Flume-Based Design Recommendations for Coarse Bands and Boulder Bars to Improve Retention of Channel Shape in Stream Simulation Culverts

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Nicholas Engdahl
Tyler Fouty
Bailee Kelty

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WSDOT Research Report

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By

DR. NICHOLAS ENGDAHL, DEPARTMENT OF CIVIL & ENVIRONMENTAL
ENGINEERING, WASHINGTON STATE UNIVERSITY

TYLER FOUTY, WASHINGTON STATE UNIVERSITY

BAILEE KELTY, WASHINGTON STATE UNIVERSITY

Washington State Department of Transportation
Technical Monitor
Julie Heilman
State Hydraulic Engineer

Prepared for

The State of Washington
Department of Transportation
Roger Miller, Secretary

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16. Abstract

The Pacific Northwest has seen a reduction of fish spawning ground which has led to a population decrease related to the number of fish barriers in the area. In response, Washington State implemented new design policies in 1999 to replace the most common barriers, culverts. New “stream simulation culverts” incorporate a sediment lining, providing an environment more conducive to movement. Streambed design must balance engineering and ecosystem factors, but there is little guidance on how to maximize the lifespan of the overall channel shape while having maximum passage during low flows. This research investigated how to incorporate coarse material (coarse bands and boulder bars) into a simulated streambed in a flume. The first objective examined if coarse bands and boulder bars could stabilize a channel without eliminating sediment transport. Three characteristics were tested: coarse material size, number of coarse bands, and the spacing between coarse bands/boulder bars. The second objective was to investigate relationships between the number, spacing of coarse bands/boulder bars and channel stabilization. Streambeds were subjected to one, two-and-a-half, five and ten-year flood frequency events. Sediment transport was quantified after each flood event using cross-section profiles and analyzed to determine net change among each cross section. Thirty coarse bands and twelve different boulder bars configurations were tested with variable amount of coarse bands/boulder bars, spacing and stream slope relative to a uniform streambed (no coarse bands). The research showed that nearly linear, coarse bands that fully spanned the channel reduced sediment transport by 56%, 54% and 50% at 2%, 3%, and 4% bedslope, respectively, conditional to differences in the geometry of the coarse bands at each slope. Boulder bars spaced one channel width apart, exhibited sediment transport reductions of 49%, 57%, and 33%, at 2%, 3%, and 4% bedslope, respectively, and exhibited different transport patterns than the linear designs. These findings indicate minimal additions of coarse bands reduce sediment transport and generally maintain U-shaped channels. Coarse band/bars at greater bedslopes require larger material and armoring layer downstream to prevent destabilization/failure.

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Executive Summary

Fish barriers prevent the migration of fish to their food supplies and to spawning grounds. The subsequent reduction of fish migration has led to widespread fish population decreases in the Pacific Northwest. In response, Washington State implemented new design policies in 1999 to replace these the most common barriers, culverts. The modern “stream simulation culverts” incorporate a sediment lining, providing an environment more conducive to migration. The design of the simulated streambed must balance engineering and ecosystem factors, but there has been little guidance on how to maximize the lifespan of the simulated streambed while preserving the overall channel shape, including a low-flow channel to maximize passage at low flows. This research investigated how to incorporate coarse material such as coarse bands (bands of sediment made of coarse material) and boulder bars (point bars that are constructed of coarse material) into a simulated streambed to determine the most effective ways to help maintain a channel in a simulated streambed. The investigation was conducted using scaled laboratory experiments in a flume. The first objective of these experiments was to examine if coarse bands and boulder bars were able to stabilize a channel without eliminating sediment transport. Three characteristics were tested: coarse material particle size, number of coarse bands, and the spacing between coarse bands/boulder bars. The second objective was to investigate relationships between the number and spacing of coarse bands/boulder bars and channel stabilization. Experimental streambeds were subjected to one, two-and-a-half, five and ten-year flood frequency events. Sediment transport was quantified using cross-section profiles, measured after each flood event, and analyzed in terms of the net change in area at each cross-section. Thirty different coarse bands configurations were tested that varied the amount, number of coarse

bands, spacing and stream slope. Four boulder bar configurations were also tested at streambed slopes of two, three and four percent. Sediment transport relative to a uniform streambed (no coarse bands) showed that linear, or nearly linear, coarse bands that fully spanned the channel reduced sediment transport 1) by up to 56% for a 2% bedslope, 2) up to 54% for a 3% bedslope, and 3) by up to 50% for a 4% bedslope, conditional to differences in the geometry of the coarse bands at each slope. Alternating boulder bars that covered half the channel, spaced one channel width apart, exhibited sediment transport reductions of 49%, 57%, and 33%, at 2%, 3%, and 4% bedslope, respectively, and exhibited different transport patterns than the linear designs. The main implication of these findings is that even minimal additions of coarse bands were able to reduce sediment transport in U-shaped channel cross-sections and generally maintained the channel shape to provide a low-flow channel. Higher bedslopes require large material to be used in the coarse bands and, in some cases, an armoring layer on the downstream side of the coarse band(s) to prevent destabilization and failure of the coarse bands/bars. A limitation of this work is the relatively narrow cross section width of the flume so further research with alternating coarse band designs will be needed in wider flumes to allow variable sinuosity. This further research could be combined with a decrease in the scale of D50 particle size of the streambed material to create conditions that represent larger flood events. Failure of coarse bands generally led to a flattening of the channel so future research is also suggested to investigate how U-shaped channels might be induced using natural processes, without labor intensive intervention. This would include investigation of the features that lead to formation of natural step-pool sequences and how to induce meandering channels to reduce the slope and velocity of water through stream simulation culverts.

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CHAPTER ONE: INTRODUCTION

1.1 Culverts are fish barriers

Development of industries and infrastructure throughout Puget Sound, Washington State, and across the Pacific Northwest has reduced the amount of salmon spawning habitat by 33% as of 2014, relative to pre-development conditions (Roni et al. 2014). As a keystone species in the area, data about salmon and their habitats are representative of many other fish species in the Pacific Northwest. The most severe impacts on aquatic ecosystems have been from the introduction of human-made barriers that block the movement paths of fish (Nehlsen et al. 1991; Bottom et al. 2005). The two main barriers to this movement are dams and road crossings. Washington State has been removing fish barriers over the past three decades. The removal of two dams on the Elwha River on the Olympic Peninsula were the largest projects to date, but removing every dam is simply not possible. While most of the public attention has been given to dams due to their vast size and environmental impact, a less obvious and far more common barrier is the thousands of culverts in Washington State. These culverts were installed as a simple solution to route water under roads, railways, and were not immediately identified as having an impact on fish habitat. Statewide there are 3,931 highway crossings on fish bearing waters. Of those, 2,057 are documented fish passage barriers (Kanzler et al. 2020).

Standard culvert design is based on pipe flow hydraulics, data that are established by the annual discharge of the stream. Two issues with the design methodology are 1) stream process was not incorporated in the design, 2) the use of annual discharge often leads to culverts being undersized for large flow events. Stream process not being incorporated in the designs of culverts has led to them being barriers due to channel migration (sediment being washed out of the culvert, deposition of sediment that fills the channel that leads to a flatten channel). Since these culverts have not been designed to accommodate the stream process, some culverts are well above the water surface (Olsen and Tullis 2013; Behlke et al. 1991). The height between the culvert and water surface is, in some cases, so large that fish cannot make the jump into the culvert. The focus of the design was making sure the culverts could support the bankful discharge of stream. Large weather events are starting to become more frequent due to climate change because the increase in air temperature driven by warming correlates with a shift in snowmelt occurring earlier (Stewart et al. 2004; Siegel and Crozier 2019). Annual mountain snowpack continues to decline and is now melting faster than historic rates, which leads to peak flows occurring in the earlier spring months (Miles et al. 2000; Praskievicz 2016; Wilhere et al. 2017), and often larger and more frequent floods in the winter/spring. Precipitation in late winter and early spring is now more commonly in the form of rain which enters the stream already carrying runoff and can lead to rain-on-snow flood events (Praskievicz 2016). A high-water velocity can also lead to streambed material being washed out or the streambed flattened which can cause shallow flow depths. Increased stream velocity, increased sediment transport, debris buildup and blockage at the inlet, and the formation of scour pools at the outlet all become important metrics by which we can measure the impact of outdated culverts on fish populations over time. The Washington Department of Fish and Wildlife (WDFW) has developed a modeling tool that uses climate data to predict bankful flow/width for 2040 and 2080 and 100-yr flood to help with the design of fish passage structures (Wilhere et al. 2017).

The hydraulics of culverts are generally well-known, so, unlike dams, flow issues can be managed by following appropriate design guidelines, but there is minimal research on how to optimize the placement of material in the culverts to achieve the desired hydraulic and sediment mobility characteristic. There has been extensive work and research on the use of engineered structures to stabilize stream channels, but little of that research directly relates to culverts. In-stream structures can increase aquatic habitat, fish passage, grade-control, and stabilization of the bed and banks (Scurlock et al. 2011). Stream structure design should meet more than one specific objective such as grade control. It should also look at maintaining channel capacity and maintaining fish passage at all flows (Rosgen 2001). Bhuiyan et al. (2009) looked at the effects of instream structures such as vanes and w-weirs have on sediment transport in meandering channels. The construction of a w-weir did not affect the upstream streambed but created scour pools downstream. U and W shaped weirs are becoming popular choices because they often address more than one of the design objectives above (Galia et al. 2016). However, the most important point is that these studies focus on streams that were not in confined settings, such as being bound by levees, flood control structures, or culvert walls. To date, no substantial research exists on the dynamics of sediment transport and channel morphology within culverts.

1.2 Stream simulation design

The dynamics of a stream restricted to a culvert are different than that of free unimpaired channels in many ways, but a major factor is that the limited cross-section results in more rapid velocity changes with discharge and this affects every aspect of sediment transport. The goal of Stream Simulation Design (SSD) is to mimic the characteristics of the unimpaired reach within the culvert while providing a low flow channel for fish movement; essentially, maintaining "natural" stream morphology in culverts. The current stream simulation design process outlined in the Water Crossing Design Guidelines (WCDG) that the WDFW has developed contains 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). To date, there is no formal guidance in the third step for how the material is placed in the culvert so the channel shape will be maintained, and the process is largely trial and error in the field, which is a costly and risky approach to SSD.

The decision-making process for installing a culvert water crossing involves several considerations. WSDOT follows the WCDG, but the Hydraulic Manual developed by WSDOT has a detailed chapter (chapter 7) in the manual for working with fish passage projects that fills in the gaps of the WCDG. Chapter 7 walks through the measures that need to be taken when working on a fish passage project. Seven sections make up the chapter and they are as follows: existing conditions, hydraulic analysis, design, other design methods, temporary stream diversions, monitoring and additional resources. The existing condition (site assessment) discusses the information that needs to be gathered from the site (WSDOT Engineers 2019). A reference reach (the study of an unimpaired portion of the stream to be restored) is used to determine the unique geomorphology of the reach being investigated. The stream reach assessment provides the classification of the stream as a step-pool, plane-bed, or step-pool reach type. Important information such as bankfull width, longitudinal profile, and sediment distribution, among other factors, are unique to the location of the new crossing (Barnard et al. 2013; WSDOT Engineers 2019); Montgomery and Buffington 1998; Barnard et al. 2015) also contribute to site assessment. WCDG has two channel type scenarios. Scenario 1: slope less than four percent, which contains the classification of plane-bed, step-pool and dune-ripple; bed material can be mobile during flood events. Scenario 2: higher-gradient, step-pool, or cascade-type channel and slope greater than four percent (Maxwell and Papanicolaou 2001; Barnard et al. 2013). Refer to the WSDOT hydraulic manual chapter 7 for a more detailed information on their process of working with fish passage projects.

This study focuses on streams that fall within the definition of scenario 1 because they are more prone to channel migration and sediment transport due to the channel material naturally found in this stream classification; scenario 2 tends to be more incised channels with, primarily, episodic sediment transport. Structures that fall under scenario 1 are subject to the use of bands of coarse material (coarse bands) to control structure and cross-sectional shape of the channel. The bands of coarse material are lower in the center to keep the flow in the center of the channel and should not be closer than one channel width apart (Barnard et al. 2013). The purpose of the coarse band design is to decrease velocity, turbulence, and increase flow depths (Cenderelli et al. 2011) so that the material in the culvert does not wash out and keeps the channel in the middle third of the culvert (Barnard et al. 2013). Further, the individual designing the channel needs to review the slope and flow data to determine the size of the particles for the coarse band (Barnard et al. 2013). WCDG states that the size of the material should be one to two times the size of the D100 (the largest particle in the stream) but there have been no experiments to support firm minimum or maximum sizes, and no recommendations on the shape and size of the coarse band itself. For a meandering channel, the use of coarse material point bars (boulder bars) is a new technique that has been used. Boulder bars are point bars that are made of coarse material (sediment material equal or greater than the D100). The purpose of the boulder bars is to maintain a meandering channel, decrease velocity and create pools for fish habitat. Proper sizing and geometry of these elements are essential for the long-term durability of a stream simulation culvert because the material must be placed in the confined space inside the culvert. After construction is complete modifications to the streambed design are limited due to the use of equipment that requires additional disturbances to the channel and this is a costly and labor-intensive process if repeated annually, so low-maintenance, resilient designs could provide significant benefits to organizations like WSDOT.

1.3 Research objective

The WSDOT hydraulics manual states that coarse bands help form the structure and maintain the gradient and are applied to scenario 1 channel types from section 1.2 when they are built from sediment that is one to two times the largest particle found in the stream (Barnard et al. 2013). However, there are no clear guidelines for the layout of the coarse bands and no systematic research on the most effective methods to stabilize channels within culverts. Without scientifically based guidelines, the success or failure of an individual layout is an expensive trial and error process with the possibility that the culvert will, once again, become a fish barrier.

The objective of this project was to begin systematically evaluating the efficiency of different coarse band designs on sediment mobility and culvert hydraulics under different flow regimes to provide more rigorous design guidance for SSCs. The key research questions were divided into two cases: straight channels and meandering channels. The first set of hypotheses (H1) were for straight channels and are: H1.1) the addition of a single coarse band, similar to the desired stream channel cross section, will maintain the target channel shape in the vicinity of the coarse band; H1.2) increasing the number of coarse bands, while keeping them within 1-3 channel widths of each other, will expand the stabilized area and increase resilience for up to several 5 to 10-year flood events; H1.3) the addition of coarse bands that span half the channel width placed on alternating sides of the channel will decrease sediment transport while inducing meandering.

The second set of hypotheses (H2) were for a meandering channel and are: H2.1) the construction of alternating boulder bars (point bars) is sufficient to maintain a meandering channel shape throughout the structure; H2.2) increasing the spacing between boulder bars will maintain the channel profile across longer distance for up to a 10-year flood event when boulder bars are kept within 1-3 channel widths of each other.

The approach for evaluating these hypotheses was to build physical, scaled experiments in a laboratory flume, basing the SSC and flow regimes on a natural stream. A channel was constructed inside the flume and exposed to a range of flood events. The primary data 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. A variety of coarse bands were added to the streambed and the elevation change of each (surface) was compared to determine which coarse band layouts were the most effective at maintaining the channel shape.

CHAPTER TWO: METHODOLOGY

2.1 Albrook Hydraulics Laboratory

The experimental work was conducted at the R. L. Albrook Hydraulics Lab on the Washington State University Campus in Pullman, Washington. The lab houses a tilting flume that is 75-feet-long, 2.9 feet wide, and 1.75-feet-deep, allowing control over the discharge of the water and the slope of the bed. The flume was the primary research apparatus.

The hydraulic systems in the lab center around a 28,000-gallon water supply sump, located beneath the end of the flume. Water is pulled from the sump utilizing up to two pumps (40 hp & 20 hp), which can be operated in series to increase flow requirements. The larger pump brings water from the storage sump to a distribution manifold, where valves are used to direct the flow of water directly to the flume, or into the other pump as required. There were four water supply configurations for the flume used in this study. *Configuration one:* water is pumped from the sump into the central manifold and flows through a large gate valve into a holding tank where the water fills a 120 ft^3 equalizing reservoir before spilling over a 5-foot-tall sharp crested weir. A 25 hp pump draws water from the bottom of the equalizing reservoir and is sent to the flume. The pump has a globe valve attached to the outflow that regulates flow out of the pump, and a butterfly valve is located off a tee about 3 ft. past the globe valve to be used as a bleed off to reduce the flow delivered to the flume. Both valves are used in tandem to regulate the flow in the flume as needed. An 8-inch diameter pipe runs to the top of the flumes. This configuration provides discharges from 0.46-0.95 ft^3/s (see red arrows in Figure 1 for arrangement). *Configuration two:* water is pumped from the sump into the central manifold. The large gate valve leading to the holding tank is closed. A 3-inch diameter pipe that runs to the top of the flume is connected to the central manifold. A gate valve located about 3 ft. from the central manifold is used to directly control the flow in the flume (see black arrows in Figure 1 for arrangement). *Configuration three:* this configuration combines both systems with the large gate value opened twelve revolutions and the bleed off valve located on the 40 hp pump supply line, before the manifold, half-open. This arrangement provides enough pressure for the 3-inch diameter pipe and keeps the equalizing reservoir full of water while supplying a flow of 2.9 ft^3/s through the flume. *Configuration four:* is the same as third except that the bleed off located on the 40 hp pump supply line is closed. This configuration delivers 4.2 ft^3/s to the flume, which is the maximum for the current plumbing.

The reported flows were calculated at each configuration by using a sharp crest weir using Eq. 1, where Q= discharge, b=width of a weir, g= gravity, H_2 = height of water behind the weir, H_1 = height of weir, and C_d= weir coefficient. Table 1 shows the values used in the discharge calculation.

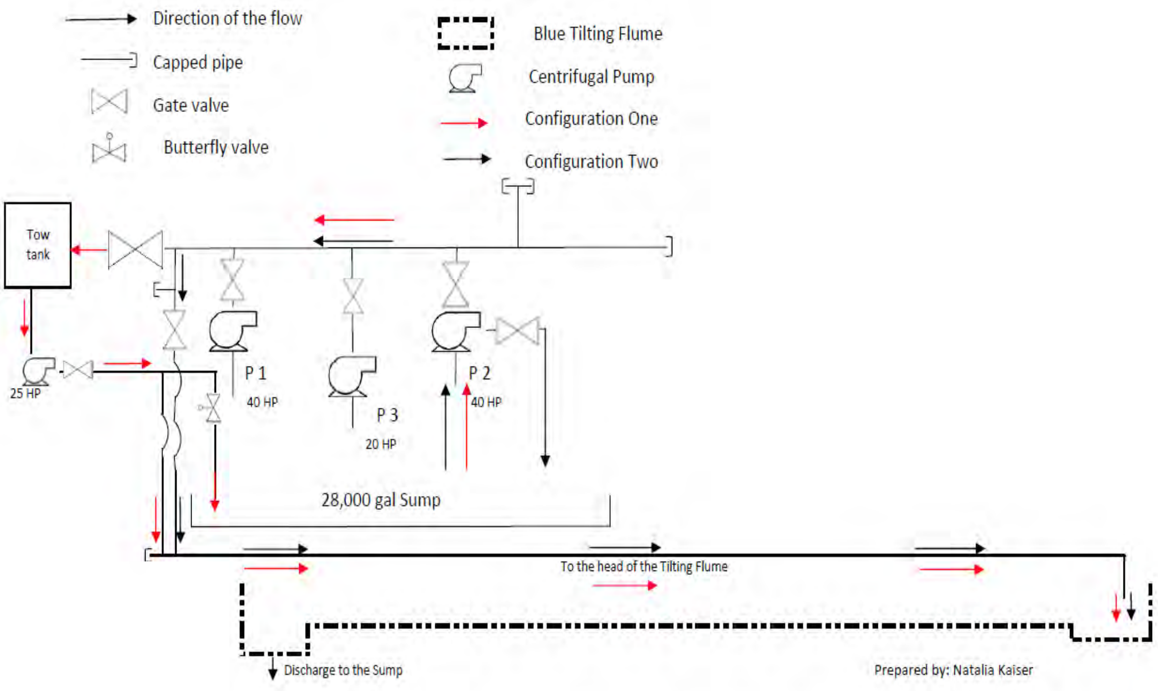


Figure 1 - Pipe Diagram that supplies water to the tilting flume. The red arrow is the flow path for configuration one and the black arrows are in configuration two. The third configuration is the combination of the first two.

$$Q = \left(\frac{2}{3}\right) * C_d * b * (2 * g)^{\frac{1}{2}} * (H_2 - H_1)^{\frac{3}{2}} \qquad \text{(Eq. 1)}$$

Table 1. Values used for calculation in Eq.6

Pipe Configuration	Cd	b (ft)	g (ft/s)	(h2-h1) (ft)	Q (cfs)
1	0.61	2.69	32.2	0.14	0.46
2	0.63	2.69	32.2	0.22	0.97
3	0.66	2.69	32.2	0.42	2.58
4	0.68	2.69	32.2	0.57	4.2

2.2 Asotin creek

The reference stream used for this study is Asotin Creek flowing through Asotin, WA, in the southeastern corner of the state (see Figure 2). The reference stream provided grain size distributions and flow statistics that could be scaled in the laboratory simulations. Asotin creek was chosen because: 1) it allowed a simple linear scaling between the grain size (i.e. lengths) of the physical system and common, commercially available gravel mixtures, and 2) its scaled flow range was within the capabilities of the hydraulics laboratory. A 5.7:1 scaling of field to lab units was applied to the length units for the experiments. Asotin County is dominated by agriculture land-use practices that include cattle grazing and dryland farming. The climate is semi-arid with the valleys receiving less than 0.98 feet of precipitation and the high elevation areas seeing over 3.74 feet annually (Bennett et al. 2018). The watershed is characterized by three geologic attributes: 1) the Columbia River Basalt group forms the plateaus and the uplands; 2); a network of streams flowing through the steep canyons down to the Snake

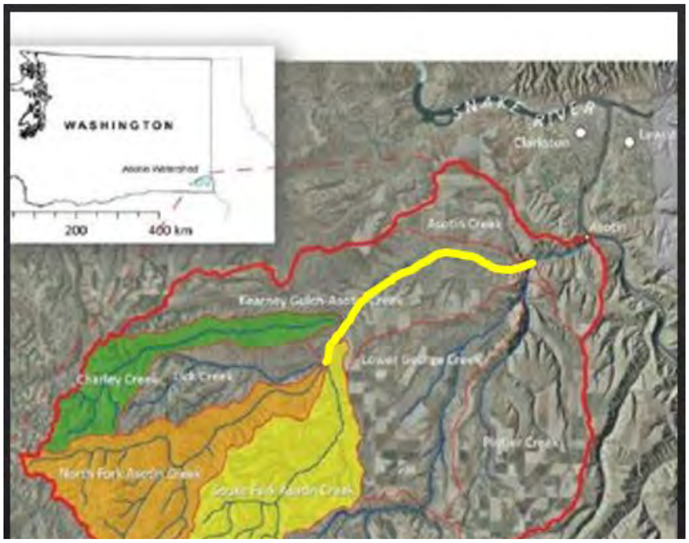
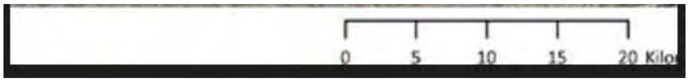


Figure 2. Asotin watershed outlined in red is in the south east corner of Washington State. Asotin creek is outlined in yellow.



River: and 3) the Snake River is the bottom of the watershed. The fish-bearing streams are small to medium size. The mean substrate (D50) for the South Fork and North Fork of Asotin Creek were calculated using the Wollman pebble count method which obtained values of 2.5 inches and 2.9 inches (Bennett et al. 2018). (Appendix B shows the sediment distribution curve used in the laboratory).

USGS gauge station 13334450 on Asotin Creek below the confluence of the North and South Forks was used to determine flood intervals. In the water year of 2017, flows were as low of 21 ft^3/s and a high of 692 ft^3/s, with the average being 76 ft^3/s (USGS Gauge). The record of peak discharge at this gauge station was entered into Frequency Curves Analyzer version 306 (Figure 3) to provide the flow discharge for flood events required for our simulation testing (Table 2b for values). A flow duration curve is a logarithmic function graph. The blue line in Figure 3 is the line of best fit for Q at the gauge station for flood return interval. The top red line is Q5 and the bottom red line is Q95 which correspond to the discharge percentile of the flow duration curve. The scaled lab flows were kept within Q5 and Q95.

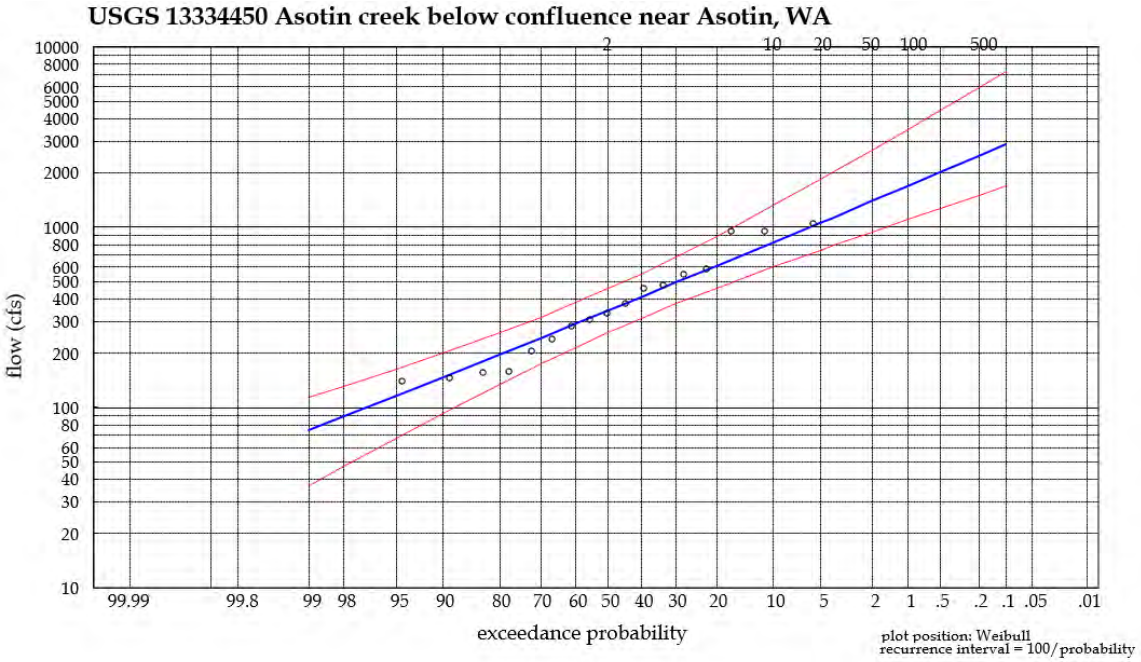


Figure 3 Flood Frequency curvy of Asotin creek. The top red line is the 5th percentile and the bottom line is the 95th percentile. The flows were kept between these two lines.

Table 2. Flood recurrence values of Asotin Creek below the confluence.

recurrence (years)	Q (cfs)	Q5 (cfs)	Q95 (cfs)
1.01	75	114	37
1.5	258	338	187
2	345	456	261
2.5	409	552	313
3.3	489	681	374
4.5	581	842	440
5	609	894	460
6	673	1015	504
7	723	1114	538
10	822	1317	602

2.3 Laboratory methods

The general approach used in this study was to create streambeds within the flume and subject them to various flows based on the reference stream. The streambeds were initially simulated without any coarse bands to establish their baseline performance, then different

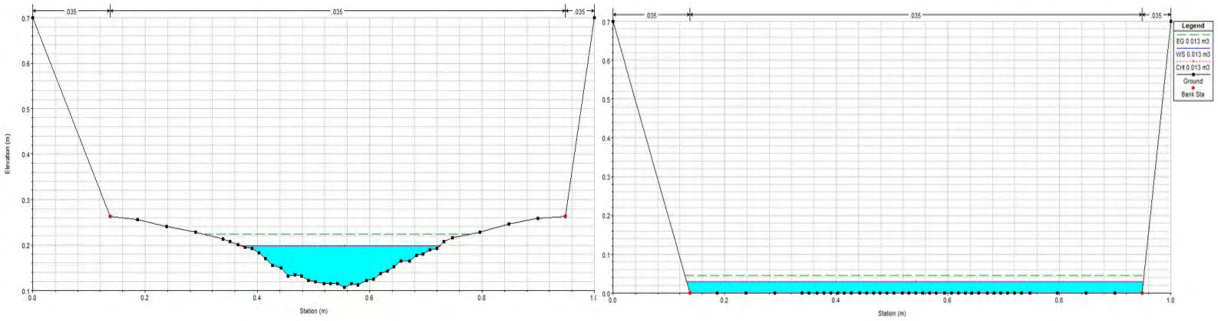


Figure 4 The figure on the left is a u-shape channel and the figure on the right is a channel that has a flat bottom. Both channels show the water depth for a flow of 0.013 cubic meters per second. The depth of water is significantly higher with the u-shape channel during this flow event. This deeper channel clearly provides the better setting for fish to migrate at this flow.

streambed configurations were tested to evaluate their effectiveness. Detailed descriptions of all the scenarios are included in the following sections and results are provided in Section 3.

A short overview of the experimental process was as follows: 1) a flat, uniform streambed was initially constructed in the flume, 2) a u-shape channel was excavated in the center of the streambed, the removed material redistributed evenly along the sides, and lightly compacted, 3) if required for the layout, coarse bands were added by excavating the streambed material in the location they were placed, placing the coarse material, then carefully backfilling around the band to ensure a continuous streambed. After these setup steps, sediment transport was quantified using cross-section measurements taken at eleven locations along the flume, and the flume was run at each discharge for an interval of 30 minutes. Flows were gradually increased and decreased to prevent abrupt shifts of sediment as the channel was emptied (or refilled) so that precise measurements could be made. After the final measurements were taken for a particular streambed configuration, the coarse bands were removed, the streambed design was re-created, and two replicates of the experiment were conducted before moving on to the next 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, evaluated at each cross-section.

Streambed construction proceeded with a flat sediment bed to a depth of 9-inches. A straight U-shape channel approximately 3-inches deep in the center and 18-inches wide was built in the middle of the streambed to provide a low flow section for fish movement (Figure 4). The material removed when constructing the U-shape was placed on the channel sides to increase channel depth so total channel depth was about 6-inches (precise measurements provided in the cross sections), providing a smooth channel profile. The middle 10 ft of the total 24 ft length of the experimental streambed was the focus area of the study. This section was selected to avoid any boundary effects as much as possible. If the study section were closer to either end, there could be more erosion or deposition due to the high forces as water enters and exits the streambed test section. At the downstream end of the simulated streambed, vertical metal bars were placed to impede water and create an upstream force to keep the overall streambed in place; gaps between the bars were wide enough (1 inch) to pass the D100 of the stream material so sediment mobility was not prohibited. Coarse bands were added after the U-channel was created and the locations depended on the particular scenario being considered.

Cross-section profiles were collected at one-foot intervals in the study section. Forty-one measurements were taken across the streambed for each cross-section profile. The measurement locations across the channel were spaced as follows: 2 inches spacing between stations 1-5 & 37-41 and 1/2 inch spacing between stations 5-37. The measurements were taken to 1/16th inch with a ± 1/32-inch precision. This data collection scheme reduced the workload in the area that exhibited less transport to increase efficiency. Three flow scenarios were used: 1) baseflow 1.5-year flood event; 2) a 2.5-year flood event; and 3) a 5-year flood event (Figure 5 shows the flood

Run 1
Baseline- 1.5-year flood

Run 2
2.5-year flood

Run 3
5-year flood

Run 4
10-year flood

Figure 5 Shows each flood event in the study section. The figure on the far left shows the channel during run 1. The middle figure shows the flow in the channel during run 2. The flow has filled the U-shape channel. The figure on the right is run 3 in the channel. This final run has submerged the whole channel and extends up the side of the flume.

events in flume); 4) a 10-year flood event. The fourth flow (a 10-year flood event) was not used during the two percent slope because of plumbing issues; however, these were resolved for the remaining runs.

Each of the three flow conditions was executed for 30 minutes for a total flow event of 1.5-hours. The time frame of 30 minutes was used because our initial observation of the streambed changes in the flume indicated that maximum movement happened during this time frame. A longer time interval did not demonstrate significant changes in the rates of movement of bed material. Cross-section profile measurements were collected before the first run, then after each run; this procedure took about 25 minutes per set of measures. Pictures were taken after each run to visually capture the changes for each flow event and after the final high flow run. After the final data collection, the experimental streambed was reset following the same procedure already described. Each trial took approximately seven hours to complete.

2.3.1 Straight Channel

2.3.1.1 Two Percent Slope

The experimental design used a straight U-shape channel as the reference geometry of the stream channel and six different coarse band layouts were evaluated. A U-shape channel was chosen since it is advantageous for low discharge events because the channel depth will be greater than a flat bottom but is also simpler to build and maintain than other cross sections like a triangular channel. Layouts in Table 3 refer to how the specific streambeds were configured; for example, Layout 0 (the base-case) is configured differently from Layout 3. The experimental setup was designed to mimic the addition of a box culvert to the reach of a stream such as Asotin Creek.

The number of coarse bands tested were four, three, two, and one, spaced between one and three-channel widths apart (see Table 3 for detail). The coarse bands were placed perpendicular to the flow of the water, and the cross-sectional structure of the coarse bands were designed to mimic the cross-section of the desired streambed channel (i.e., u-shape, see Appendix A). The design of the coarse band was taken from a stream structure referred to as a Cross Vane. The plan view of a Cross Vane looks like an upside-down “U” (Figure 6), but structure follows the channel geometry in the cross-section view. Cross Vane shapes are used for grade control, bank erosion, entrenchment ratio, and moving the velocity from the banks to the center of the channel (Rosgen 2001). The expected change to the velocity is a decrease due to the presence of the larger material in the coarse band, which increases the drag force. The reduced velocity is likely to lead to a lower sediment transport rate, thereby building a stable channel bed (Church et al. 1998). Importantly, small particles can still be transported downstream, but the upper range of the sediment distribution (coarse) will generally stay in place, allowing some natural sediment migration over the coarse bands while maintaining the simulated streambed within the culvert. The major difference between our experimental coarse band(s) design and the cross vane is that they do not extend upstream. In a plan view they look like a straight line across the channel (Figures 7 and 8). Undersized culverts are a confined area with limitations (length and width), which lead to having little room for structures designed for a natural stream channel. The replacement of the cross vane with a course band(s) reduces the amount of material needed and time of construction. Placing the coarse band(s) in a straight line across the channel has multiple benefits; they may be constructed after the channel is built, which facilitates mimicking the channel shape and no limit to the number of coarse band(s) being applied to the culvert. Both designs provide a similar function to channel hydraulics, but the coarse band(s) are more cost effective compared to u-shape cross vanes. The plan view of a cross vane vs. coarse band(s) shows more material is needed for construction of a cross vane.

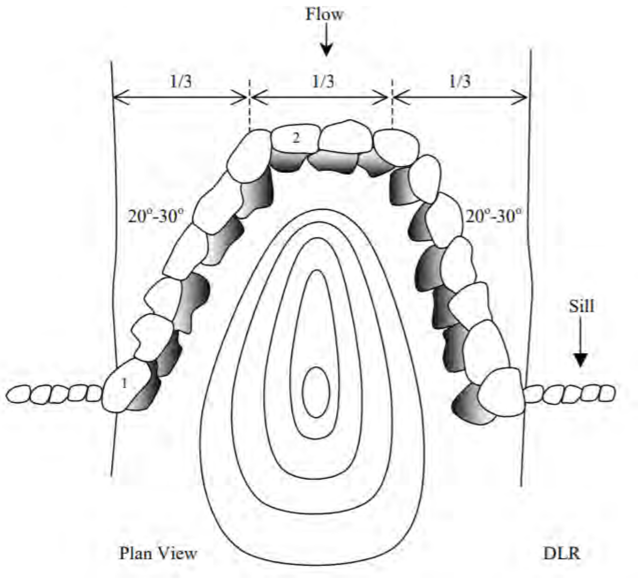


Figure 6 Plan view of a Cross Vane from (Rosgen 2001)

Table 3 Inventory of the experimental runs (Layouts) that were tested in this study for straight channels.

Layout Number	Description
2% slope straight channel - U-shape cross section	
0	Baseline - no coarse band(s)
1	One coarse band(s)
2	Two Coarse band(s) spaced one channel width apart
3	Two Coarse band(s) spaced two channel widths apart
4	Two Coarse band(s) spaced three channel widths apart
5	Three coarse band(s) spaced one channel width apart
6	Four coarse band(s) spaced one channel width apart
3% slope straight channel - U-shape cross section	
7	Baseline - no coarse band(s)
8	Two coarse band(s) spaced three channel widths apart. Coarse bands are made with D200 material.
9	Two coarse band(s) spaced three channel widths apart. Coarse bands are made with D250 material.
10	Three coarse band(s) spaced one channel width apart. Coarse bands are made with D250 material.
11	Three coarse band(s) spaced one channel width apart. Coarse bands are made with D250 and are level with the surrounding streambed.
12	Two coarse band(s) spaced two channel widths apart. Coarse bands are made with D250 and are level with the surrounding streambed.
13	Two coarse band(s) spaced three channel widths apart with bowtie (A) design located on downstream side of coarse band(s). Coarse bands are made with D250 material and bowtie (1.0) is an armoring layer made of D200 material.
14	Two coarse band(s) spaced three channel widths apart with bowtie (B) design located on downstream side of coarse band(s). Coarse bands are made with D250 material and bowtie (2.0) is two layers made of D200 material.
15	Two coarse band(s) spaced two channel widths apart with bowtie (A) design located on downstream side of coarse band(s). Coarse band(s) are made with D250 material and bowtie (1.0) is an armoring layer made of D200 material.
16	Two coarse band(s) spaced three channel widths apart with bowtie (C) design located on downstream side of coarse band(s). Coarse bands are made with D250 material and bowtie (3.0) is a mixture of D200 and streambed material.
17	Three coarse band(s) spaced one channel width apart with bowtie (A) design located on downstream side of coarse band(s). Coarse bands are made with D250 material and bowtie (1.0) is an armoring layer made of D200 material.
18	Three coarse band(s) spaced one channel width apart with bowtie (C) design located on downstream side of coarse band(s). Coarse bands are made with D250 material and bowtie (3.0) is a mixture of D200 and streambed material.

19	Four coarse band(s) spaced one channel width apart with bowtie (A) design located on downstream side of coarse band(s). Coarse bands are made with D250 material and bowtie (1.0) is an armoring layer made of D200 material.
4% slope straight channel - U-shape cross section	
20	Baseline - no coarse band(s)
21	Three coarse band(s) spaced one channel width apart with bowtie (A) design located on downstream side of coarse band(s). Coarse bands are made with D300 material and bowtie (1.0) is an armoring layer made of D250 material.
22	Three coarse band(s) spaced one channel width apart with bowtie (A) design located on downstream side of coarse band(s). Coarse bands are made with D300 material and bowtie (1.0) is an armoring layer made of D250 material. The furthest coarse band downstream has an armoring T-Funnel layer made of D300 material.
23	Three coarse band(s) spaced one channel width apart with bowtie (A) design located on downstream side of coarse band(s). Coarse bands are made with D300 material and bowtie (1.0) is an armoring layer made of D250 material. The furthest coarse band downstream has an armoring box layer made of D300 material.
24	Three coarse band(s) spaced one channel width apart with bowtie (A) design located on downstream side of coarse band(s). Coarse bands are made with D300 material and bowtie (1.0) is an armoring layer made of D250 material. The furthest coarse band downstream has an armoring U-shape layer made of D300 material.
25	Three coarse band(s) spaced one channel width apart with bowtie (A) design located on downstream side of coarse band(s). Coarse bands are made with D300 material and bowtie (1.0) is an armoring layer made of D250 material. The furthest coarse band downstream has an armoring box layer made of D300 material.
2% slope straight channel - U-shape cross section Alternating Coarse band(s)	
38	Two coarse band(s) spaced one channel width apart.
39	Two coarse band(s) spaced two channel widths apart.
40	Two coarse band(s) spaced one channel width apart.
41	Three coarse band(s) spaced one channel width apart.
42	Four coarse band(s) spaced one channel width apart.

The particle size of the material used for the coarse bands was D150 (1.5 inches). The area of sediment removed for the coarse bands was 2-3 particle diameters wide and had a depth of 2 particle diameters below the streambed elevation in the center of the channel; extending deeper did not affect stability but we recommend going deeper than this to prevent out washing from below (which occurred in some later experiments). Coarse band material replicated the channel shape and were situated above the streambed material 1.5-2 particle diameters (Figure 7). The elevated “lip” on the coarse bands was included to help create step-pool sequences and to reduce early sediment transport from any initial bed instability. On average, the construction of a streambed took about 1.5 hours to build with two people working.

Figure 7 Coarse band design that replicates the channel shape and sits about the streambed 1.5-2 particle diameters.

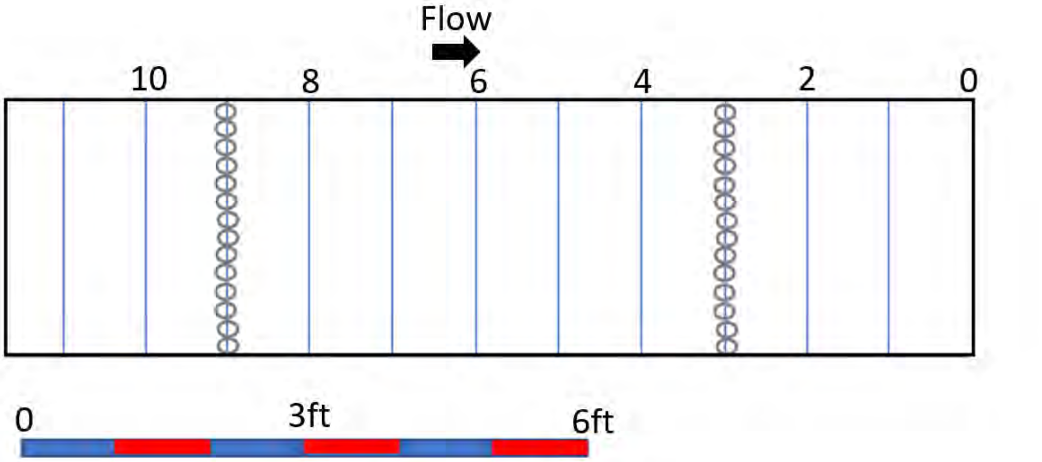


Figure 8. The location of the cross-section where the measurement is collected. The cross-sections are evenly spaced one foot apart. This is a plan view of Layout 3.

2.3.1.2 Three percent Slope

The next set of experiments repeats the previous section but at a higher bed slope of 3%. The procedure was identical: the U-shape channel was constructed, the location of the coarse bands is determined based on the trial/layout, excavated, and appropriately sized material placed. The particle size material used for the coarse bands is the D250 (2.5 inches); the larger size relative to the 2% case was necessary due to the higher velocities (see section 3 for details). The area of sediment removed for the coarse bands was 2 particle diameters wide and had a depth of 1-2 particle diameters below the streambed elevation in the center of the channel. Coarse band material mimics the channel shape and sits flat to the streambed material. Erosion on the downstream side of the coarse band was observed, caused by the velocity of the water flowing over the coarse band(s). To reduce the erosion of the streambed material a "bowtie" design was developed. The design looks like the bottom half of a bowtie (Figure 9), which provides the sides of the channel protection from the high velocity of the water flowing over the coarse band(s) and funnels the flow into the center of the channel. The bowtie had three designs: (A) was D200 particles laid over the streambed material to form an armor layer; (B) was two armor layers of

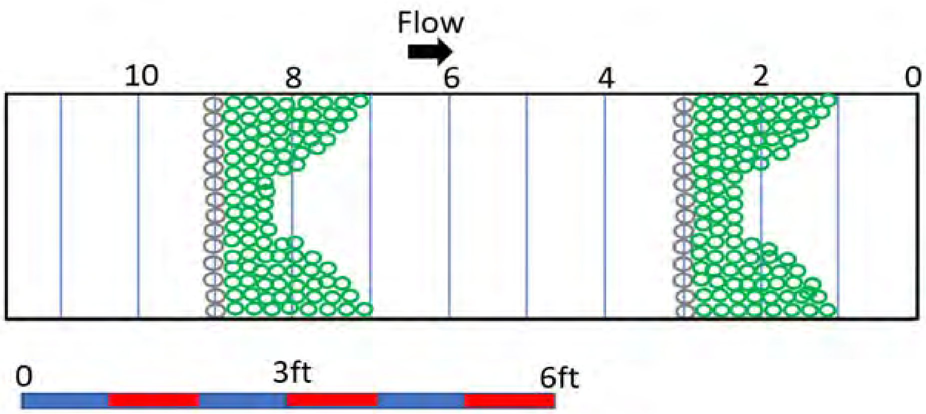


Figure 9 Bowtie design is located on the downstream side of coarse bands and its cross-section mimics the target channel shape.

D200 particles; and (C) was D200 particles mixed with the streambed material. On the downstream side of the coarse band sediment was removed in the shape of the bottom half of a bowtie to one particle diameter below the coarse band (see figure 9). The bowtie had a length of 2/3 of a channel width on the sides of the flume and 1/3 of a channel width in the center. The center of the bowtie had a width of 3 particle diameters. Particles were placed in an arc to the sides of the flume. Figure 10 shows an example layout of the bowtie configuration. The material used in the construction of the bowtie is D200 and additional details are given in sections 3 and 4. On average, the construction of a streambed took about 1.5 hours.

Figure 10 Bowtie design is an armoring layer that replicates the channel shape. The bowtie uses the D200 particle size.

2.3.1.3 Four percent Slope

The next set of experiments further increased the bed slope to 4%, retaining the bowtie design outlined in the previous section since it outperformed the straight coarse bands (see Section 3.1.2). The material used for this design was D300 for the coarse bands and D250 for the bowtie since the velocities are much higher in these scenarios. In initial runs, the coarse band and bowtie at the bottom of study section experienced significant erosion, which led to the failure of the coarse band. Three designs were tested to replace the bowtie design and reduce the erosion of the coarse band. These designs were constructed with D300 material. The first was a T-funnel, just like the name it looks like a funnel in plan view (Figure 11). The center of the T-funnel was three particle diameters wide and 2/3 of a channel wide long downstream, on the side of the flume the funnel extends three particle diameters downstream and particles are placed in a concave arc to join the sides to the center of the T-

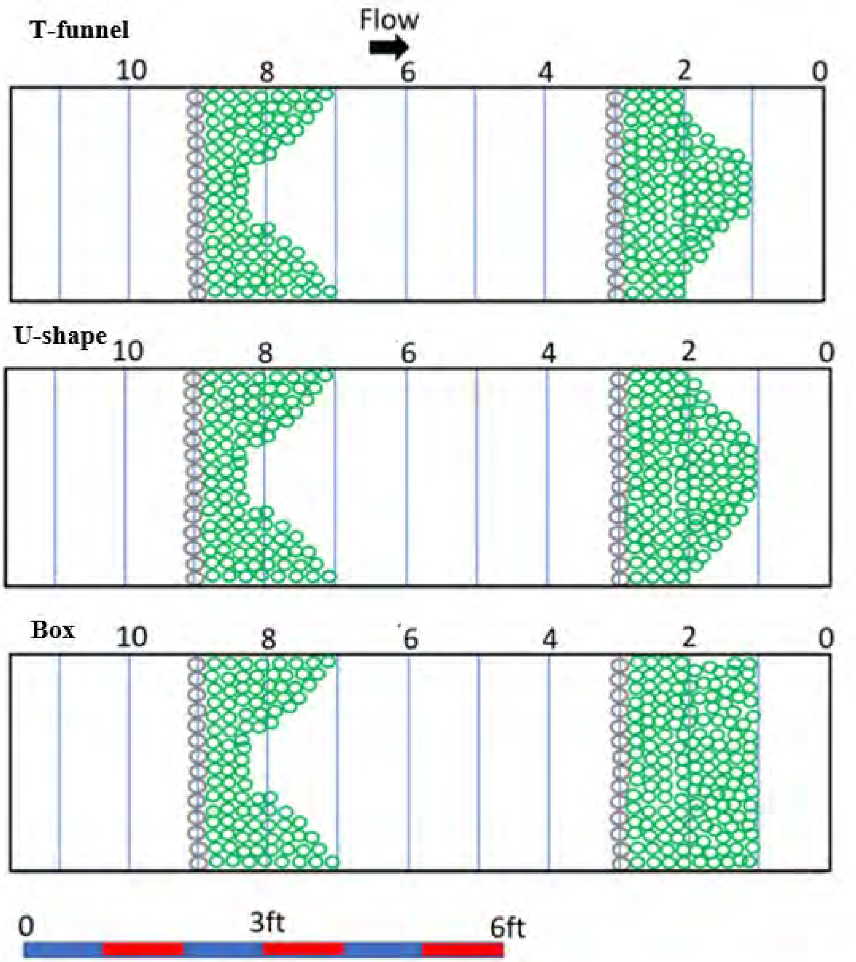


Figure 11 The top figure shows the T-funnel at the downstream coarse band. The middle figure shows the U-shape at the lowest coarse band and the bottom figure shows the box design below the downstream coarse band.

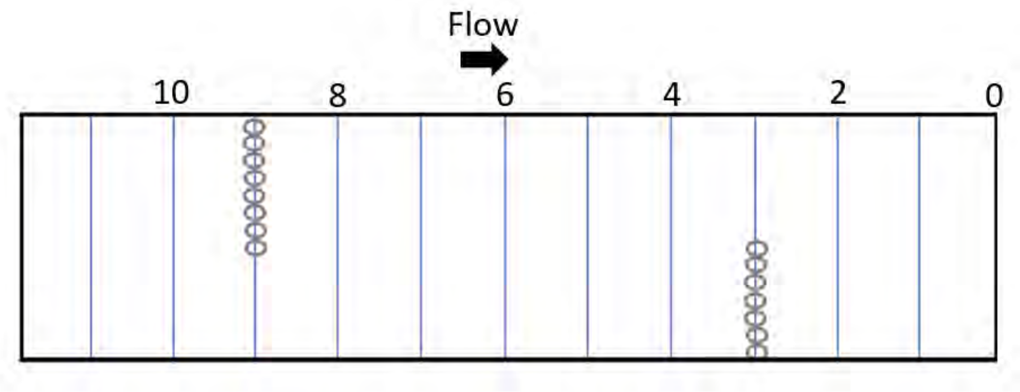


Figure 12 Plan view of alternating coarse bands that are spaced two channel widths apart.

funnel. The second design was a u-shape, this design followed the construction of the T-funnel but the arc to the side of the channel was convex (Figure 11). The final design that was tested was a box. An armoring square box layer of material is placed over the channel downstream of the coarse band (Figure 11). This design focused on reducing the velocity of the water flowing over the coarse band and reducing the erosion of streambed material.

Figure 13 Construction of boulder bars spaced three channel widths apart.

2.3.1.4 Alternating Coarse bands

The last permutation of coarse band layouts was an alternating configuration using the same designs as the two percent slope. The alternating bands were made from the D150 material, had a depth of 2-particle diameters below the streambed elevation in the center of the channel, a width of 2-3 particle diameters, and their finished height was 1.5-2 particle diameters above the streambed. However, unlike previous layouts, the coarse bands only extend halfway across the stream channel (Figure 12). The coarse bands were place on alternate sides from each other to help form a straight channel into a meandering channel over time. The spacing between the coarse bands and the number of coarse bands were both examined in the experimental trials.

2.3.2 Meandering Channel

The next set of experiments focused on a meandering, U-shape channel, like that described in the previous section; however, here the meander is created manually whereas in 2.3.1.4 an initially straight channel was used to induce meandering. Note that these are small

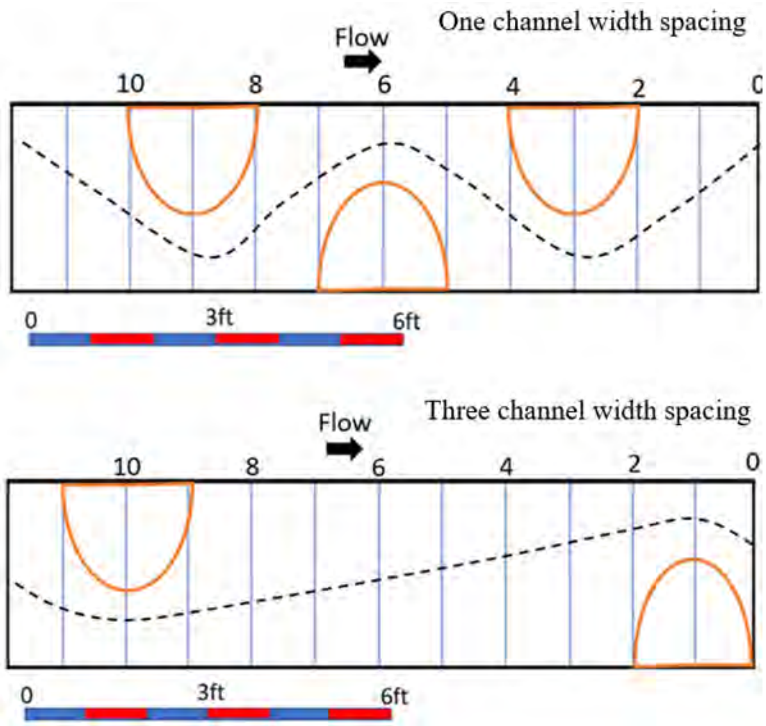


Figure 14 The top figure is a plain view of boulder bars spaced one channel width apart. The bottom figure is boulder bars that are spaced three channel widths apart. The dashed line is the center of the U-shape channel.

meanders given the limited cross-sectional width of the flume. The meandering channels have a tendency of becoming flat. With a flat channel fish are not provided with a significant water depth to move through during a low flow evet. The use of coarse band(s) designs from the straight channel section would lead to erosion of streambed material on the downstream side of the point bars. To ensure the point bars would not see a significant amount of erosion boulder bars were used. The boulder bars were made up of D200-300 material and extend slightly past half the channel width and had a length of 2/3 of a channel width along the flume wall. The height of the boulder bars at the flume wall were four particle diameters. Figure 13 shows the construction of a boulder bar. The boulder bar's purpose is to keep a meandering channel throughout the culvert. The sinuosity of the channel changes depending on the layout being looked at. Description of the layouts tested can be found in table 4. For example, the sinuosity of a channel with three boulder bars at one channel width is larger than a channel with two boulder bars at three channel widths. Two channel types were investigated in this research: 1) one channel width spacing between boulder bars, and 2) three channel widths spacing between boulder bars (Figure 14). Two channel widths spacing could not be examined due to time constraints.

Table 4 Inventory of the experimental runs (Layouts) that were tested in this study for the meandering channels.

Layout Number	**Description**
4% slope Meandering channel	
26	Boulder bars spaced one channel width apart. Boulder bars are made of D200-D300 mixture of material.
27	Baseline- three channel widths spacing
28	Boulder bars spaced three channel widths apart. Boulder bars are made of D200-D300 mixture of material.
29	Baseline- one channel width spacing
3% slope Meandering channel	

30	Boulder bars spaced three channel widths apart. Boulder bars are made of D200-D300 mixture of material.
31	Boulder bars spaced one channel width apart. Boulder bars are made of D200-D300 mixture of material.
32	Baseline- one channel width spacing
33	Baseline- three channel widths spacing
2% slope Meandering channel	
34	Baseline- one channel width spacing
35	Baseline- three channel widths spacing
36	Boulder bars spaced one channel width apart. Boulder bars are made of D200-D300 mixture of material.
37	Boulder bars spaced three channel widths apart. Boulder bars are made of D200-D300 mixture of material.

2.4 Sediment transport Estimation

The cross-section data were analyzed with the assistance of the MATLAB programming environment. Baseline channel stability and sediment transport information of the streambed without coarse bands was gathered to provide data for evaluating cross-sectional area changes and sediment transport. To calculate the difference in the area, the cross-sectional area after a flow event was subtracted from the initial cross-sectional area. The change in area at each cross-section was integrated to obtain the area changed for the total streambed. This number was also converted into a percent of area changed. Figure 15 is a flow chart showing how the difference in area was calculated. The migration of the channel shape over the flow state provides detailed information about where sediment is deposited and eroded during its transport. The volume and channel shape are compared with the results gathered when coarse bands were added to the experimental streambed. A key point is that all transport data are expressed relative to the baseline (no coarse bands) scenario, so positive percent reductions mean the coarse bands give a performance advantage with greater percentages giving 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 (Figure 16).

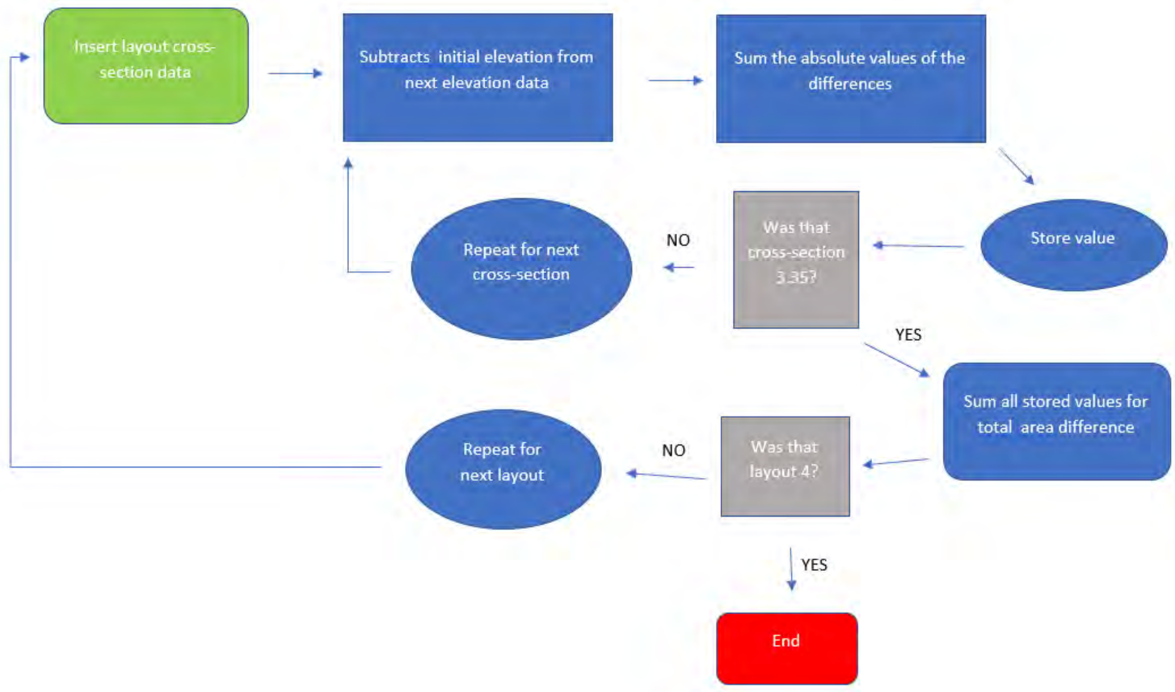


Figure 15. A flow chart of the calculations for the cross-sectional area difference for each flood event.

CHAPTER THREE: RESULTS

This chapter describes the results of each section separately following the order outlined in section 2.3.

3.1 Straight Channel results

The results for straight channels with fully spanning straight or linear coarse bands are organized by the bedslope of the flume used for the tests. These are 2%, 3% and 4% slopes.

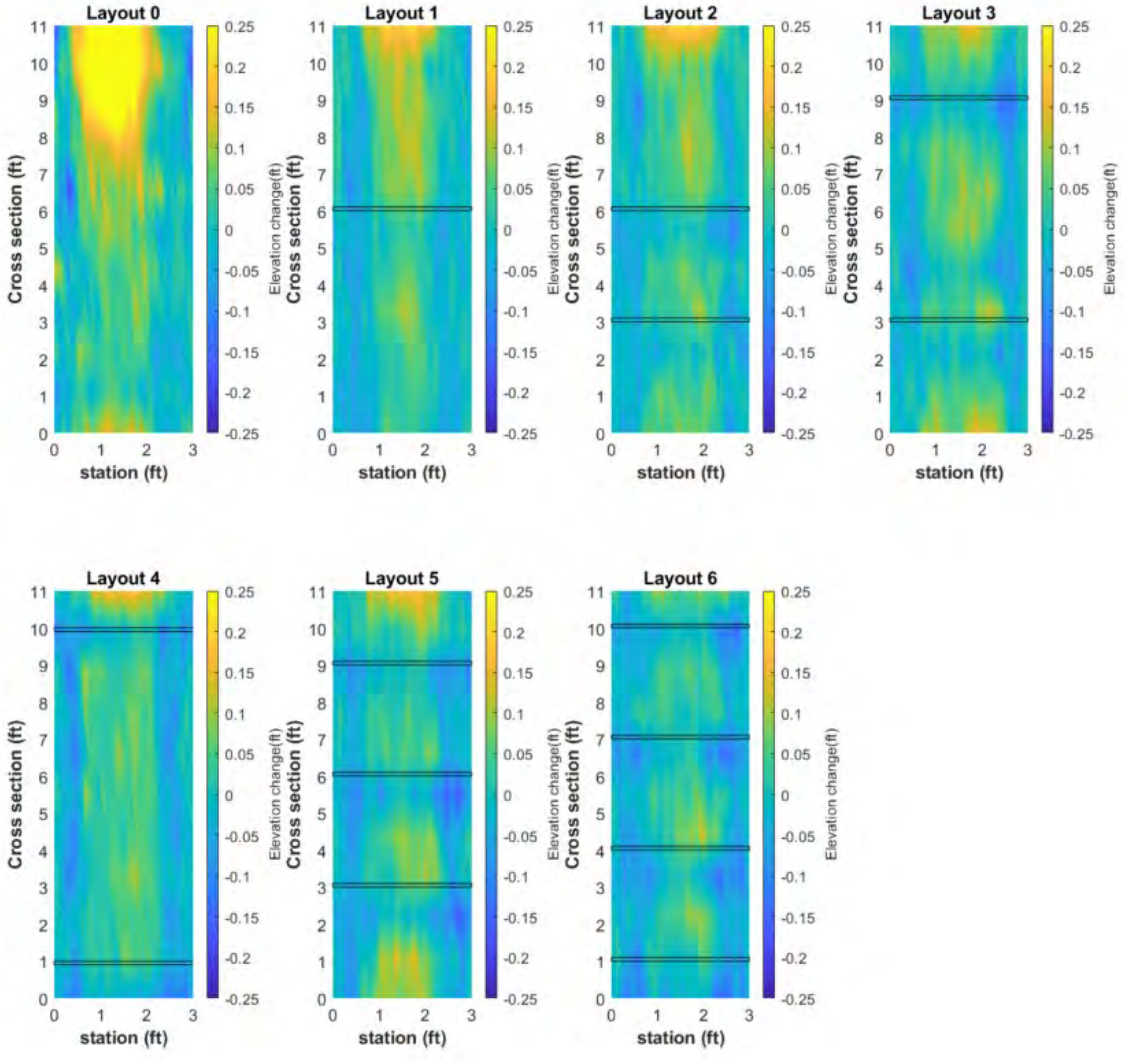


Figure 16. The elevation difference between the baseline streambed and the streambed after a five-year flood event. The black rectangles show the location of coarse bands in each layout. Layout 0 in the upper left shows a mass of sediment traveling down the center of the channel. The other six graphs show the mass of sediment transported is reduced due to the addition of coarse bands. Each layout shows there is erosion on the sides of the channels and downstream of the coarse bands. The center of the channels has a mixture of deposition and a minimal erosion.

Included after these is a 2% case with partially spanning, alternating coarse bands. Recall that each layout represents the averaged behavior over three experimental trials.

3.1.1 Two Percent Slope results

Addition of coarse bands in a straight U-shape channel reduced sediment transport and maintained channel shape. At a five-year flood event layout 0 had a mass of sediment moving down the center of the channel as shown Figure 16 as layout 0, which shows the difference in streambed elevation between the baseline and the five-year flood event plotted in a color map; deposition occurs for positive values. The addition of coarse bands reduced the mass and sediment moving down the center of the channel and erosion on the side of the channel. Layout 0

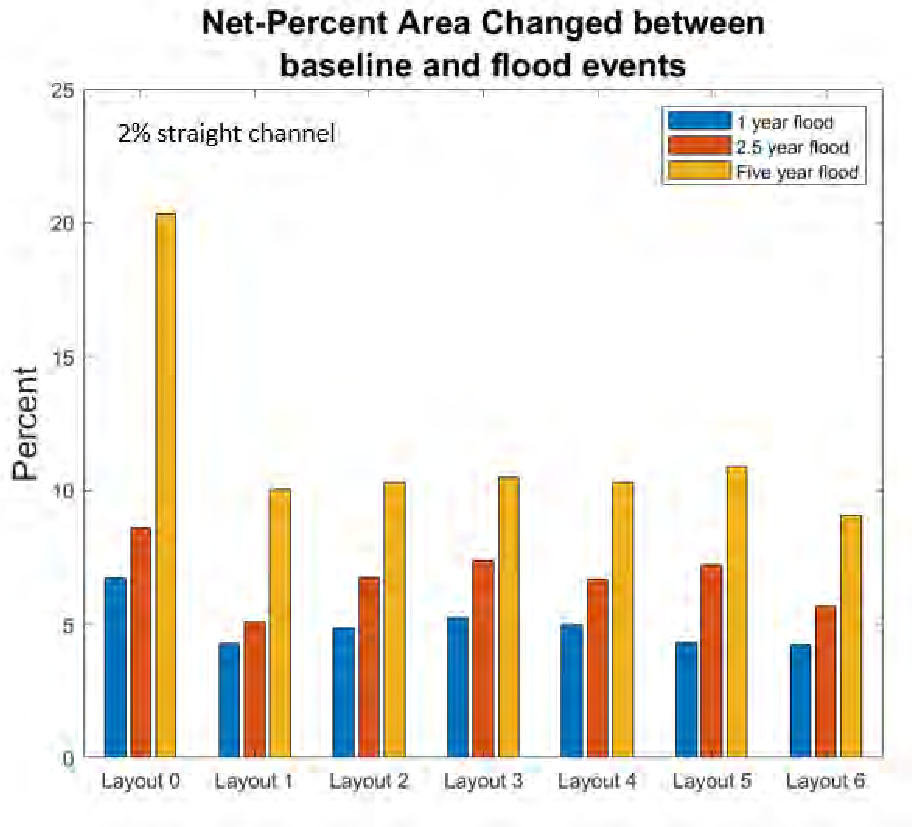


Figure 17. The percent difference of cross-sectional area changes between baseline elevation and each flood event for every layout. Layout 0 shows that a five-year event will significantly change the observed channel. With the addition of coarse bands, the channel will have about half the change of Layout 0. There is difference of about 3 percent between the lowest and highest percent cross-sectional area changed for the coarse band layouts.

had the largest net percent cross-section area change and layout 6 (four coarse bands spaced one channel width apart) had the lowest change (Figure 17). It is clear from Figure 17 that there was only small variability among the different layouts in terms of net mobility, but it should be noted that there were different patterns of change associated for each layout shown in Figure 16. Layouts 5 and 6 created the most ideal patterns for step-pool sequences.

Sediment transport reductions from the addition of coarse bands did lead to the channel shape being maintained better relative to layout 0 in all cases. Figure 18 shows an example comparison of the baseline cross-section in blue and the cross-section after a five-year flood event in red. The water heights are associated with the cross-section of the five-year flood. The graph on the top in Figure 18 is Layout 0, showing that the channel became flat due to deposition in the center of the channel. The graph on the bottom in Figure 18 is layout 4, showing that the

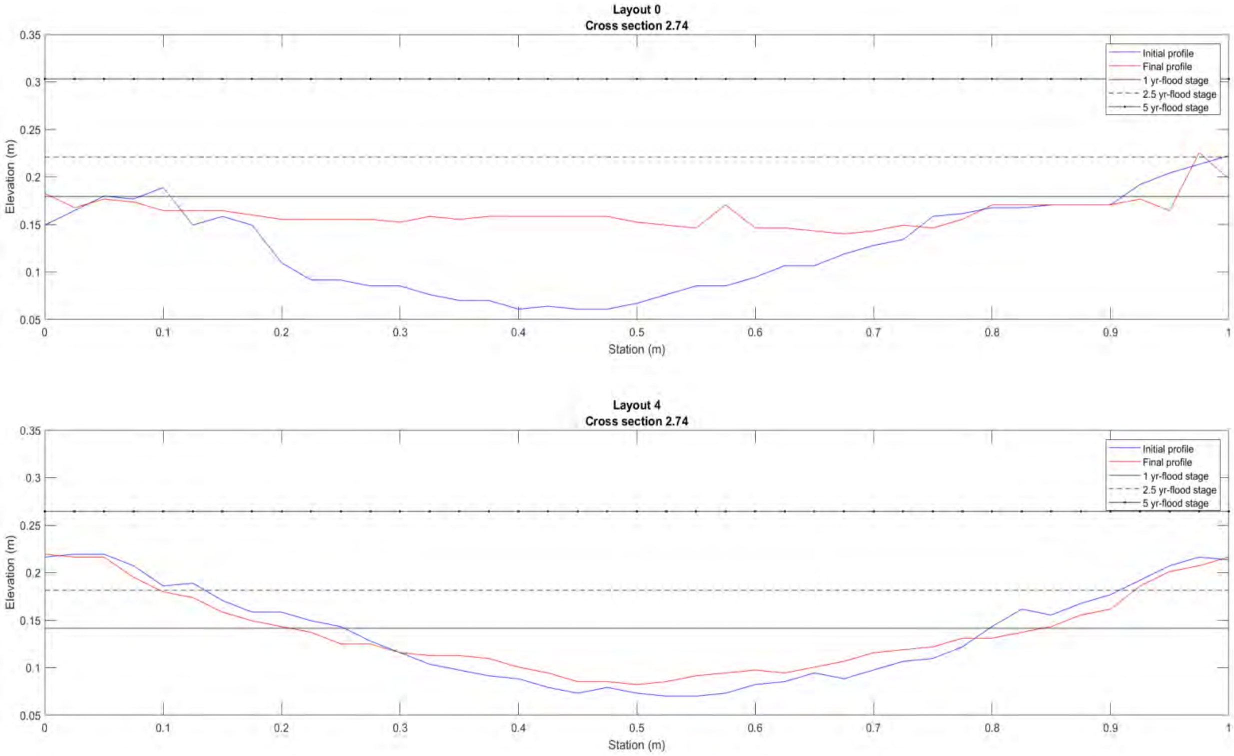


Figure 18. The graph on the top shows the streambed elevation at the initial profile and final profile for Layout 0. The center of the channel has significant deposition which turns the cross-section flat. The depth at a 1-year flood stage is about 0.6 inch. The chart on the bottom shows the streambed elevation at initial profile and final profile for Layout 4. This layout experiences little erosion and deposition throughout the cross-section. The channel shape is still maintained, which supports a low flow channel that is about 0.1 m deep.

channel had little erosion and deposition and still maintained the channel shape. The depth of the water at a one-year flood event in layout 4 was also greater than the depth in layout 0. Similar

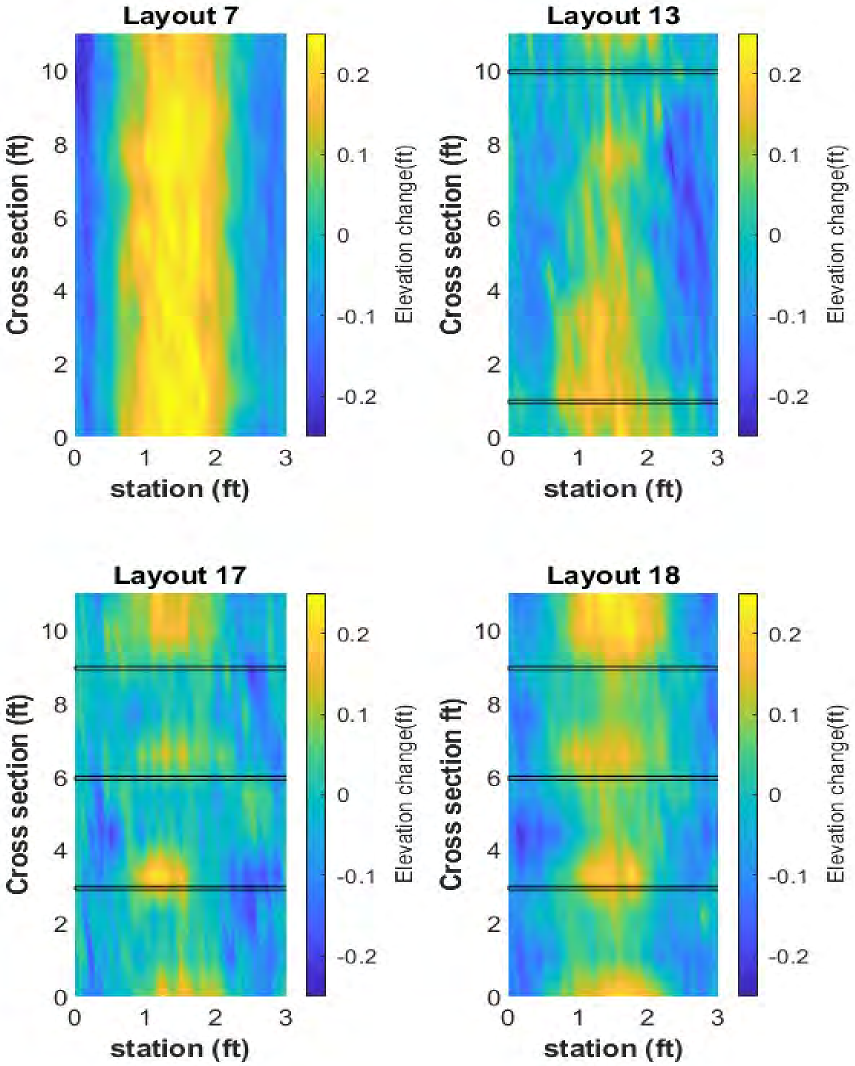


Figure 19 Layout 7 in the top left had no coarse bands. Deposition occurs in the center of the channel with erosion on the sides of the channel. Layout 13 shows the effect of spacing coarse band bowtie (1.0) three channel widths apart. Little deposition occurs right after the first coarse band, and it increase towards the bottom coarse band. Layout 17 was a coarse band bowtie (1.0) spaced one channel width apart. Little erosion and deposition took place throughout the channel. While Layout 18 was coarse bands bowtie (3.0), deposition occurs in the center of the channel and erosion occurs where the bowtie design was placed.

trends were observed for other cross sections with coarse bands, but, as before, there were differences in the patterns of sediment deposition/erosion between the coarse bands.

3.1.2 Three percent slope results

The base-case scenario for the 3% bed slope and a straight U-shape is denoted in layout 7. Given the consistent performance of coarse bands under low flood-frequency in the 2% slope case, a 10-year flow event was added to the test suite for the 3% cases. Without coarse bands, most of the middle of this U-shape channel was flat after the five-year flood event, while a ten-year flood event made the channel completely flat; Figure 19 shows the streambed elevation difference between the baseline and the ten-year flood plotted in a color map. The center of the channel became filled with sediment, while the banks of the channel experienced erosion. Coarse bands with the bowtie design reduced the deposition in the center of the channel and erosion on the banks of the channel (Figure 19); note that only the four best surface profiles are included in

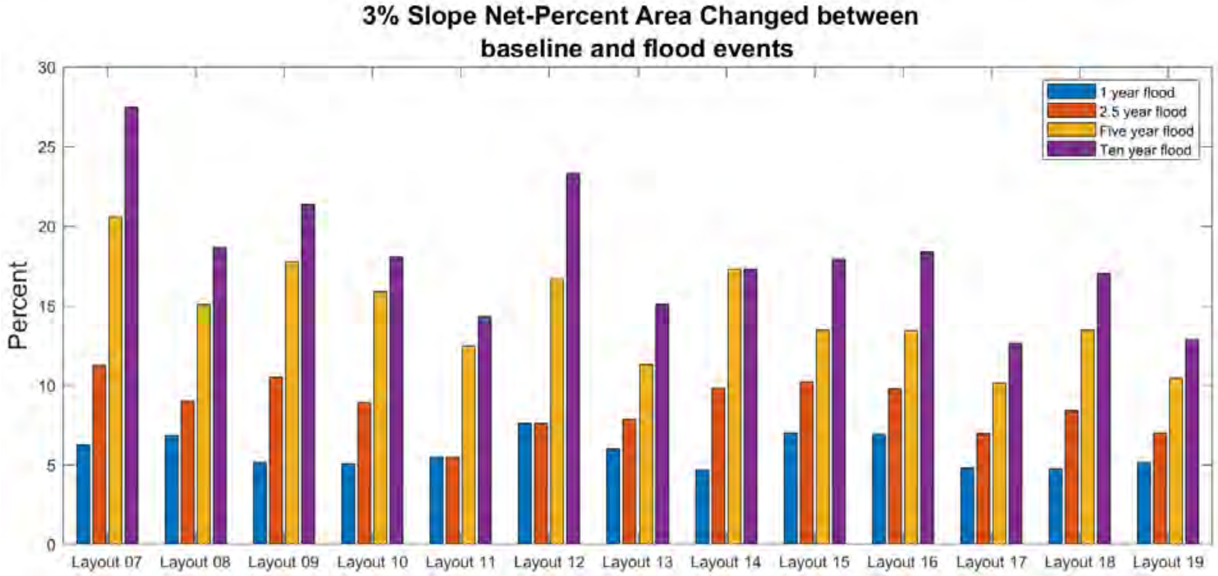


Figure 20 The percent difference of cross-sectional area change between baseline elevation and each flood event for every layout. Layout 7 shows that a ten-year event will significantly change the observed channel. The addition of coarse bands and the bowtie design reduce sediment transport. The lowest net-percent change is Layout 17.

Figure 19 to maximize clarity. Layout 7, the base-case, had the highest net percent cross-sectional area changed during a ten-year flood event and layout 17 had the lowest change out of the twelve test layouts (Figure 20). Of the twelve test layouts, layout 11, layout 13, layout 17 and layout 18 are the designs that reduce the sediment transport the most (Figure 20). There are clear similarities between the patterns of layout 6 and layout 19, indicating that step-pool sequences are likely to form, even at 3% slopes.

3.1.3 Four percent slope results

Layout 20 (4% baseline straight u-shape channel) had the largest net percent area changed during a ten-year flood event with a slope of four percent. The velocities were significantly higher and significant channel flattening was observed for the base-case (layout 20). Deposition occurred in the center of the channel; while the banks experienced erosion (Figure 21). Adding coarse bands with the bowtie design reduced the sediment transport as expected, and the lowest net percent area changed was layout 23 (Figure 22). Layout 23 is constructed with the bowtie design on the upper two coarse band(s), but the bottom coarse band was a square box on the downstream end. Layout 22 (t-funnel below downstream coarse bands) experienced deposition in the center of the channel at the upper end of the study section and erosion on the banks where the t-funnel design did not overlay the streambed material. Layout 24 (U-shape design below downstream coarse bands) performed similar to layout 23 with the addition of erosion taking place on the banks of the channel where the U-shape met streambed material. For both layout 22 and 24 the designs did not reduce the velocity of the water enough to reduce the erosion of the bank below the downstream coarse band. This led to these designs having a larger

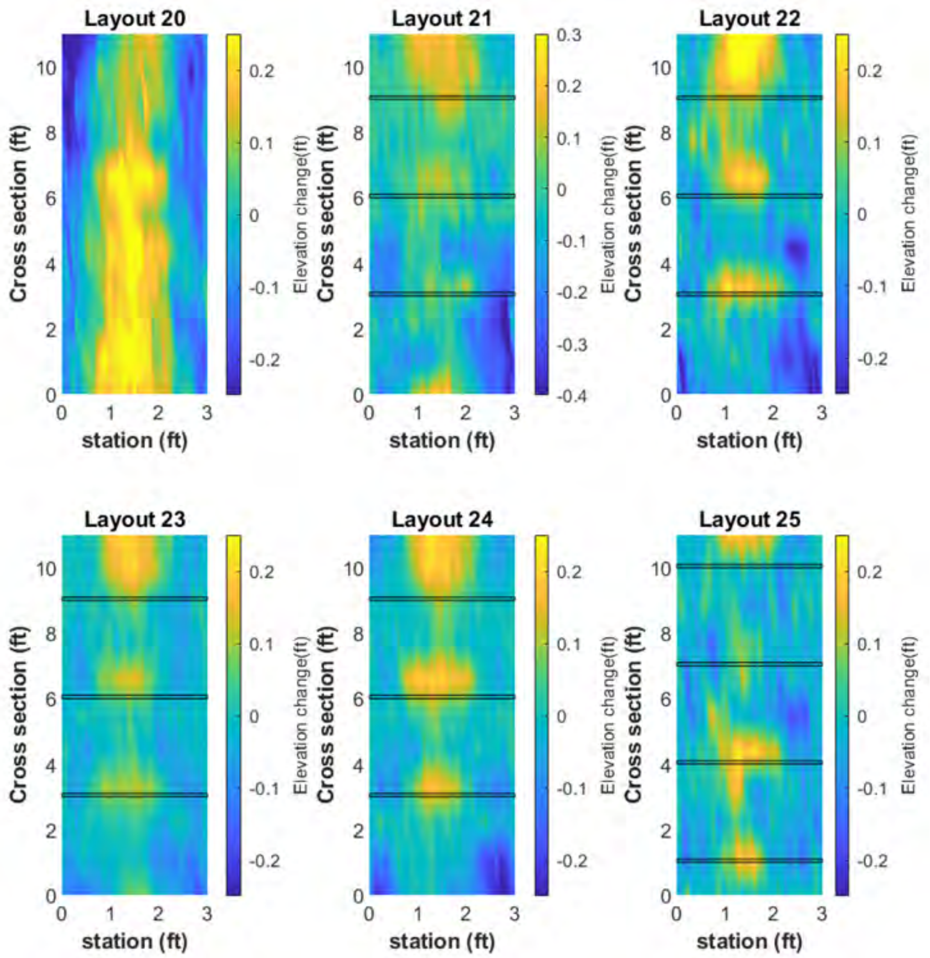


Figure 21 Layout 20 was a straight channel without coarse bands and after a ten-year flood event the channel was flat. The graph shows the center of the channel had deposition and the sides were eroded. Layout 21 was three coarse bands bowtie (1.0) and the figure shows the bottom coarse band is eroded away on the right side of the channel. Layout 23 was the design that reduced sediment transport the most. The figure shows deposition occurred on the upstream side of the coarse bands and little to no erosion took place on the sides of the channel.

net-percent area change than layout 23. Layout 25 (four coarse bands spaced one channel width apart) with the box design downstream performed like layout 23 with a slight increase in net-percent area charged.

3.1.4 2% Alternating Coarse band results

Alternating coarse bands were added to a two percent bedslope straight channel to evaluate whether natural processes can transform a straight channel into a meandering channel. The alternating designs reduced bulk sediment transport by 40-58% (Figure 23), which is about the same range in a sense for coarse bands that extend across the whole channel width (46-56%). Figure 24 shows each layout had little deposition in the center of the channel and erosion on the sides of the channel. The intent of the alternating coarse bands was to transform a straight channel into a meandering channel, but it did not function as intended. The design preformed similar to coarse bands that fully spanned the channel with. The layout 38 (two alternating bands spaced one channel width apart) reduced sediment transport by 58%, which is 2% more than

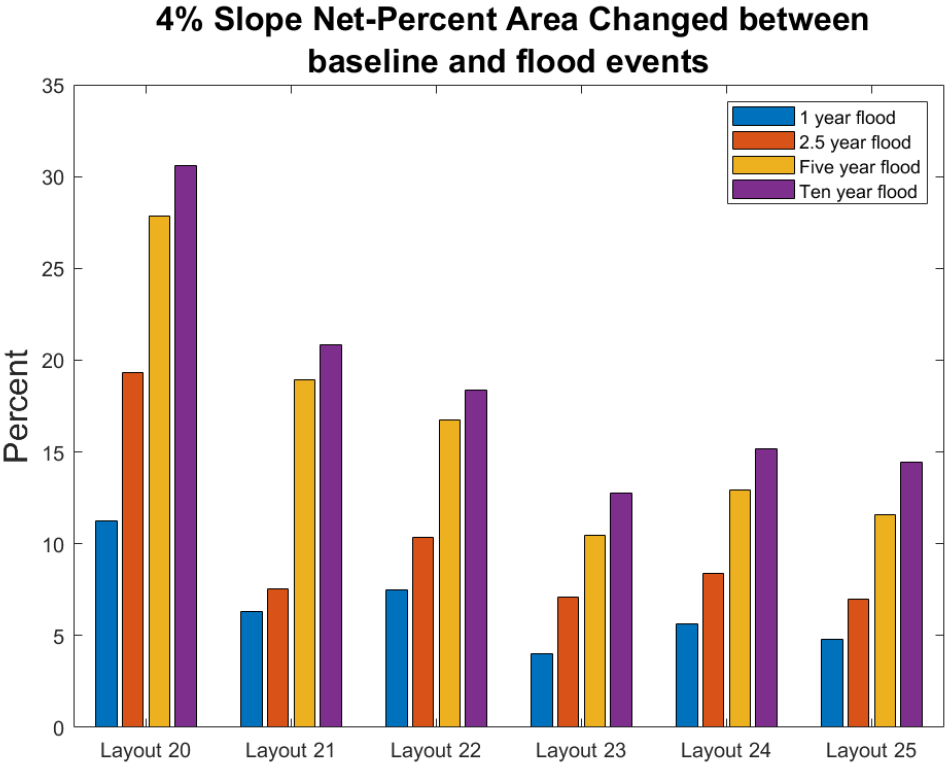


Figure 22 The percent difference of cross-sectional area change between baseline elevation and each flood event for every Layout. Layout 20 shows that a ten-year event will significantly change the observed channel. With the addition of coarse bands bowtie (1.0) design reduced sediment transport further. The changing of the downstream bowtie design reduced sediment transport is reduced further. The Lowest net-percent change is Layout 23.

layout 6 (four coarse bands at one channel width spacing). Layout 41 had deposition occurring on the upstream side of the coarse band and little erosion taking place across from the coarse band. Layout 39 (two alternating coarse bands two channel widths apart) and Layout 40 (two alternating coarse bands three channel widths apart) had more deposition in the center of the channel, then layouts that contained only one channel width spacing. Little to no erosion occurred on the sides of the channel in both layouts, indicating a stable channel at the coarse bands despite the change in flow direction.

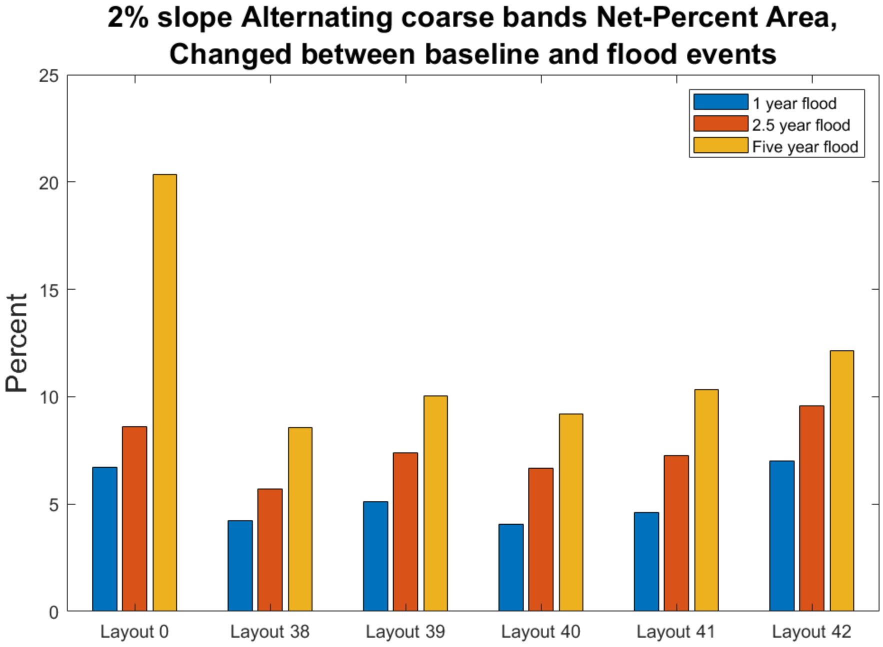


Figure 23 The percent difference of cross-sectional area change between baseline elevation and each flood event for every layout. Layout 0 shows that a ten-year event will significantly change the observed channel. The addition of alternating coarse bands reduced sediment transport.

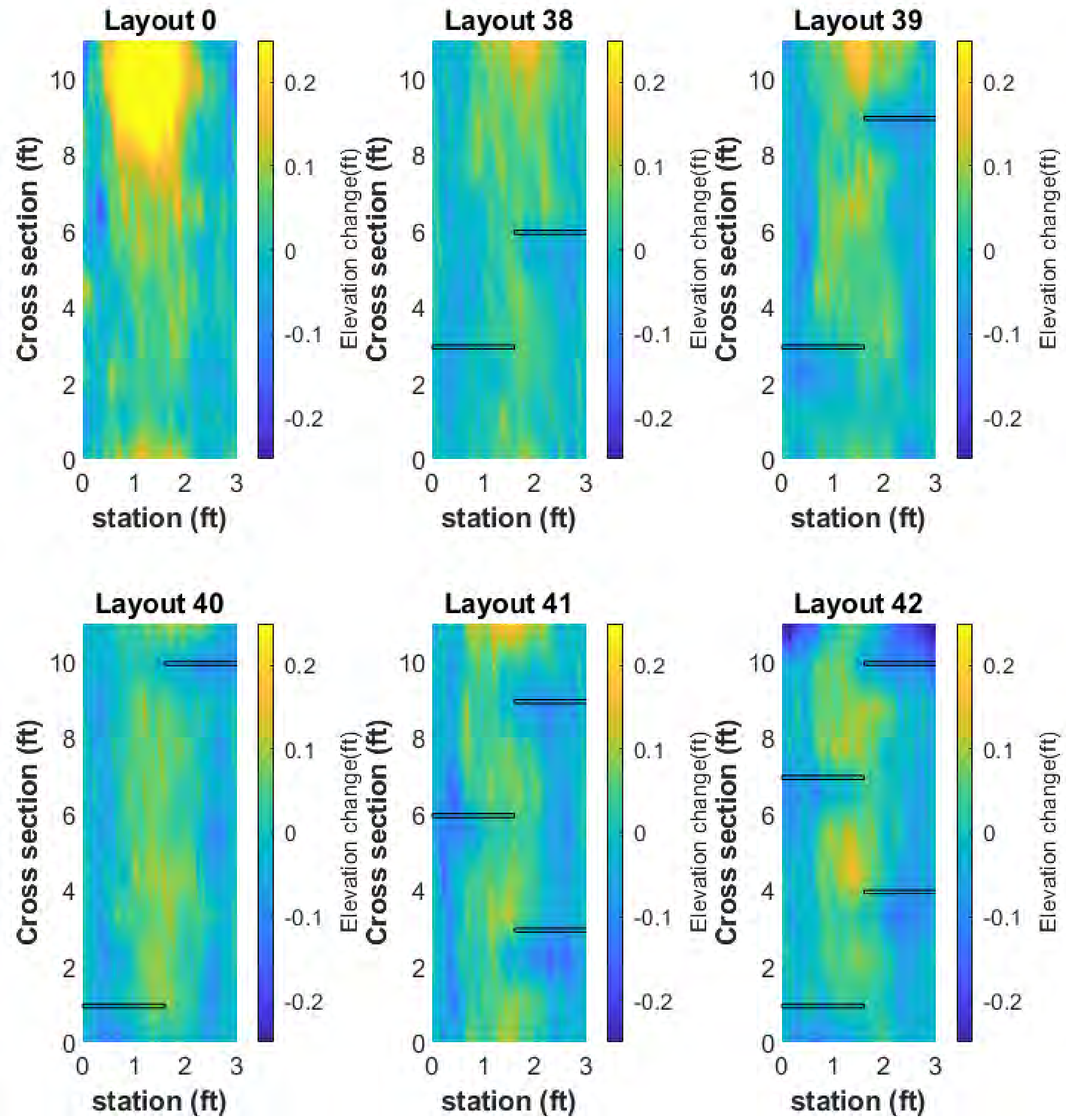

Layout 0
Layout 38
Layout 39
Layout 40
Layout 41
Layout 42

Figure 24 Layout 0 was a straight channel without coarse bands and after a five-year flood event. A mass of sediment is moving down the center of the channel. That mass of sediment was reduced in the rest of the layouts. The black rectangles show the location of the alternating coarse bands. Layout 41 was three coarse bands at one channel spacing. Deposition occurs around the coarse bands and erosion on the sides of the channel. From cross-section three to nine the color scheme shows the start of a meander.

3.2 Meandering Channel results

The same permutations of bedslopes were used for coarse bands added to a prescribed meandering channel. Alternating, partially spanning coarse bands were omitted from these tests since the straight channel experiments showed that they offered no significant advantage.

3.2.1 Two percent slope results

Stream channels without boulder bars layout 34 (baseline for one channel width spacing) and 35 (baseline for three channel widths spacing) were stable up to a five-year flood event before they became flat. Figure 25 shows these two designs experienced erosion on the banks of

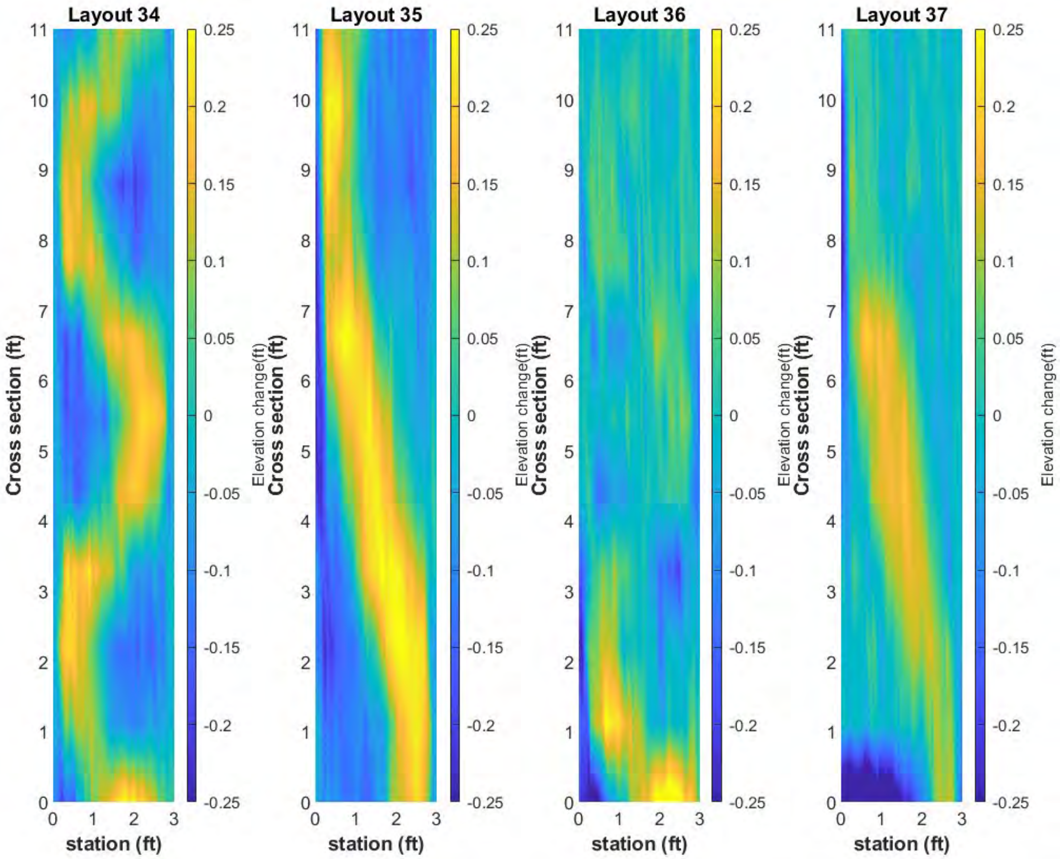


Figure 25 Layouts 34 and 35 are meandering channels without boulder bars. Both layouts had deposition occur in the center of the channel and erosion on the sides of the channel. Layout 36 was boulder bars spaced one channel width apart and little to no change took place in the upper 2/3rd of the channel. Deposition increased in the channel at the bottom of the study section. Layout 37 is boulder bars spaced three channel widths and between boulder bars the channel had deposition occur with little change on the sides of the channel.

the u-shape channel and deposition filled the channel. The largest net area change occurred in Layout 37, but the two Layouts were within two percent of each other (Figure 26). The lowest net-percent area change occurred in Layout 36. Figure 25 shows Layout 36 had little change in most of the upstream portion of the study section. At the lower section of the study area, deposition occurred in the u-shape channel. The channel in Layout 37 between the boulder bars also flattened after a ten-year flood event. This flattening was due to the deposition in the u-shape channel as the banks were eroded. The banks in this layout had little to no change in the upper ten feet of the study section, but the boulder bar at cross-section one started to fail. Material from the downstream side of the boulder bar was transported (which is indicated by the

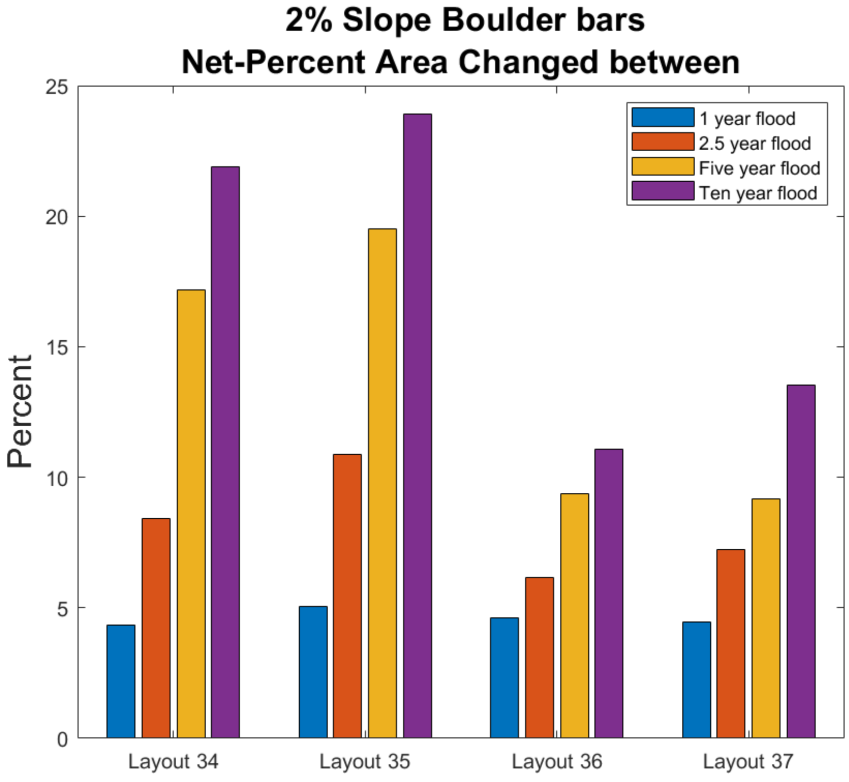


Figure 26 Layout 34 and 35 shows that a ten-year event will significantly change the observed channel. The addition of boulder bars to both channel types reduce bulk sediment transport. The lowest reduction was Layout 36.

deep blue color on the colormap Figure 26). The movement of material appeared to be caused by unstable stacking of material on the downstream side.

3.2.2 Three percent slope results

Layouts 32 (baseline for one channel width spacing) and 33 (baseline for three channel widths spacing) became flat after a five-year flood event. These results are shown in Figure 27 where erosion is distinguished by the color blue, and deposition is distinguished by the color green/yellow on the color bars. Layout 33 had a larger amount of bank erosion than layout 30 but

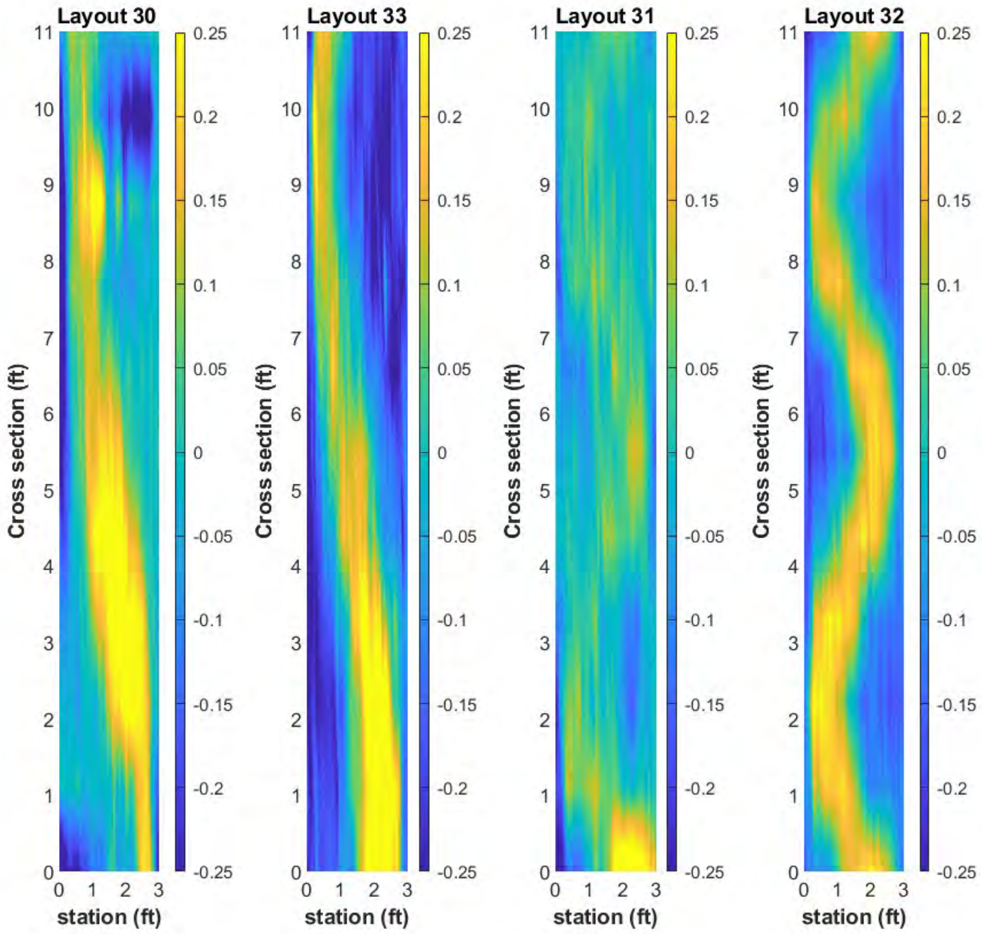


Figure 27 Layouts 33 and 32 are meandering stream channels without boulder bars. The sides of the channel eroded, while deposition occurs in the center of the channel. Both layouts were flattened after a ten-year flood event. Layout 30 is boulder bars spaced at three channel widths. The center of the channel was filled with sediment between the boulder bars. Layout 31 had little change throughout the channel.

less deposition occurred in the channel. There was little variability among the different layouts and bulk sediment transport of layout 32 and 33 was within ~3% of each other (Figure 25). The u-shape channel in between boulder bars in layout 30 also became filled with sediment after a ten-year flood event (Figure 26). Layout 31, by contrast, experienced little erosion, and deposition throughout the channel. The bulk sediment transport difference between both boulder bar designs was ~9% and the lowest reduction of sediment transport occurred for layout 31 (Figure 28).

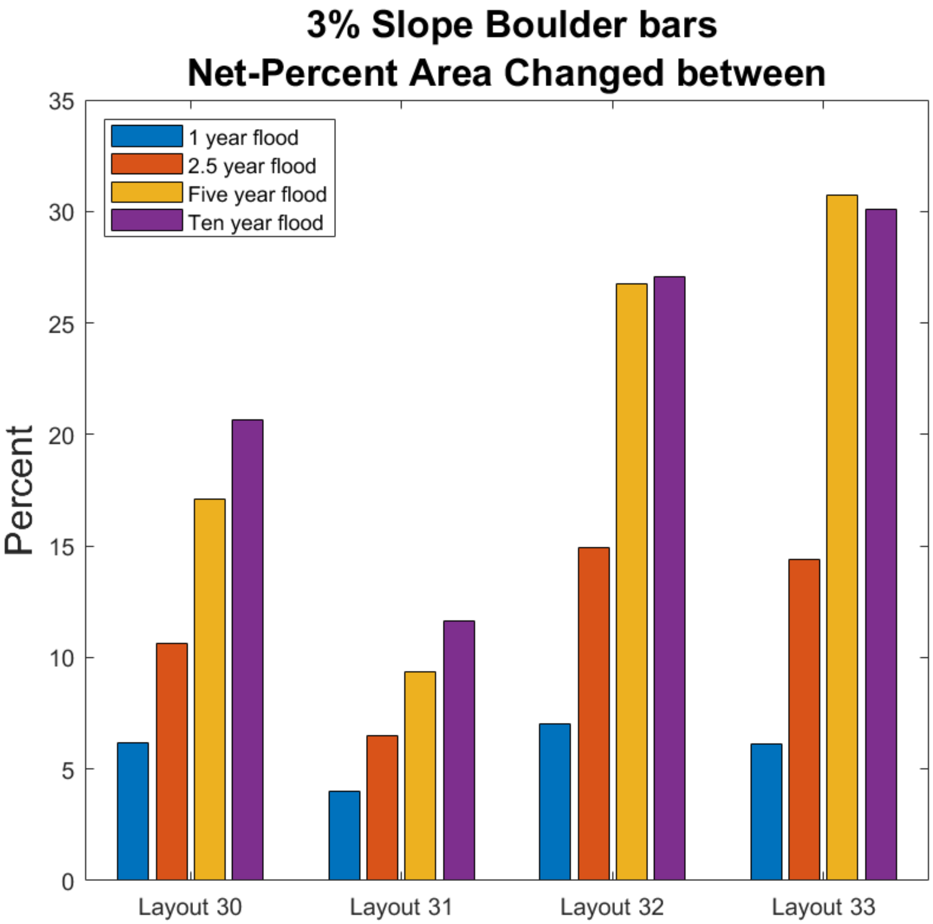


Figure 28 Layout 32 and 33 shows that significant sediment transport occurs for a stream without boulder bars. The addition of boulder bars reduced bulk sediment transport. The lowest reduction occurred during Layout 31.

3.2.3 Four percent slope results

Layouts 27 (baseline for one channel width spacing) and 29 (baseline for three channel widths spacing) became flat after the five-year flood event. A ten-year flood event was not performed for layout 27 because the channel was completely flat after the five-year event (Appendix C shows the streambed height and surface difference after each flood event). Deposition in the u-shape channel and erosion of the banks occurred in both layouts (Figure 28). Layout 26 had the largest net-percent area changed (Figure 29), due to the failure of the boulder bars (Figure 30). After a five-year flood event, boulder bars spaced one channel width apart

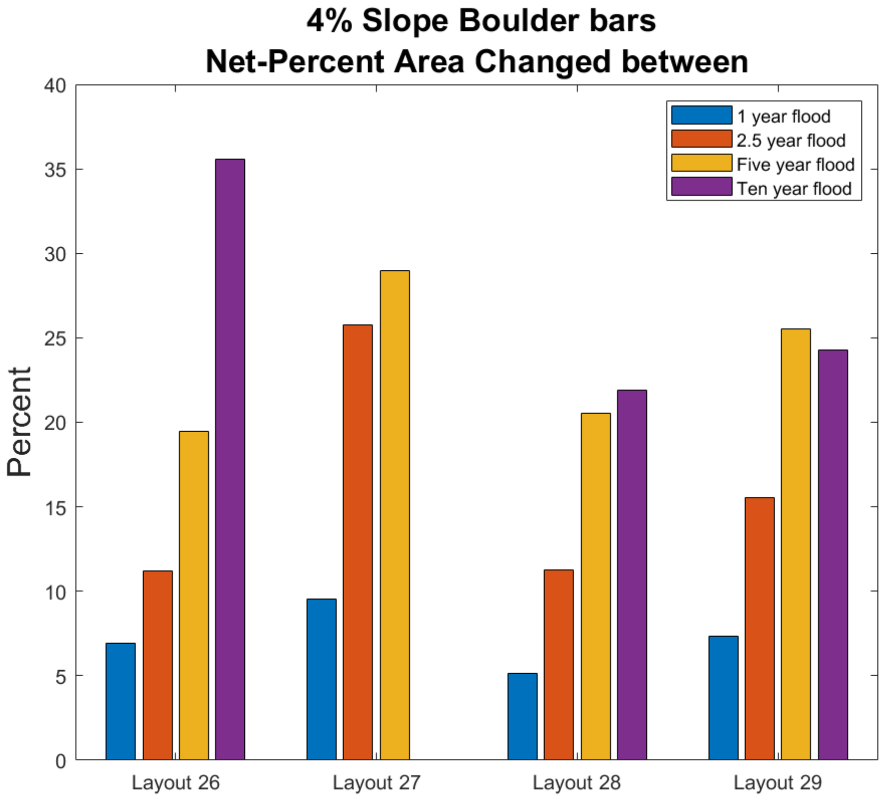


Figure 29 Layout 27 did not have a ten-year flood event due to the channel was completely flat after a five-year flood event. Layout 26 had the highest sediment transport due to failure at the boulder bars. Layouts 28 and 29 were within 4% of each other at after a ten-year flood event.

reduce sediment transport by ~32%. Boulder bars with three channel widths spacing only reduced bulk sediment transport by ~9%.

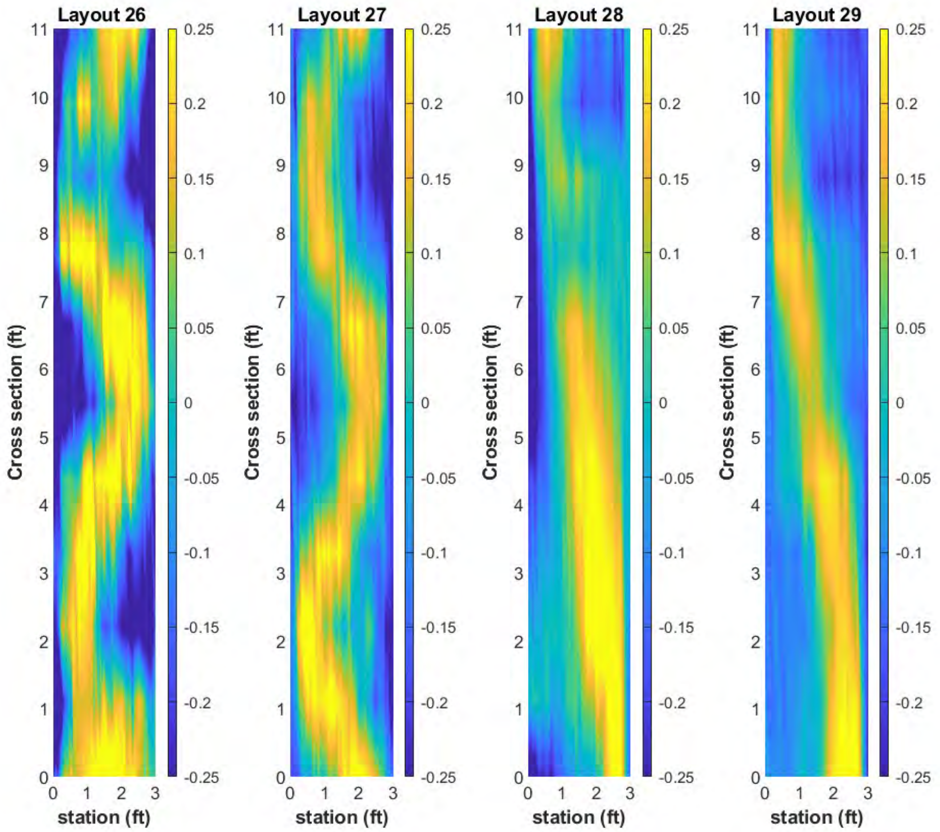


Figure 30 Layout 26 had significant deposition in the center of the channel and erosion on the sides of the channel. Boulder bar material was moved into the channel. Layout 29 had no boulder bars, and the channel was flattened after a ten-year flood event. Layout 28 kept the channel between boulder bars filled with streambed material, but this led to channel flattening

CHAPTER FOUR: DISCUSSION

4.1 Straight U-shape channel

The first question posed in this document was: what are the dynamics that contribute to the flattening of SSDs? A laboratory experiment with no coarse bands (Layout 0) offers some clear insights into the relevant behaviors of streambed channel morphology with a slope of 2%. Results in Figure 16 show that Layout 0 tended to become flat at the upper end of the stream and this progressed downstream as the experiment continued. The key point is that the primary mechanism for this flattening was the downstream movement of sediment, as determined by visual observation of particles moving downstream. Some lateral transport did also occur as particles rolled down the sides of the u-shaped channel, which seemed to initiate some of the downstream motion. As the channel filled and the sediment "plug" moved downstream, the small drop along the downstream edge created a locally higher bed slope that slightly accelerated the flow and mobilized sediment; these dynamics are similar to migrating dunes but exhibit an increasingly elongated "bench" instead of a crest. These observed behaviors suggest that, given l enough time, the stream channel shape would become completely flat, likely resulting in an elongated fish passage barrier at low flows. However, the main finding was that downstream, not lateral (i.e., channel collapse), sediment movement was the cause of the flattening under baseline, simulated streambed conditions.

4.1.1 2% Straight U-shape Channel

Hypothesis (H1.1) was that the addition of coarse bands would maintain the channel shape imposed by the shape of the coarse band(s). Numerous examples confirming this hypothesis exist in these results but even Layout 1 in the study confirmed the expected behavior, despite having only a single coarse band in the middle of the study section. Figure 16 clearly shows that any number of coarse bands added to a straight channel reduced sediment transport and increased channel stability, but there were some differences in the spatial distributions. In the simplest case, the mass of sediment entering the top of Layout 0 was greatly reduced by the addition of a coarse band in Layout 1 and the rest of the study area experienced a mixture of small-scale erosion and deposition, which are more consistent with the target “natural” stream morphology than the flattening observed in Layout 0. An important result is that lateral transport (channel destabilization) became the dominant mechanism once the downstream migration of the base-case was reduced. The key finding here is that even a single coarse band significantly limited downstream sediment movement and changed the transport regime from downstream dominated to laterally dominated sediment movement. However, this should not be interpreted as meaning that only one coarse band is necessary to control SSC channel shape in practice.

Different combinations of coarse bands all reduced mobility, but it is important to note that there were changes in the spatial distribution of sediment among the designs, and this has implications for design considerations. Layout 1 was able to reduce sediment transport downstream, but it resulted in little to no sediment transport within a short distance near the coarse band. This leads to sub-hypothesis (H1.2), which focused on increasing the number of coarse bands and varying their spacing, probing the “range” of stability contributed by each coarse band. Two coarse bands were spaced from one up to three-channel widths, shown in Layouts 2, 3, 4 respectively, and across this range downstream sediment transport continued to be reduced (though not as significantly as the initial decrease from adding a single coarse band), with slight increases in lateral transport (channel erosion) near the coarse bands. This erosion was caused by an increase in water velocity as water flowed over the coarse band and its speed accelerated to accommodate the slightly reduced cross-section since the coarse bands were slightly elevated above the channel bottom to promote pool formation. As water exited the constriction of the coarse bands, the speed of the diverging flow was sufficient to remove materials from the channel sides on the downstream face of the coarse band, though the coarse bands were, generally, not mobile. The force dissipated rapidly, and the erosion became less prominent moving downstream from the coarse band. Lateral transport from erosion did not move significant amounts of material very far in these regions near the downstream face of the coarse band, but some downstream migration of eroded material may have occurred. The area of influence of the erosion was evaluated by changing the spacing and Layout 4 (two coarse bands spaced at three channel widths) showed that the center of the channel has little deposition and also less erosion on the banks of the channel compared to Layout 2 and 3. Layout 4 had the largest spacing of coarse bands among these and exhibited the smallest net change in cross-sectional movement, meaning that it was the most stable. This suggests that placing coarse bands too close together might increase transport, but keep in mind that this was only relative to other coarse band designs; all designs reduced transport relative to the base-case (Layout 0) and all of the multi-band cases generally offered improvements over a single coarse band.

Continuing the evaluation of H1.2, the dimensions of the flume and size of the test section allowed evaluation of two other permutations of the coarse band spacing: three and four coarse bands at one channel width spacing each (layouts 5 and 6, respectively) and both layouts formed a step-pool sequence. The velocity of a stream decreased on the upstream side of the coarse bands, which allowed sediment particles to settle on the channel floor, and then the velocity was increased while flowing over the coarse bands. This increased flow created a small scour pool in the center of the channel on the downstream end of the coarse bands, forming the step-pool sequence in the steam channel while preserving the channel profile. Step-pool sequences found in a natural stream have a spacing of 5-8 channel widths (Yang 1971; Gregory et al. 1994; Leopold et al. 2012), but since the experimental sequences are artificially imposed by the coarse bands there is no reason to expect larger spacing would evolve.

The last sub-hypothesis for straight, u-shaped channels, H1.3, focused on coarse band(s) that cover half the channel width and alternated which side of the channel they were on. The concept behind this design was to manipulate an initially straight channel into a meandering channel using natural processes over time. The coarse band(s) would, ideally, reduce the erosion taking place around their location and increase the erosion by relocating the faster moving water to the opposite side of the channel, which would increase erosion and form a point bar. The alternating coarse bands were successful in reducing sediment transport and maintained the channel shape but failed to transform a straight channel into a meandering channel. The lack of meanders is thought to be mainly an artifact of the highly confined cross section used in the experiments and this result should not be considered sufficient evidence to dismiss the alternating band concept. A less biased evaluation of the design should be conducted in the future using further scaled down sediment distributions and/or a wider cross section.

4.1.2 3% Straight U-shape Channel

Thirteen layouts were tested at the 3% slope to evaluate hypothesis H1.1 (channel stability as a function of the number and arrangement of coarse bands) under higher velocities and higher bed shear stress. Layout 10 (three coarse bands at one channel width spacing) performed well in the 2% case and was a logical first test at the three percent slope. Unlike the 2% case, the coarse band washed out after the five-year flood event and the streambed was flattened after the ten-year event. After this failure, the particle size for the coarse bands was increased from D150 to the D250 size of the streambed material. The increase in size created a larger step in the channel at the coarse band, which resulted in water flowing over the bands at higher velocity. The increased speed resulted in channel erosion on the downstream side of the coarse bands. This erosion was significant enough to undercut the coarse bands, which then failed, and some of the coarse band material began to move downstream along with the other sediment. The erosion on the downstream side was combated with several prototype designs, the result of which were the bowtie coarse band structure (Figure 9). The bowtie configurations that were tested: A) D200 particles laid over the streambed material to form an armor layer, B) two armor layers of D200 particles, and C) D200 particles mixed with the streambed material. Bowtie A (layout 17) was ultimately found to be the best design for stability, Design C was also used in multiple coarse bands designs, but Design B was discarded. The armoring layer gave the underlying streambed material protection from the increased water velocity. This design forces the fast-moving water back to the center of the channel while reducing the erosion on the sides of the channel. The performance of the variably spaced coarse bands (H1.2) was generally like similar to that for the 2% slope.

4.1.3 4% Straight U-shape Channel

Layout 17 (three coarse band(s) bowtie A at one channel width spacing) preformed the best at a three percent slope, which was a logical starting point for evaluating H1.1 at four percent slope. The coarse band at the bottom of the study section began to fail after the ten-year flood event, contrasting with the 2% case where the coarse band stayed in place and deposition occurred in the center of the channel; this corresponded to little erosion on the sides of channel above the coarse band and only small changes on the downstream side of the coarse band. The cause of the failure was that material from the bowtie were transported downstream and the coarse band(s) started to follow. The size of particles in the coarse band was then increased to the D300 size and the t-funnel, u-shape and box designs were tested to reduces the failure of the lowest coarse band(s). The bowtie material was also increased from D200 to D250. These designs were focused on adding more particles to the center of the channel (see figure 11) to protect the channel shape, which performed well.

The increased material size and the increased amount of material in the bands resulted in an armoring effect with sediment particles great than or equal to D250. The t-funnel, u-shape and box designs tested reduced sediment transport up to 58% and maintained the channel shape, but a key tradeoff is that the cost and construction time would be greater.

4.2 Meandering channel

The previous hypothesis (H1.1-H1.3) evaluation were conditional to a straight u-shape channel and coarse bands designs. The second hypothesis (H2) examined meandering channels at bed slopes of two, three and four percent for two meandering stream channel types: H2.1) point bars spaced one channel width a part, and H2.2) point bars spaced three channel widths apart. Additional lengths could not be accommodated in the flume but note that most stream simulation culverts are also not, for example, greater than 10 times longer than they are wide.

4.2.1 One channel width spacing between boulder bars

The first sub-hypothesis (H2.1) for meandering channels examined a channel with point bars spaced one channel width apart. The meandering channel without boulder bars (Layout 34) became flat due to erosion of the point bars and deposition of sediment in the channel (Figure 25). The mechanics of the flattening process was identical when the slope was increased to three and four percent slopes, with the only difference an increase in bulk sediment transport and the process occurred at a faster rate. For example, at three percent slope (Layout 32) the channel was flat after a 5-year flood event, which led to the net-percent area changed being within a 2% (Figure 28) and at a four percent slope the channel was completely flat after a 5-year flood event.

The addition of boulder bars to the channel reduced the erosion of the point bars and also reduced deposition in the center of the channel. The channels below 4% bedslope exhibited little erosion and deposition throughout the majority (upstream) of the study section. Deposition was observed in the lower portion of the study section in the channel, reflecting the small amount of material transported out of the upper portion of the study section. Interestingly, boulder bars at two percent slope performed marginally worse than at a three percent slope. Bulk sediment transport was reduced by 49% (relative to no bars) for a two percent slope, and the reduction of bulk sediment transport was 57% for the three percent slope case. A channel with a slope of four percent boulder bars failed after a 5-year flood; the boulder bars had washed out and the channel became flat.

4.2.2 Three channel width spacing between point bars

Finally, the second sub-hypothesis (H2.2) addressed extending the spacing between point bars to three channel widths. Extending the spacing of the boulder bars reduced the sinuosity of the stream and the amount of material needed for construction. Channels without boulder bars had the same behaviors as the channel spaced one channel width apart. The point bars were eroded, and channels were filled with sediment, forming a flat channel, and this occurred for all channel slopes. The flattening process of the stream occurred at a faster rate when the slope was increased. For example, at a two percent slope the channel was completely flat after 10-year flood event while at a three percent slope the channel was completely flat after a 5-year flood event and at four percent the channel was relatively flat after a 2-year flood event.

The addition of boulder bars reduced the erosion of the point bars but did not prevent channel deformation. The channel between the boulder bars was partially filled with sediment and the sides were eroded, leading to some flattening. These channel dynamics occurred for all channel slopes and the flattening process occurred at accelerated rates as the slope was increased, exactly as in the control case. The downstream boulder bar at the two percent had erosion while the upstream boulder bar had erosion after a ten-year flood event for both three and four percent slopes. This shows clearly that a four percent bedslope with this kind of grain size distribution is likely too high to try and initiate or maintain any kind of sinuosity in a culvert.

CHAPTER FIVE: CONCLUSIONS

5.1 Assessment of hypotheses

The research described in this report investigated the ability of coarse band and boulder bar designs to support streambed channel stabilization, effective sediment transport, and maintain a low flow channel in stream simulation culverts.

Hypotheses H1.1-H1.2 addressed the impacts of the addition of coarse bands to maintain a desired straight u-shape channel shape. Our research indicates: i) the addition of coarse bands was successful in maintaining a specified channel shape at all bedslopes, and specifically that ii) the addition of coarse bands led to a reduction in sediment transport by 46-56 for a two percent slope, 38-54% for a three percent slope, and 12-58% for a four percent slope.

Sub-hypothesis H1.2 focused on the impacts of varying spacing of coarse bands and their ability to maintain a desired channel shape over a longer stream section. The layout with the highest reduction in sediment transport for each slope was Layout 6 (four linear coarse bands one channel width spacing), with 56% for a two percent slope, Layout 17 (three coarse bands with bowtie (A) spaced one channel width apart) with 54% for a three percent slope and Layout 23 (three coarse bands with bowtie (A) box spaced one channel width apart) with 58% for a four percent slope. Layout 4 (two coarse bands spaced three channel widths apart) required less material than Layout 6, but only reduced the sediment transport by 49% (compared to 54% in Layout 6).

The second hypotheses H2.1-H2.2 addressed the impacts of boulder bars on meandering channels that have a spacing of one and three channel widths. A channel with boulder bars spaced three channel widths apart reduced sediment transport by 43% for a two percent stream slope, a three percent slope reduced transport by 31%, and a four percent slope only achieved a 10% reduction. The efficiency of boulder bars spaced one channel width also depended heavily on the slope of the stream. A two percent slope had a 49% reduction of sediment transport, 57% at a three percent slope, and only 33% at a four percent slope. Clearly the slope is a major factor in these meandering designs, and it is not recommended that meandering channels be targeted for slopes above four percent.

5.2 Potential limitations

All experimental work has limitations that should be considered when extrapolating them to the field, or any other, conditions. The primary limitation of these experiments is the size of the flume. This presents limitations to the depth of sediment, the maximum sinuosity of the stream, the constricted cross section, and the maximum discharge. The total height of the flume is 22 inches, and the maximum depth of the streambed material was about 11 inches on the sides and 4 inches in the center of the channel. Culverts in field installations are more likely to have comparatively thin layers and deeper flow depths, which could increase the shear stress on the bed. The maximum flows at a 2% slope created waves within a few inches of the top of the flume, so larger flows could not be achieved. However, note that the increased velocity of the steeper slopes likely represents a comparable range of shear stress to deeper flows in lower sloped channels. A stream-power scaling could be used to extrapolate the performance of the steeper slopes to the lower slope cases, but the limited depths and velocities remain a limitation since we could not achieve discharges above a 10-year event for Asotin Creek.

The width of the flume is also a potential limitation since it did not allow much lateral migration. Whether or not this impacts the interpretations of the results depends on the aspect ratio (length to width) of a particular culvert. The experimental results are likely to be good analogs for culverts where the width is significantly smaller than the length of the simulated streambed, but these results will not necessarily be as reliable in wider aspect ratio settings. If the channel within the culvert is generally confined, the results may still be good analogs, but highly meandering channels could not be created in this study and should be investigated in the future using wider experiments and/or smaller grain sizes.

The reference site also introduces some potential limitations. The study area was chosen to match the flow regimes the lab could safely achieve and the sediment that was available from local aggregate suppliers. This led to the selection of Asotin Creek as the reference stream, but the number of peak flows used to generate the flood frequency was less than thirty, so the statistical analysis is not necessarily robust. While the observed flows are certainly representative of recent conditions, the period of record was not long, and the flood frequency is biased by this narrow window of time. Climate change may increase the flood frequency flow values due to the increase of precipitation and/or accelerated snowmelt, thus 5-year events in the future may, for example, have magnitudes closer to current 10-year events.

Natural rivers have a replenishing supply of sediment, and this cannot be precisely replicated in a flume. Sediment can be added but it may skew the results. Early testing showed that adding a supply of sediment to the flume, regardless of how, did not have an appreciable impact on the measured sediment transport behaviors. This lack of sensitivity is mostly likely because we were already focusing only on transport in the study section in the middle of the larger streambed in the flume. Sediment transport rates were simply not high enough to move much of the added material into the study area because the existing sediment “plug” had yet to be displaced into it. As such, even though the lack of a supply of sediment is an experimental limitation, the careful selection of the study reach as a subset of a larger streambed ensured that this limitation did not affect the results.

One final limitation is that the buried depth of the coarse bands used in this study did not extend all the way to the bottom of the flume and the burial depths were not varied in most cases. The coarse material not reaching the bottom is not likely to have impacted these results because only a small number of trials exhibited any instability of the coarse bands, but there is an open question regarding how deep the bands should be placed in natural streambeds. Given the lack of mobility of the bands themselves, it may not be necessary for them to completely reach the bottom of a simulated streambed, but this cannot be assessed from the current work, so it is suggested that installations continue to create coarse bands that are as deeply embedded in the streambed as is practical for site-specific conditions.

5.3 General recommendations for SSC design

The following sections summarizes the recommendations for straight u-shape and meandering channels for each slope that was tested.

5.3.1 2% straight u-shape - channel recommendations

The best design in terms of maintaining the target channel shape was layout 6 which used four coarse bands that were spaced by one channel width apart. The remaining designs were very close to the same performance and the range of variability was only 7%. Given this minimal differential, it is likely excessive to space coarse bands by a single channel width and it is likely that comparable long-term stabilization can be achieved at two channel width spacings. Thus for straight channels with slopes less than or equal to two percent, spacings of two channel widths are expected to perform well and up to three channel widths may be allowed. In both cases, the coarse bands should be made of no less than the D150 of the streambed material.

5.3.2 3% straight u-shape - channel recommendations

The design that performed the best was layout 17 which used three coarse bands arranged in the bowtie A configuration that were spaced one channel width. Bowtie A used D250 material for the linear portion of the coarse bands and the downstream armoring layer (bowtie) was made from D200 material. The bowtie design provided protection for the channel downstream of the coarse bands, which prevented downstream failure of the bands. Linear coarse bands were not effective in this case, nor were the other designs tested. Coarse band spacings greater than two channel widths are not recommended.

5.3.3 4% straight u-shape - channel recommendations

The best designs for this case were coarse bands arranged in the bowtie A, or the box configuration, spaced one channel width; both are generally comparable in this case. The material used for the construction was D300 for the coarse bands, D250 for bowtie A and D300 for the box. Designs that have a spacing greater than one channel width are not recommended because of the high velocities and high erosion rates at these slopes.

5.3.4 Meandering channel recommendations

Layouts 31 and 36 reflect the best guidance for meandering channels at 2% and 3% bedslope, respectively. These designs used boulder bars spaced by one channel width composed of a mixture of D200-D300 (ratio is 1/3 for each class D200, D250 and D300). Meanders should not be expected to be sustained for slopes greater than 4% nor for increased coarse band spacing at 3%; however, three channel widths may be permissible at 2% slopes.

5.3.7 Recommendations for further research

The primary questions unresolved by, or uncovered during, this work are:

- What is the maximum allowable spacing for which coarse bands provide a stabilizing impact on channel shape? Does this fully stabilize channels in between the sections or is there significant erosion/deposition that will occur in between the coarse bands?
- How deeply into the streambed should coarse bands be embedded in order to maximize their long-term effect? This includes stabilizing the channel and ensuring the band itself remains intact to minimize labor/maintenance.
- Can coarse bands be used to stabilize high sinuosity channels in wide floodplains? What are the tradeoffs between decreasing slope using a meander and the changes in erosion along the bends of the meanders?
- Can material other than coarse bands be used to produce similar stabilizing effects on streambeds? This might include a combination of natural materials like tree branches or the introduction of vegetation.
- How can meandering be induced from a channel that has become straight? How can a u-shaped channel be induced in a channel that has been flattened over time?

These questions are expected to provide further insights into the holistic functioning of coarse bands, as a principle, and guide more effective, less labor-intensive designs in the future.

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APPENDICES

Appendix A – Coarse band layout design sketches

Appendix B – Sediment distribution curve

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

Appendix A – Coarse band layout design sketches

Coarse band design for each layout is provided in Appendix A. The sketches for each layout are shown in plan, cross-section, and 3D view.

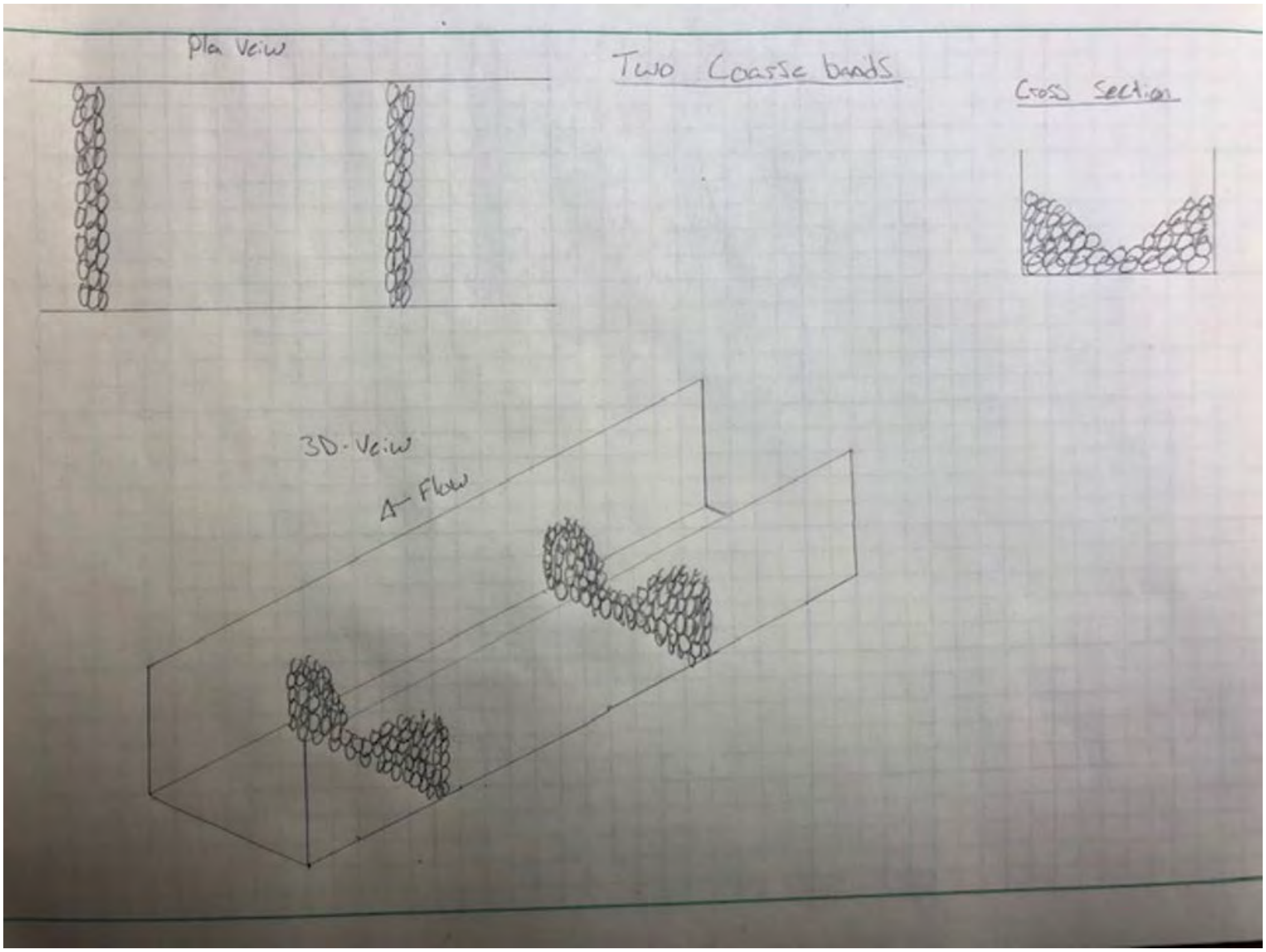


Figure 31 shows the construction of layout 2.1. In the upper left of the figure shows the plan view of the of the layout where the coarse bands are spaced one channel width apart. The figure in the upper right is a cross-section view of the coarse band that mimics the U-shape channel. The figure in the bottom middle is a 3D view of the coarse band layout.

Three Coarse Bands

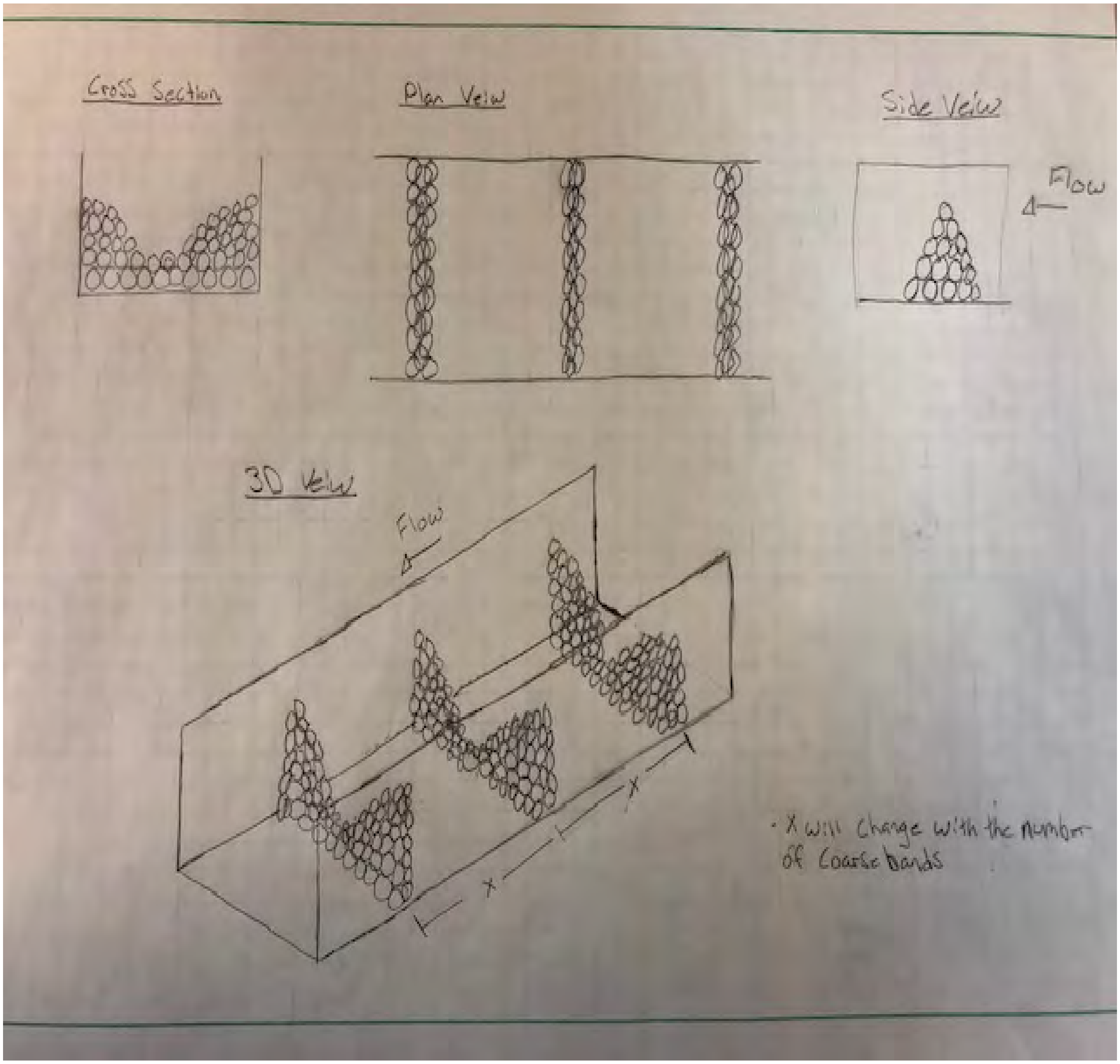


Figure 32 shows the construction of layout 3. In the upper middle of the figure shows the plan view of the of the layout where the coarse bands are spaced one channel width apart. The figure in the upper left is a cross-section view of the coarse band that mimic the U-shape channel. The upper right figure shows a side view of the coarse band. The bottom middle shows a 3D view of the layout.

Four Coarse Bands

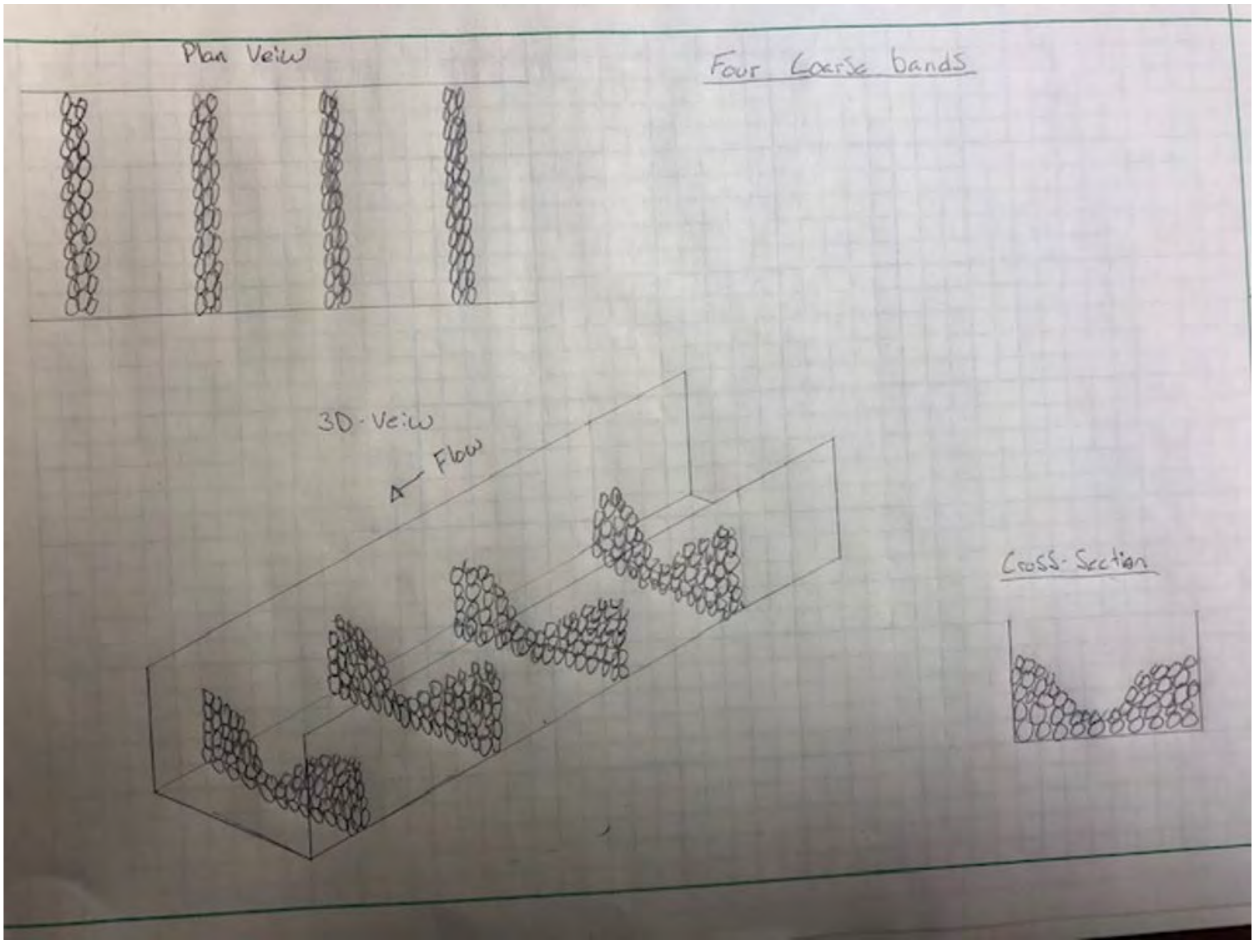
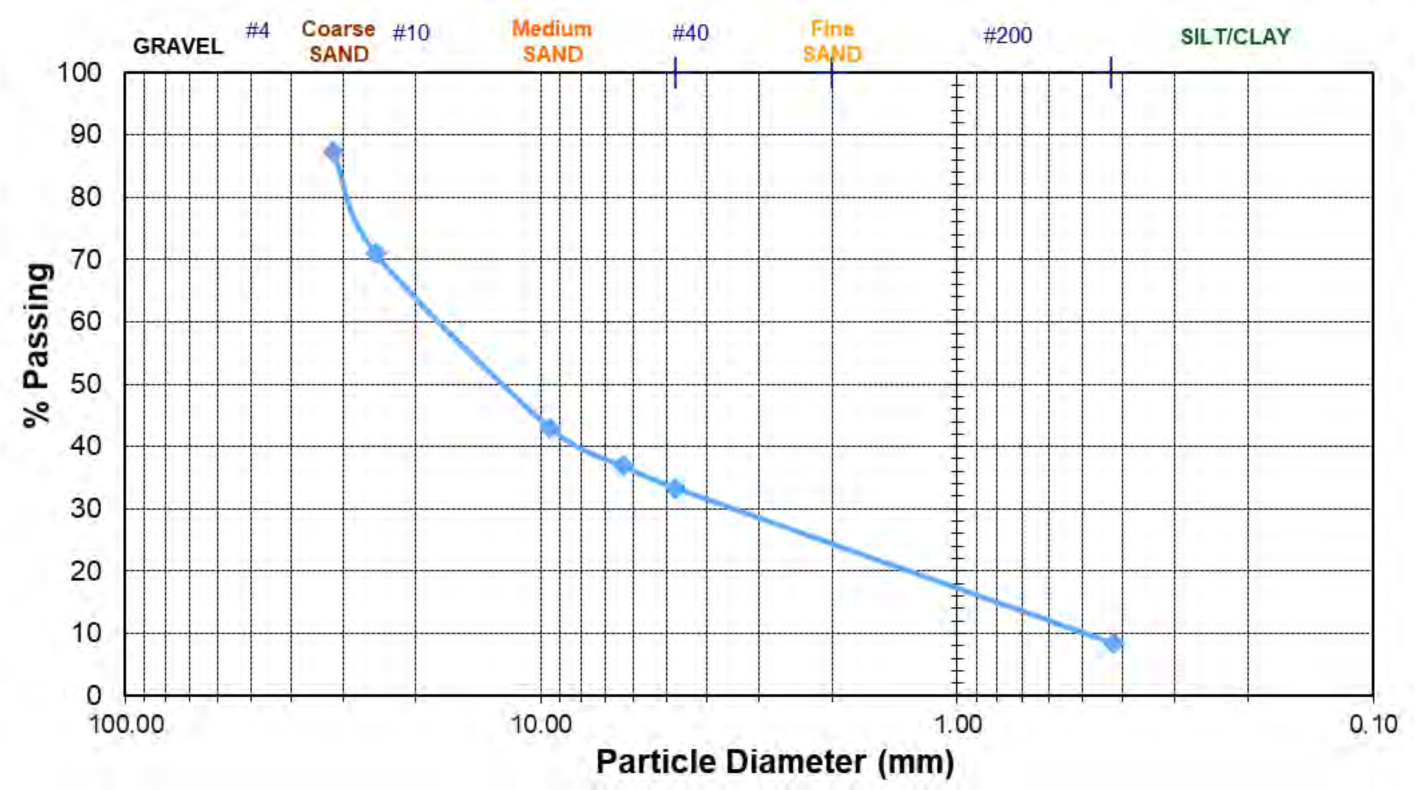


Figure 33 shows the construction of layout 4. In the upper left of the figure shows the plan view of the of the layout where the coarse bands are spaced one channel width apart. The figure in the bottom right is a cross-section view of the coarse band that mimics the U-shape channel. The figure in the bottom middle is a 3D view of the coarse band layout.

Appendix B– Sediment distribution curve

This distribution curve shows the grain class of sediment that was used in the study.

Table 5 Sediment distribution curve of the material used in this research.



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

In all cases, the height of the streambed gives the understanding of the contour of the streambed (first figure in the series, even numbered). The surface difference shows where the stream channel is changing, the amount of change and the direction (odd numbered figures).

These graphs show the height of the streambed at each flood event for Layout 0.

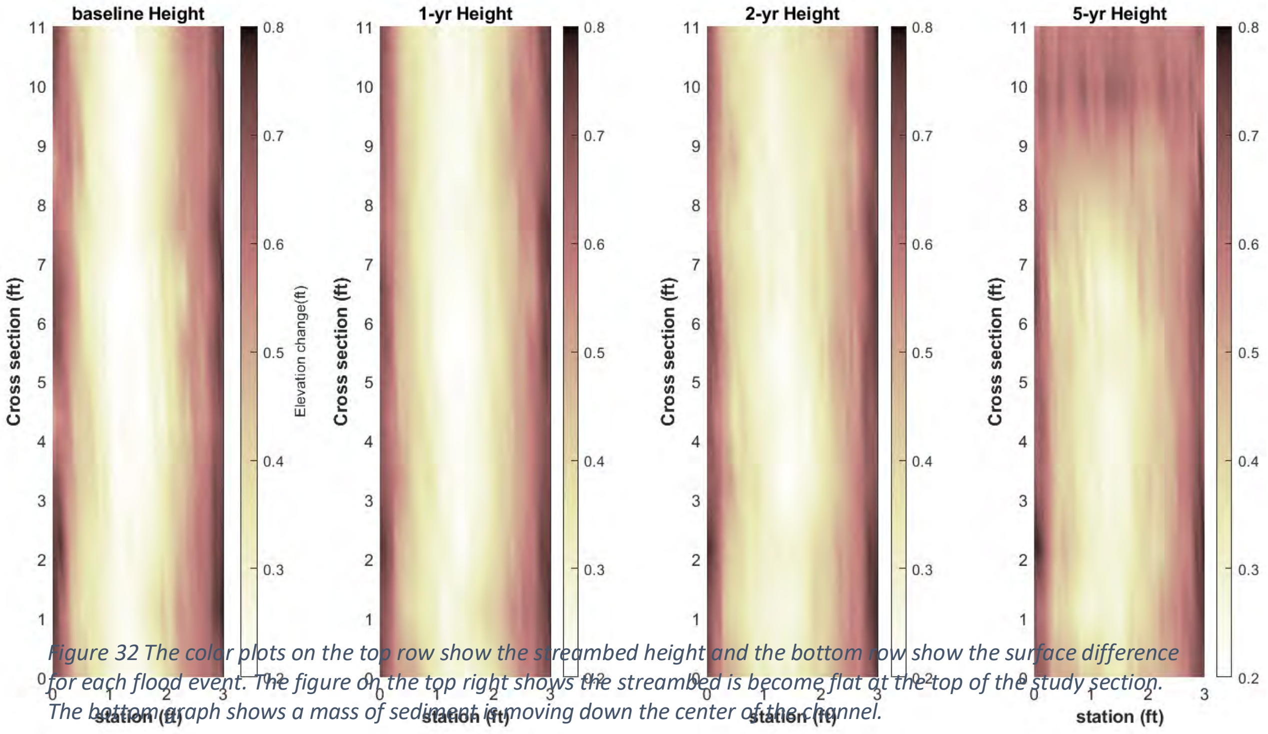


Figure 32 The color plots on the top row show the streambed height and the bottom row show the surface difference for each flood event. The figure on the top right shows the streambed is become flat at the top of the study section. The bottom graph shows a mass of sediment is moving down the center of the channel.

Figure 34 The color plots on the top row show the streambed height and the bottom row show the surface difference for each flood event. The figure on the top right shows the streambed is becoming flat at the top of the study section. The bottom graph shows that a mass of sediment is moving down the center of the channel.

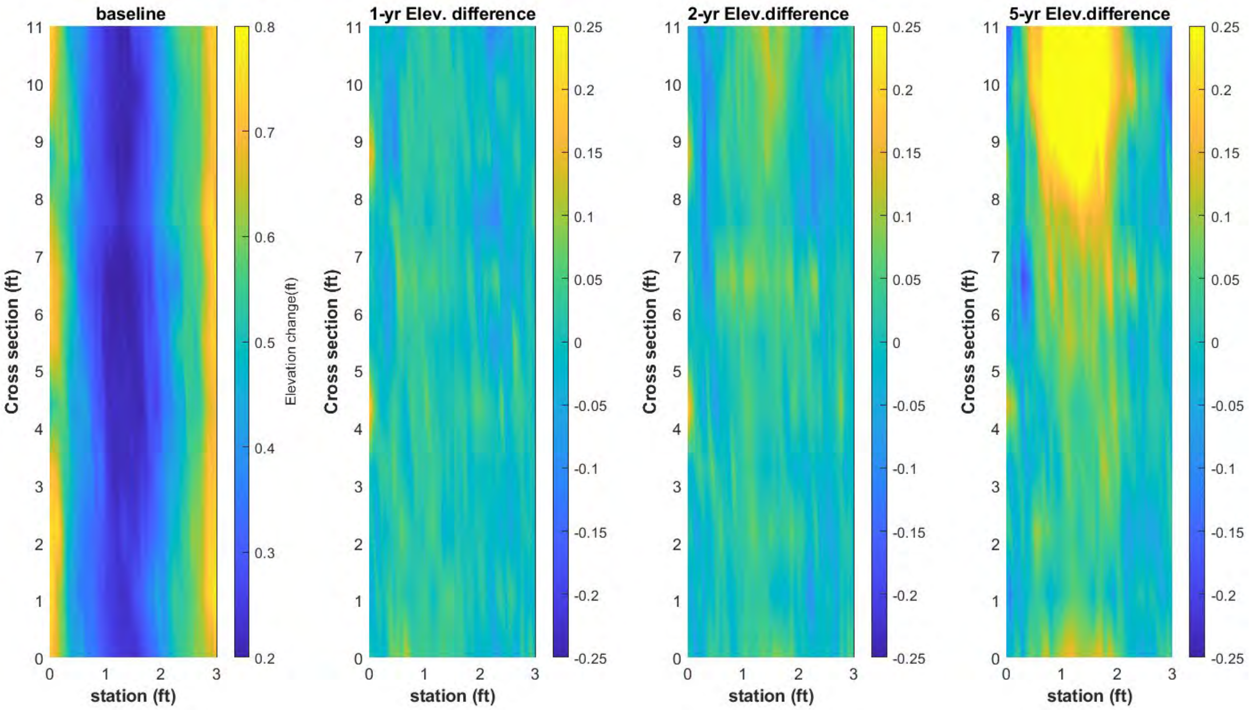


Figure 35 These color plots show the differences of streambed height after each flood event. The stream has little change after a one-year flood event. Deposition increased a little after the two-year flood event and a large mass of sediment deposition occurred after a five-year flood event.

These graphs show the height of the streambed at each flood event for Layout 1.

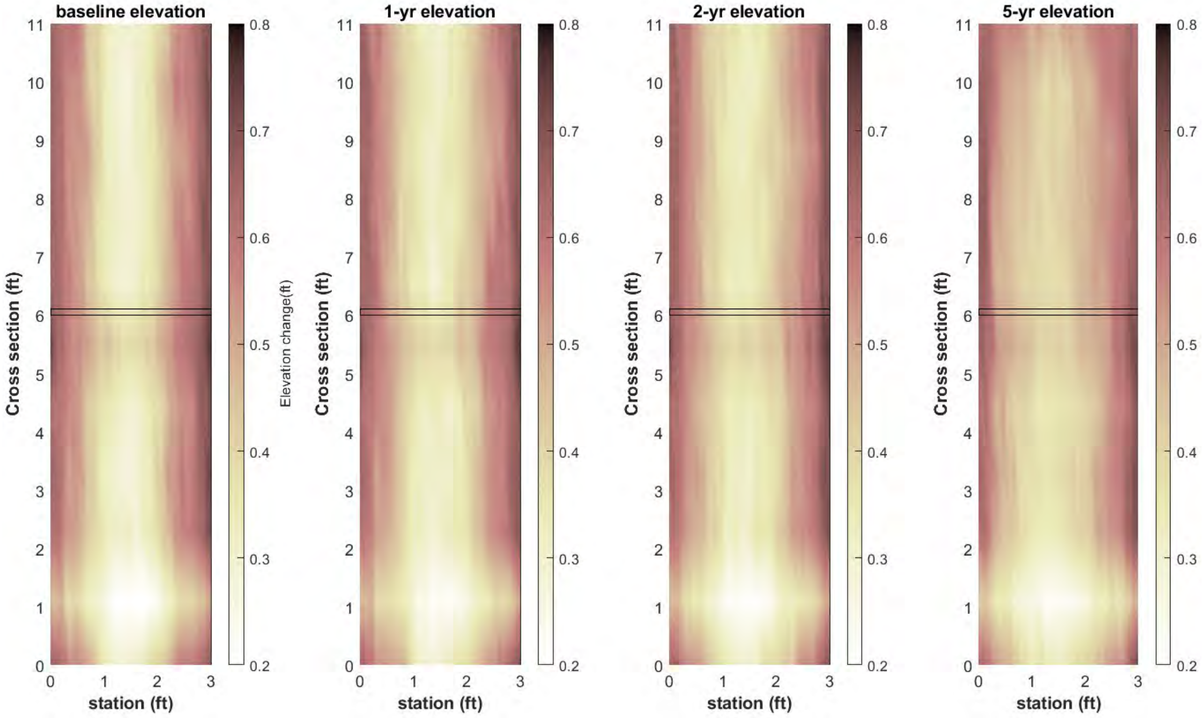


Figure 36 The color plots on the top row show the streambed height and the bottom row show the surface difference for each flood event. The first three figures in the top row shows there is little change in the height of the stream bed, while the last figure show an increase in streambed height in the center of the channel.

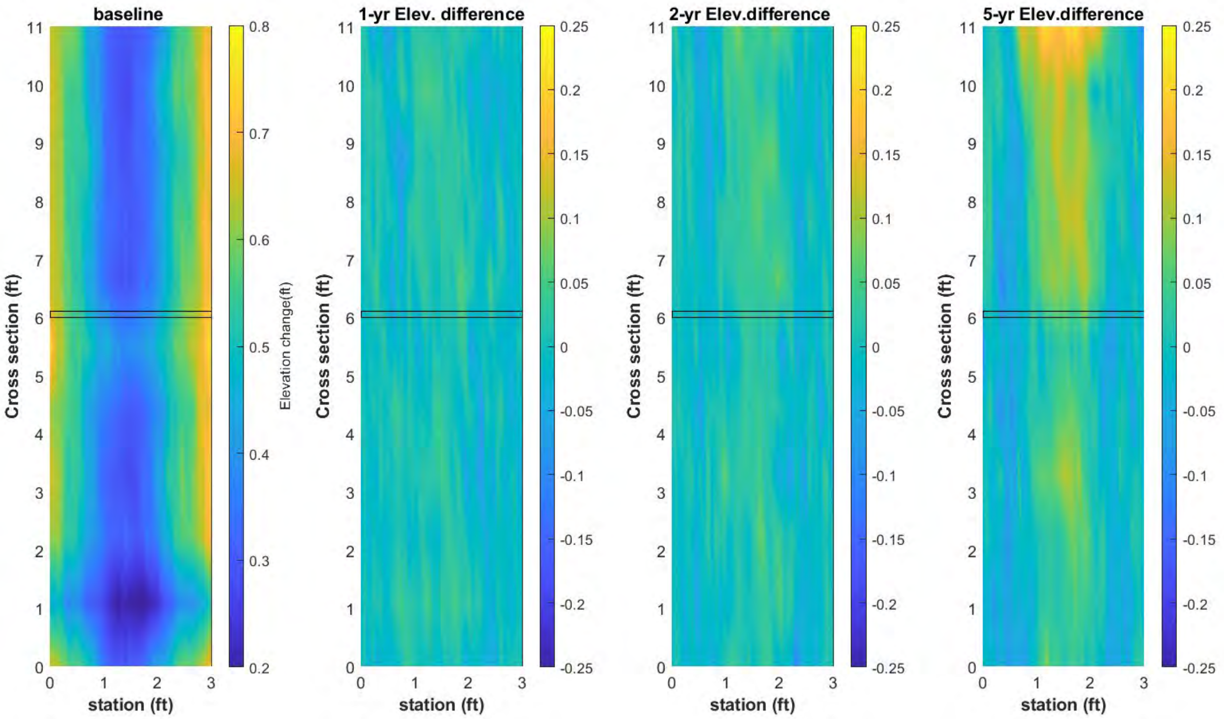


Figure 37 The surface differences show little erosion and deposition occurs over the first two flood events and these changes increase during the five-year event. Deposition on the downstream side of the coarse band is less than the channel above the coarse band.

These graphs show the height of the streambed at each flood event for Layout 2.

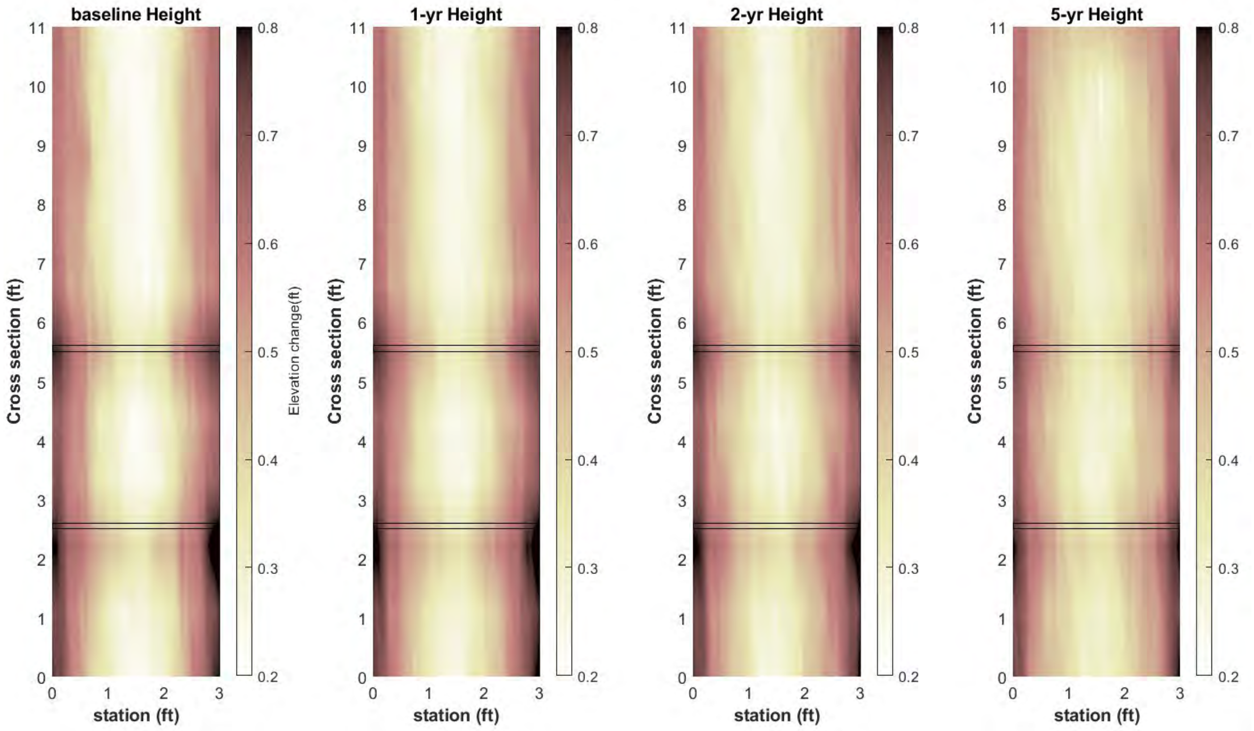


Figure 38 The height of the center of the channel increase a little after each flood event. The channel in between the coarse bands has only changed in the center of the channel.

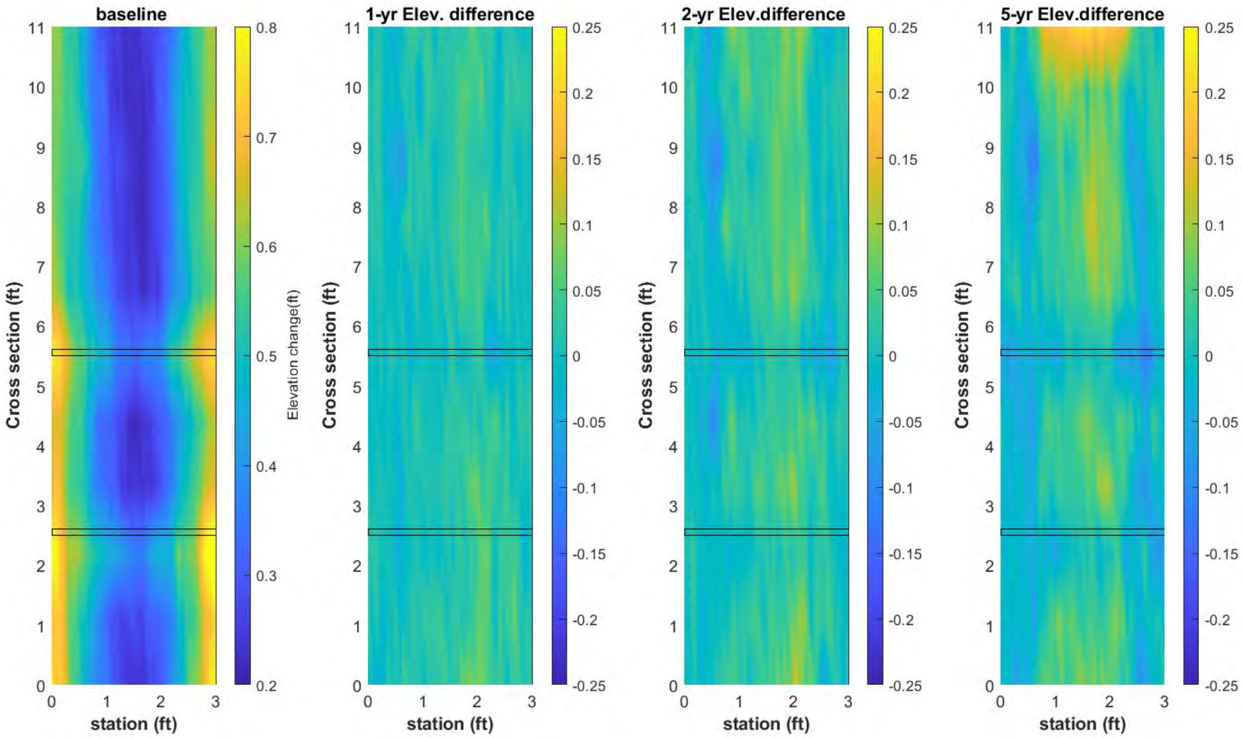


Figure 39 The channel has little change up to the five-year flood event. After a five-year flood event the center of the channel had an increase of deposition and in between the coarse bands little change occurred.

These graphs show the height of the streambed at each flood event for Layout 3.

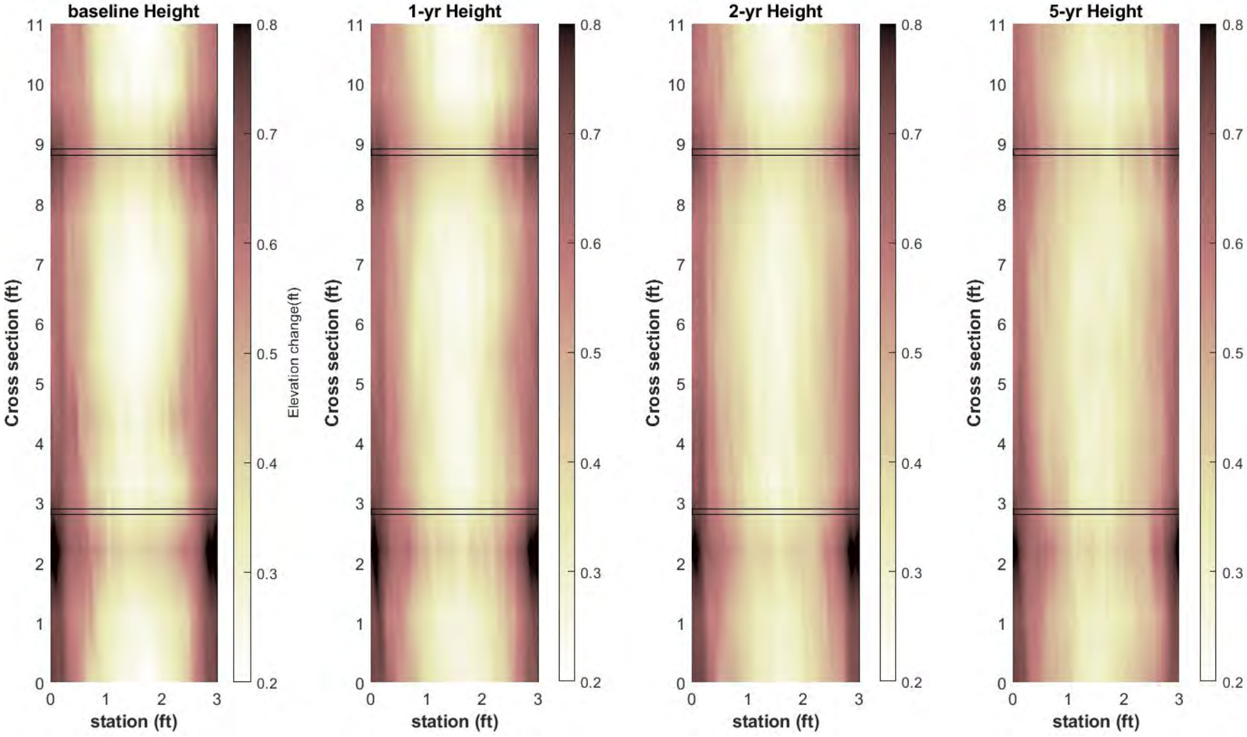


Figure 40 The height of the steam channel over each flood event increased from the previous.

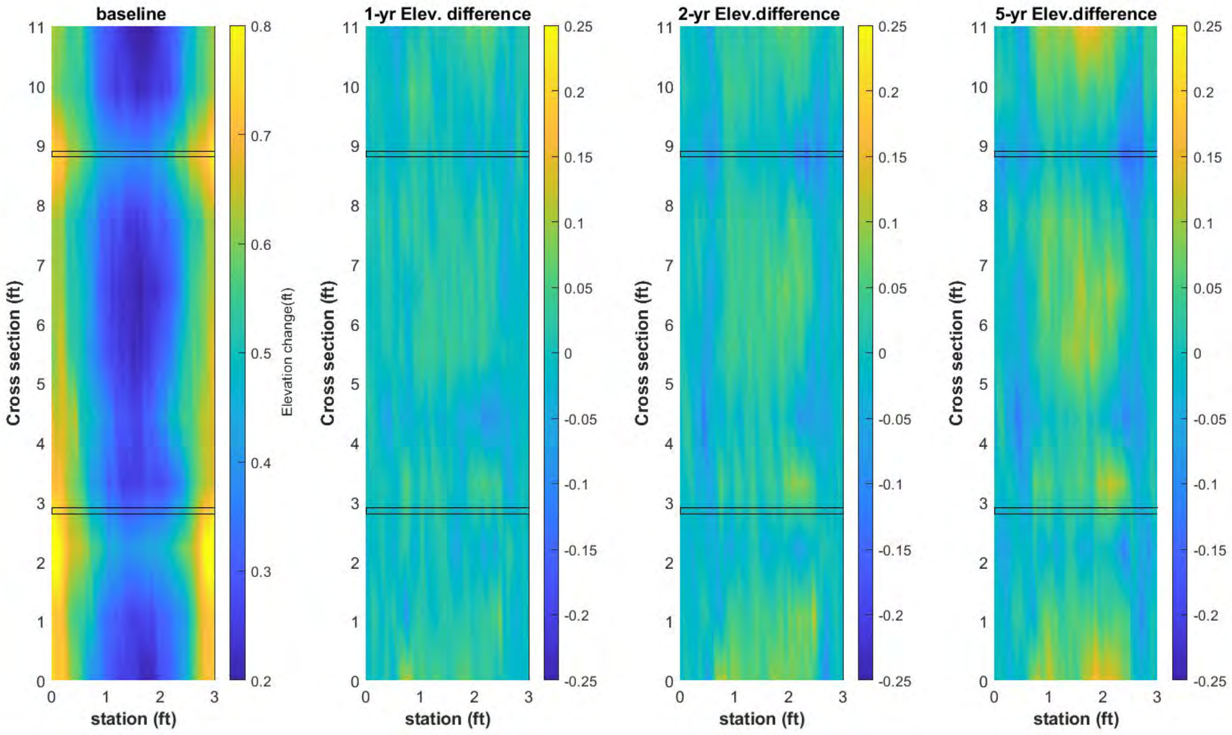


Figure 41 The channel has little change through the first two flood events. An increase in deposition occurred in the center of the channel throughout the study section. Little change occurs around the coarse bands with deposition on the upstream side and little erosion downstream.

These graphs show the height of the streambed at each flood event for Layout 4.

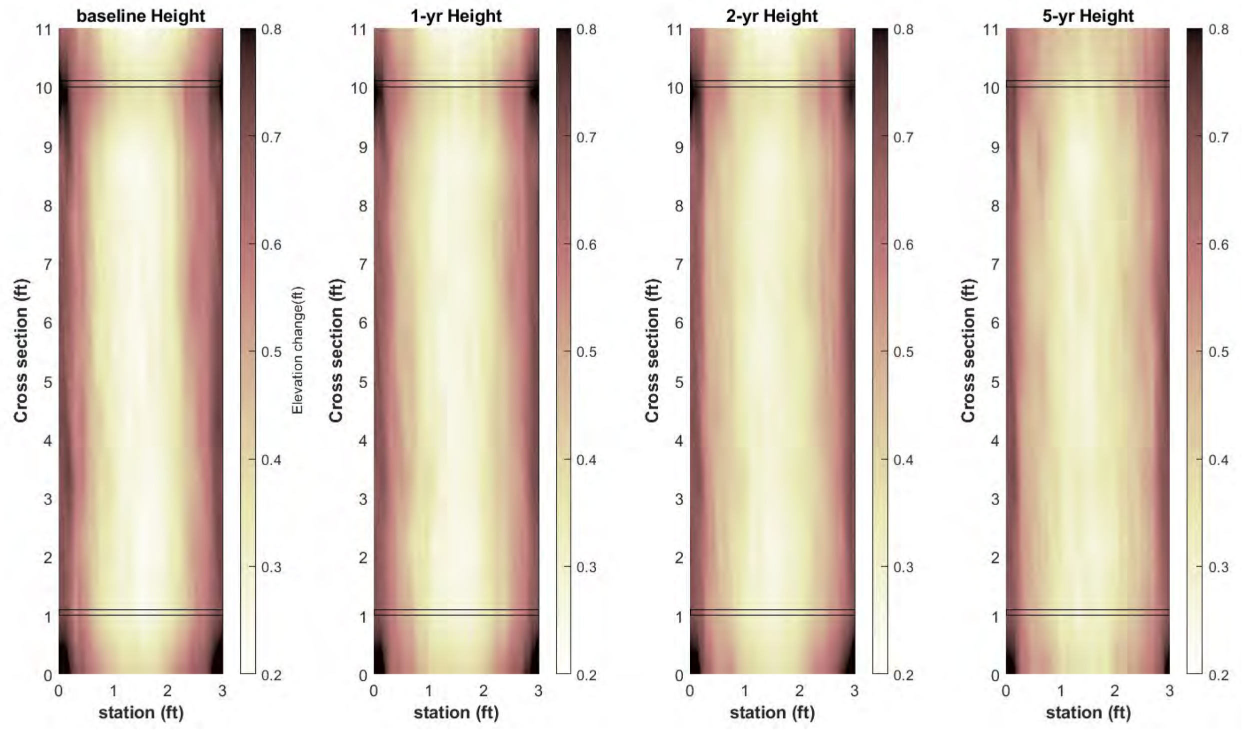


Figure 42 The stream height of the streambed between coarse bands had an increase for each flood event.

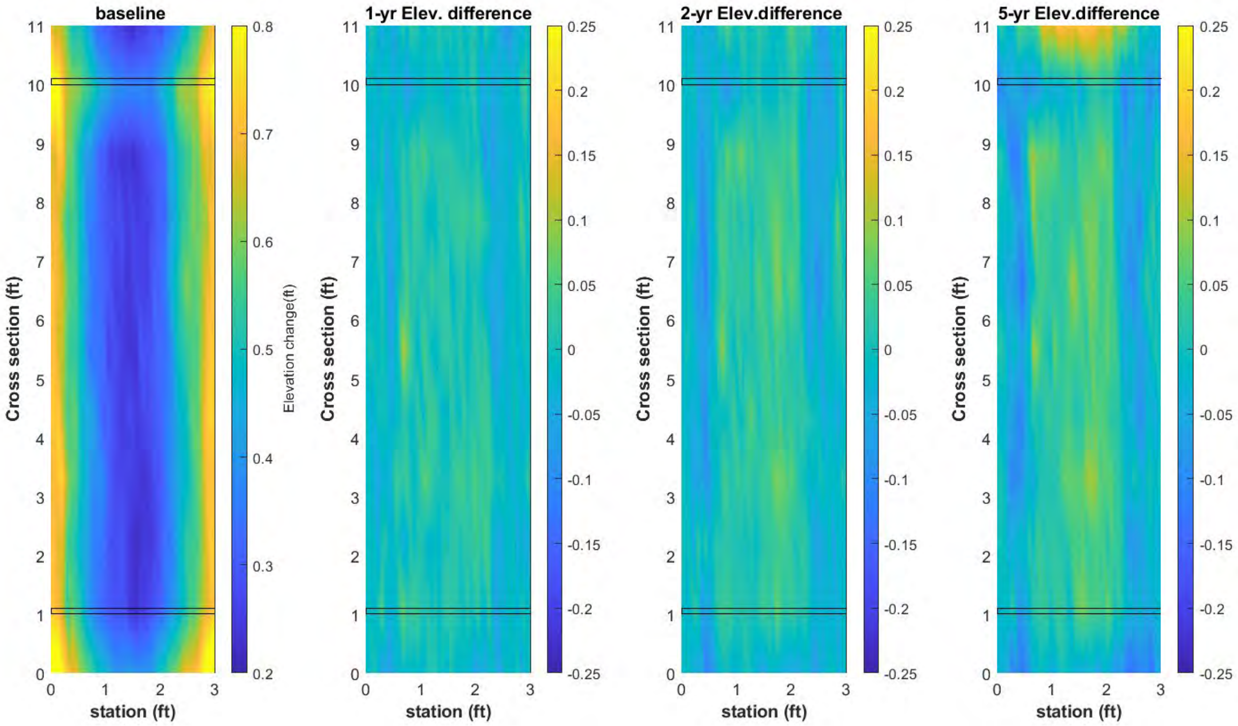


Figure 43 The channel between the coarse bands has little change through each flood event. The channel shape is maintained after a five-year flood event.

These graphs show the height of the streambed at each flood event for Layout 5.

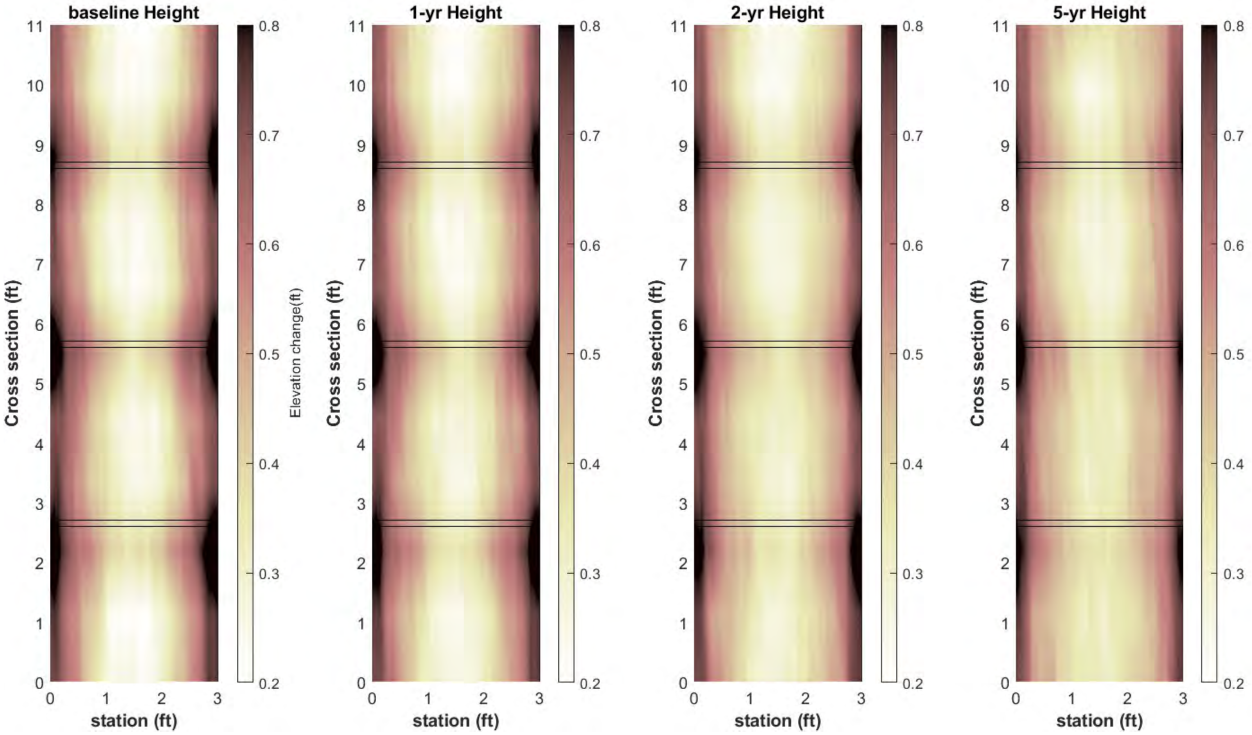


Figure 44 The height of the streambed between the coarse bands increased over each flood event. The channel after a five-year flood had a higher streambed height between the lower coarse bands.

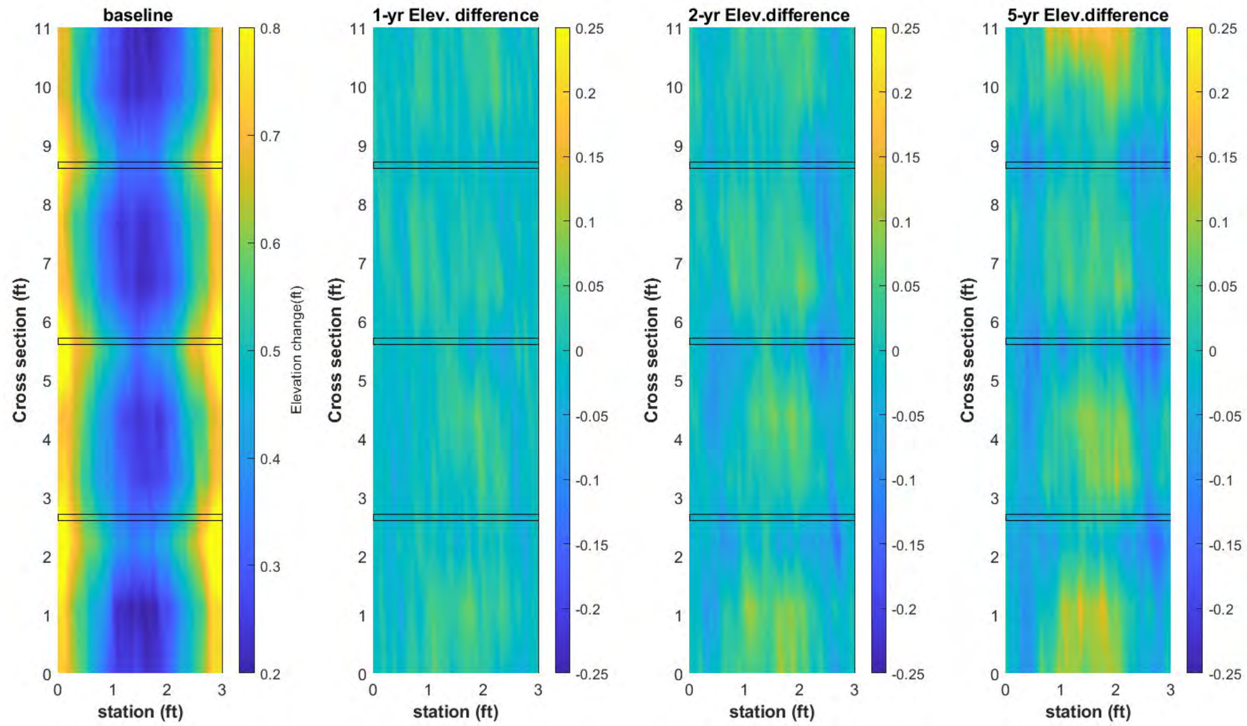


Figure 45 Little change occurs over a two-year flood event. The channel had an increase in deposition between the lower coarse band(s) and on the downstream side of lowest coarse bands. An increase of erosion occurred on the right side of the channel on the downstream side of the middle and lowest coarse bands.

These graphs show the height of the streambed at each flood event for Layout 6.

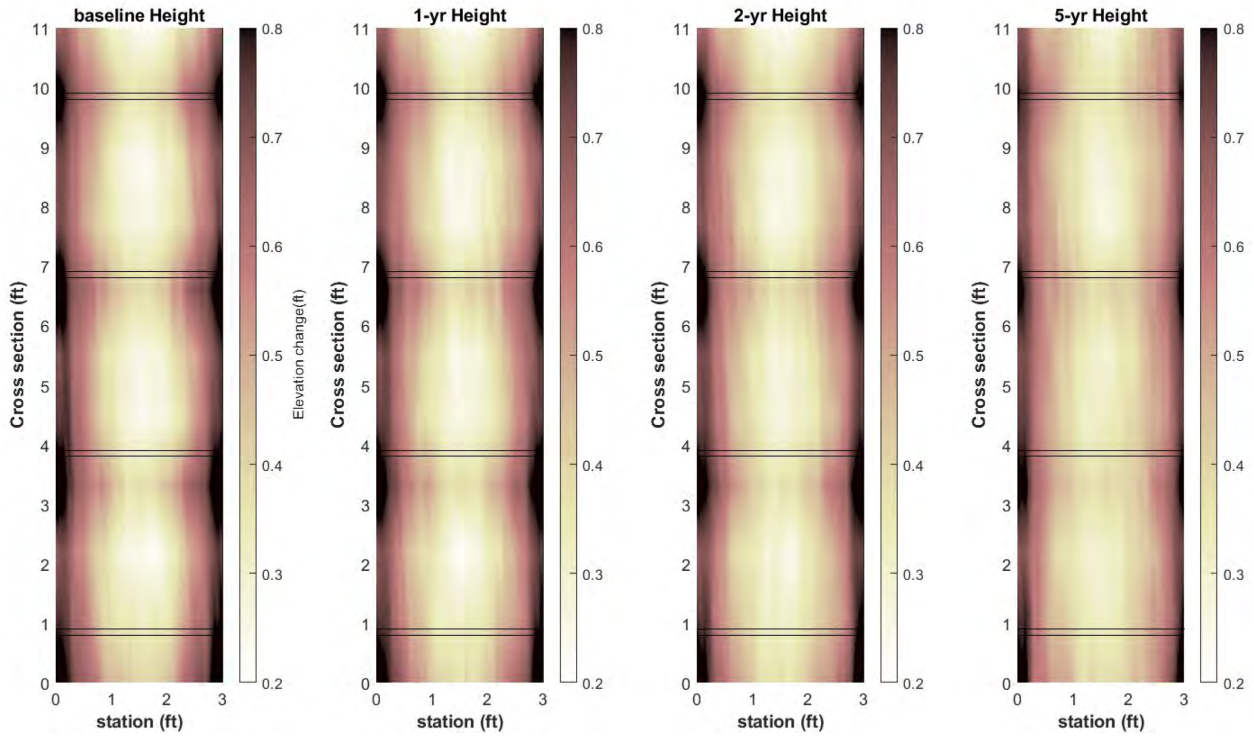


Figure 46 The height of the streambed between the coarse bands increased over each flood event. The channel after a five-year flood had a higher streambed height between the lower coarse bands.

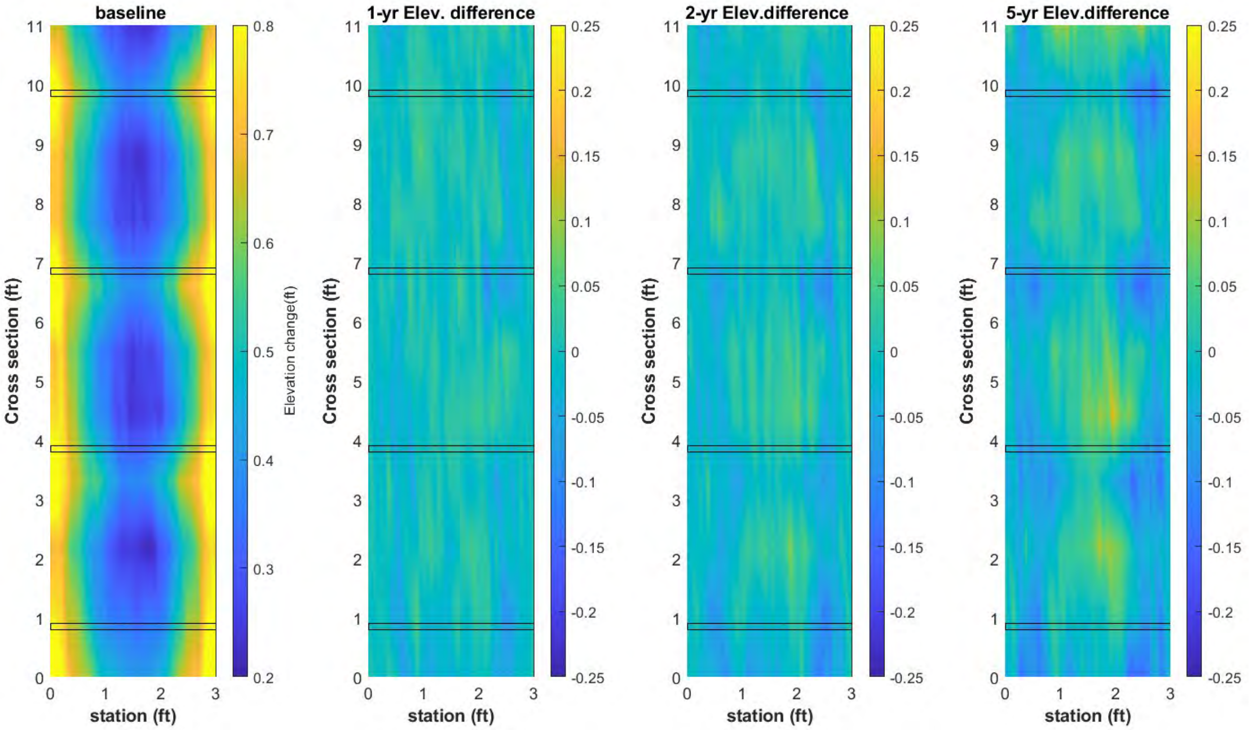
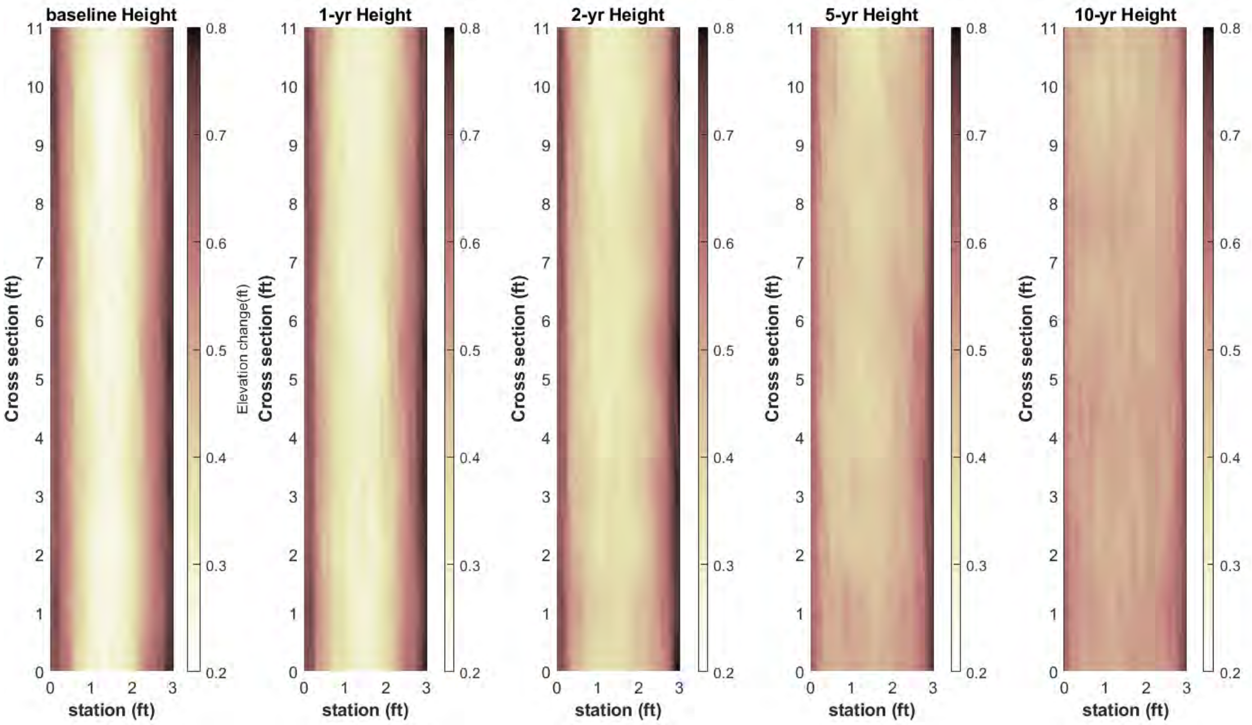


Figure 47 The channel between the coarse bands has little change through each flood event. The channel shape is maintained after a five-year flood event.

These graphs show the height of the streambed at each flood event for Layout 7.


baseline Height

1-yr Height

2-yr Height

5-yr Height

10-yr Height

Figure 48 The streambed has little change in height over a one-year flood event. The center of the channel after a two-year flood event increased. The channel became completely flat after a five-year flood event.

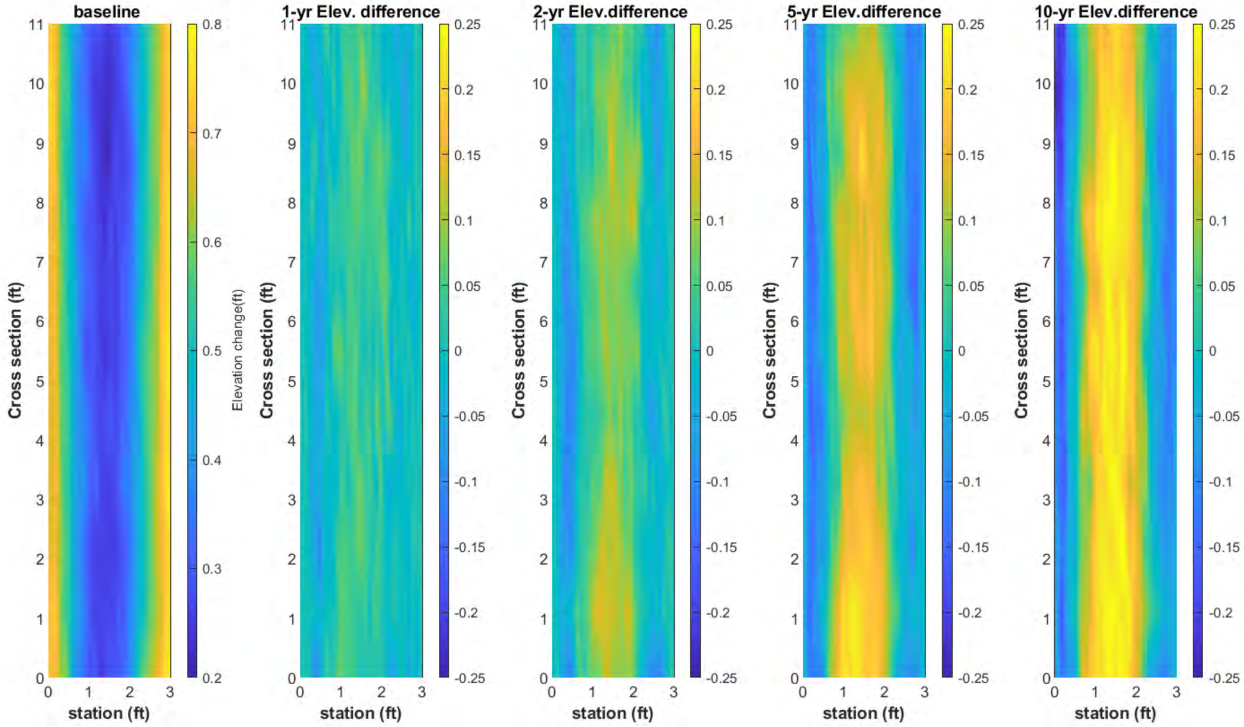


Figure 49 The center of the channel is filled with sediment and the sides are eroded. The amount of change increased after each flood event.

These graphs show the height of the streambed at each flood event for Layout 8.

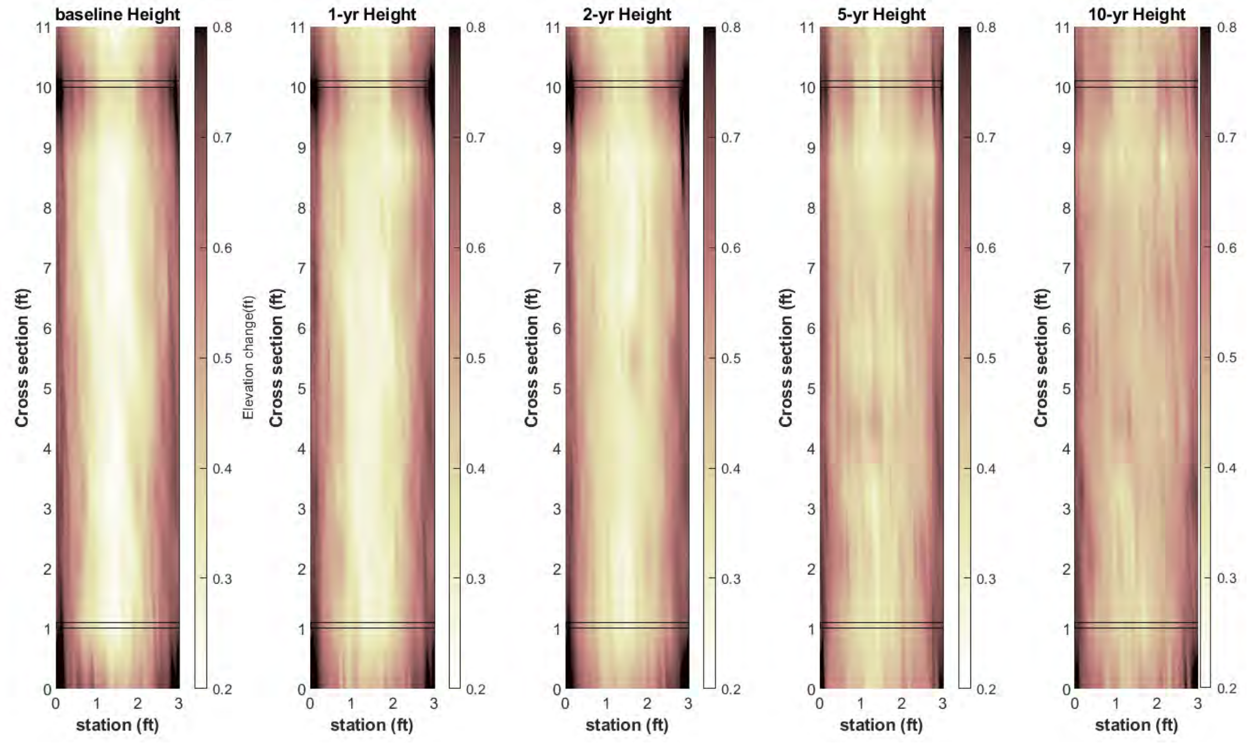


Figure 50 The channel between coarse bands is raised after each flood event. The height of the coarse bands was decreased after the five and ten-year flood event.

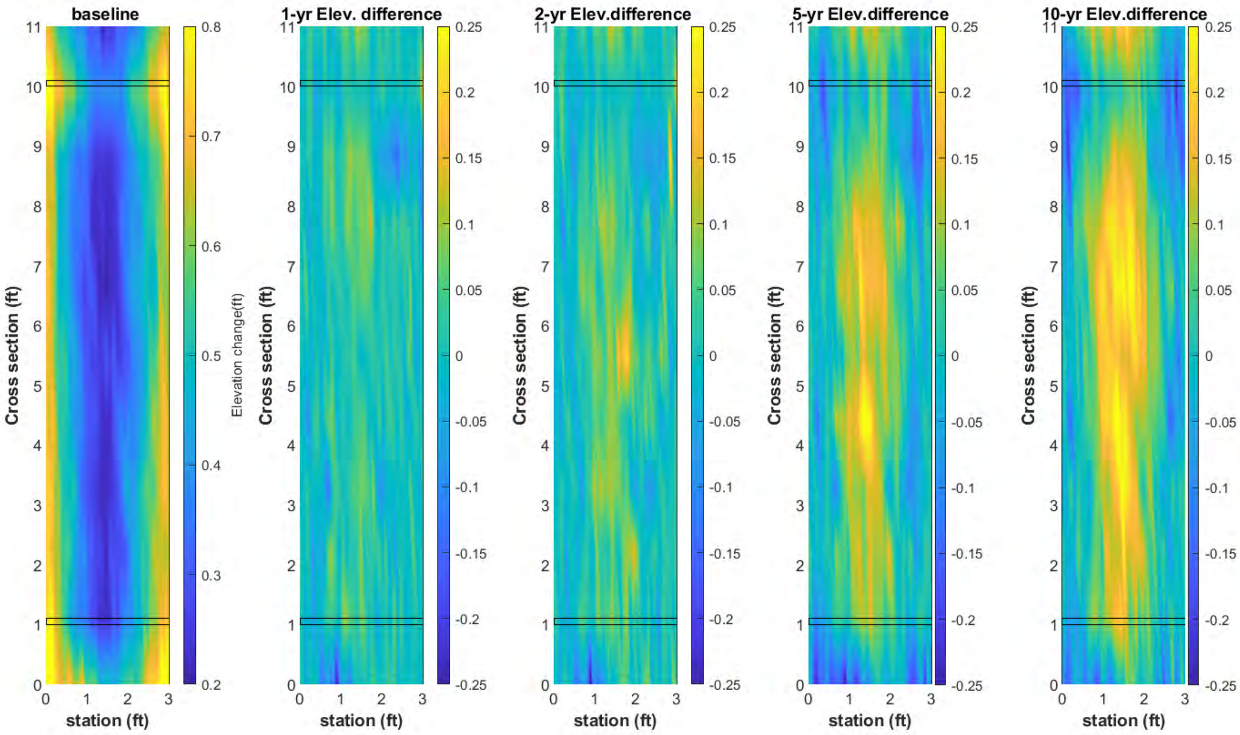


Figure 51 The streambed had little change after a one-year flood event and an increase in deposition in the center of the channel for a two-year flood event. Erosion at the coarse bands started after a five-year flood and deposition in the center of the channel. These dynamics increase over a ten-year flood event.

These graphs show the height of the streambed at each flood event for Layout 9.

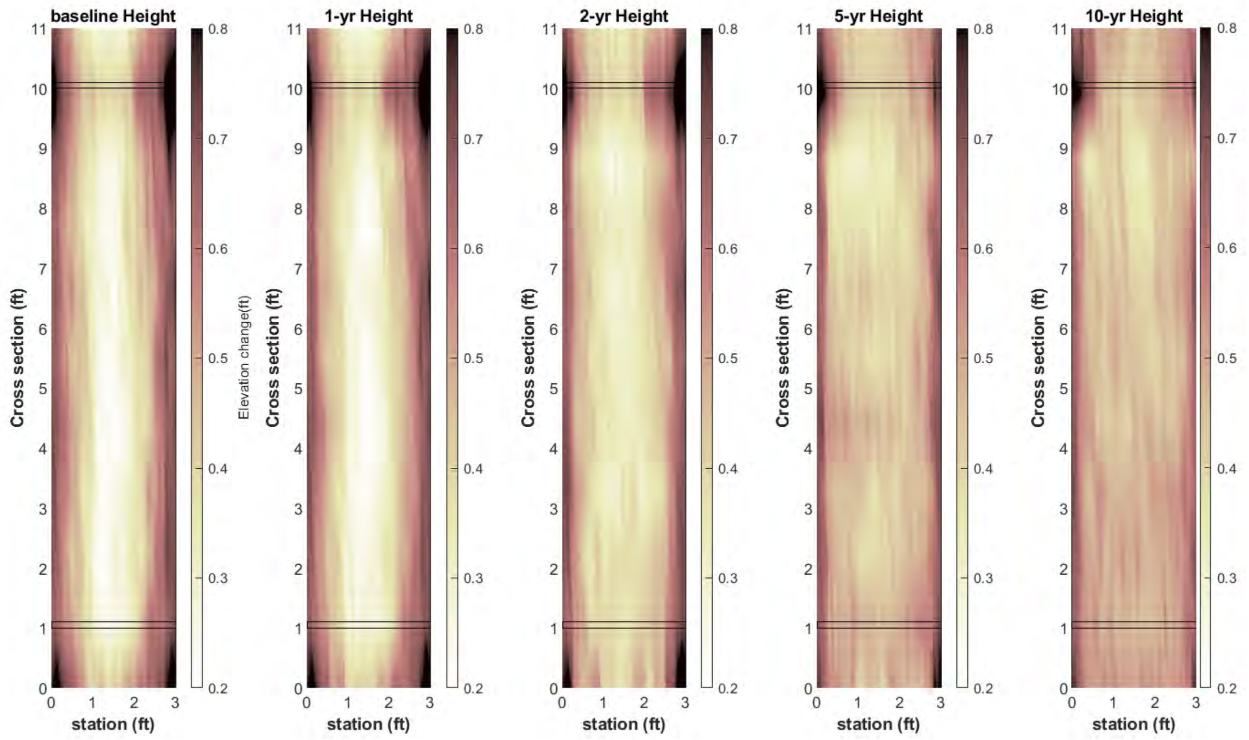


Figure 52 These graphs show the height of the streambed after each flood event. The height of center of the channel increased after each event and the height of the coarse bands and edges of the ?? decreased after the five and ten-year event.

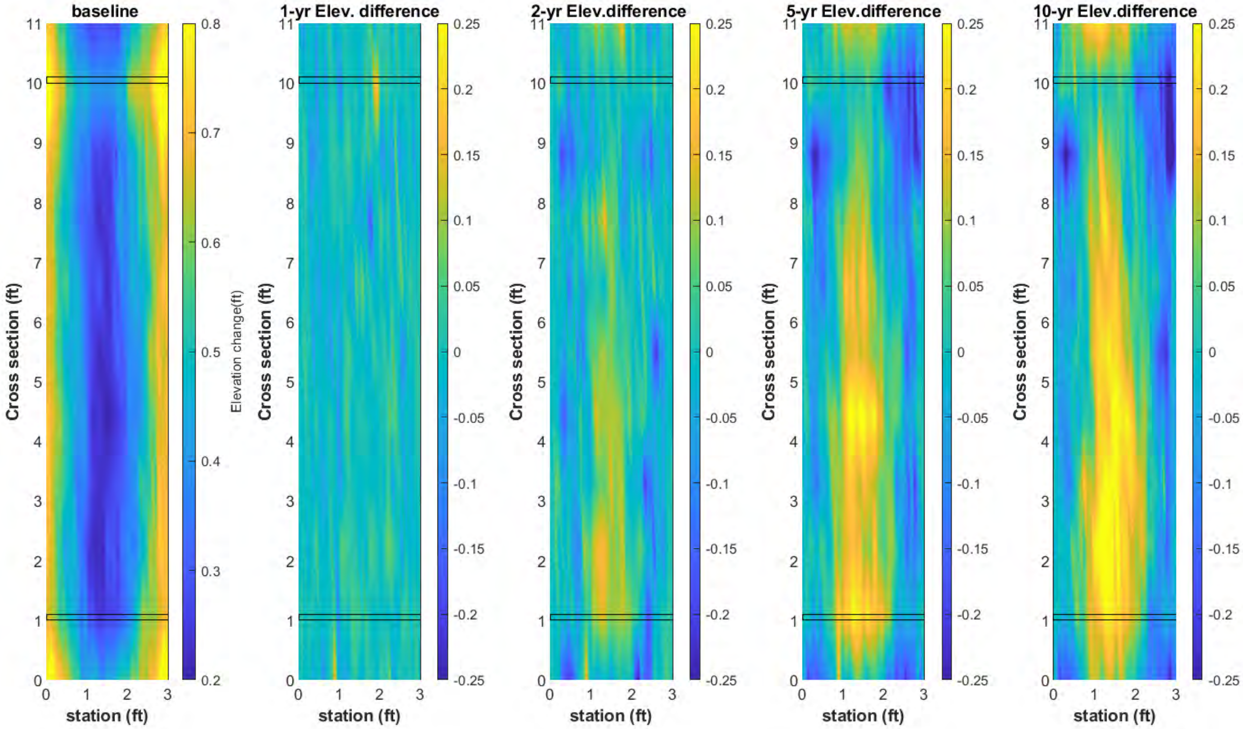


Figure 53 The channel had little change over a one-year event, while the channel had an increase of deposition above the lower coarse bands. Deposition continued to increase and work its way up stream after the five-year flood event. Erosion took place at and around the upper coarse bands. Both erosion and deposition increase during the ten-year flood event.

These graphs show the height of the streambed at each flood event for Layout 10.

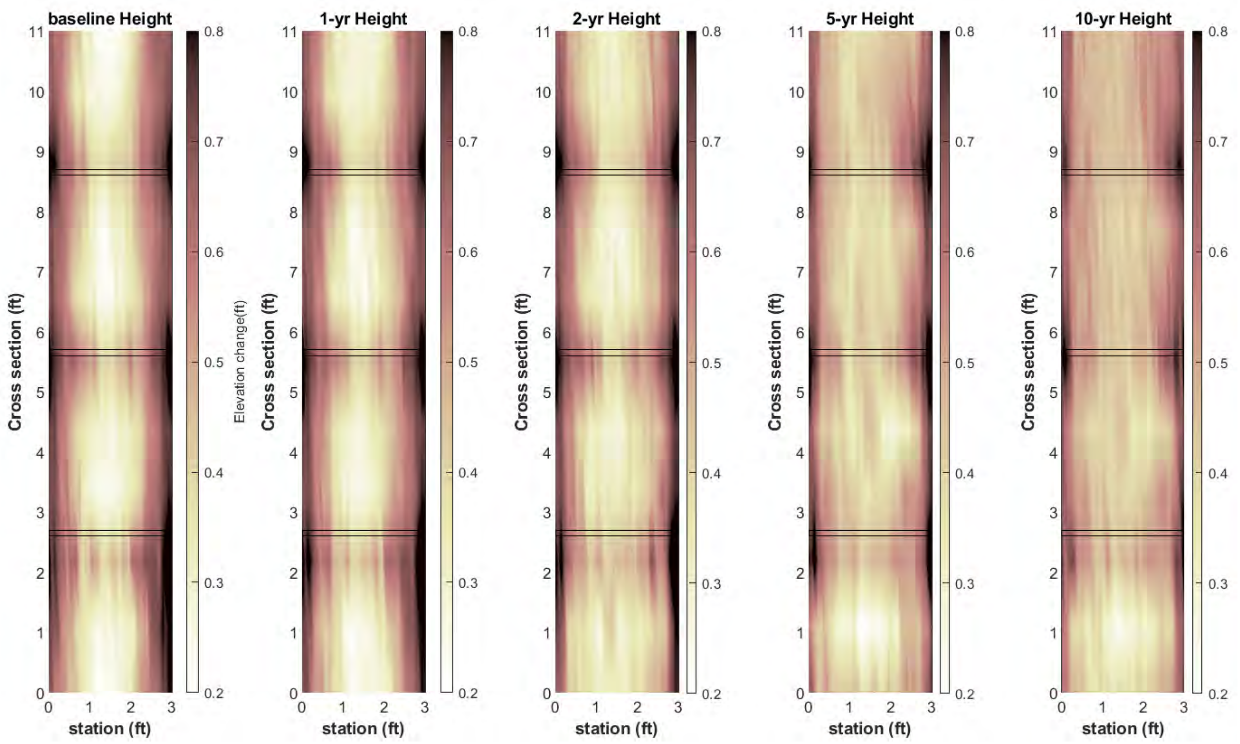


Figure 54 The height of the streambed was stable until the five-year flood event. At the five-year flood event the channel between the coarse bands increased. The height continued to increase during the ten-year flood event. The height of the channel below the downstream coarse bands still had a u-shape channel.

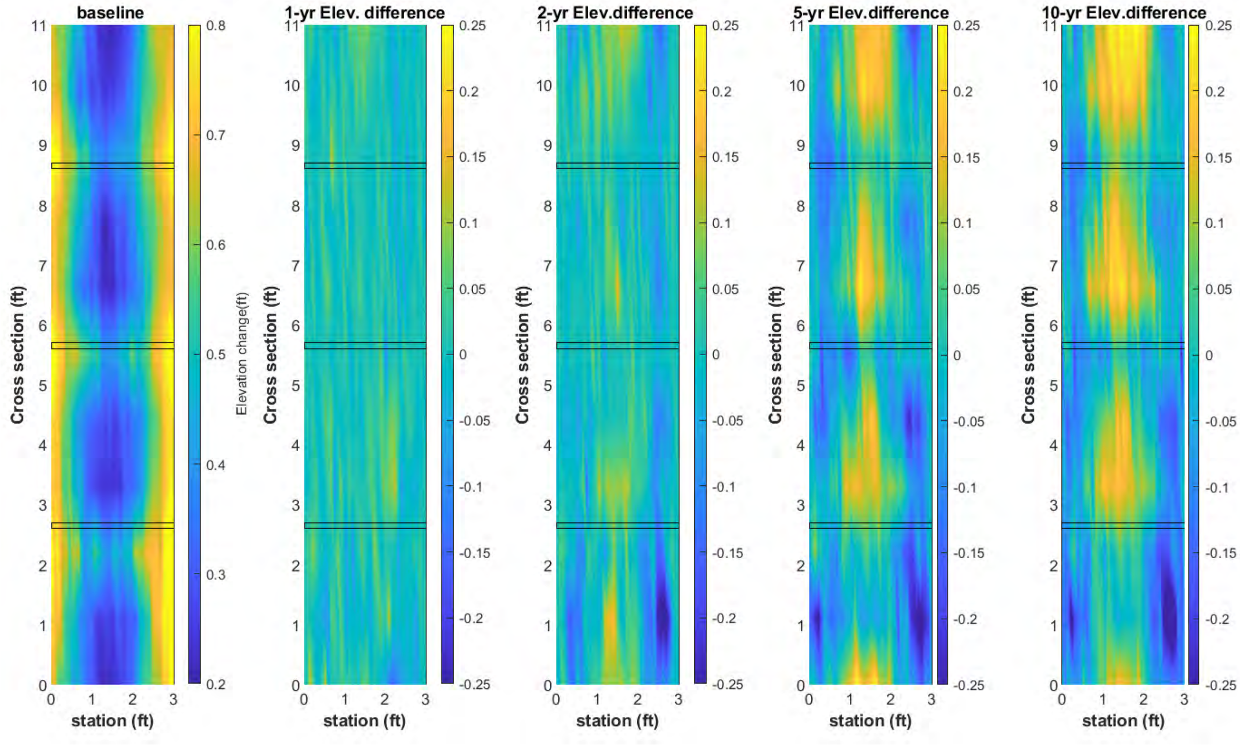


Figure 55 The channel had little change over the first two flood event but during the two-year flood event erosion had occur at the bottom of the study section. During a five-year flood event the channel had deposition in the center of the channel and erosion on the sides of the channel. These dynamics continued at the ten-year flood event.

These graphs show the height of the streambed at each flood event for Layout 11.

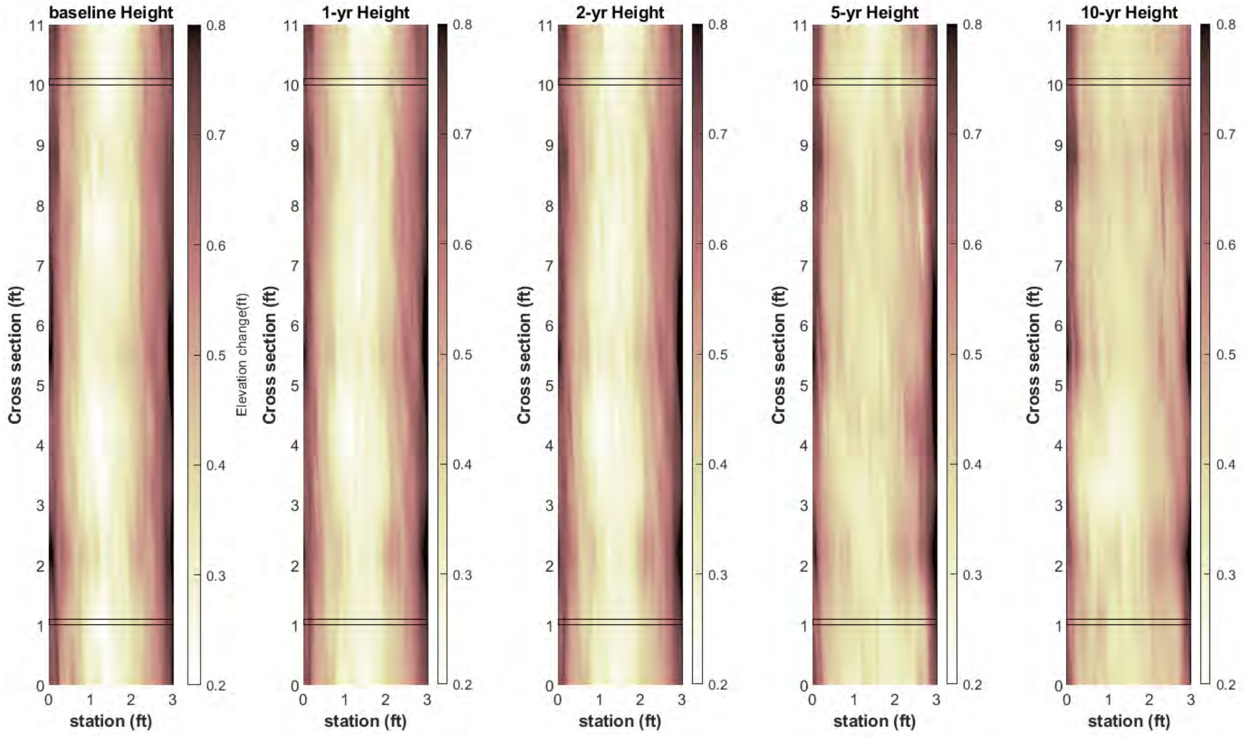


Figure 56 The channel height was stable until the five-year flood event. An increase in streambed height occurred at the five-year flood event. The increase in streambed height continued for the ten-year flood event but erosion around cross-section 3 & 4 also occurred.

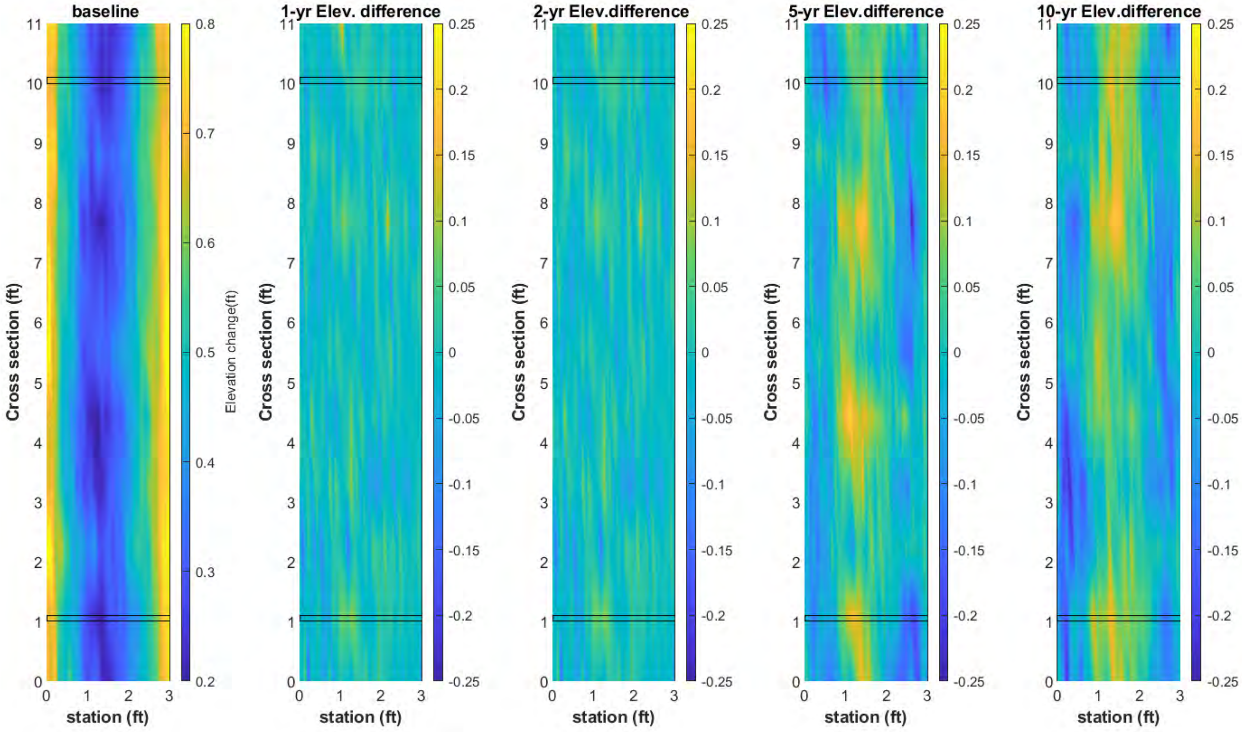


Figure 57 Little change took place over the first two flood events. The last two flood events are where most of the change occurred. Deposition in the center of the channel and erosion on the sides of the channel occurred at both flood events.

These graphs show the height of the streambed at each flood event for Layout 12.

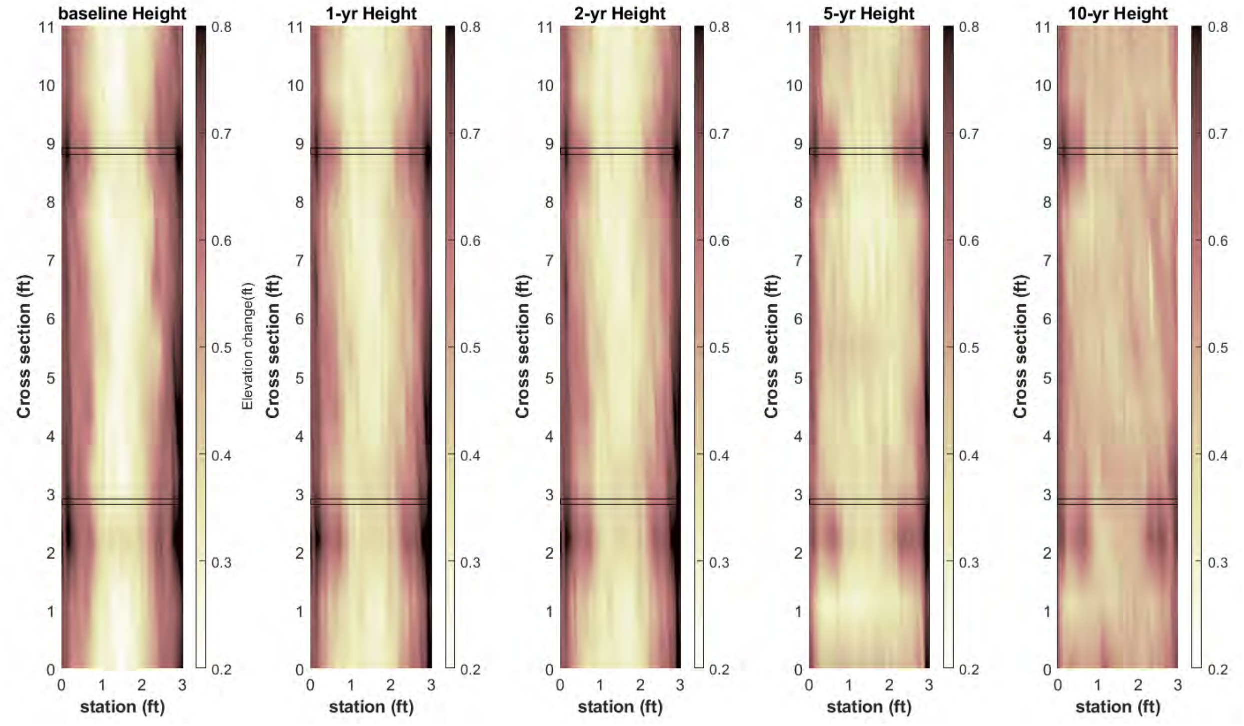


Figure 58 The height of the center of the channel increased over the first three flood events. At the ten-year flood event the height of the channel increased, and the coarse bands height decreased.

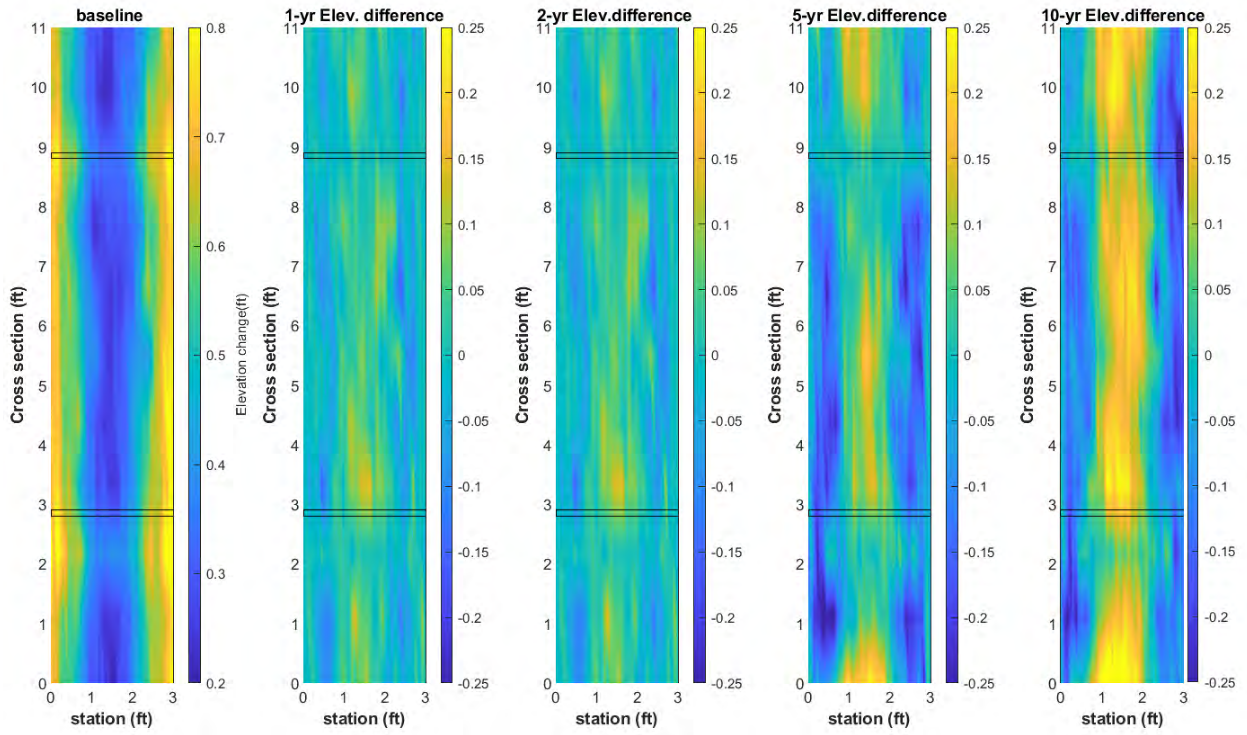


Figure 59 The channel was stable until the five-year flood event. Little deposition in the center of the channel but erosion on the sides of the channel occurred at a faster rate. For the ten-year flood event deposition increased in the center of the channel and erosion was the same as the five-year flood event.

These graphs show the height of the streambed at each flood event for Layout 13.

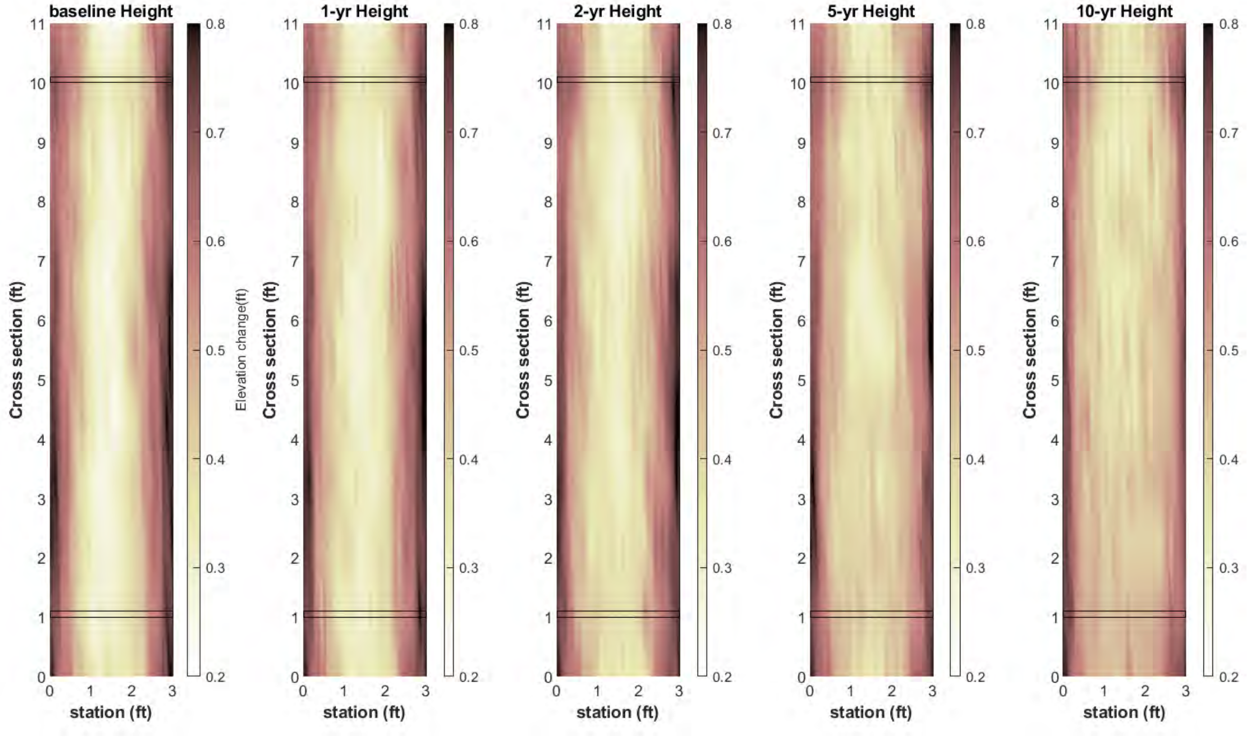


Figure 60 The height of the center of the channel increased over each flood event.

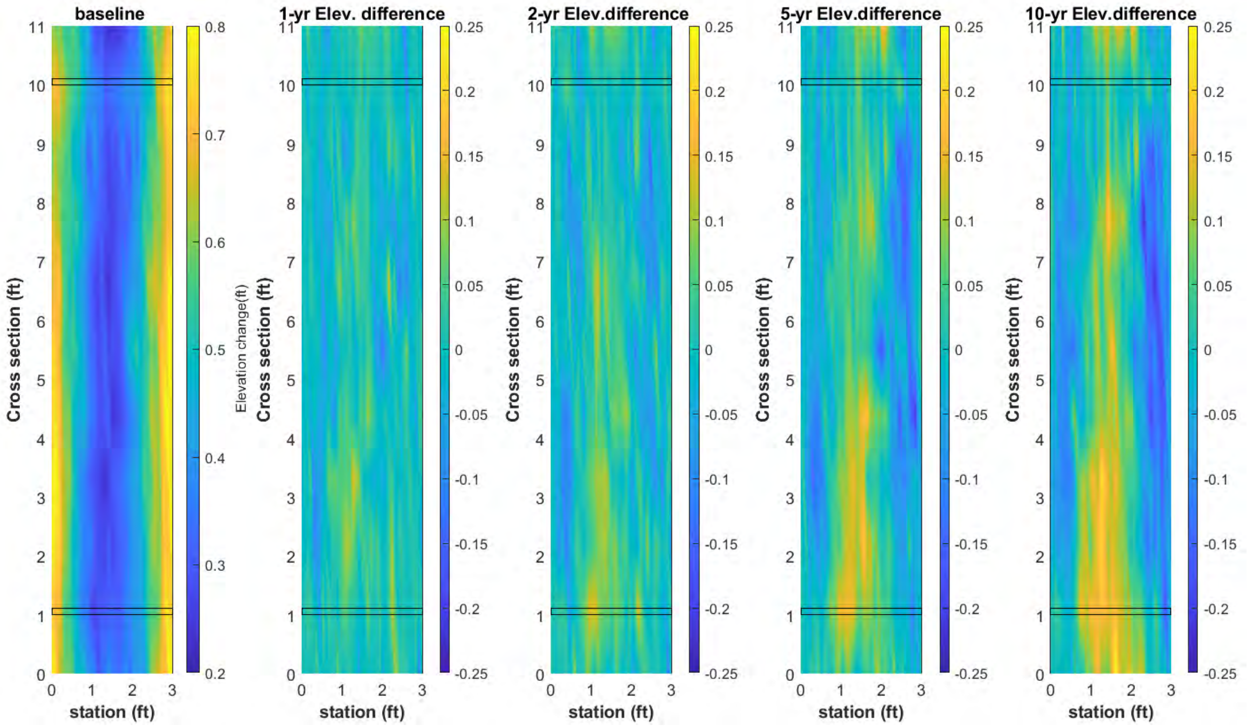


Figure 61 The channel was stable until the five-year flood event. Little deposition in the center of the channel but erosion on the sides of the channel occurred at a faster rate. For the ten-year flood event deposition increased in the center of the channel and erosion was the same as the five-year flood event.

These graphs show the height of the streambed at each flood event for Layout 14.

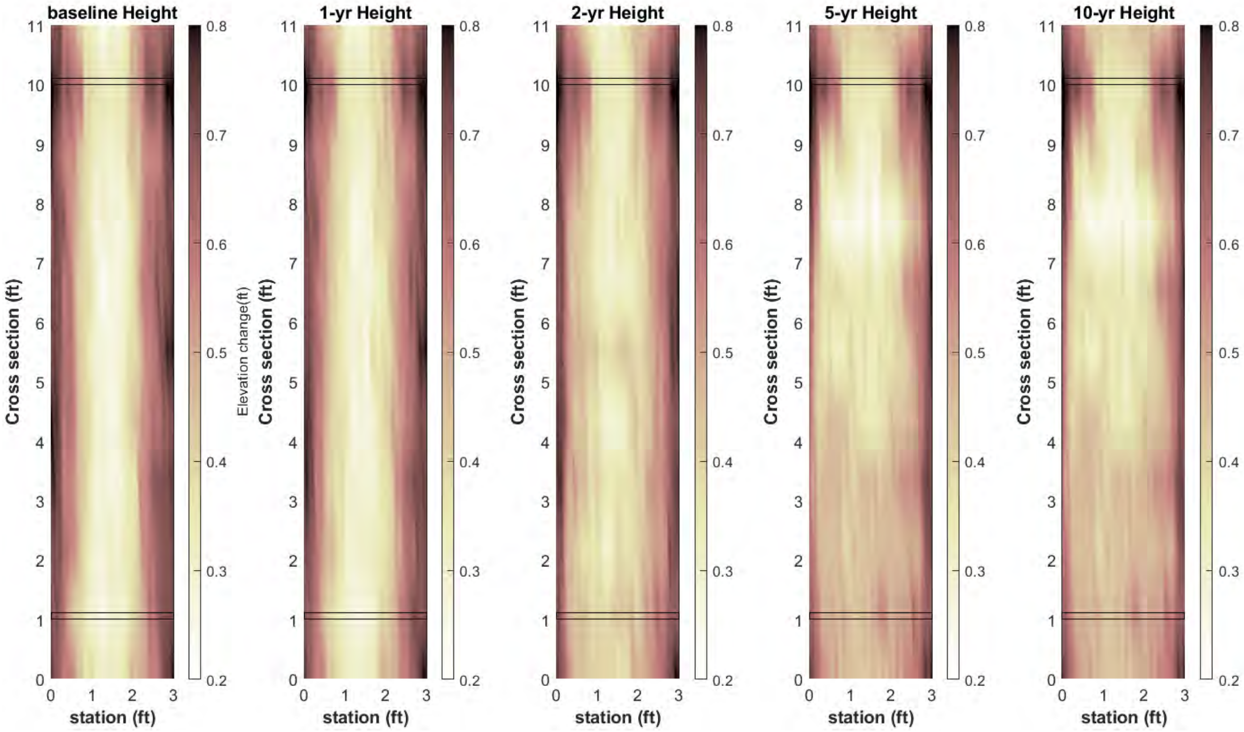


Figure 62 The height of the center of the channel increased over the first two flood events. At the five and ten-year flood event the height of the channel increased but downstream at the upper coarse bands the height decreased at cross-section 8.

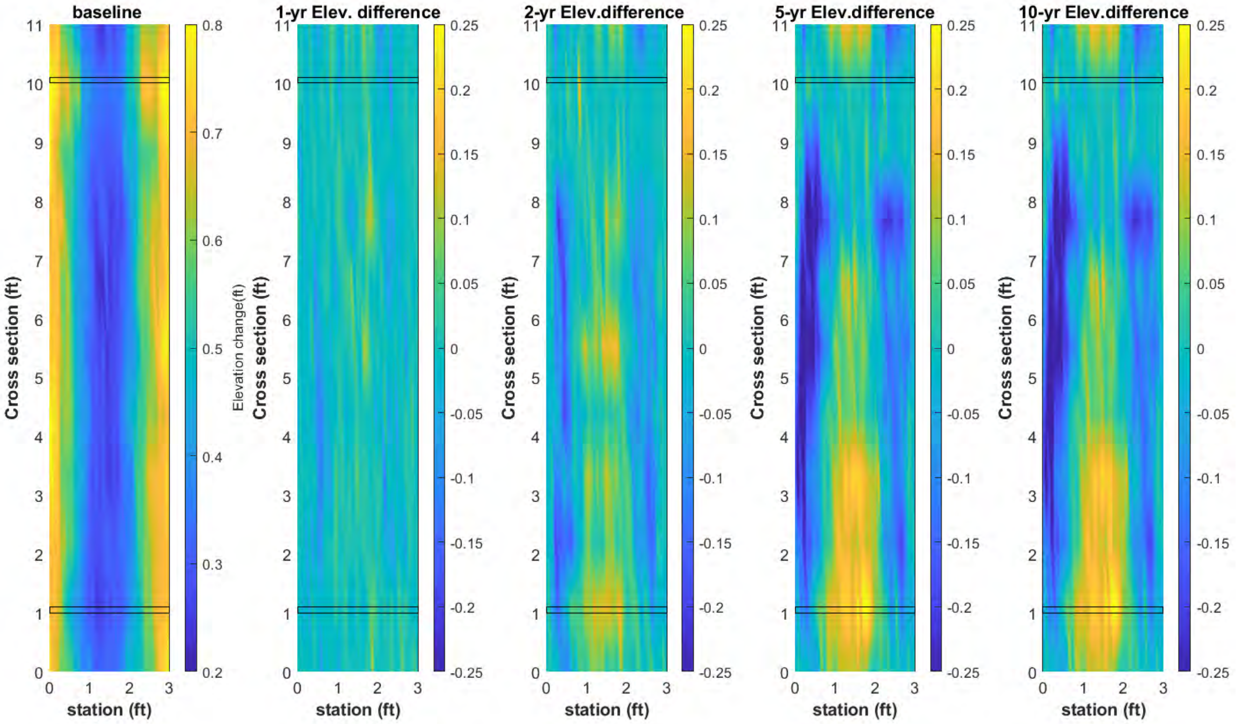


Figure 63 The channel was stable until the five-year flood event. Little deposition in the center of the channel but erosion on the sides of the channel occurred at a faster rate. For the ten-year flood event deposition increased in the center of the channel and erosion was the same as the five-year flood event.

These graphs show the height of the streambed at each flood event for Layout 15.

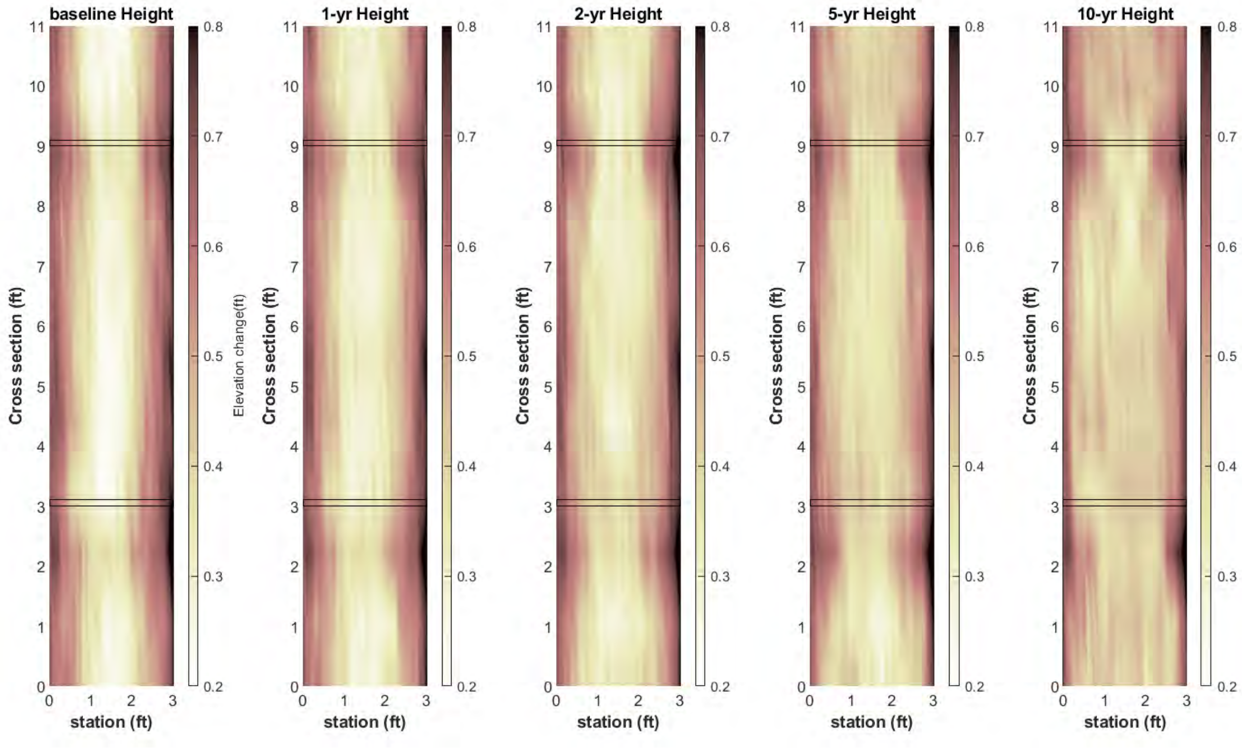


Figure 64 The center of the channel height increased each flood event. The height of the side of the channel decreased after the ten-year flood event.

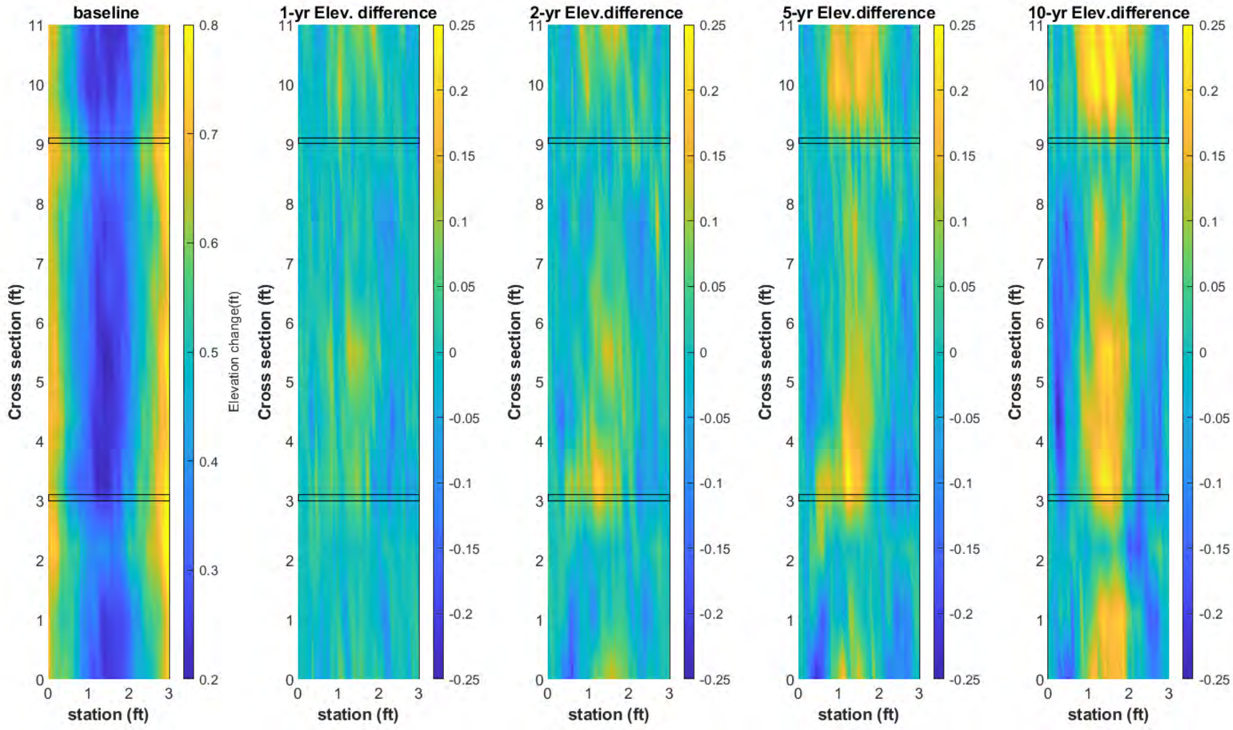


Figure 65 The channel was stable until the five-year flood event. Little deposition in the center of the channel occurred above the coarse bands. The deposition continued in the center of channel and erosion on the side of the channel took place after the ten-year flood event.

These graphs show the height of the streambed at each flood event for Layout 16.

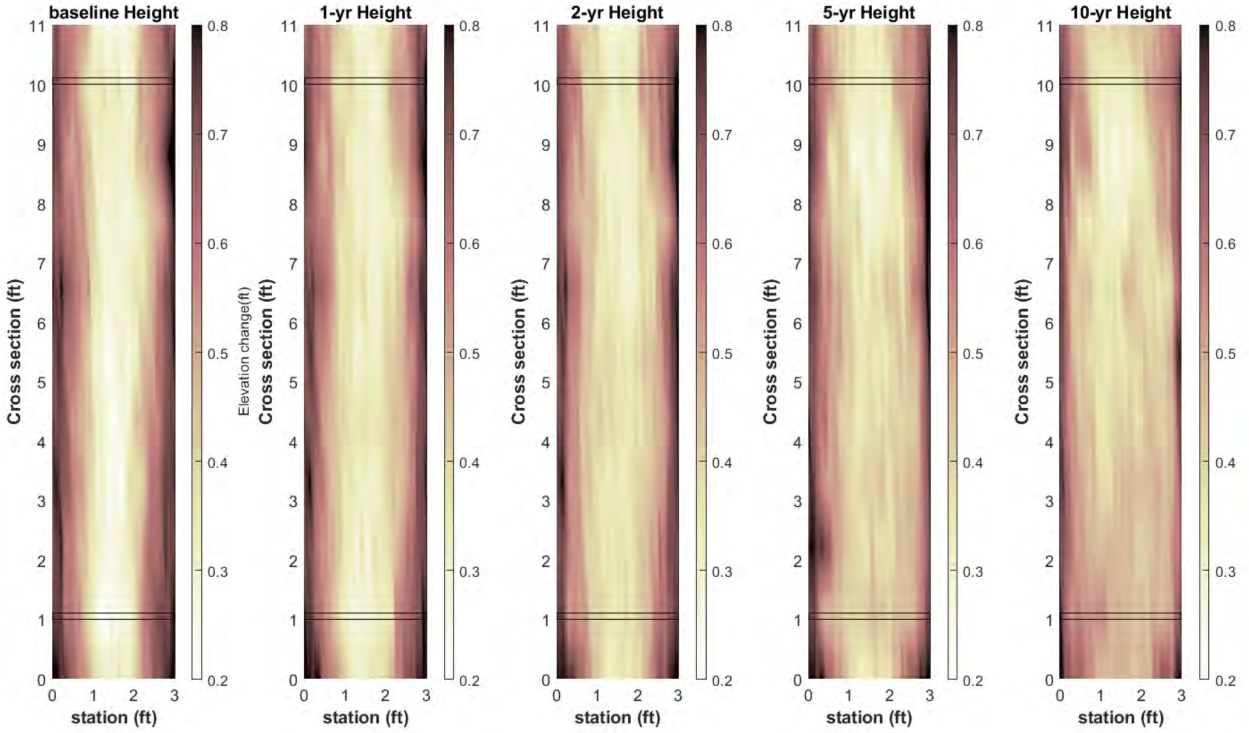


Figure 66 The height of the center of the channel increased and the sides decreased over the flood events.

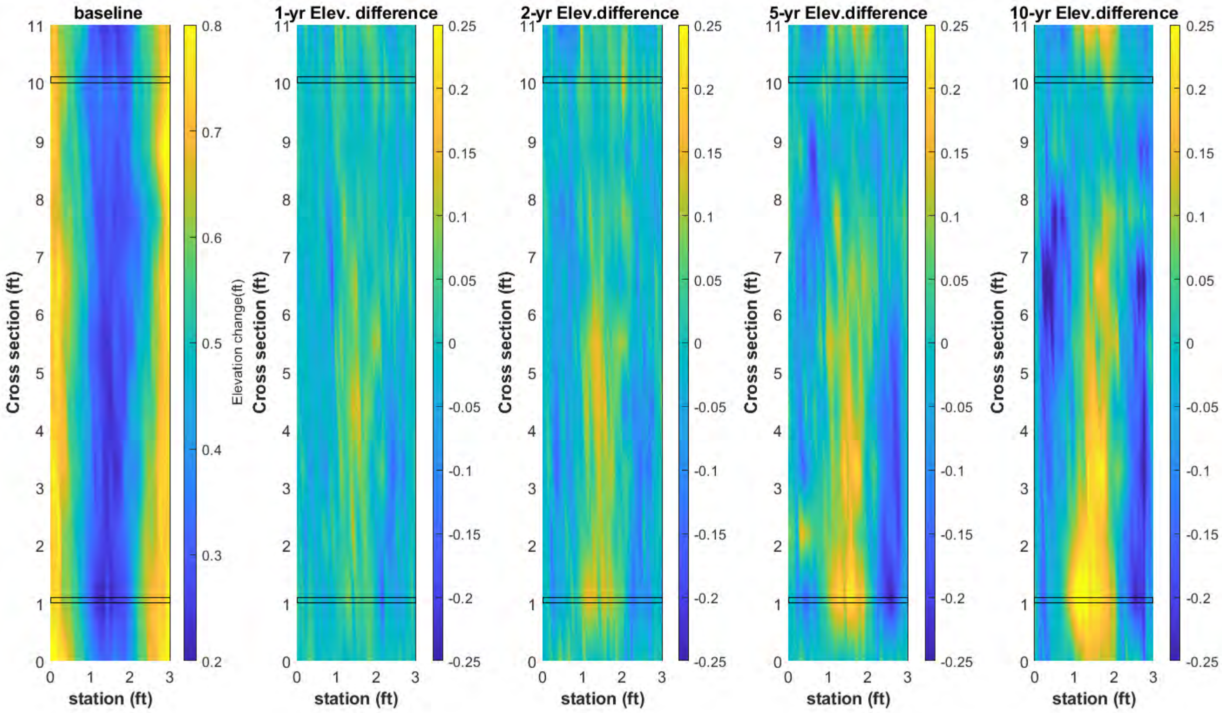


Figure 67 Little change occurred over the first two flood events. Deposition in the center of the channel increased over the final two flood events. Erosion of the sides of the channel happened after a five-year event and continued for the ten-year event.

These graphs show the height of the streambed at each flood event for Layout 17.

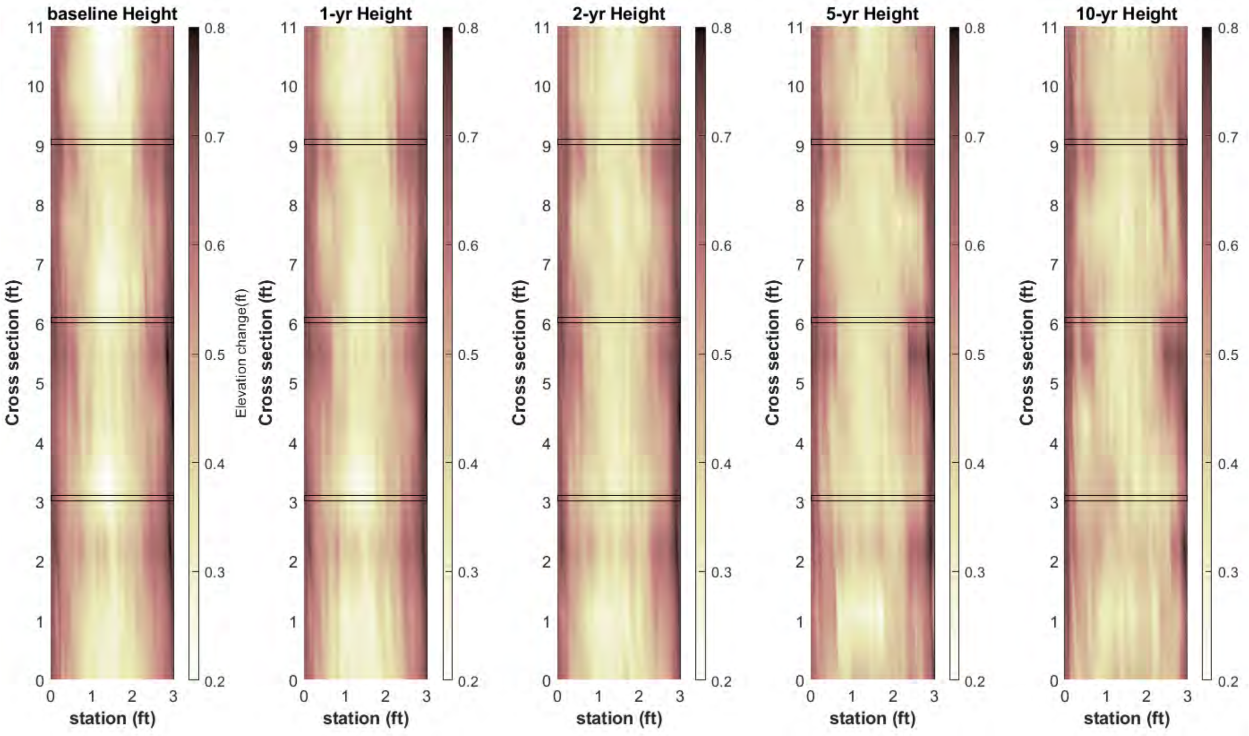


Figure 68 The channel had little increase in height over each flood event.

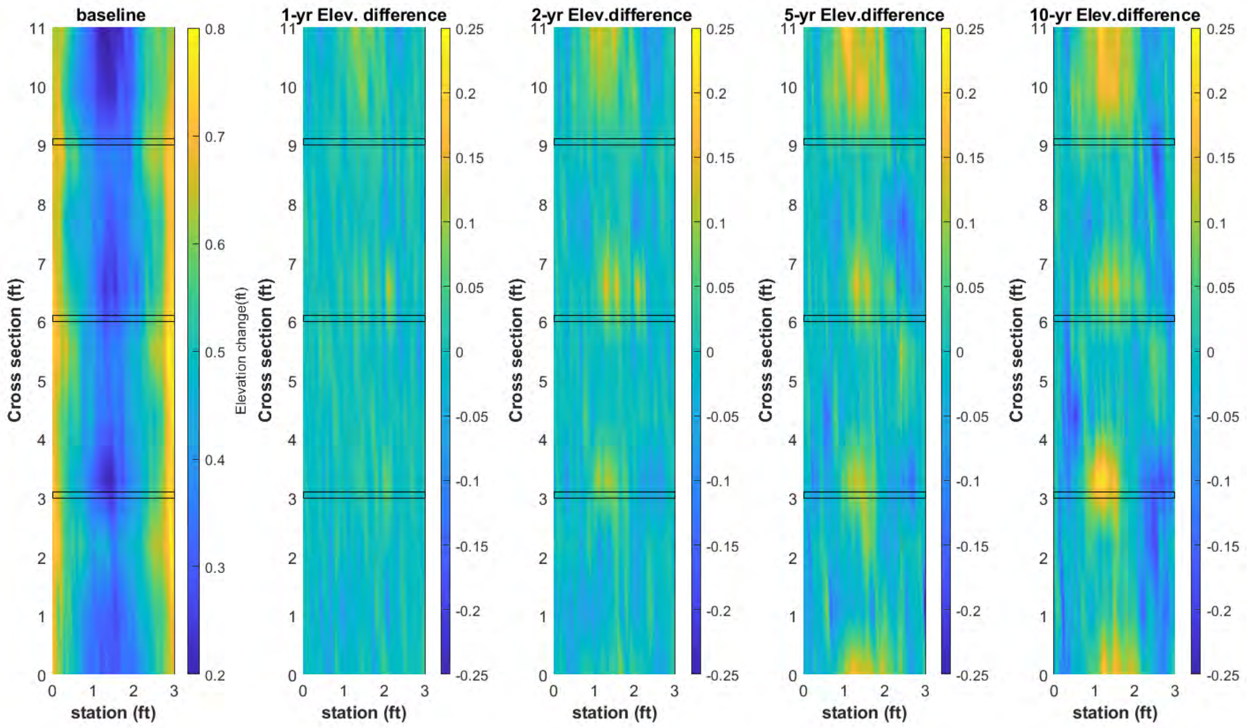


Figure 69 The channel was stable for the first two flood events and had a little increase in deposition and erosion over the final two flood events.

These graphs show the height of the streambed at each flood event for Layout 18.

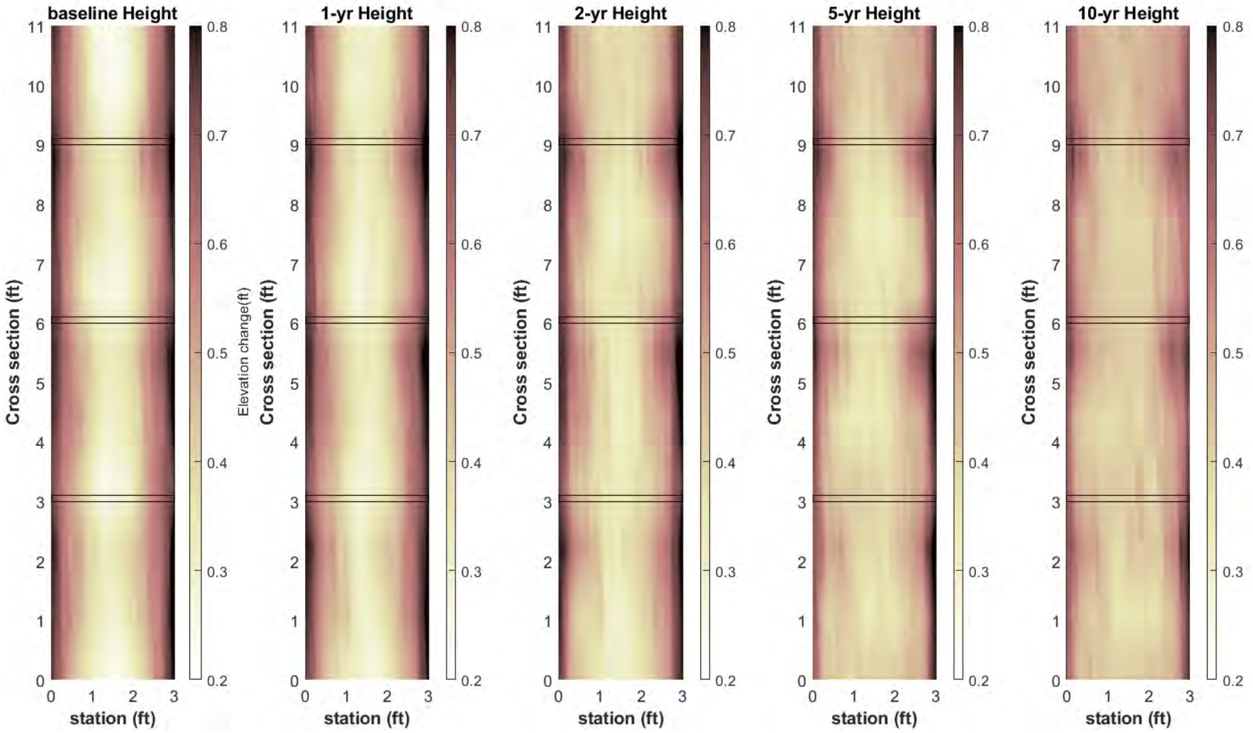


Figure 70 The channel had little increase in height over each flood event. The channel had more change at and above the coarse bands than any other part of the channel.

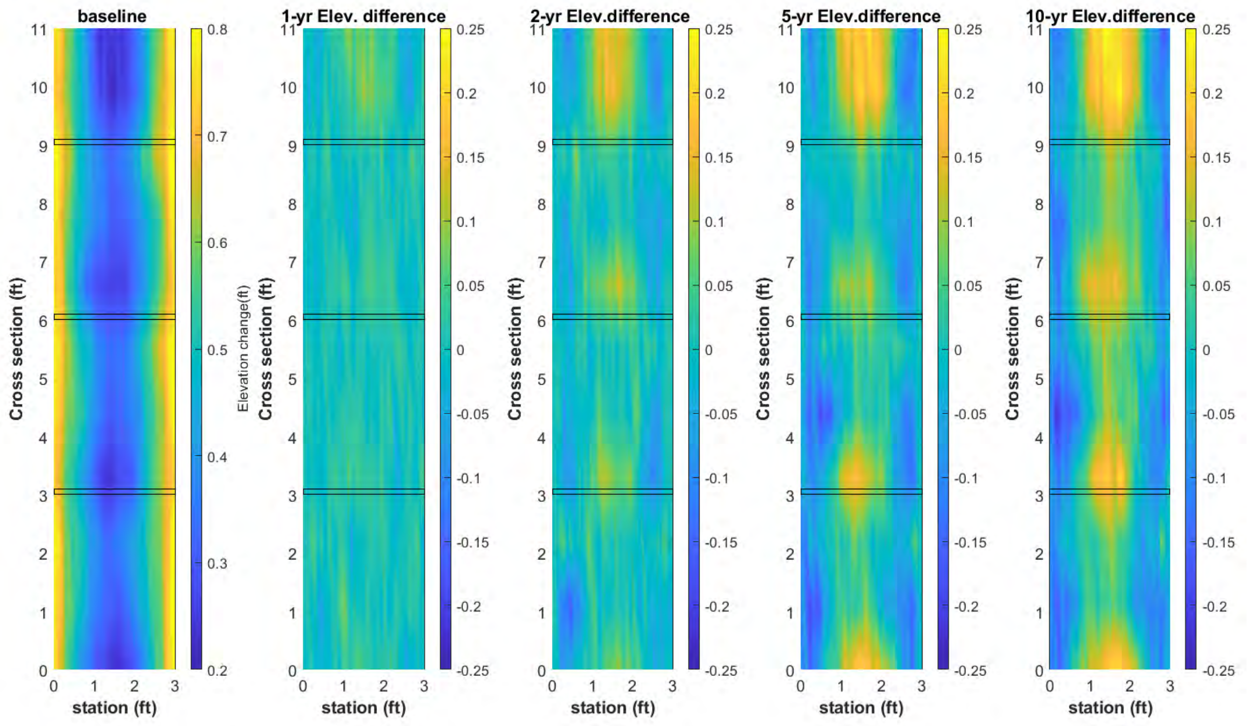


Figure 71 Elevation differences across the different coarse band layouts.

These graphs show the height of the streambed at each flood event for Layout 19.

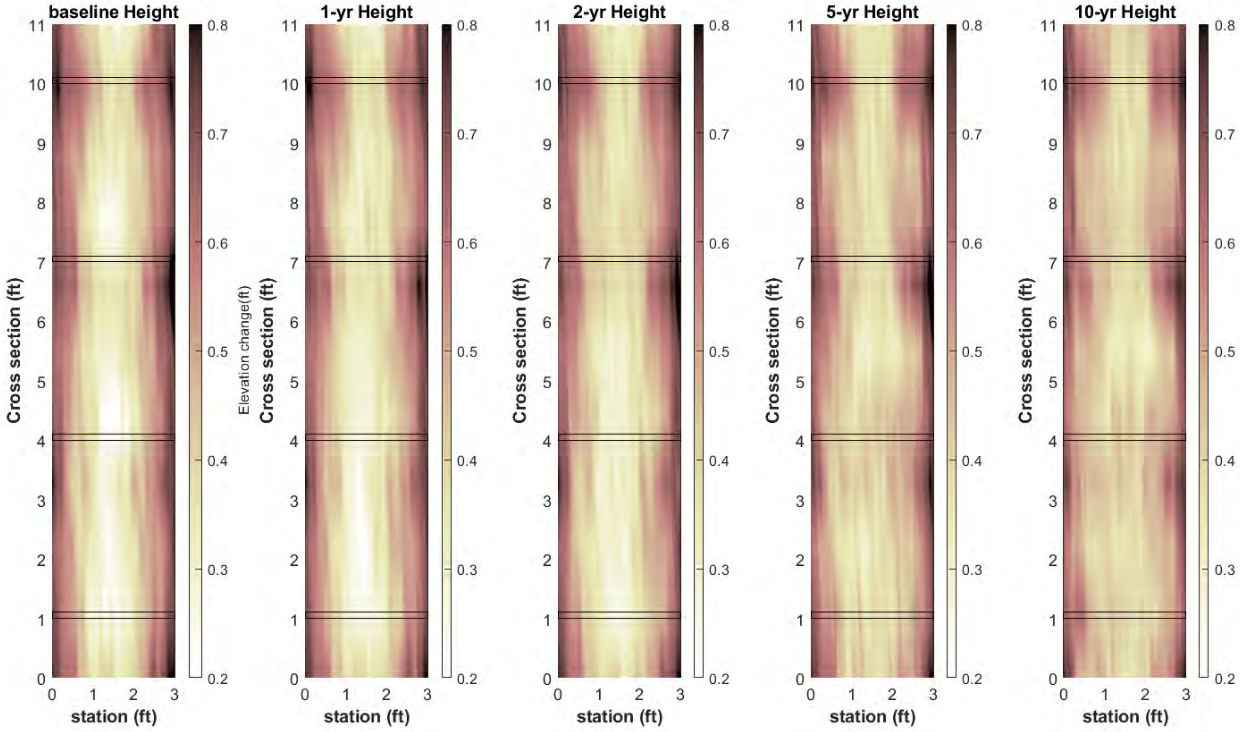


Figure 72 The height of the channel increased between each coarse bands after each flood event.

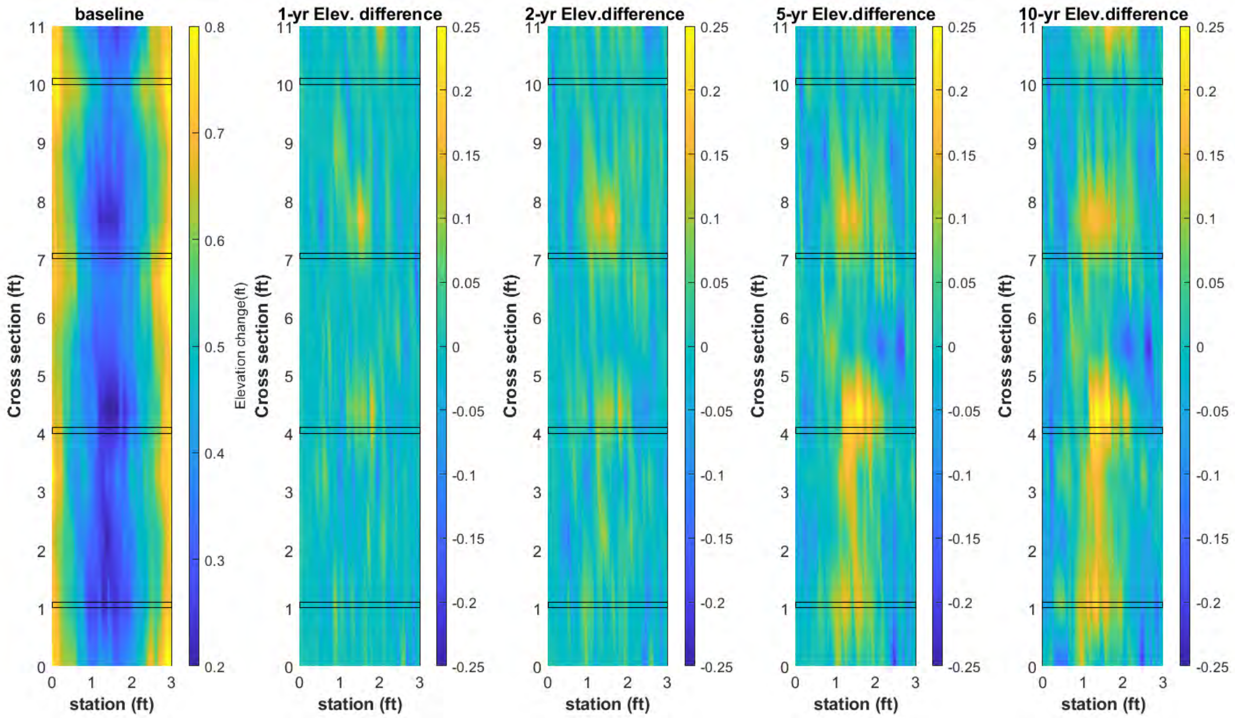


Figure 73 Deposition in the channel had an increase after the five-year flood event and continued during the ten-year flood event.

These graphs show the height of the streambed at each flood event for Layout 20.

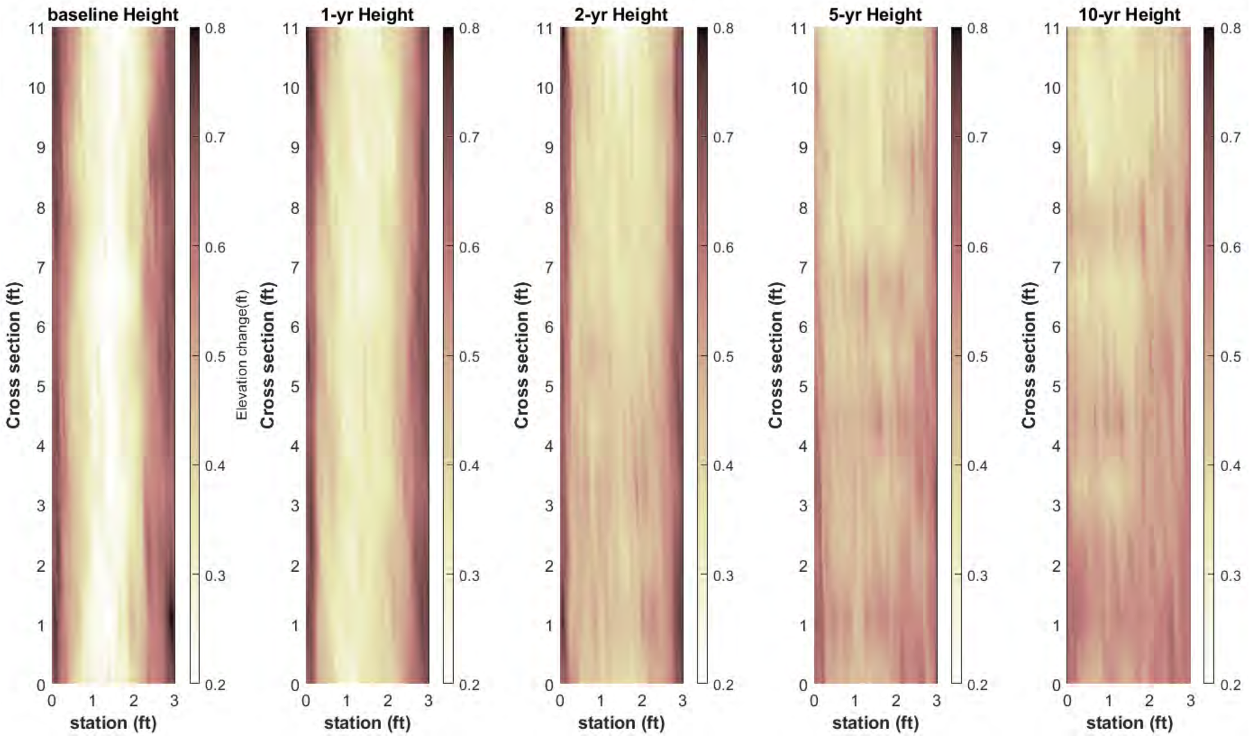


Figure 74 Deposition of sediment in the center of the channel occurred over all flood events. The channel became flat after the five-year flood event.

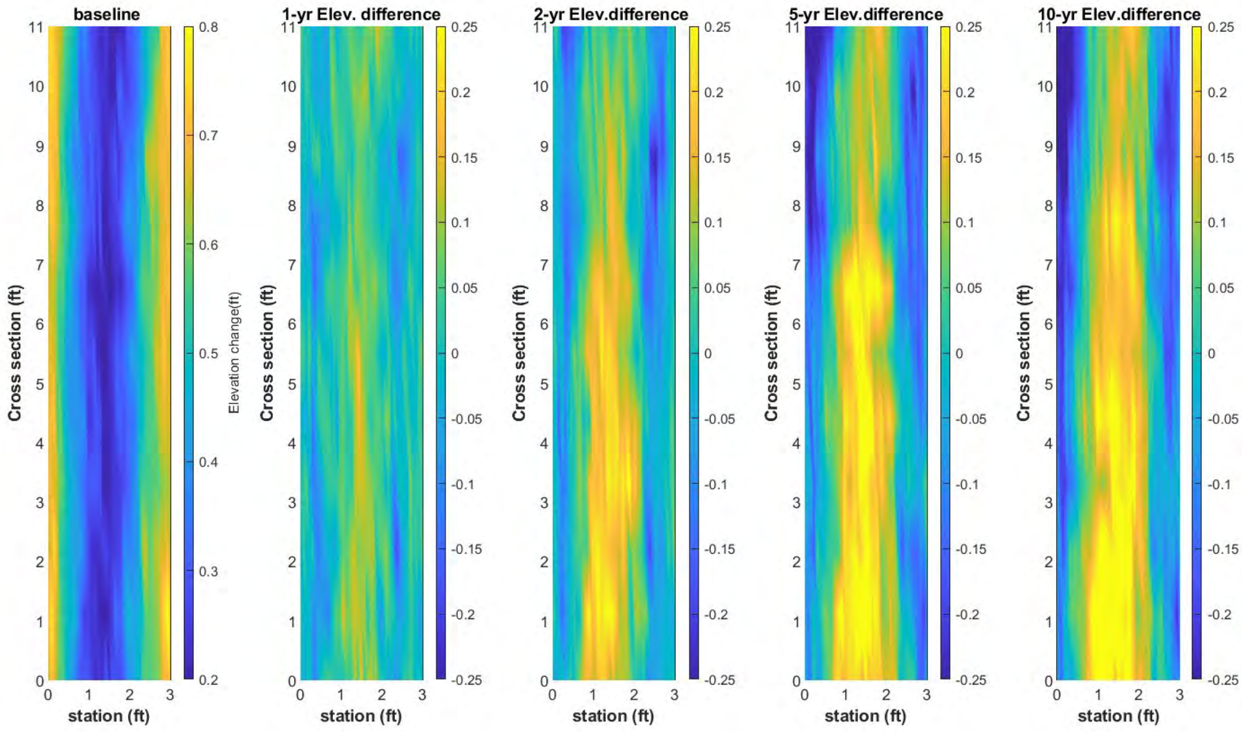


Figure 75 The channel was stable after the two-year flood event. Deposition in the center of the channel and erosion on the sides took place for the two through ten-year flood events.

These graphs show the height of the streambed at each flood event for Layout 21.

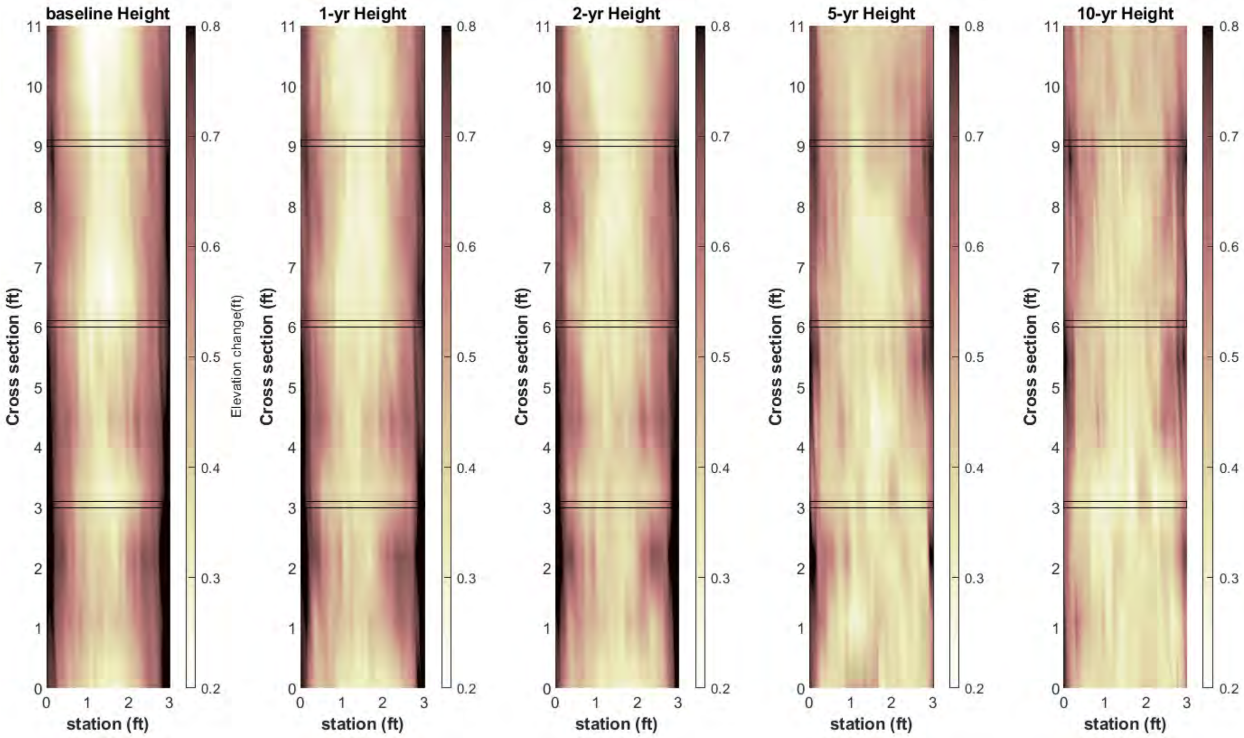


Figure 76 The channel height had little change over the first two flood events. The channel height increase at the top of the study section and decreased from cross-section 5 down for both the five and ten-year flood event.

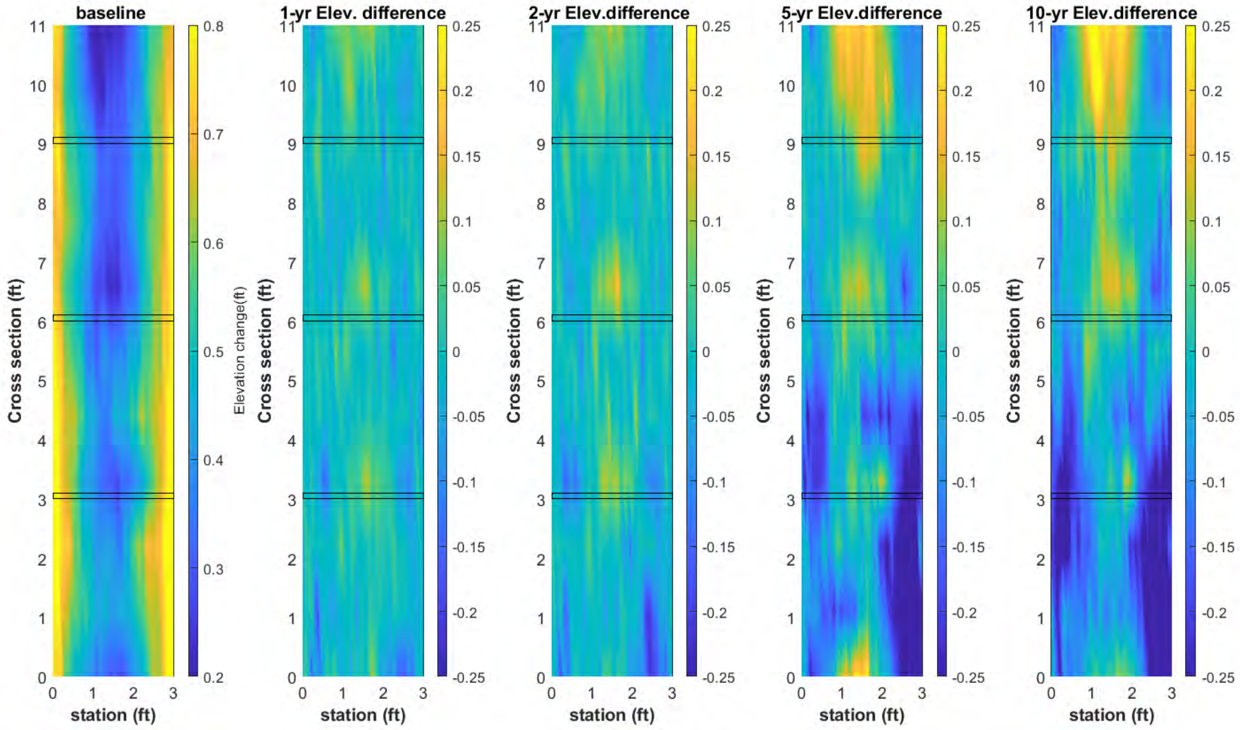


Figure 77 The channel was stable for the first two flood events. Erosion on the bottom half of the study section and deposition on the top end occurred for the channel after both five and ten-year flood event.

These graphs show the height of the streambed at each flood event for Layout 22.

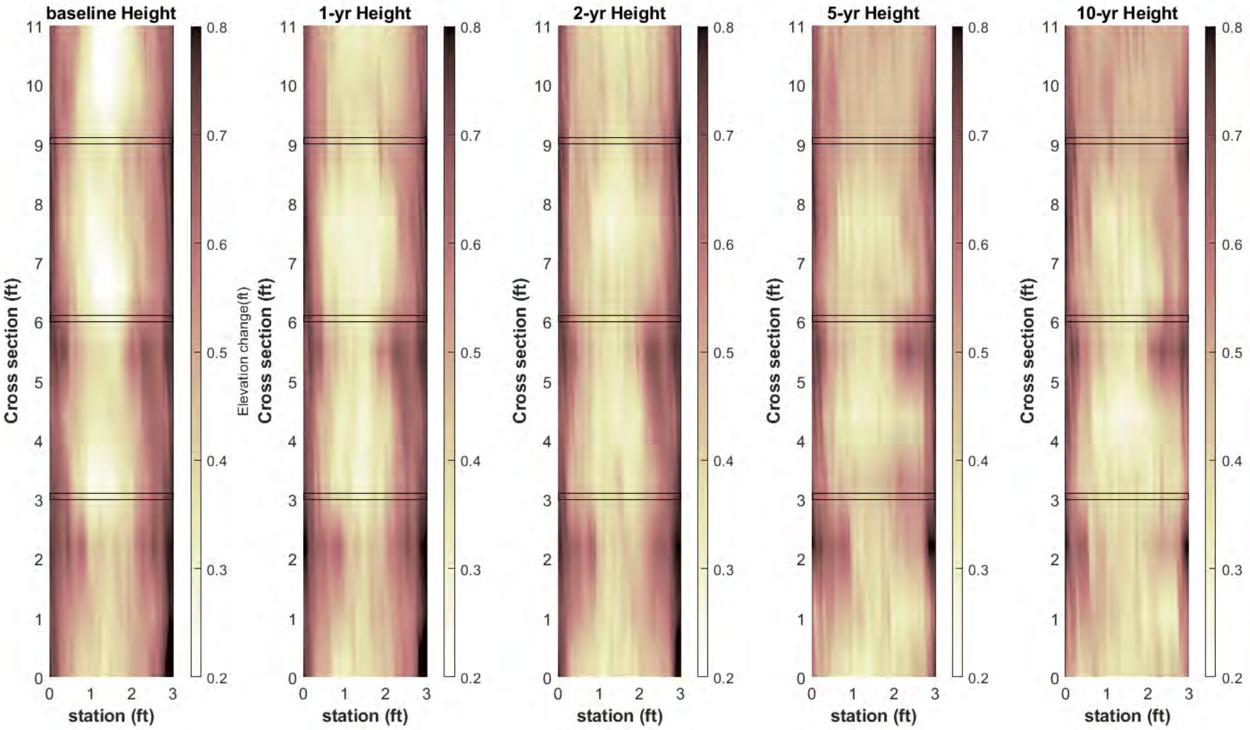


Figure 78 The height of the streambed in between coarse bands increased over each flood event. The height of the coarse bands decreases after the five-year flood event.

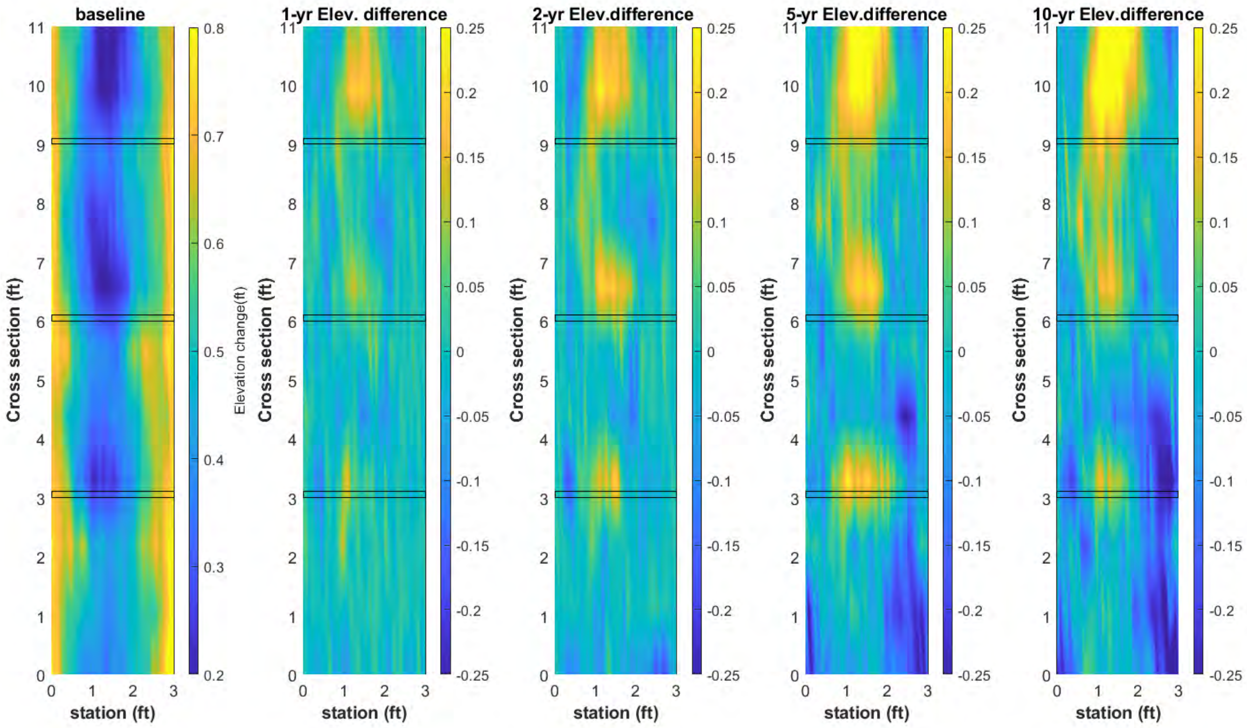


Figure 79 Deposition in the center of the channel started to occur after the first flood event. The deposition increased and worked its way downstream for each flood event. Erosion on the sides of the channel began after the five-year flood event and increased after the ten-year flood event.

These graphs show the height of the streambed at each flood event for Layout 23.

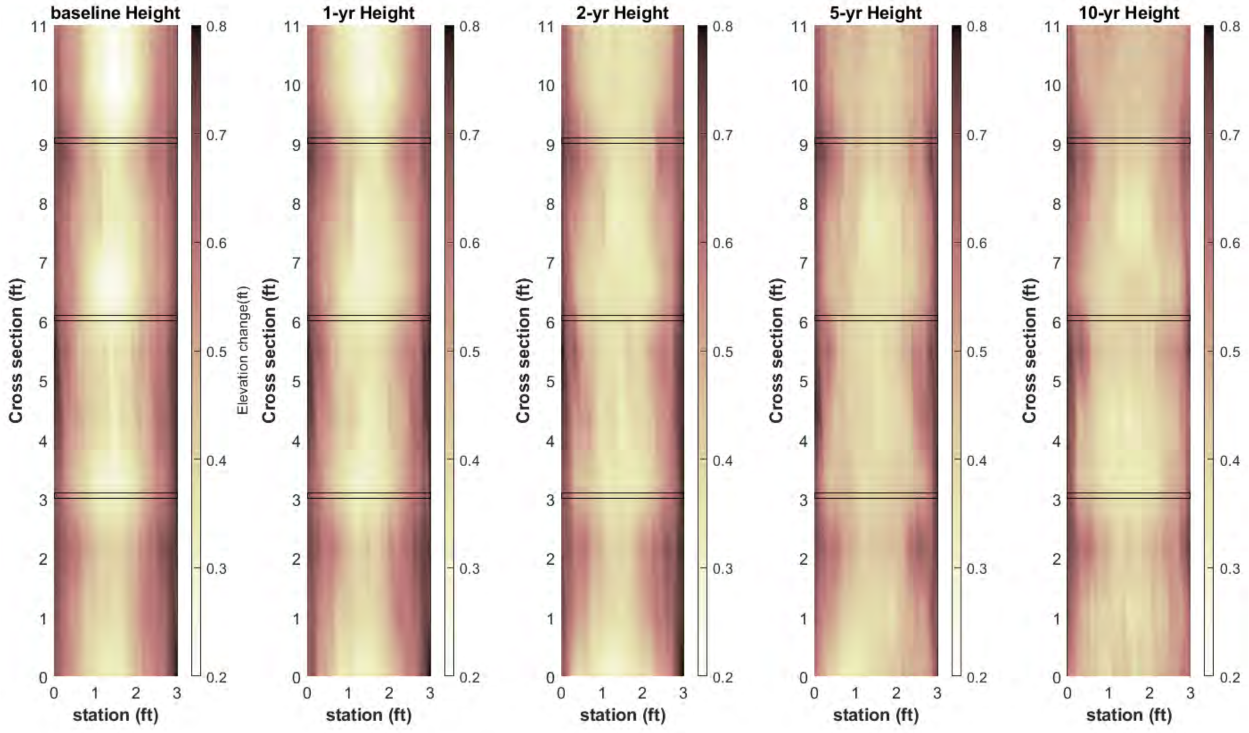


Figure 80 The channel height above the bottom coarse bands increased over each flood event. The height below the bottom coarse bands decreased after the five and ten-year flood event.

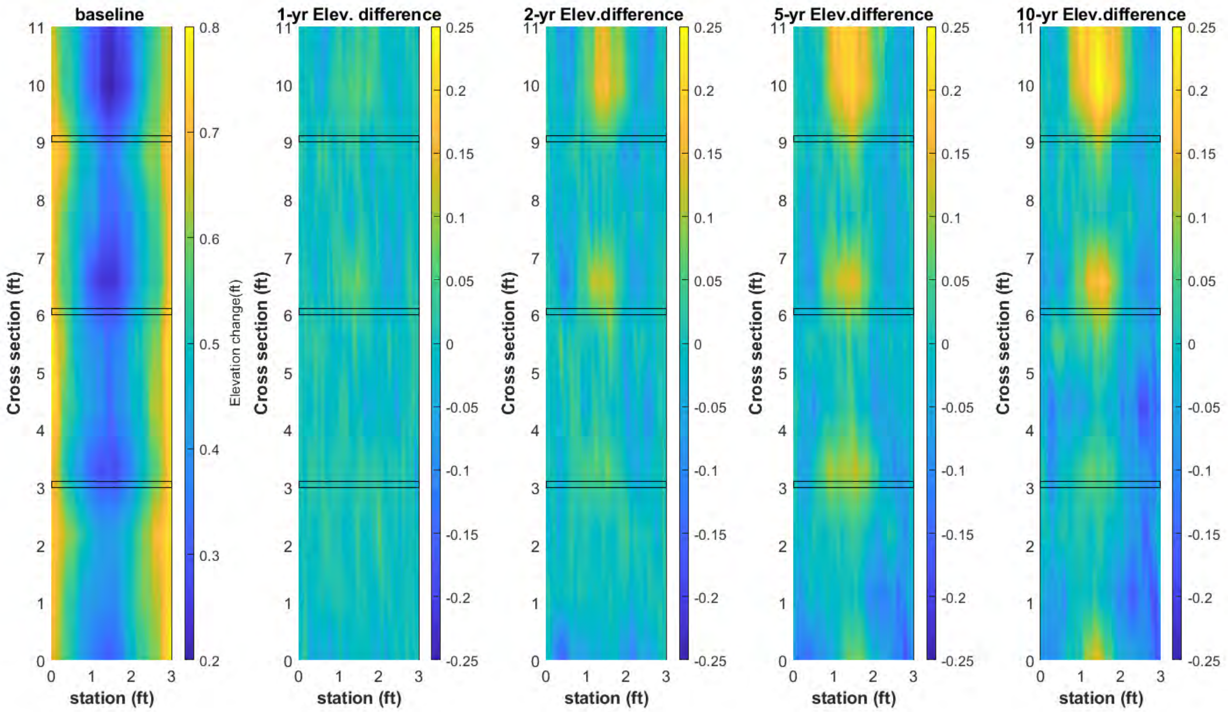


Figure 81 The channel experienced deposition upstream of the coarse bands after the two-year flood event. Deposition increased over the next two flood events. Erosion of the sides of the channel occurred after the five-year flood and continued after the ten-year flood event.

These graphs show the height of the streambed at each flood event for Layout 24.

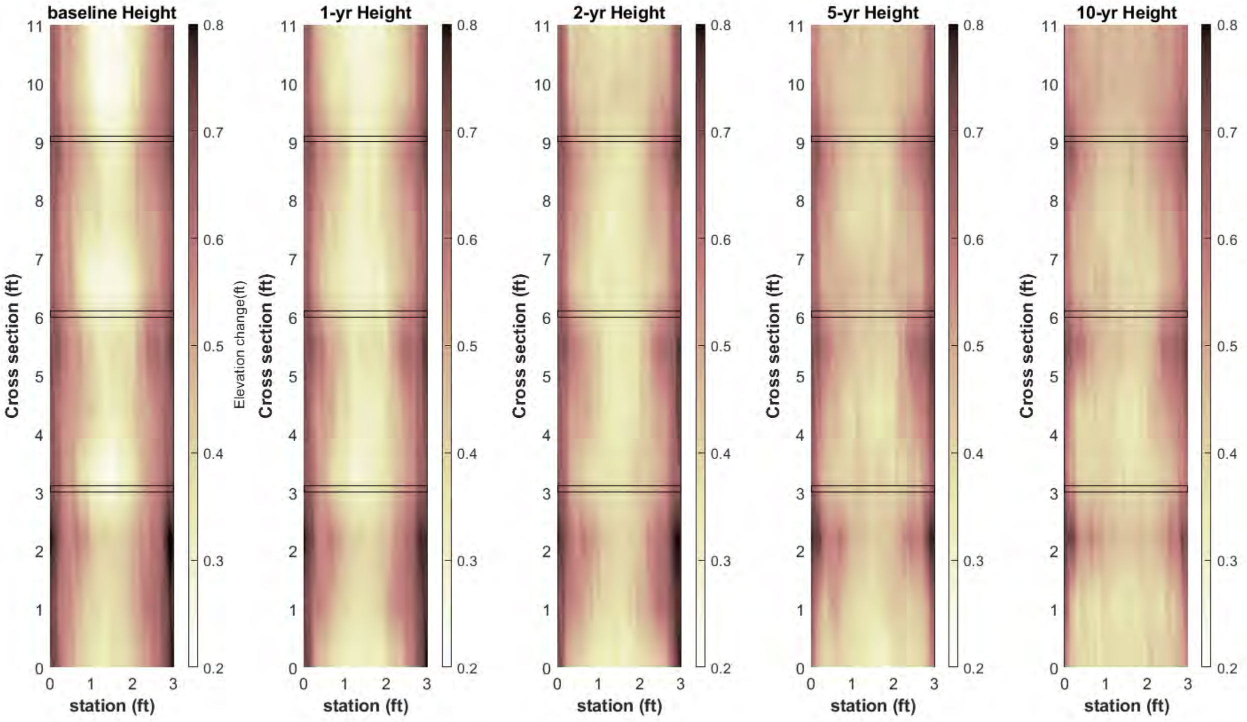


Figure 82 The channel height above the bottom coarse bands increased over each flood event. The height below the bottom coarse bands decreased after the five and ten-year flood event.

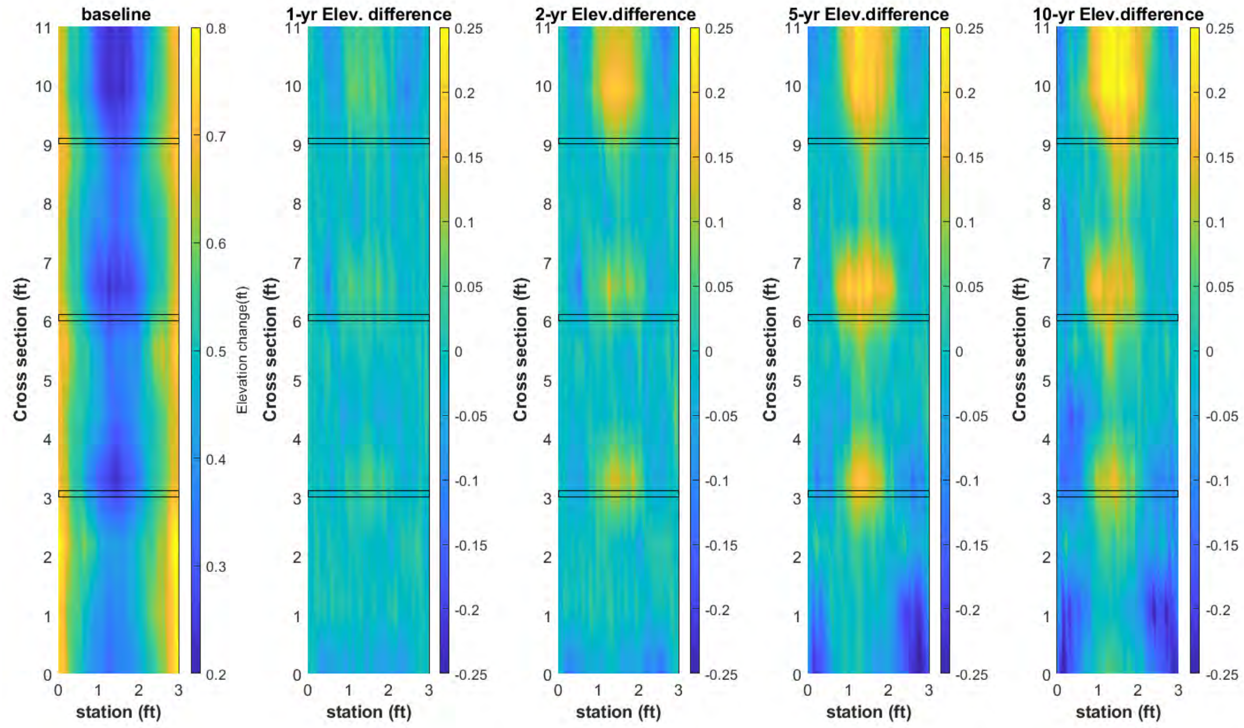


Figure 83 The channel experienced deposition upstream of the coarse bands after the two-year flood event. Deposition increased over the next two flood events. Erosion of the sides of the channel occurred after the five-year flood and continued after the ten-year flood event.

These graphs show the height of the streambed at each flood event for Layout 25.

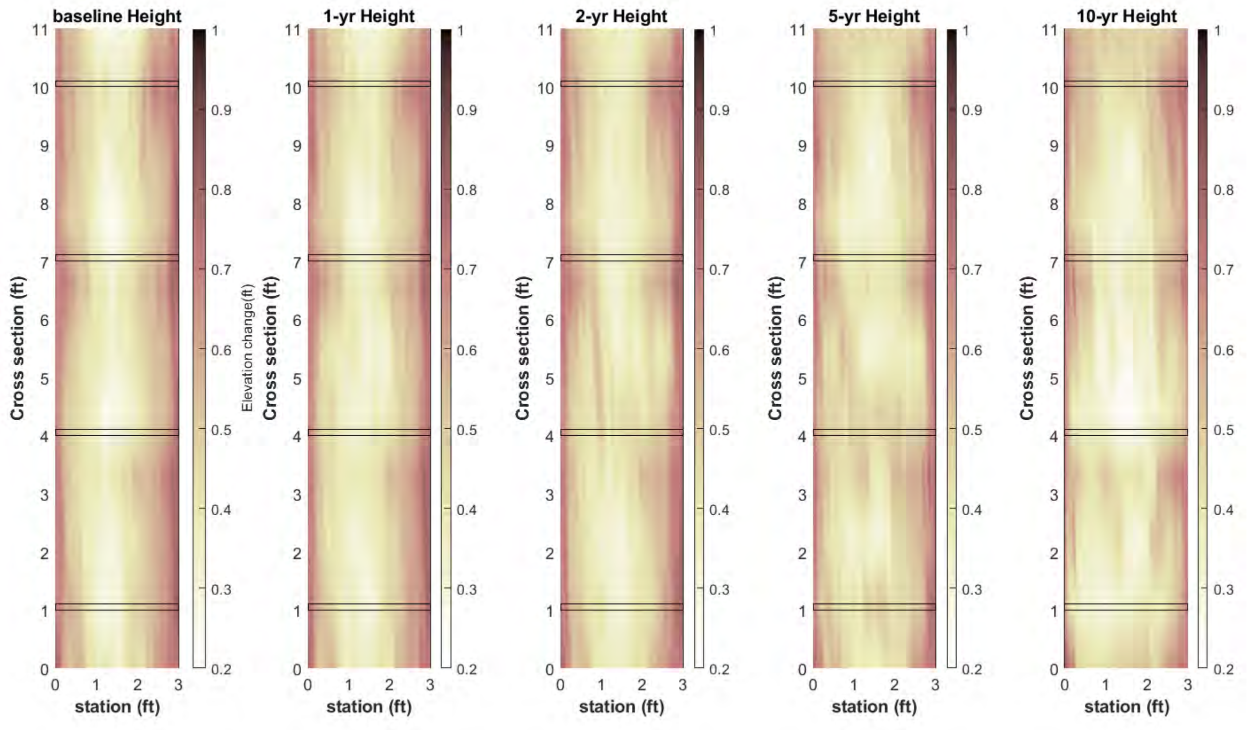


Figure 84 The channel height had little increase change over the first two flood events. The height of the streambed decreased from the five-year flood to the ten-year flood event.

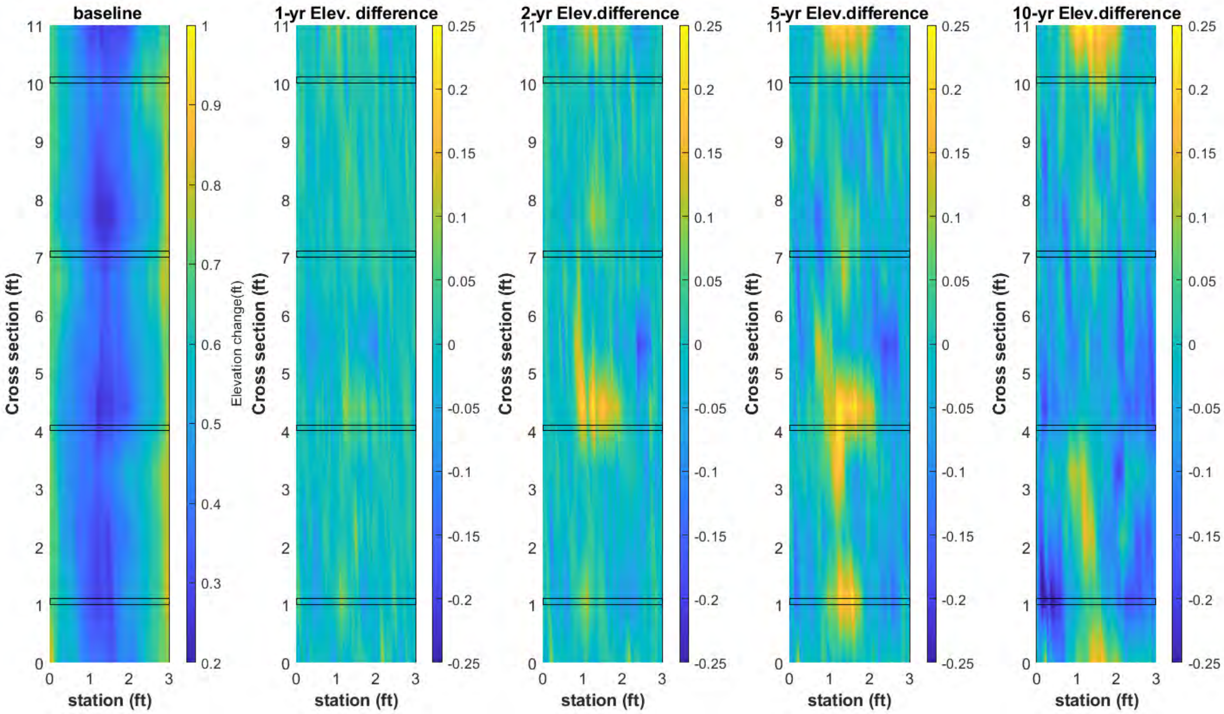


Figure 85 The channel was stable over the first two flood events. At the five-year flood event erosion occurred at the second and third coarse bands and deposition at the third and fourth coarse bands. The channel after a ten-year flood had an abundant amount of erosion take place.

These graphs show the height of the streambed at each flood event for Layout 26.

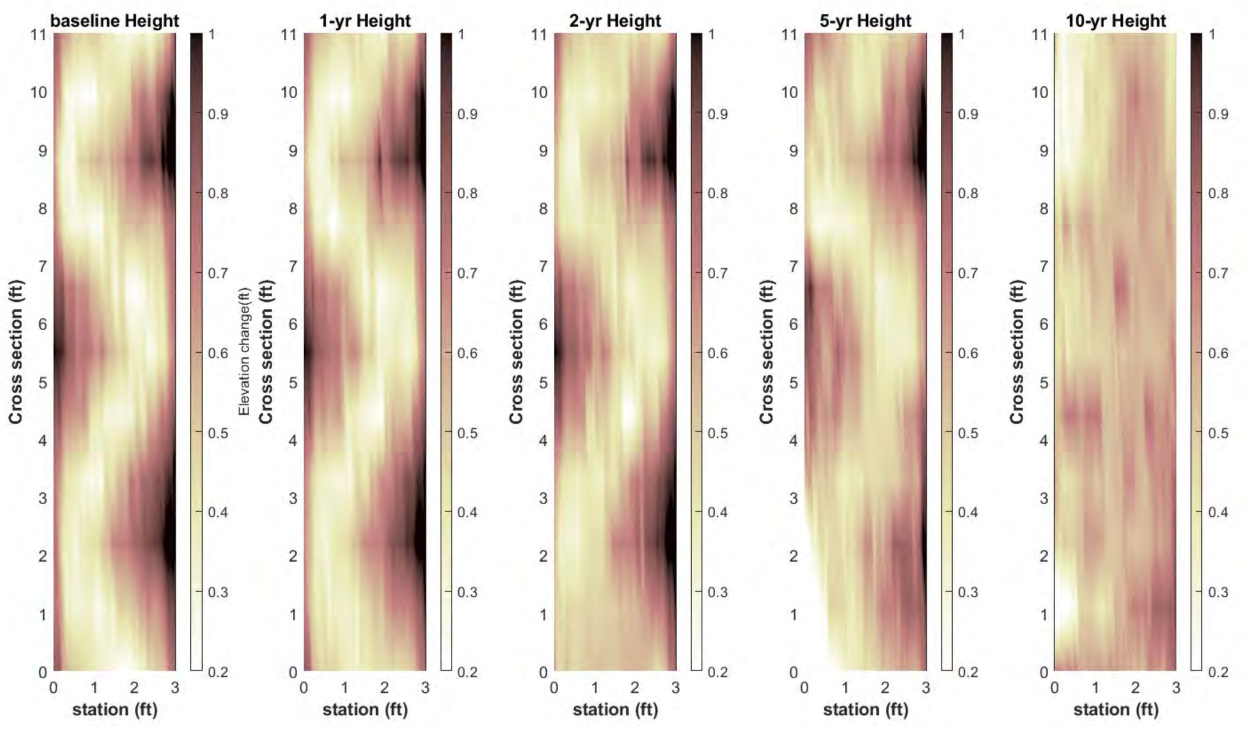


Figure 86 The channel increased slightly over the first two flood events. The lower half of the channel after a five-year flood event was flat. The whole channel was flat after the ten-year flood event

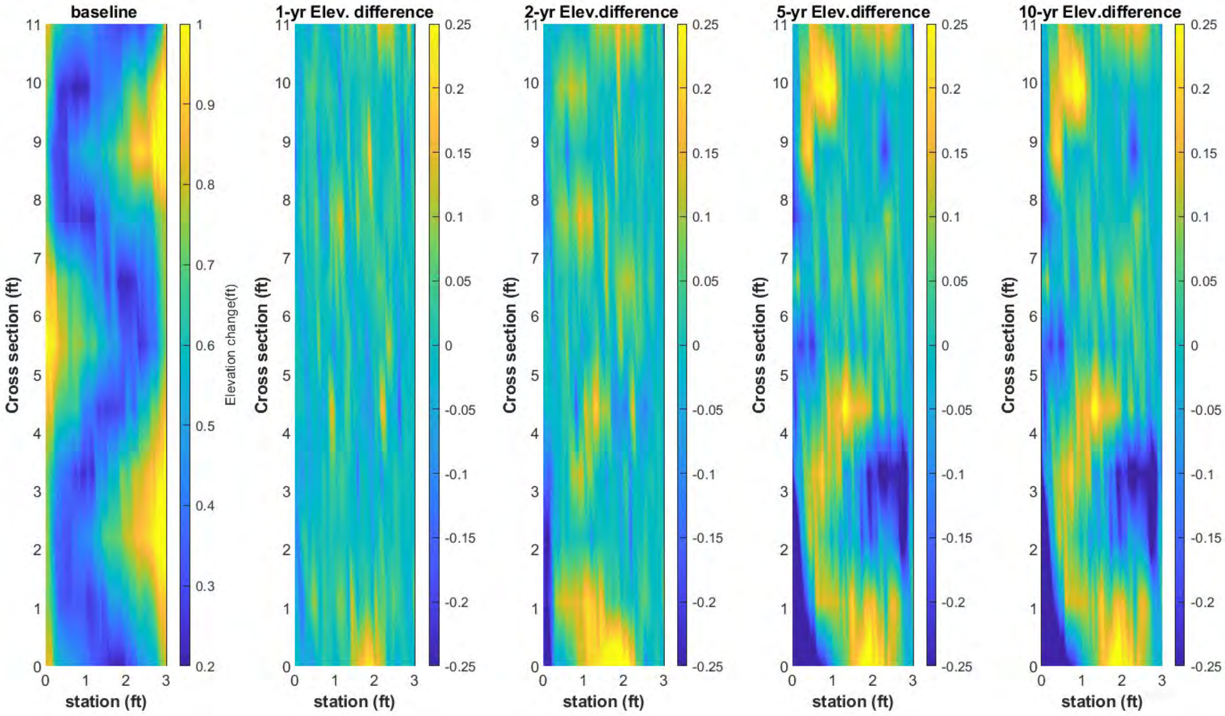


Figure 87 The channel was stable for the first flood event but during the two-year flood event deposition in the u-shape channel increased at the bottom of the study section. Deposition in the u-shape channel and erosion on the sides of the channel worked its way up the channel to cross-section 5 in both the five and ten-year flood event.

These graphs show the height of the streambed at each flood event for Layout 27.

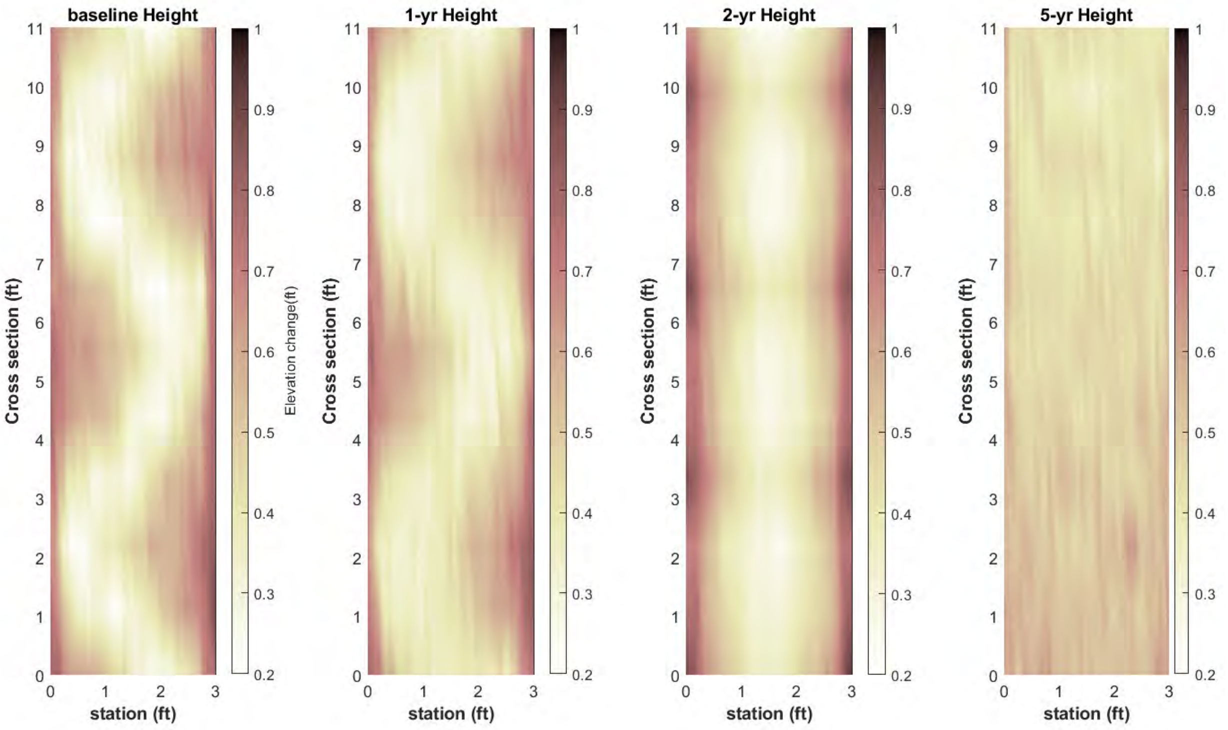


Figure 88 The channel height started to increase during the two-year flood event. The channel was flat after the five-year flood event.

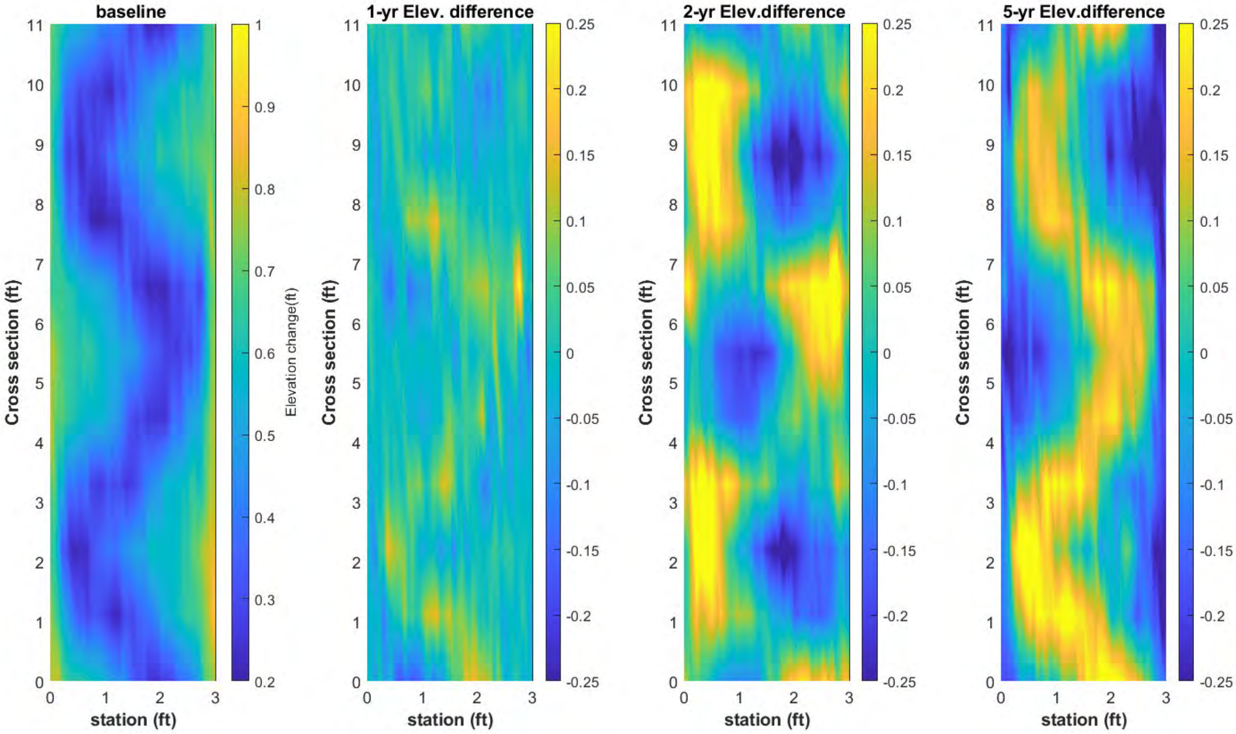


Figure 89 All change occurred during the two-year flood event, and some was enhanced by the five-year flood event.

These graphs show the height of the streambed at each flood event for Layout 28.

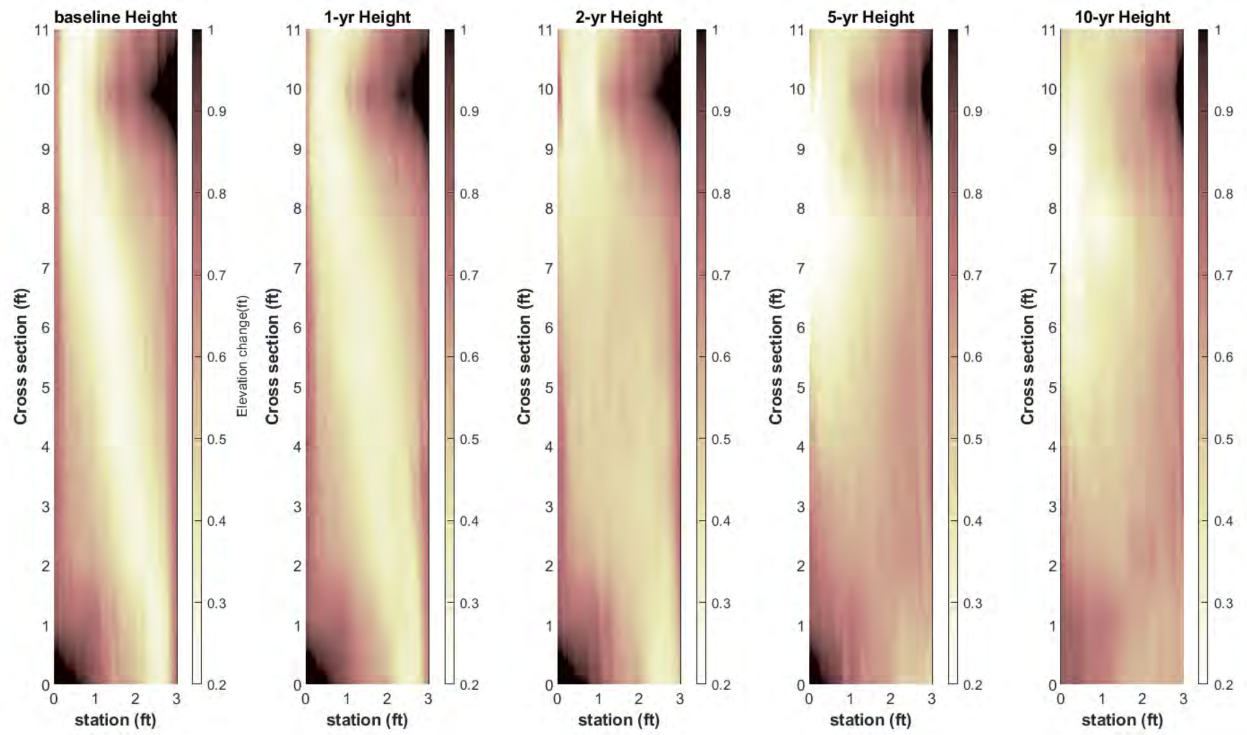


Figure 90 The u-shape channel height increased during each flood event until it became flat after the five-year event.

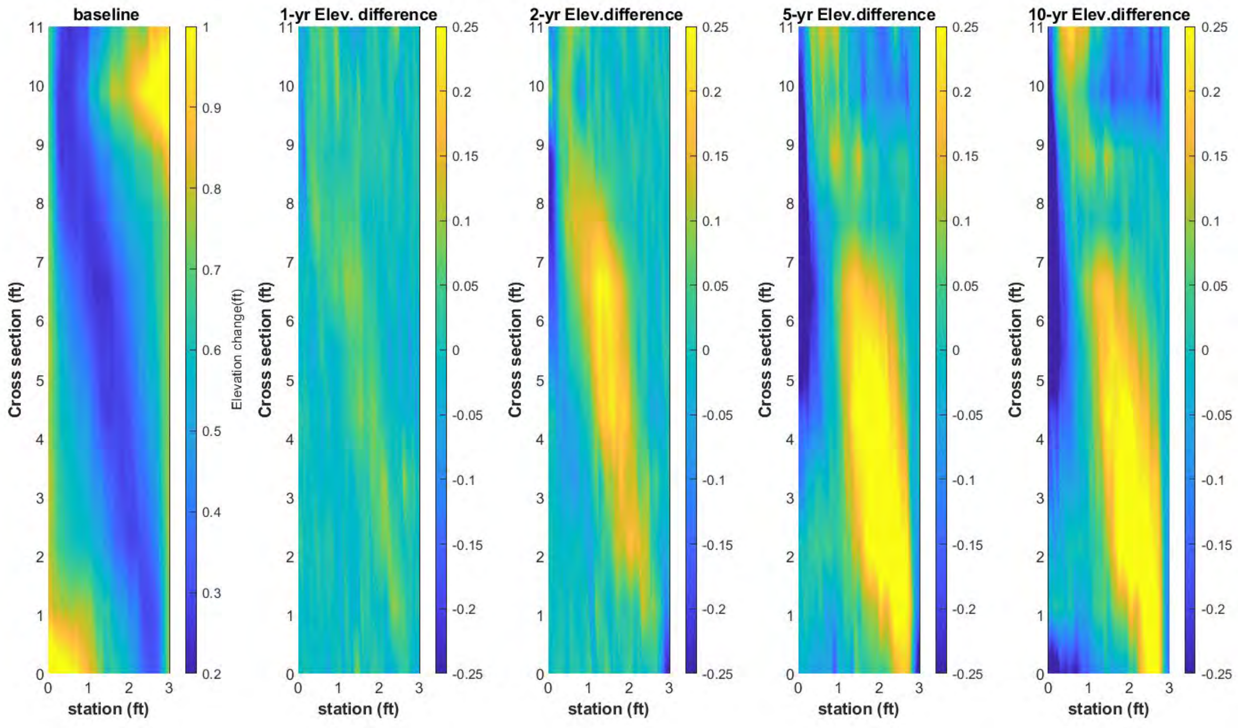


Figure 91 The u-shape channel between boulder bars became filled with sediment. Erosion on the left bank between boulder bars started after the five-year event.

These graphs show the height of the streambed at each flood event for Layout 29.

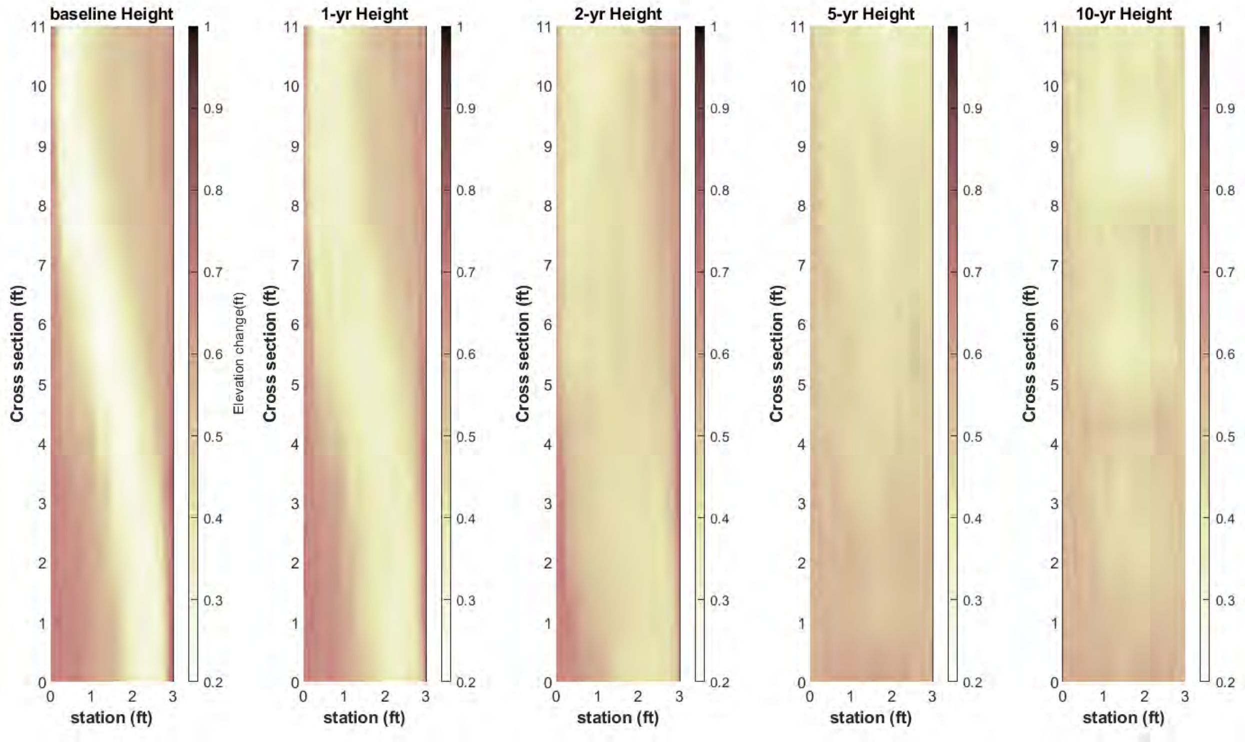


Figure 92 The channel height started to increase during the two-year flood event. The channel was flat after the five-year flood event.

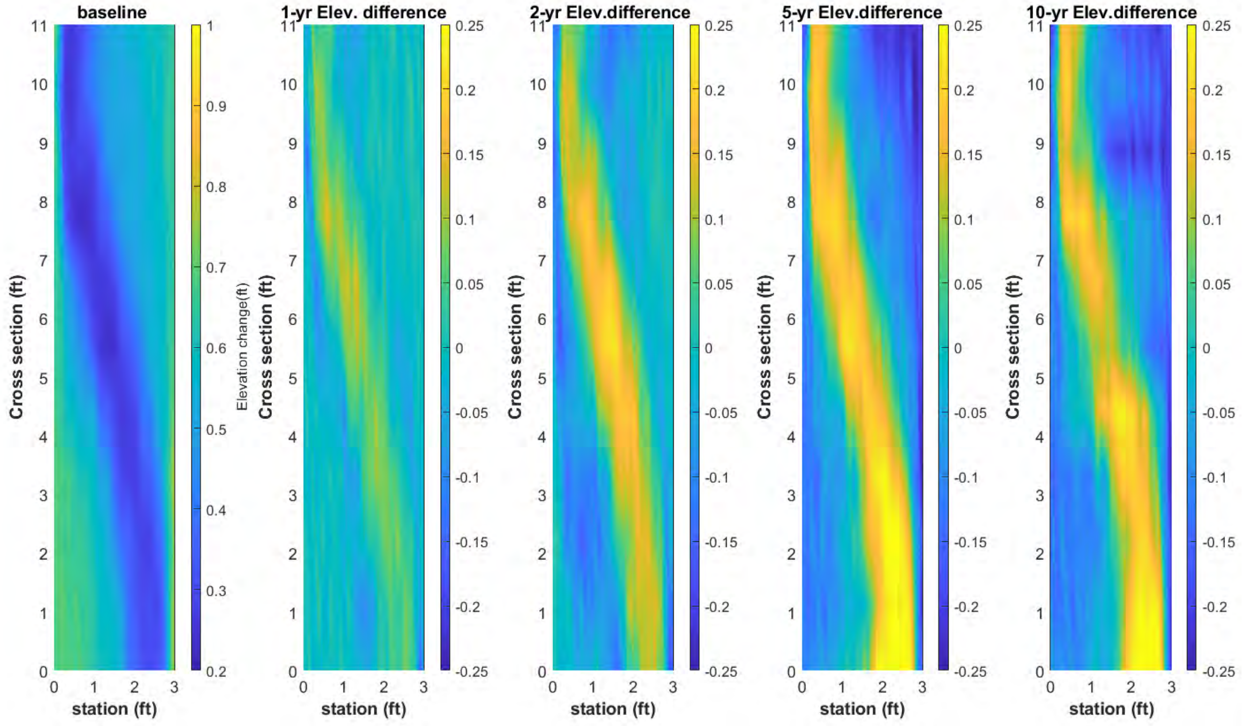


Figure 93 The channel had deposition in the u-shape channel and erosion on the banks. These dynamics increased after each flood event.

These graphs show the height of the streambed at each flood event for Layout 30.

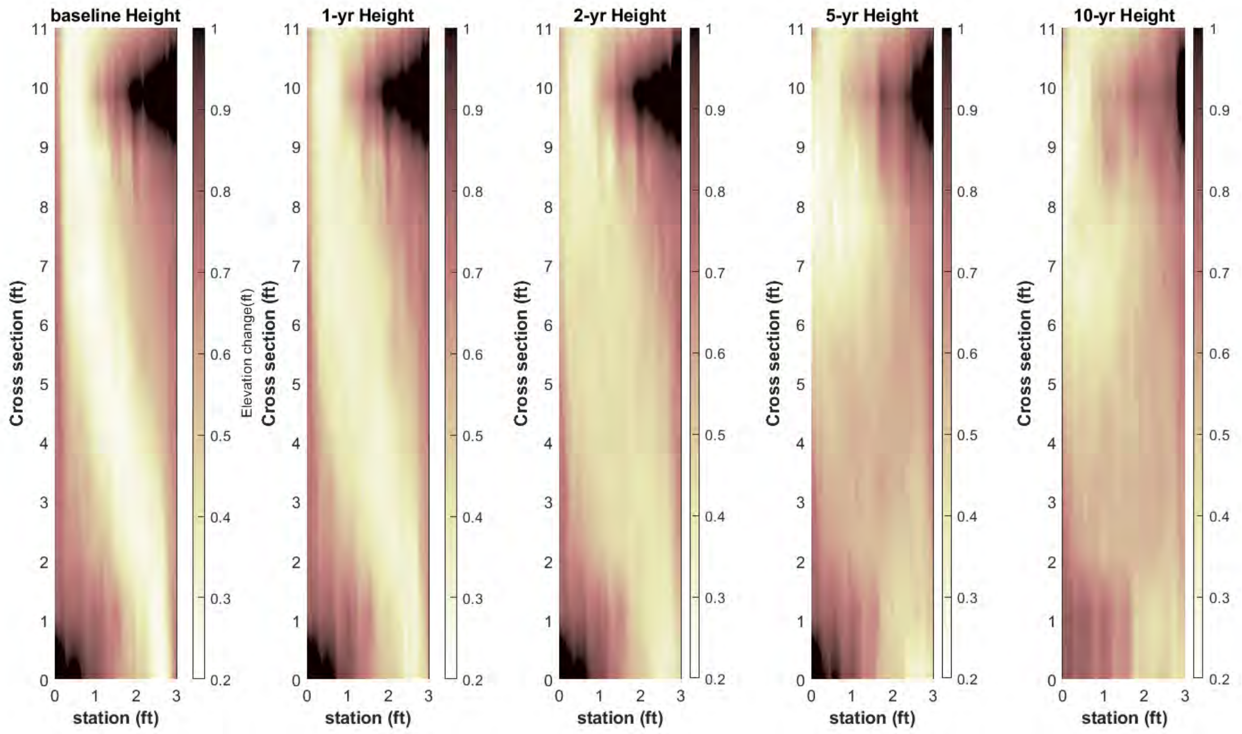


Figure 94 The height of the streambed between boulder bars increased and the channel was flat after the five-year flood event. The boulder bars height began to decrease after the five-year flood event and continued through the ten-year flood event.

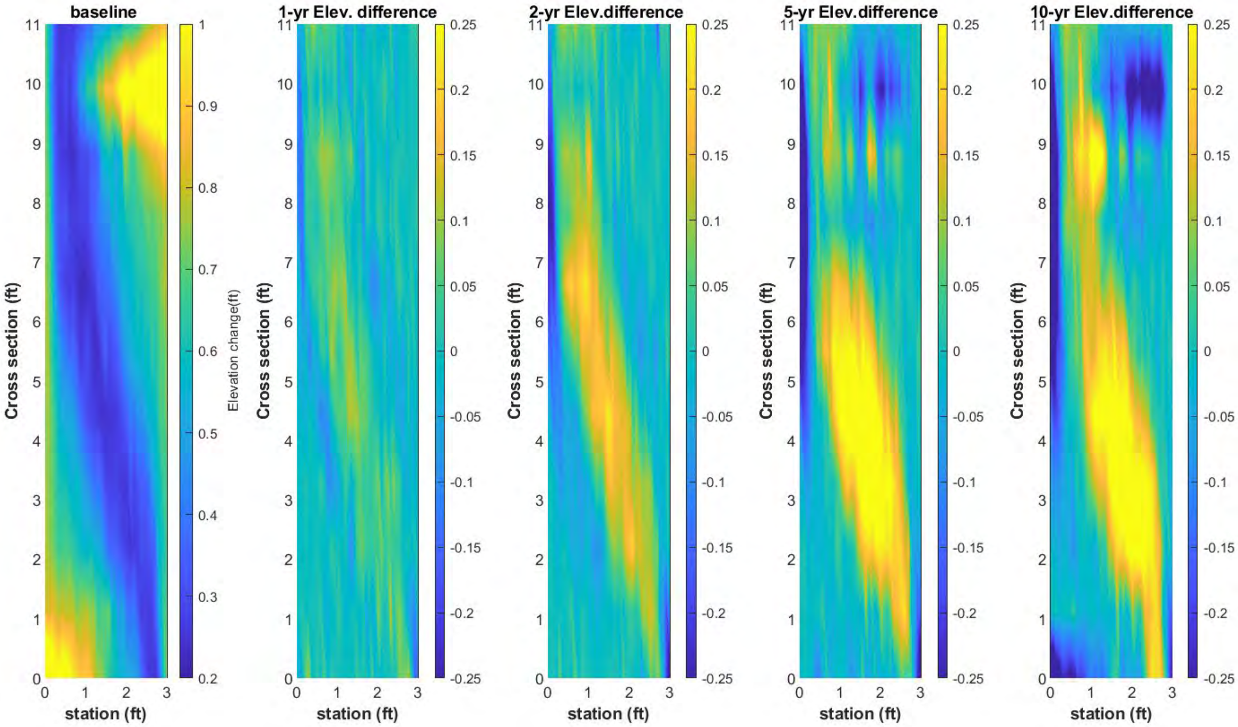


Figure 95 Deposition in the channel increased over each flood event and erosion on the sides started after the five-year event.

These graphs show the height of the streambed at each flood event for Layout 31.

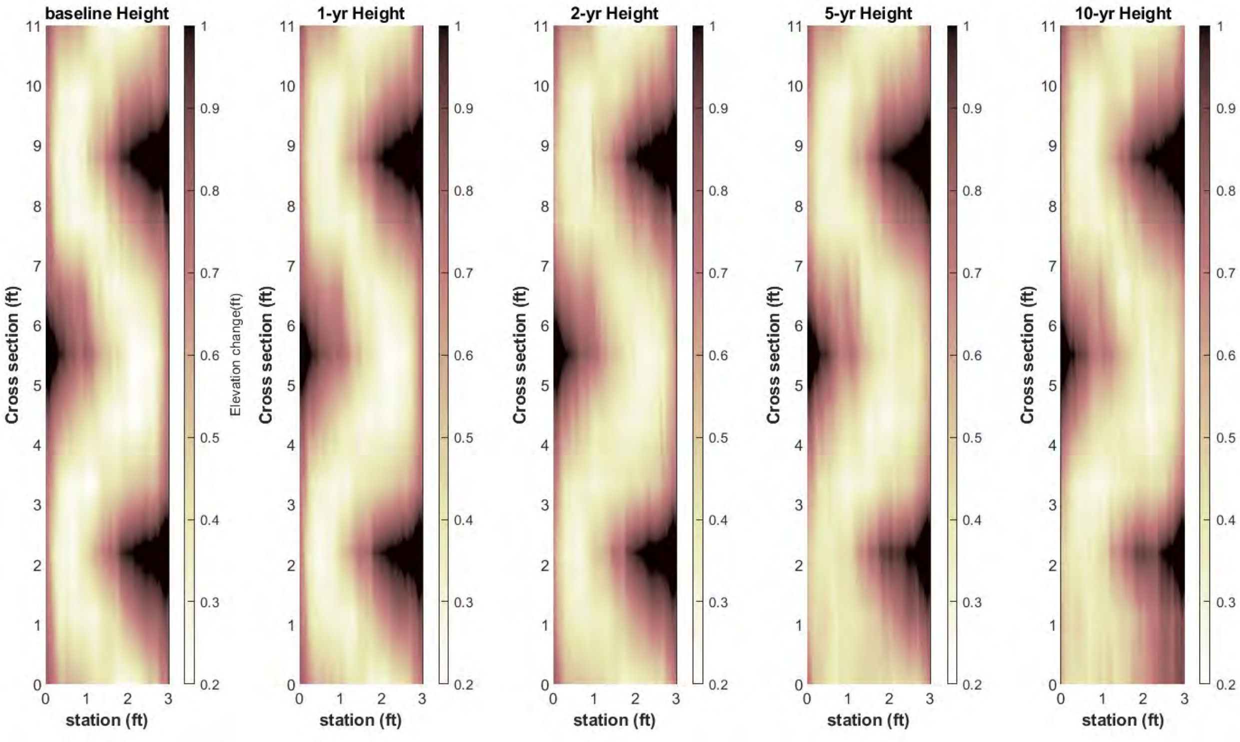


Figure 96 The height of the u-shape channel was stable through all flood events.

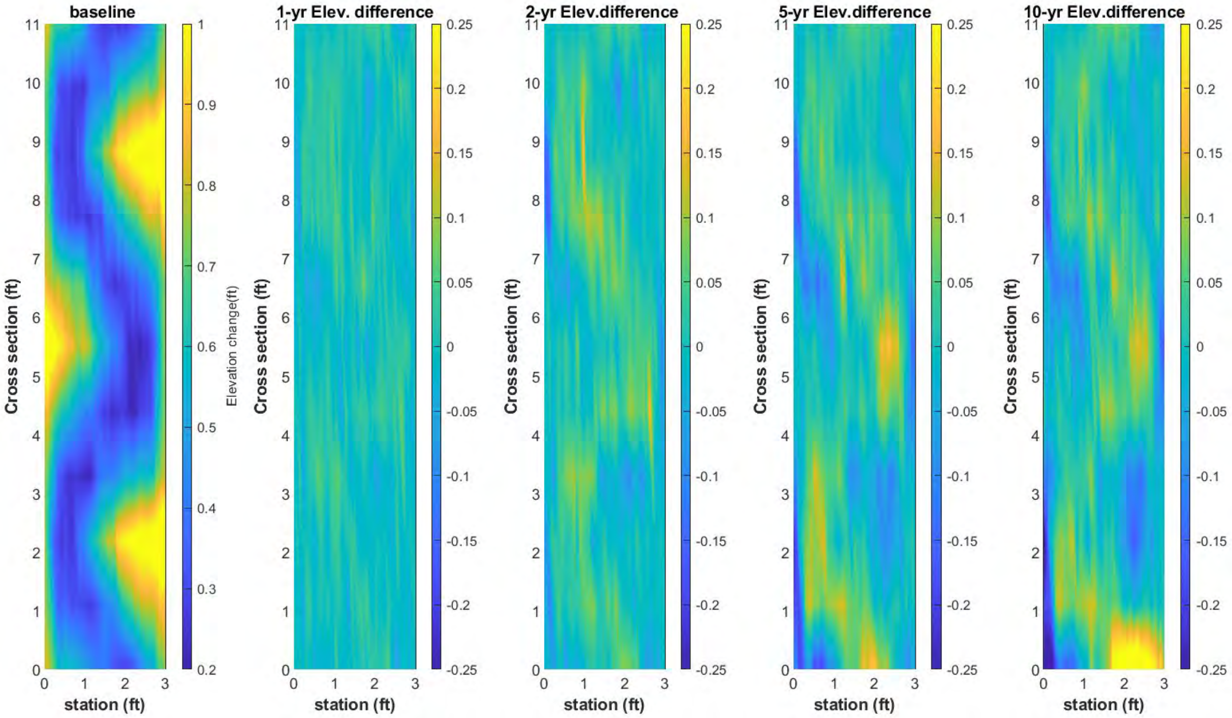


Figure 97 The channel had little change over the first three flood event. The ten-year flood had an increase in deposition at the very bottom of the study section.

These graphs show the height of the streambed at each flood event for Layout 32.

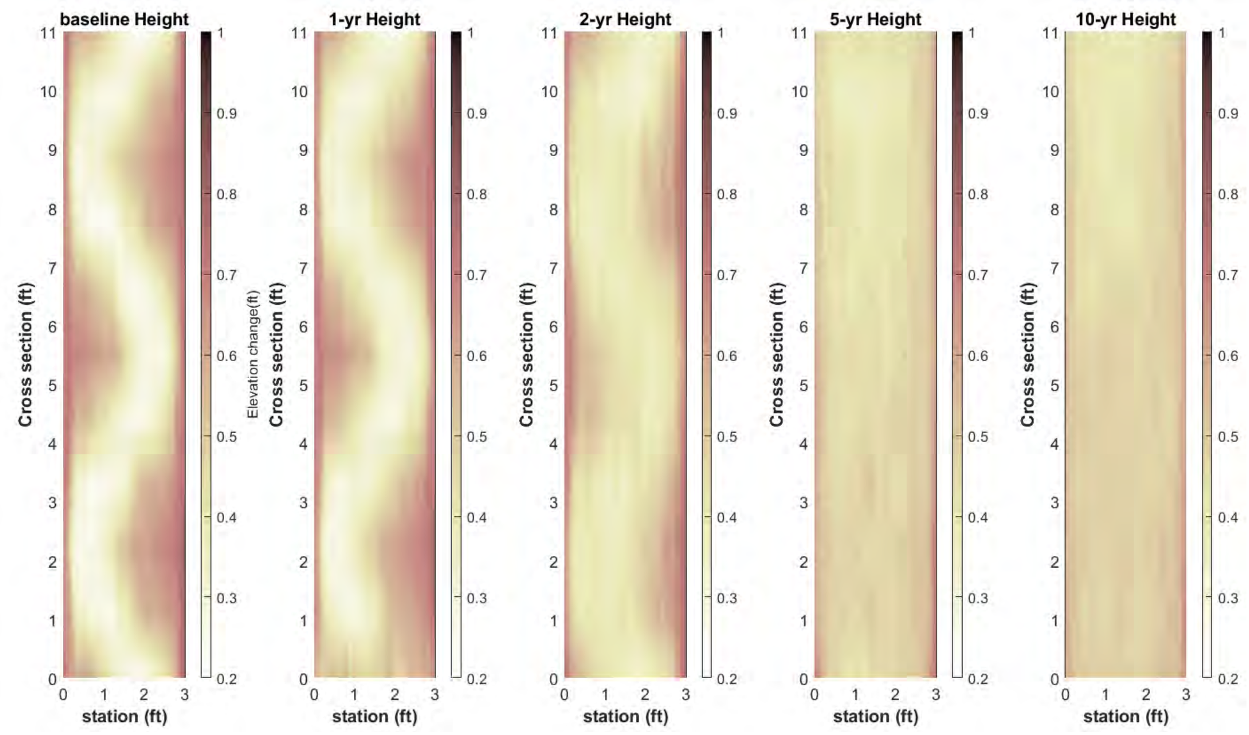


Figure 98 The channel height started to increase during the two-year flood event. The channel was flat after the five-year flood event.

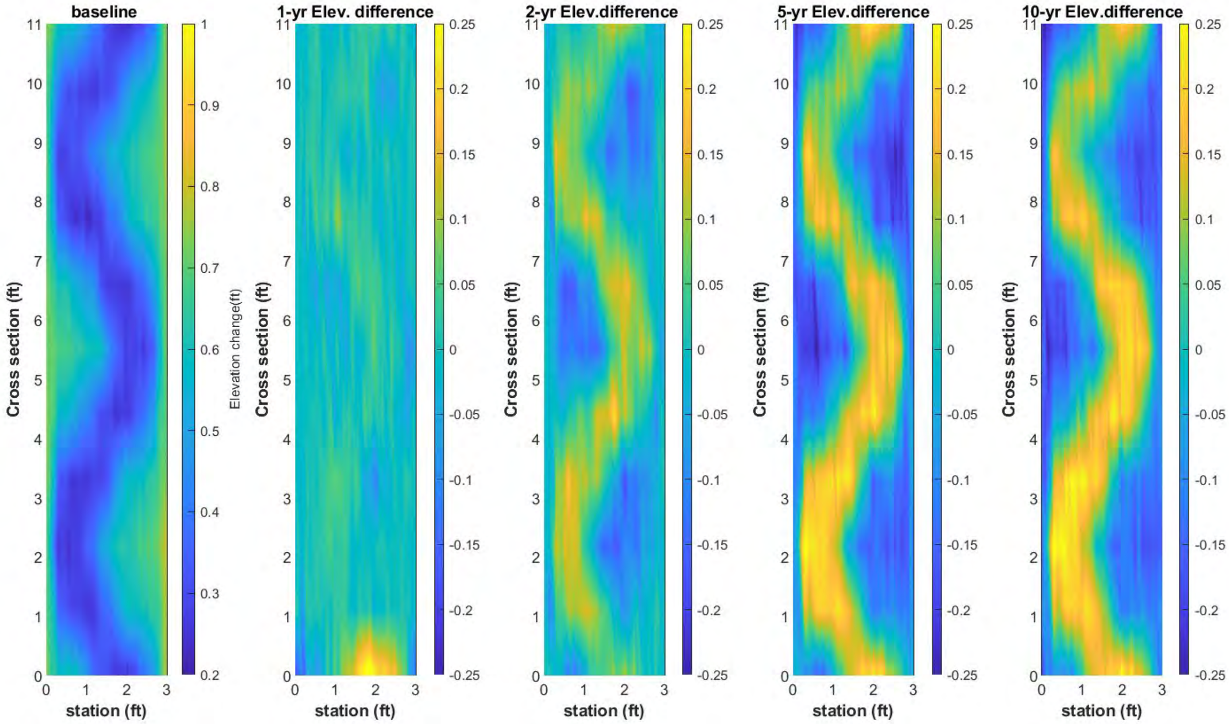


Figure 99 The channel was stable for the first flood event. Deposition in the center of the channel and erosion on the sides started after the two-year flood event. The rate of these dynamic changes increased over the final two flood events.

These graphs show the height of the streambed at each flood event for Layout 33.

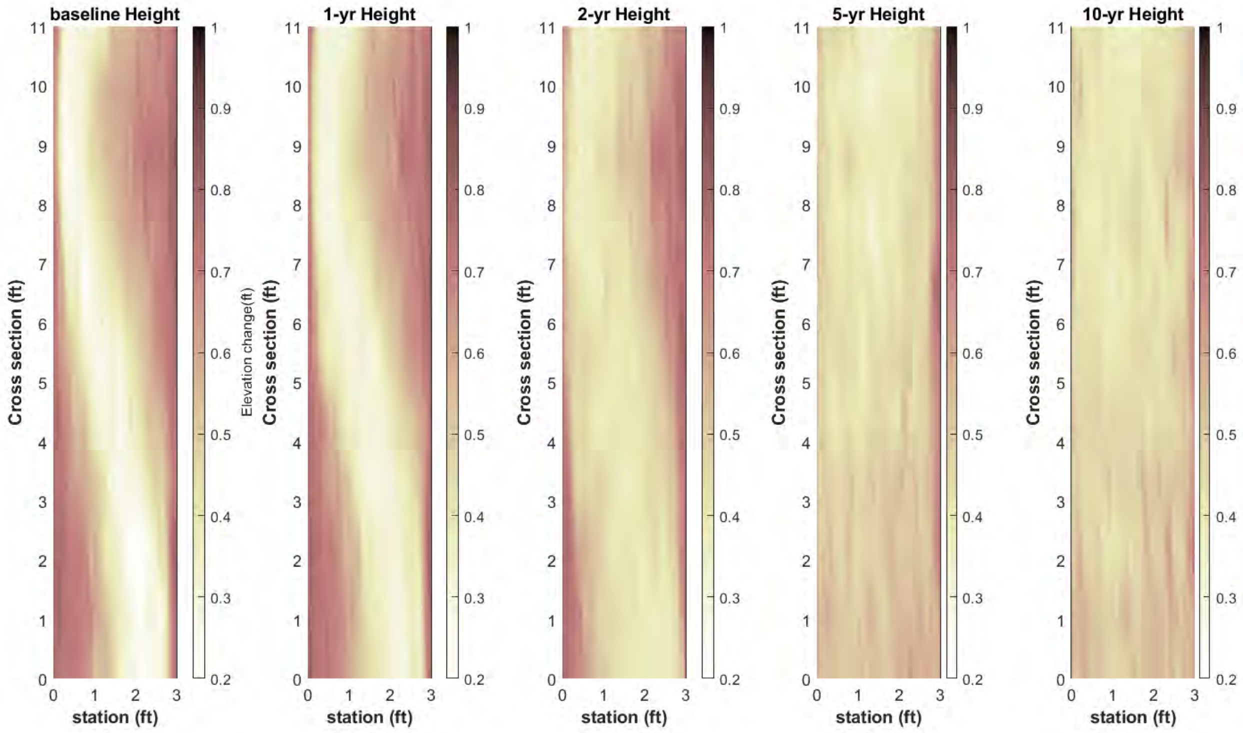


Figure 100 The channel height started to increase during the two-year flood event. The channel was flat after the five-year flood event.

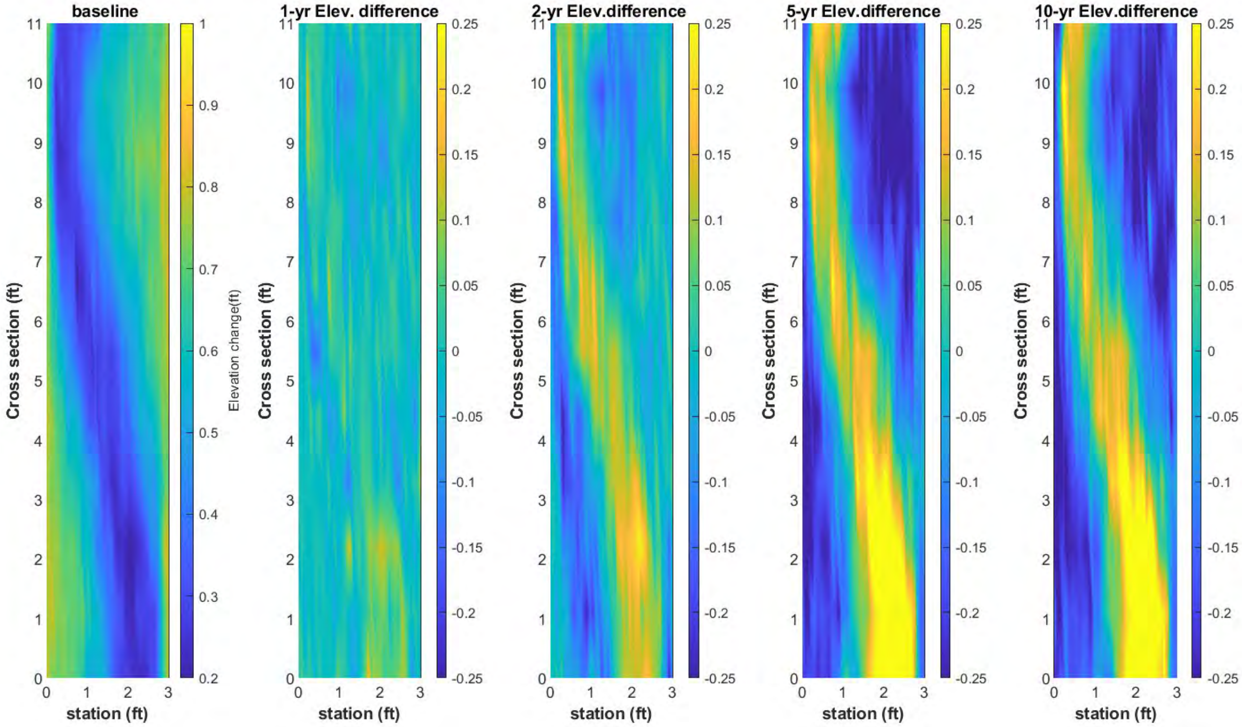


Figure 101 The channel during the two-year flood event had little deposition in the channel and erosion on the banks. A large amount of deposition and erosion occurred over the five and ten-year flood event.

These graphs show the height of the streambed at each flood event for Layout 34.

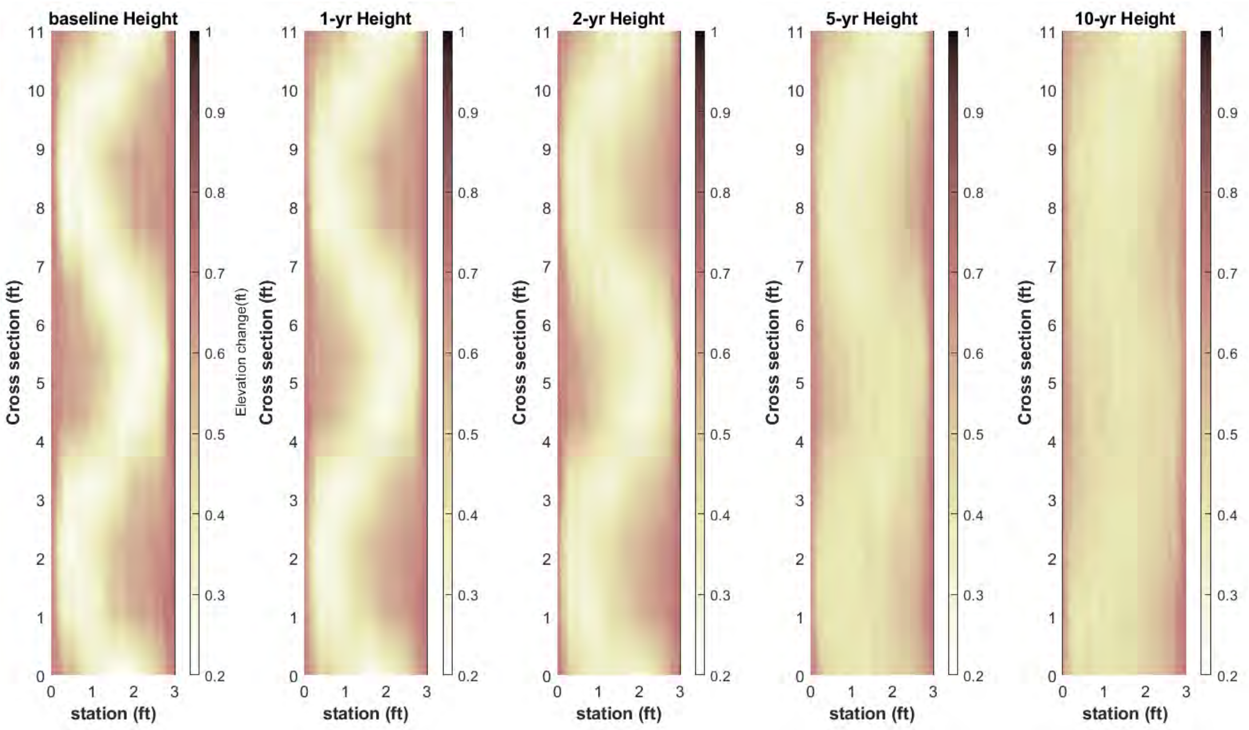


Figure 102 The channel height was stable until the five-year flood event when the channel became flat.

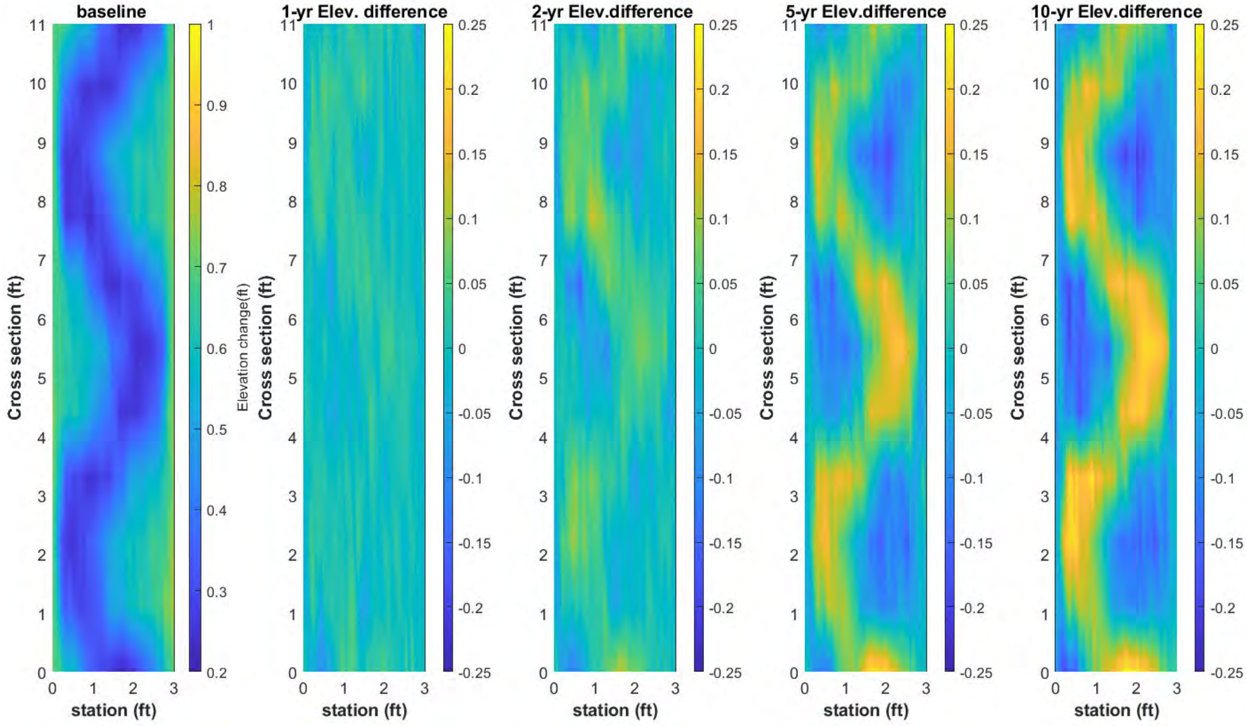


Figure 103 The channel had little change over the first two flood events. Deposition in the u-shape channel and erosion on the banks occurred for the five and ten-year flood event.

These graphs show the height of the streambed at each flood event for Layout 35.

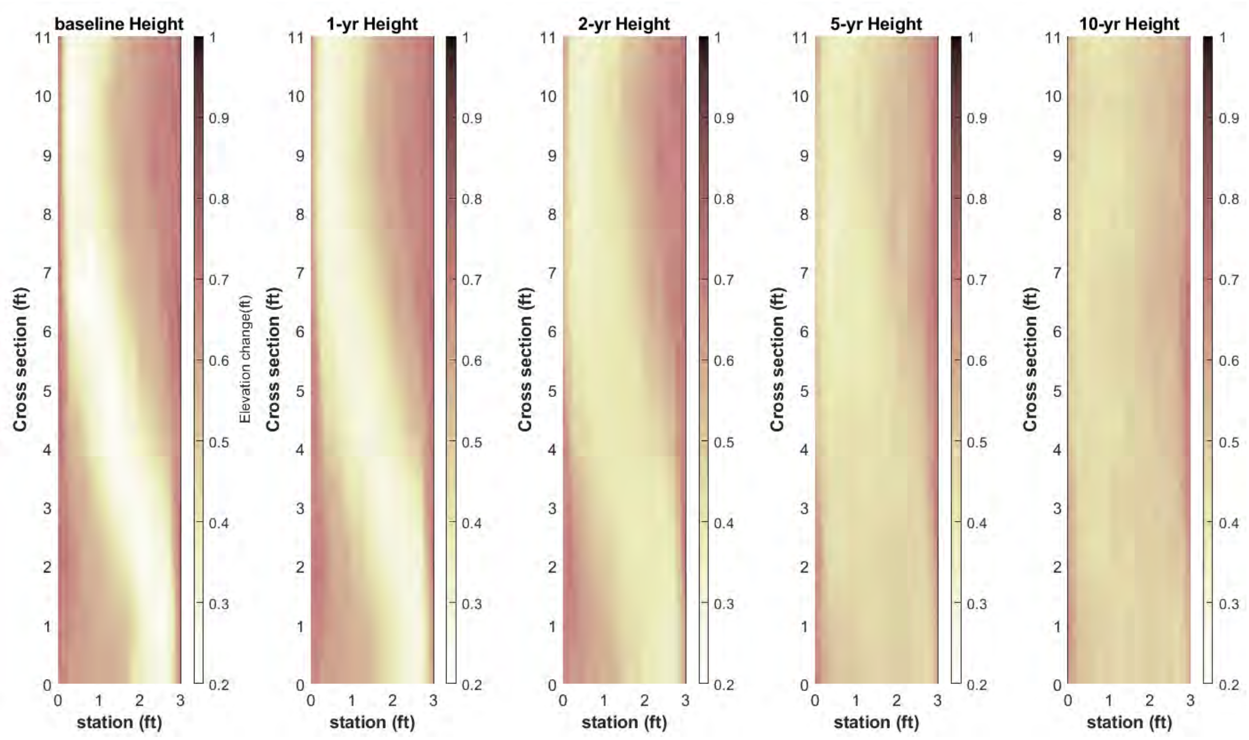


Figure 104 The channel height had little change over the first flood event but was increase during the two-year flood event. The channel was flat during the five-year flood event.

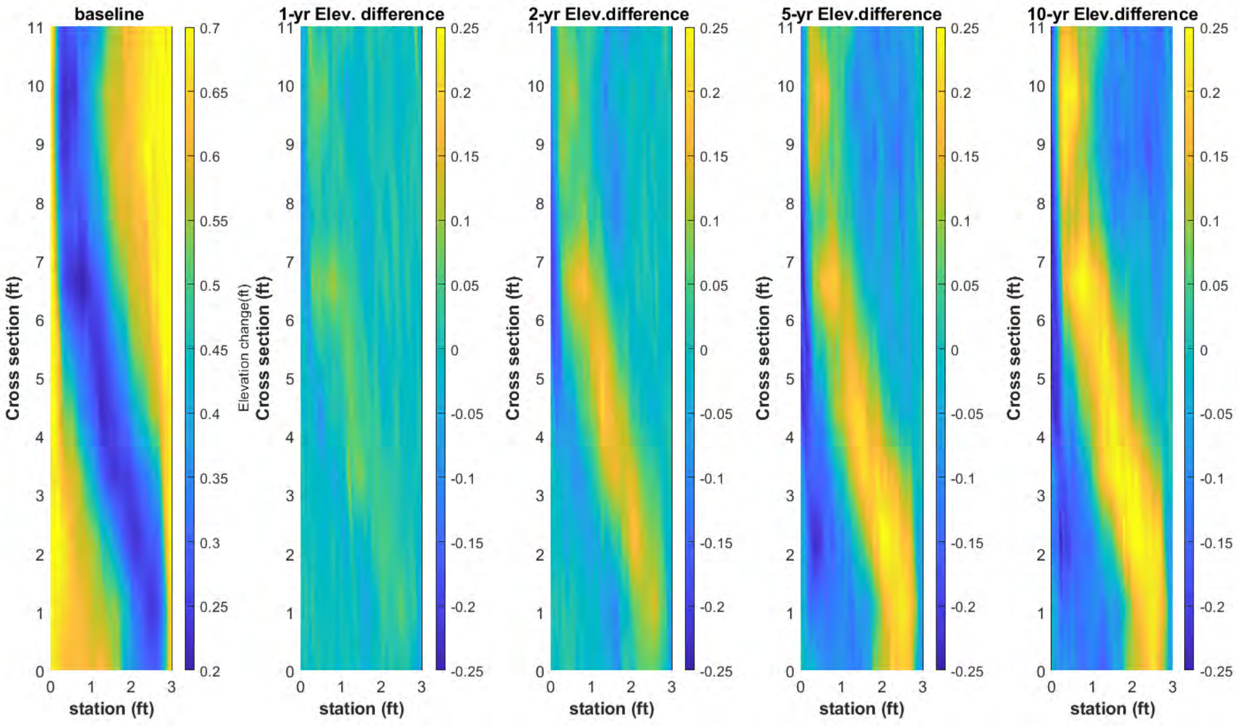


Figure 105 The u-shape channel below the upper boulder bar had deposition and it increased over each flood event. The side of the channel started to erode after the five-year flood event, and it continued during the ten-year flood event.

These graphs show the height of the streambed at each flood event for Layout 36.

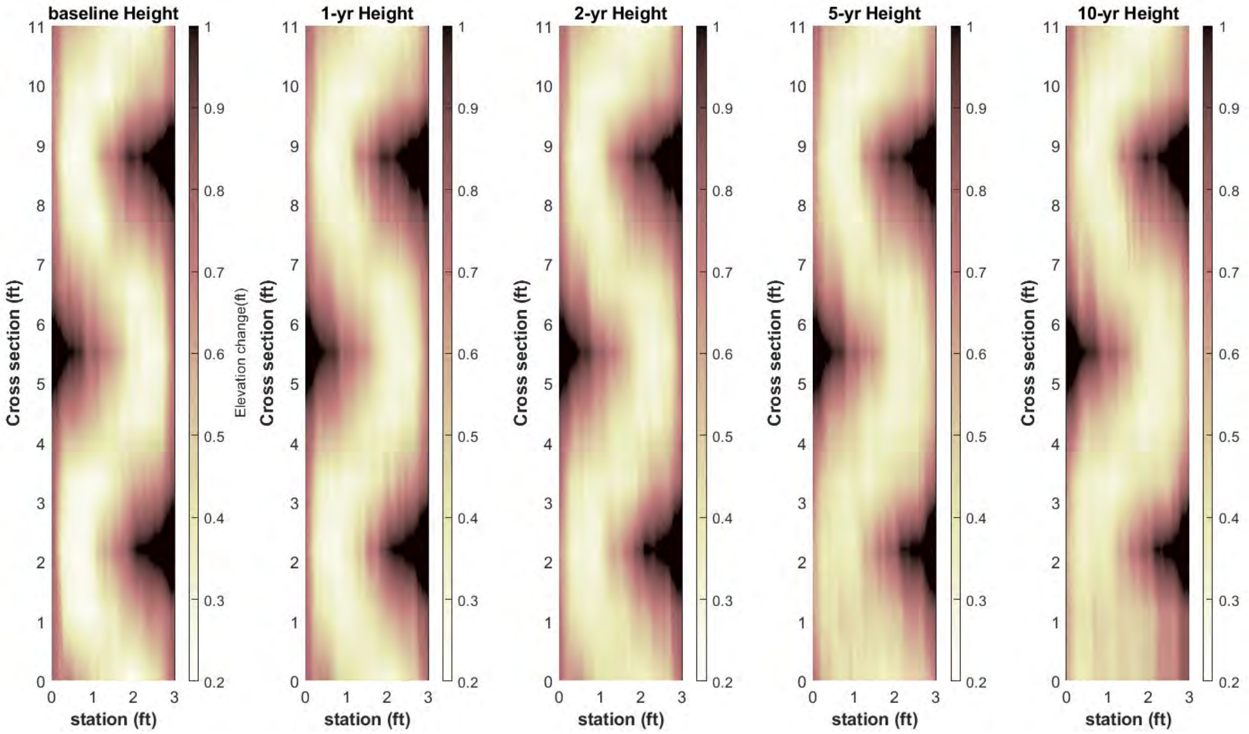


Figure 106 The channel was stable for the first two flood events. The upper 2/3 of the five and ten-year flood event were stable and the lower section had an increase streambed height.

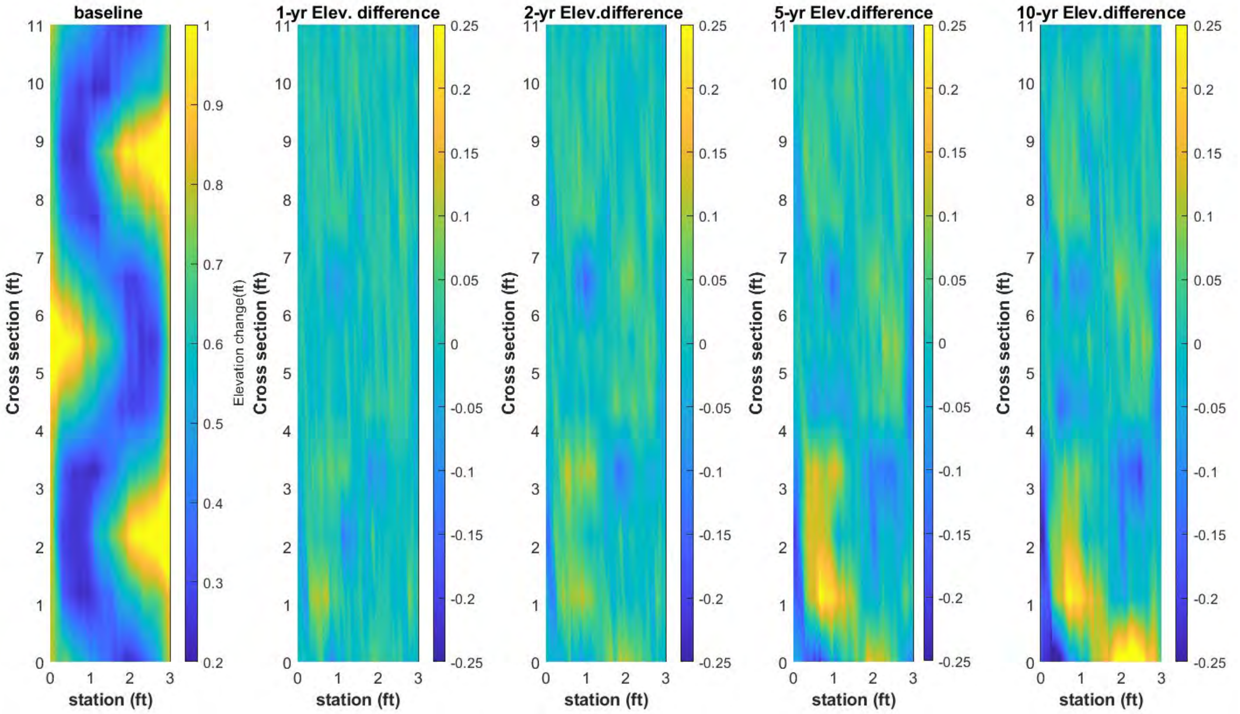


Figure 107 The channel had little change over the first two flood events. The lower 1/3 of the channel after the five and ten-year flood event had an increase in deposition. The stream above this was stable.

These graphs show the height of the streambed at each flood event for Layout 37.

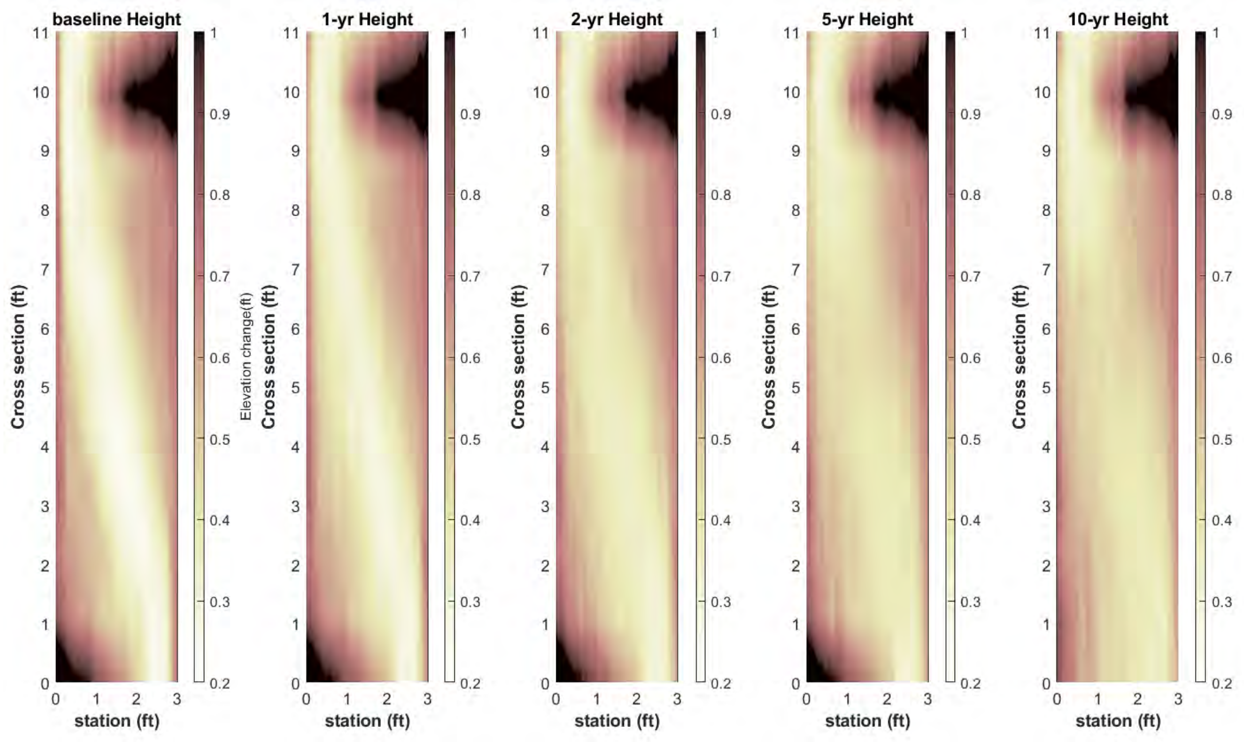


Figure 108 The streambed height in the center of the u-shape channel increased over each flood event. The height of the lower boulder bar in the ten-year flood event decreased.

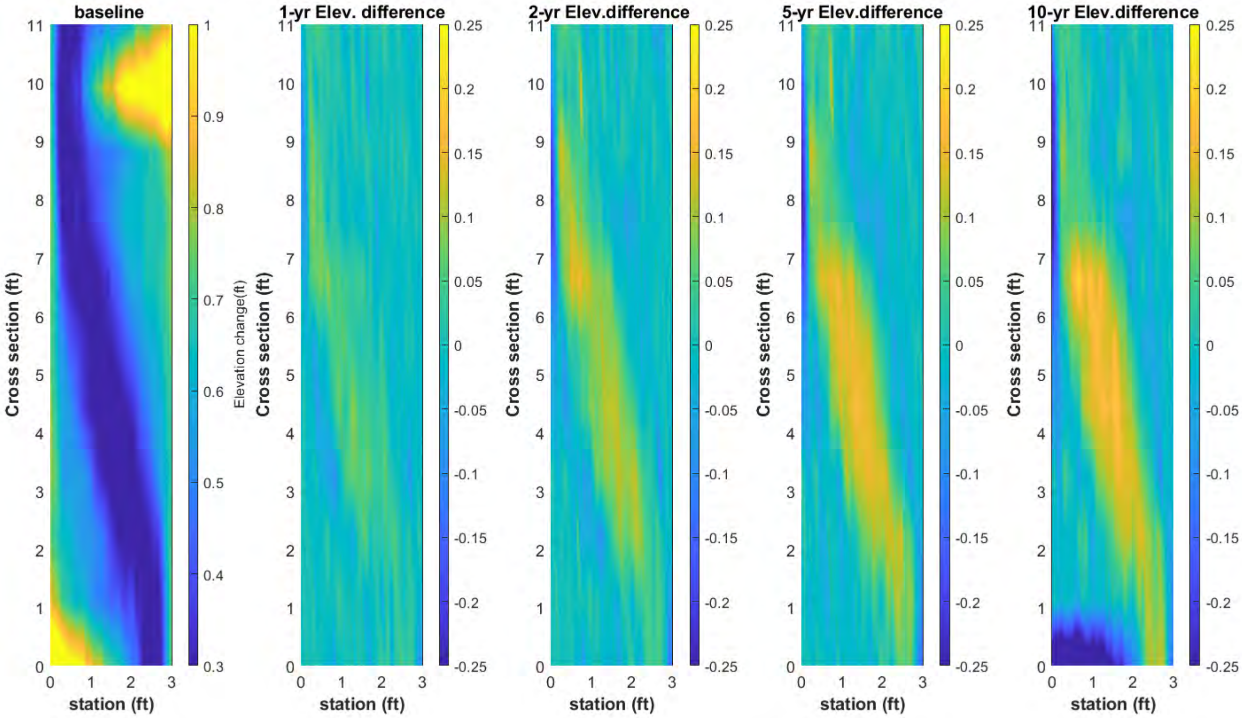


Figure 109 Over the flood events the u-shape channel between boulder bars had an increase in deposition. Erosion was very little over each flood event except for the ten-year flood event. The bottom boulder bar failed and was transported downstream.

These graphs show the height of the streambed at each flood event for Layout 38.

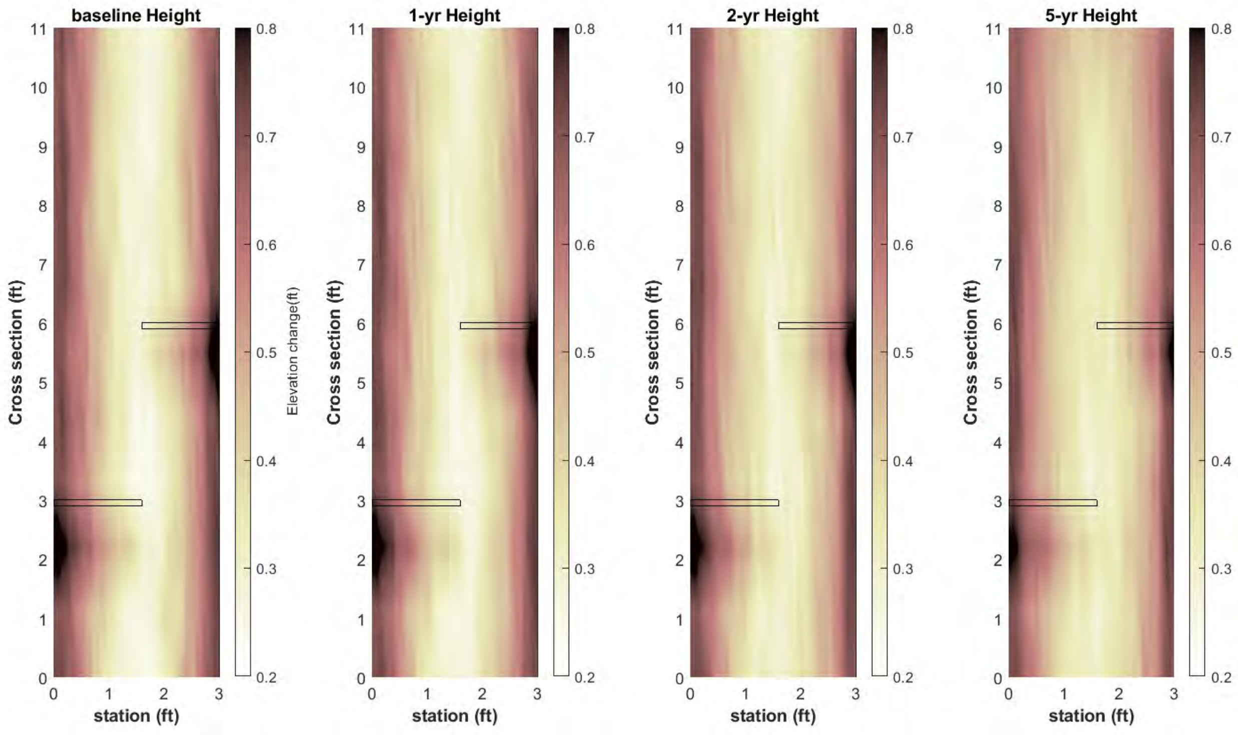


Figure 110 The height of the streambed increased at a steady rate over each flood event.

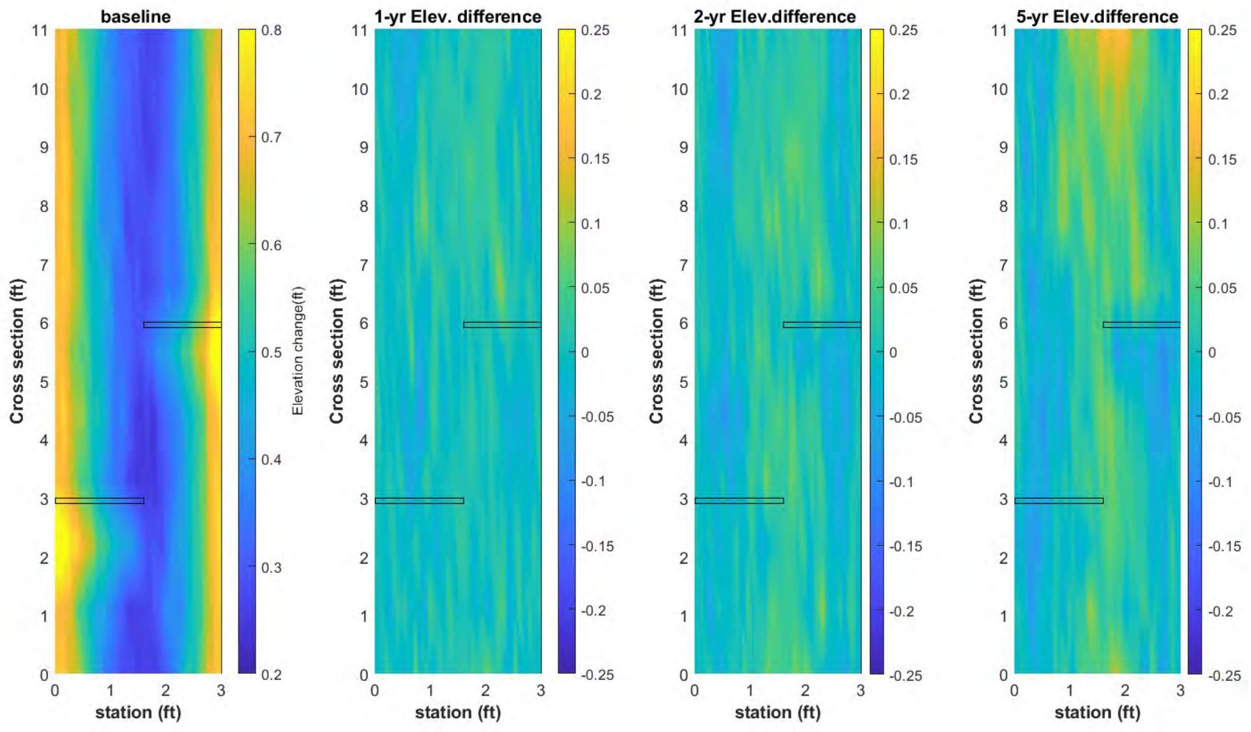


Figure 111 The channel had little change over the first two flood events. For the five-year flood event deposition above the top coarse bands occurred. The rest of the channel had little change.

These graphs show the height of the streambed at each flood event for Layout 39.

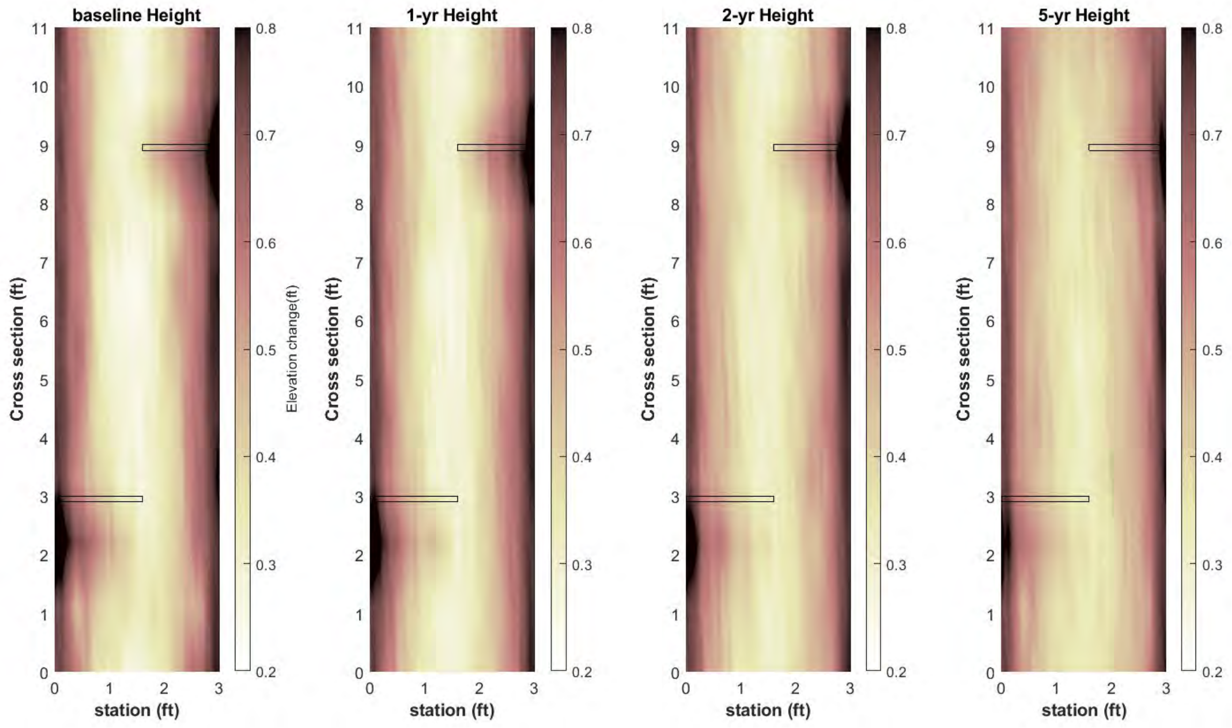


Figure 112 The height of the streambed increased at a steady rate over each flood event.

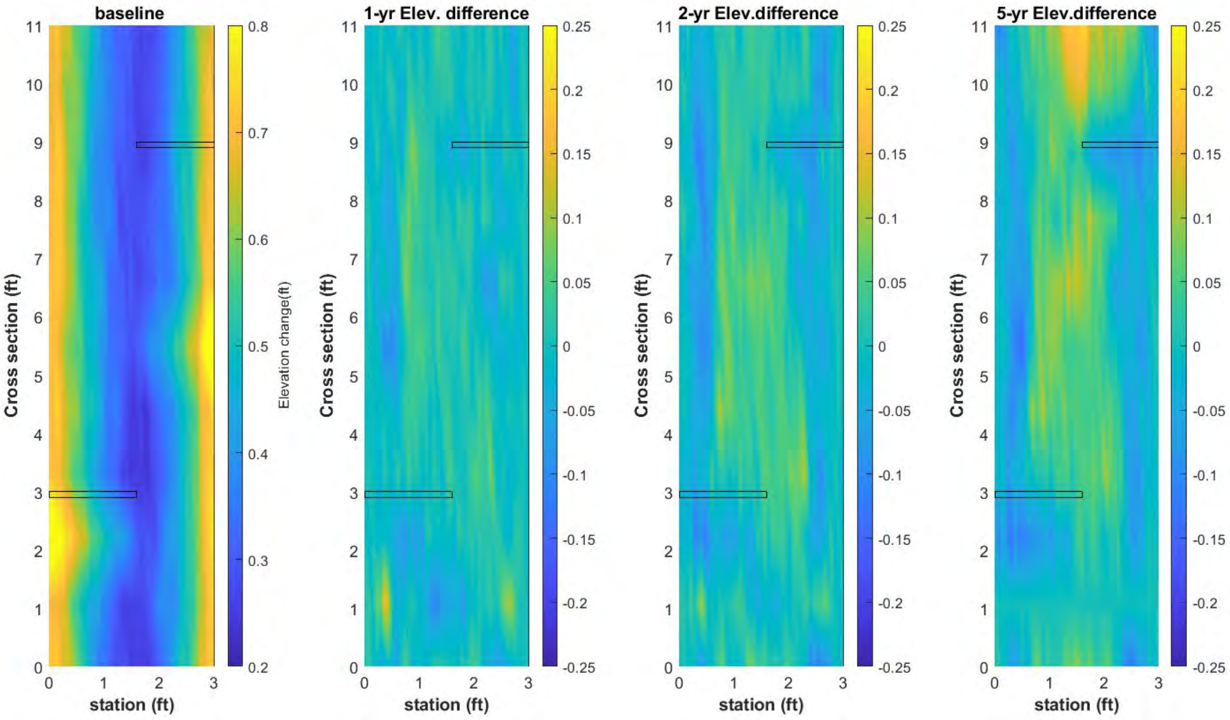


Figure 113 The channel had little change over the first two flood events. At the five-year flood event deposition occurred in the center of the channel and at the top of the study section.

These graphs show the height of the streambed at each flood event for Layout 40.

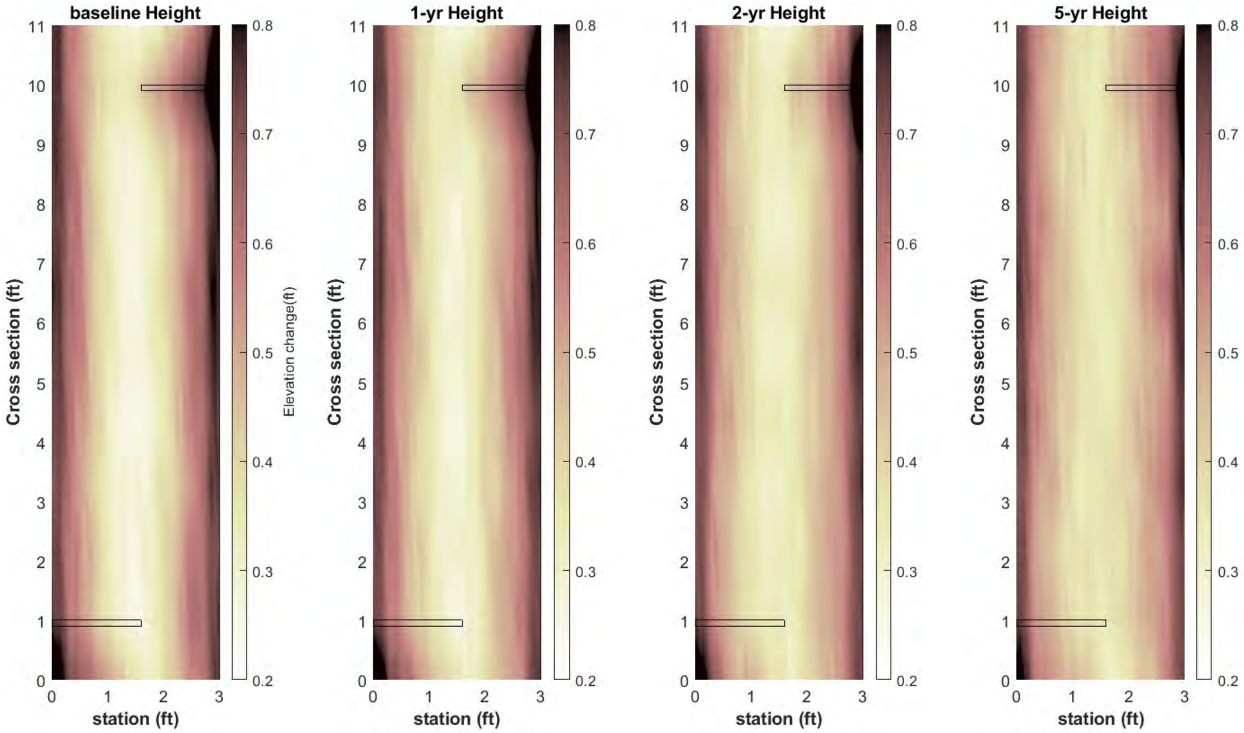


Figure 114 The height of the streambed increased at a steady rate over each flood event.

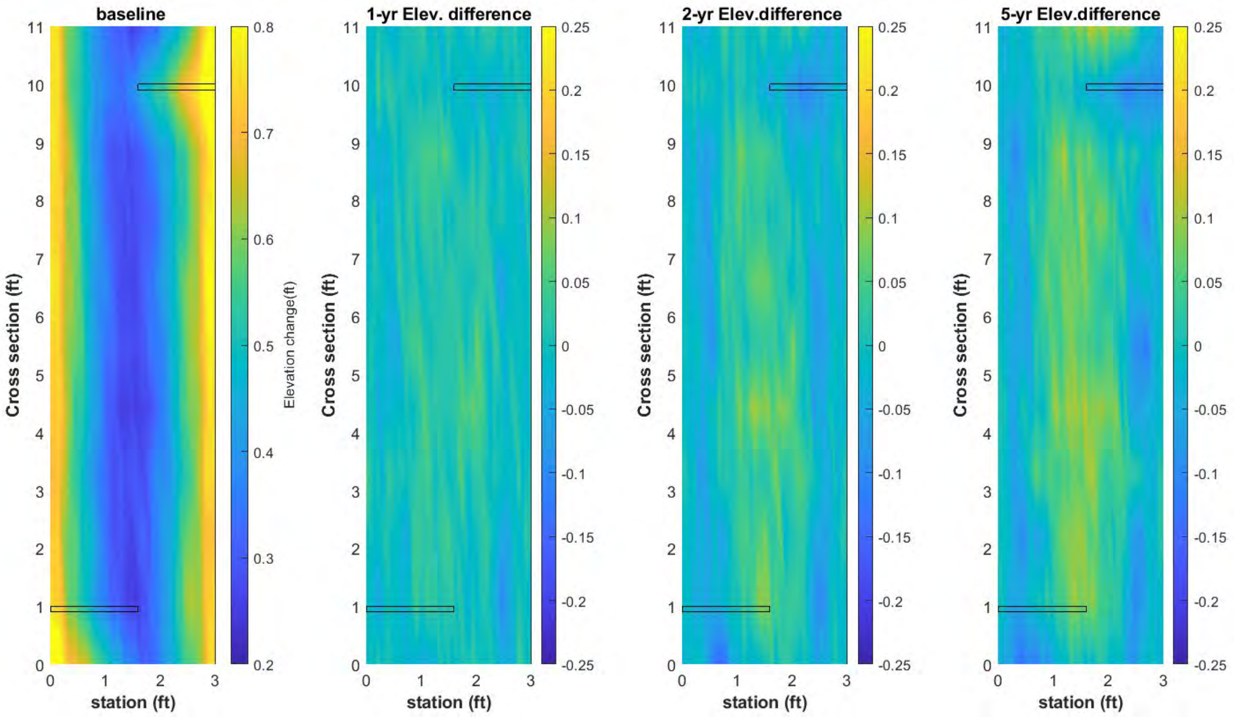


Figure 115 The channel had the most change during the five-year flood event. The channel had little change prior to the five-year flood event.

These graphs show the height of the streambed at each flood event for Layout 41.

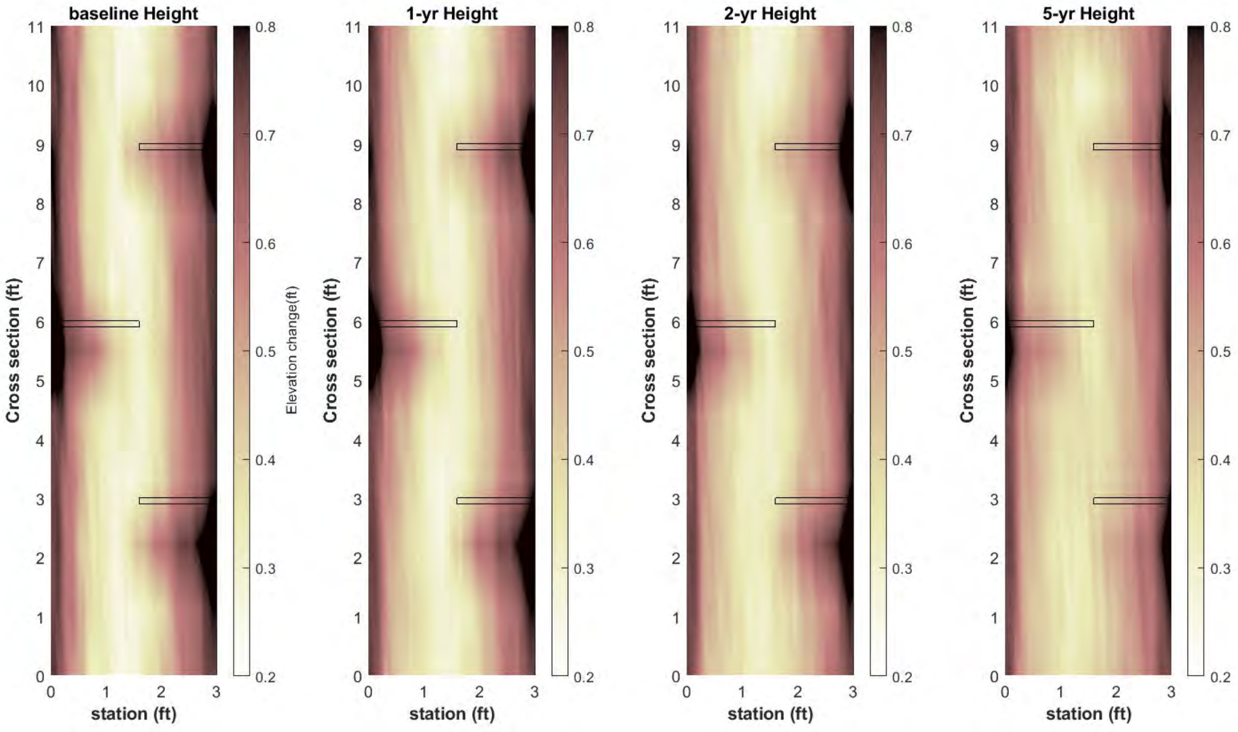


Figure 116 The height of the channel increased slightly over each flood event, with the most increase happening after the five-year flood event.

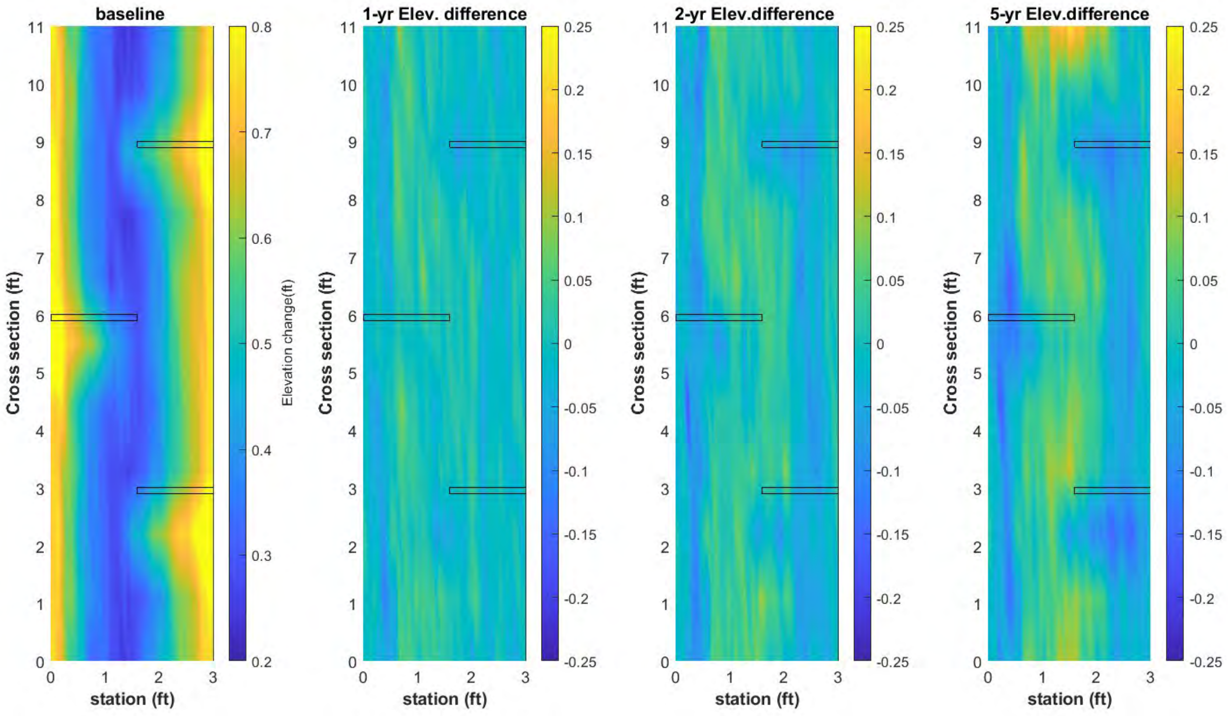


Figure 117 The channel was stable for the first two flood events with little deposition during the five-year flood event.

These graphs show the height of the streambed at each flood event for Layout 42.

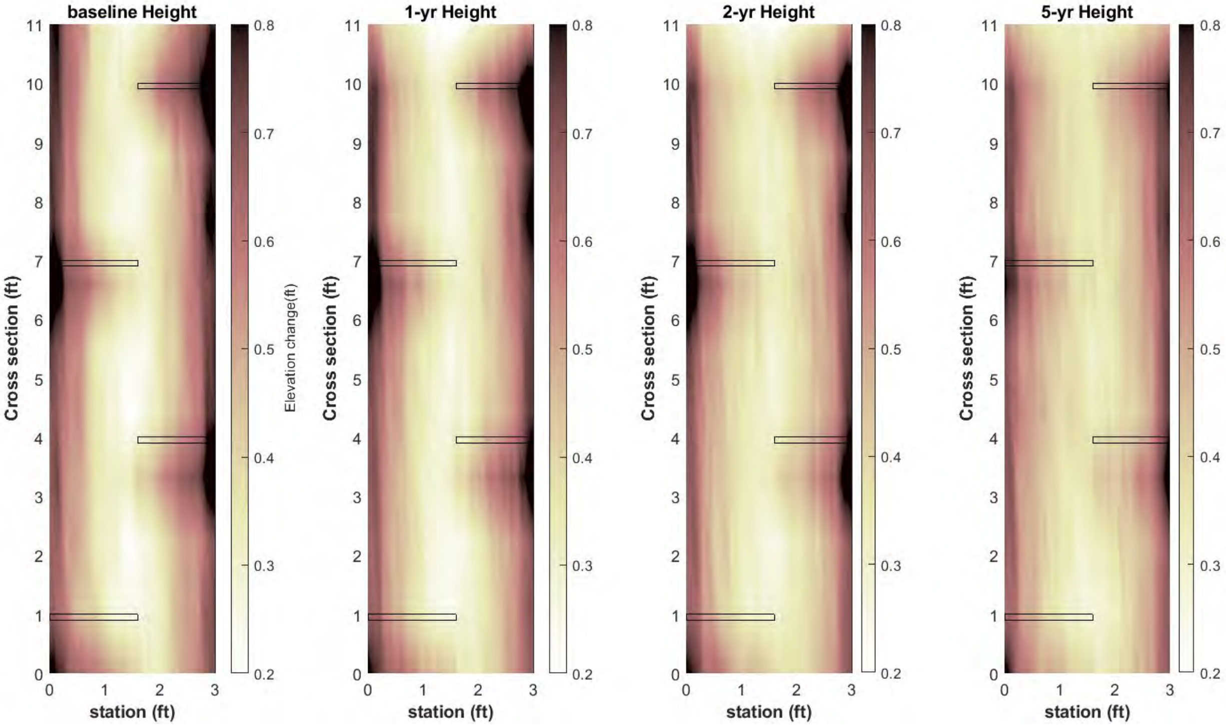


Figure 118 The channel height increased very little over the first two flood events. The height during the five-year event increased more than the other flood events

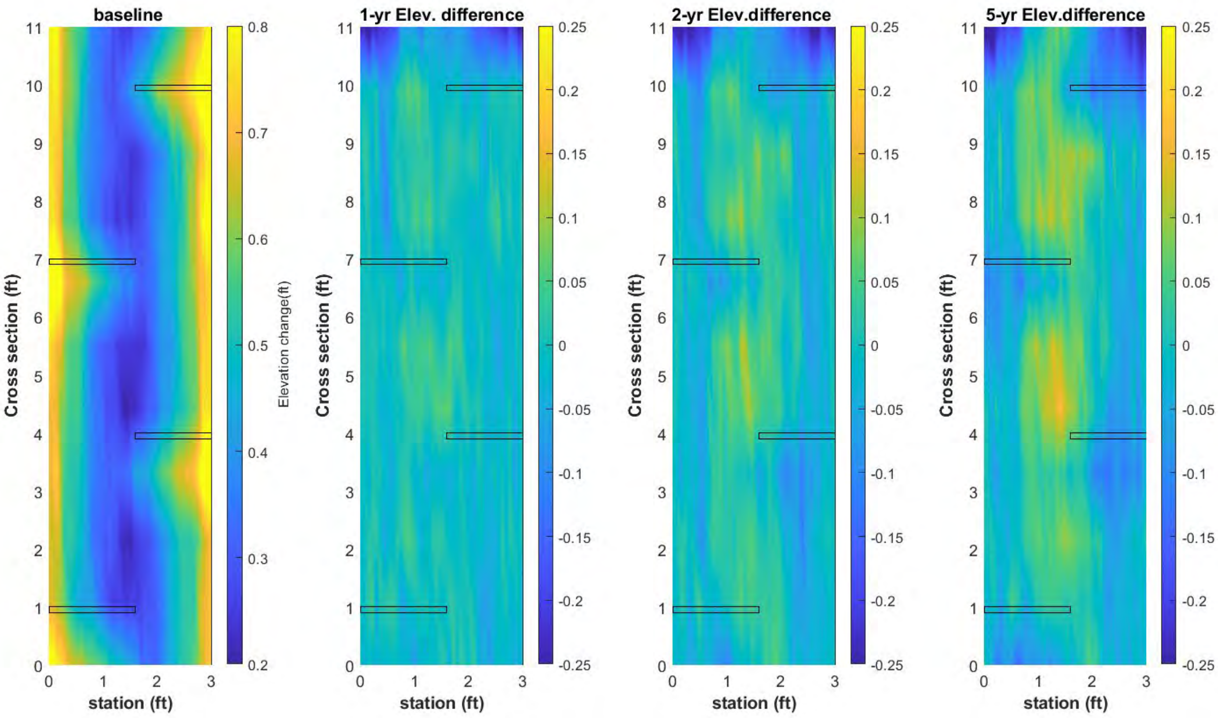


Figure 119 The channel was stable over the first two flood events. Deposition increased in the center of the channel for the five-year flood event.