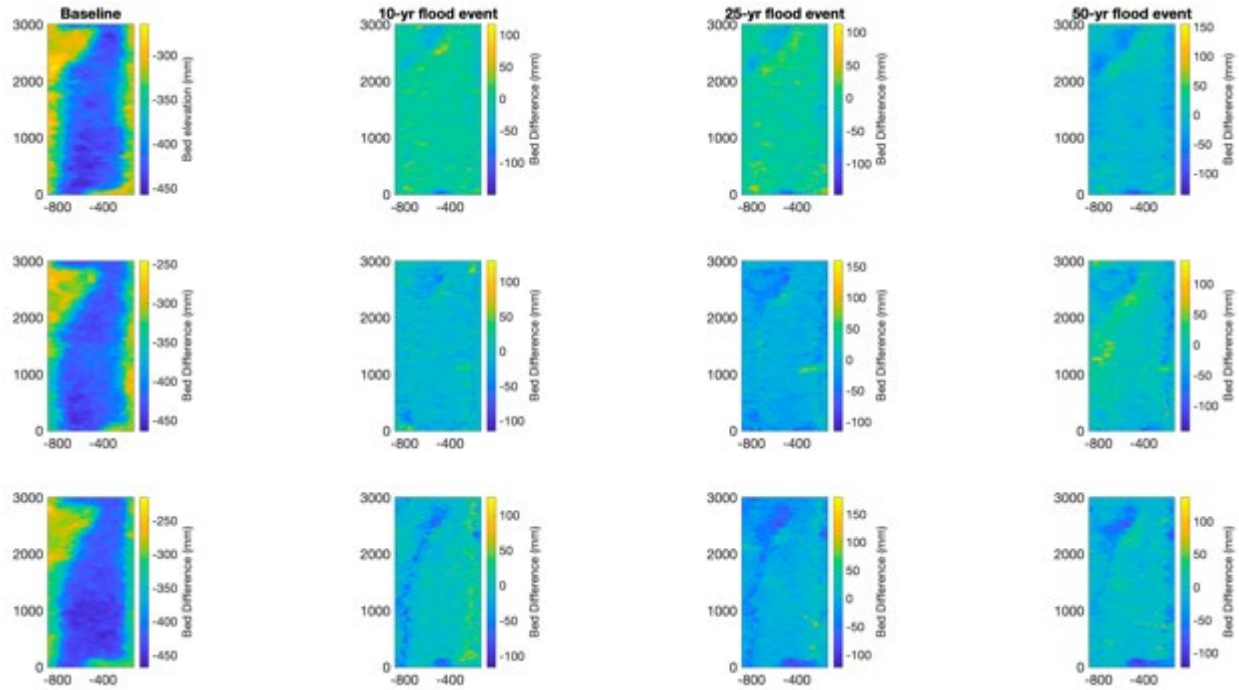


Figure 116 Surface Difference between baseline and flood events. Erosion was dominant in trials two and three for each flood event and at the 50-yr flood event for trial one.

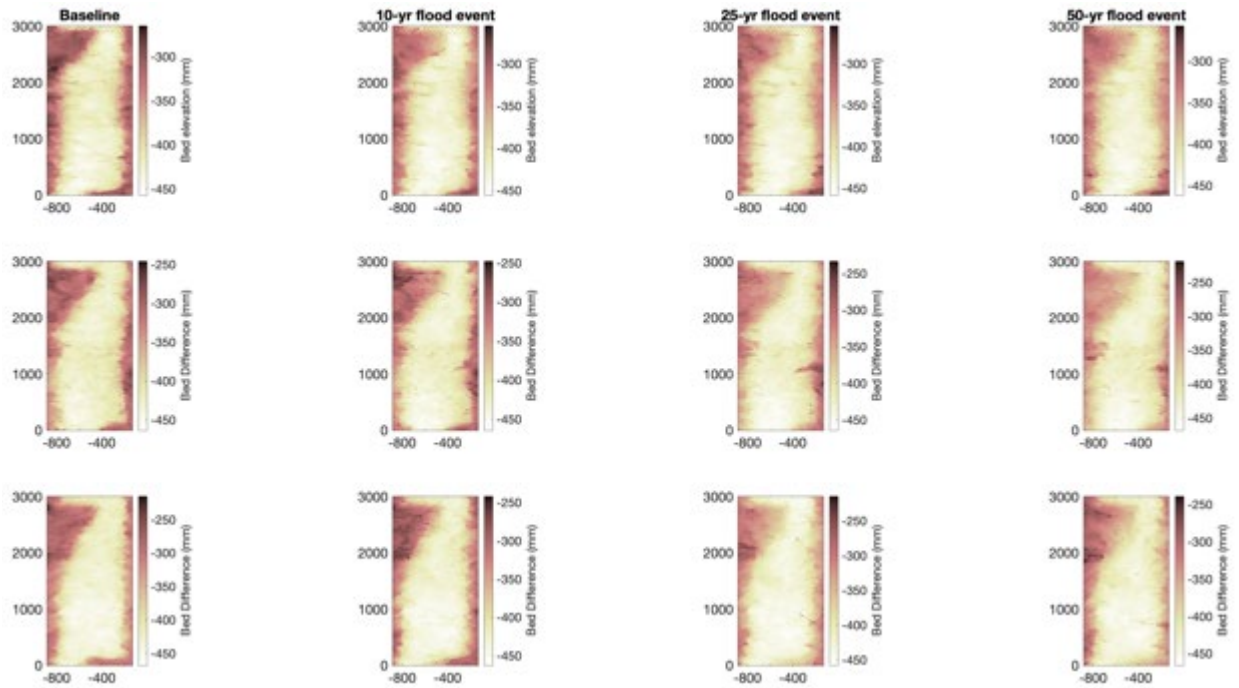


Figure 117 Surface elevation at each flood event. The elevation of the meander bars decreases with the increase in flood events.

Layout 50

This layout is a meander bar design at one culvert-width with a sediment-organic material ratio of 1:1 ratio . The channel is at a 2% slope.

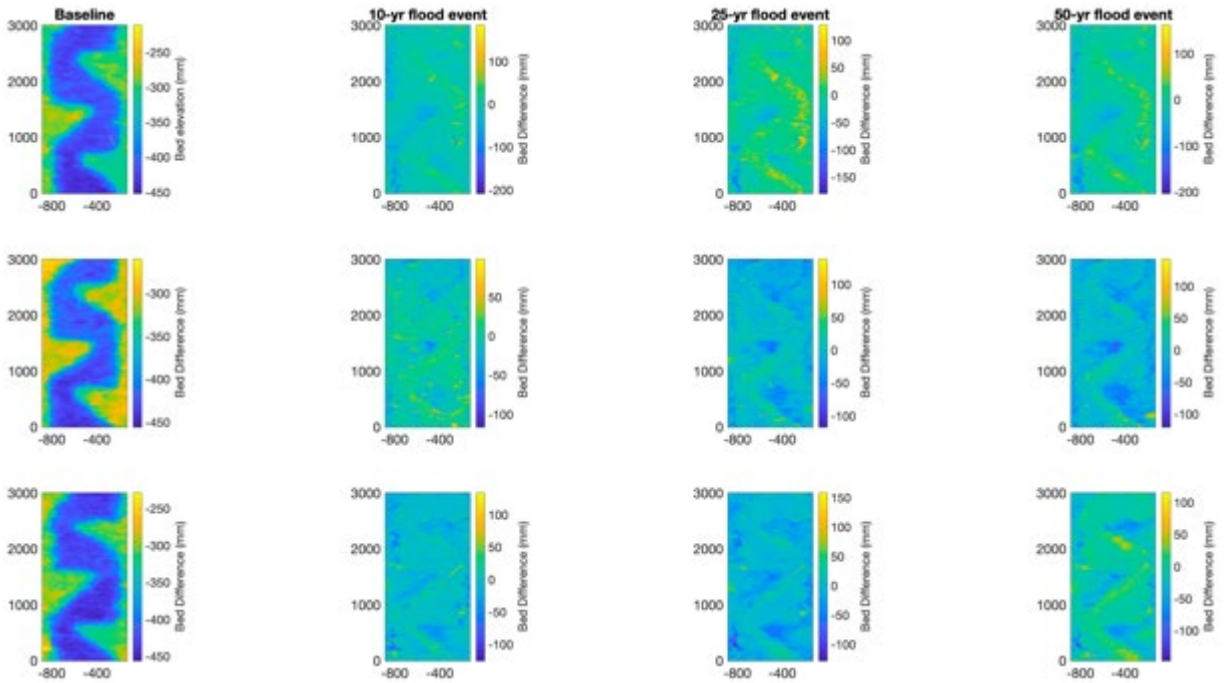


Figure 118 Surface difference between the baseline and each flood event. Deposition is predominant for the first trial at each flood event and for the 50-yr flood for trial three.

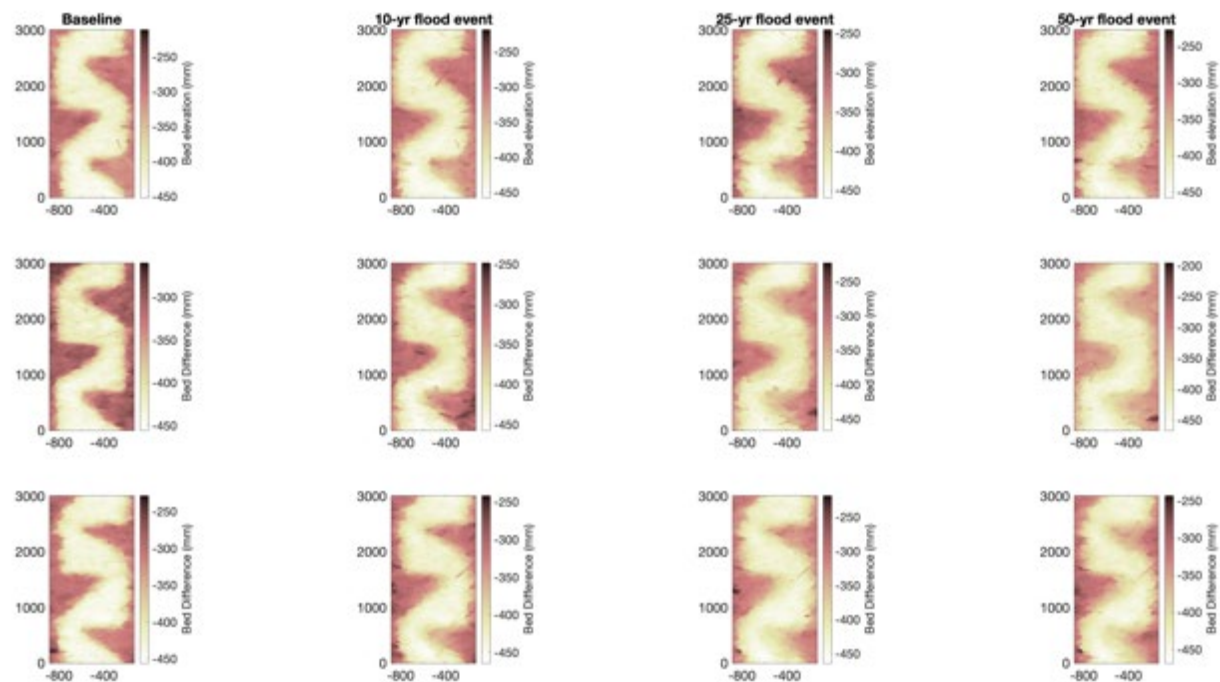


Figure 119 Surface elevation at each flood event. The meander bar elevation decreases in each flood event and the center of the channel increases.

Layout 51

This layout is a straight channel with a sediment-organic material ratio of 1:3 . The channel is at a 2% slope.

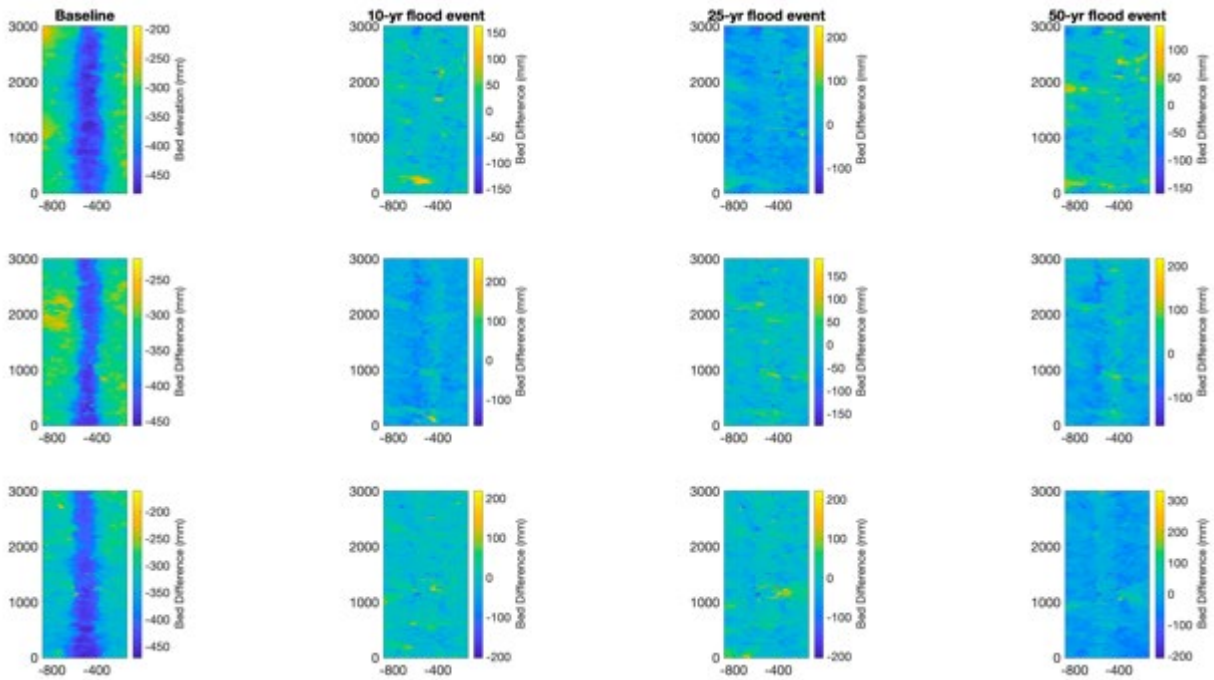


Figure 120 surface difference between the baseline and flood events. Erosion is dominant in all flood events for each trial.

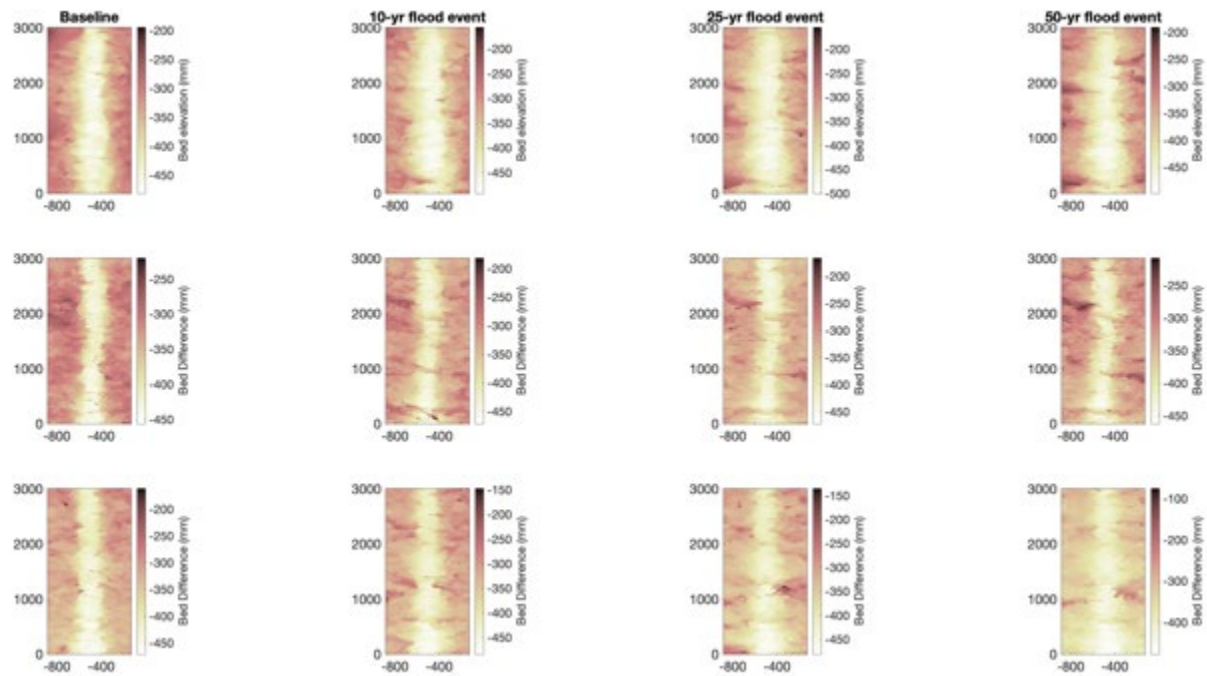


Figure 121 surface elevation at each flood event. The bank elevation decreases with the increase in flood events.

Layout 52

This layout is a meander bar design at three culvert-width with a sediment-organic material ratio of 1:3 . The channel is at a 2% slope.

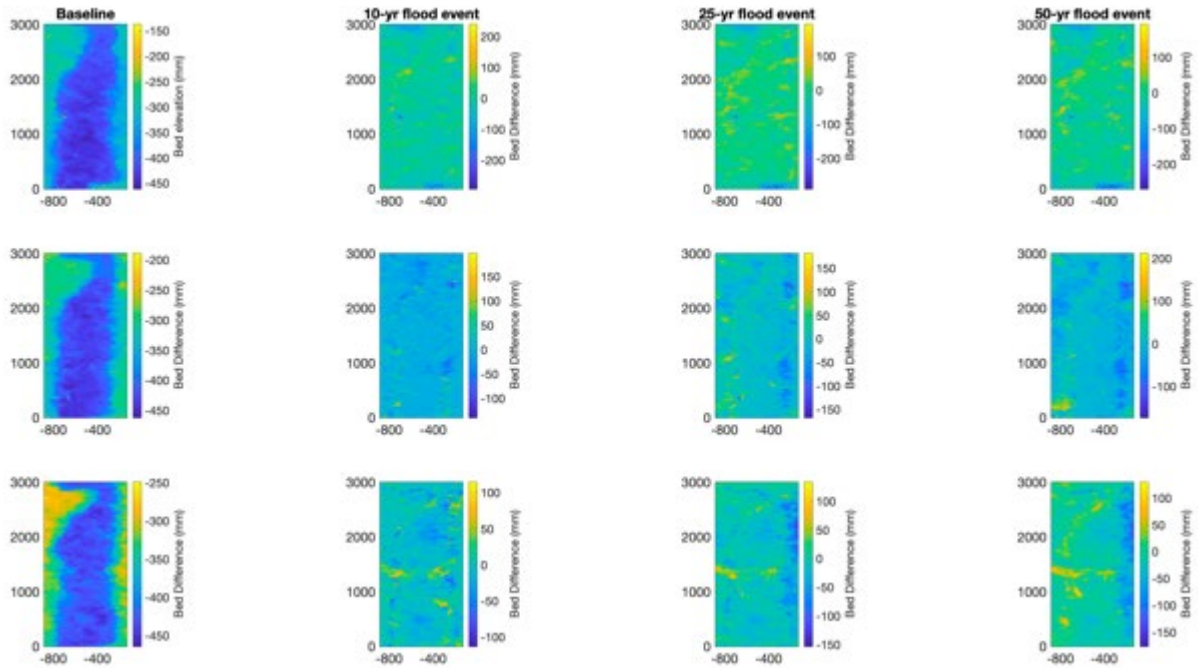


Figure 122 surface difference between the baseline and flood events. For the first trial deposition was predominant for all flood events but erosion was dominant in the other two trials.

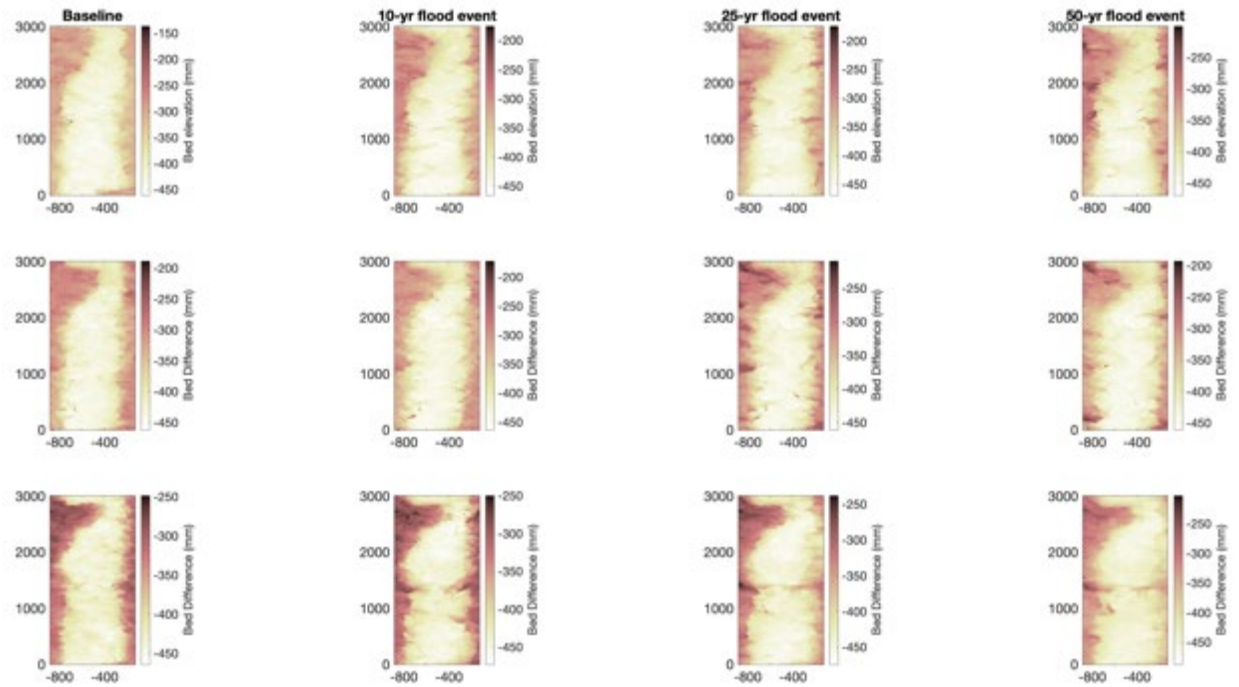


Figure 123 surface elevation at each flood event. The elevation of the center of the channel increased with flood events and the banks of the channel decreased.

Layout 53

This layout is a meander bar design at one culvert-width with a sediment-organic material ratio of 1:3. The channel is at a 2% slope.

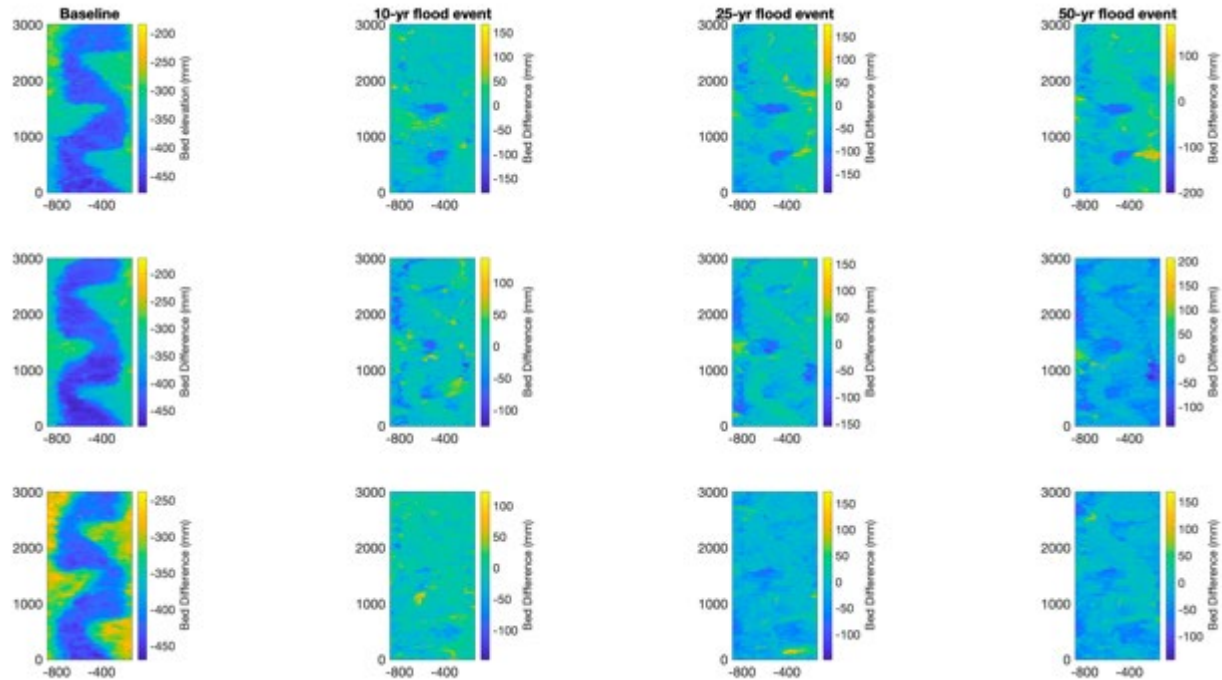


Figure 124 surface difference between the baseline and each flood event. Erosion increases with the increase of flood events.

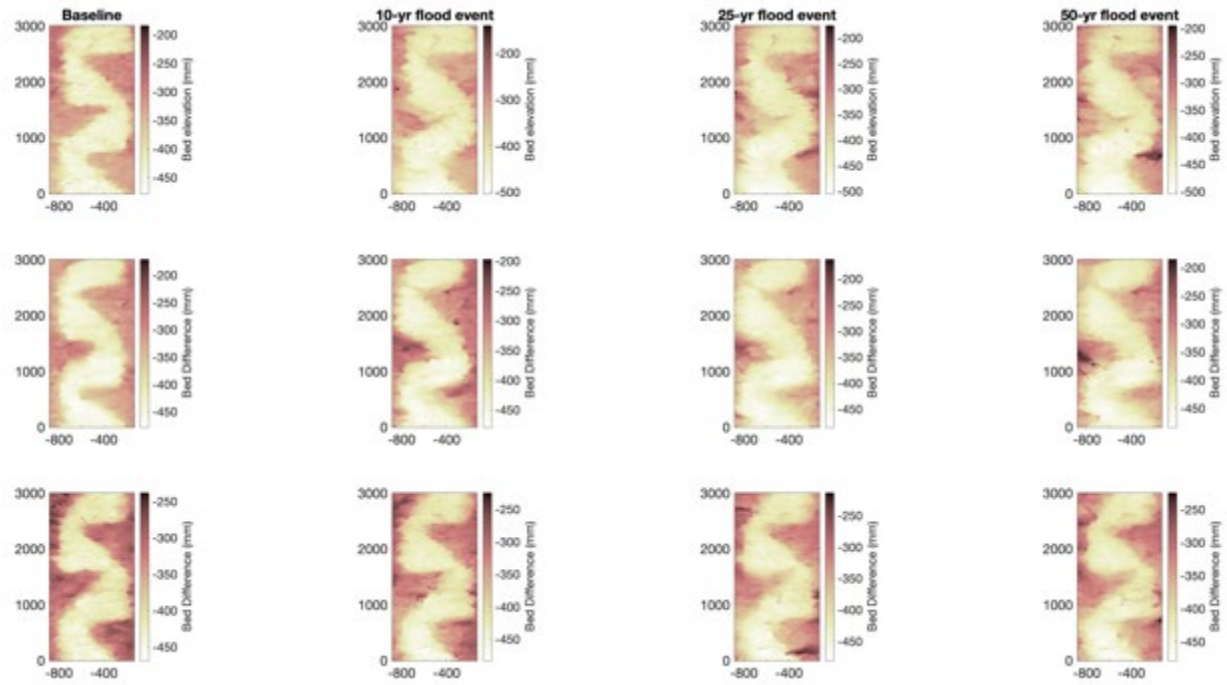


Figure 125 surface elevation of the channel at each flood event for layout 53. The elevation on the meander bar decreases with the increase in flood events.

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