Step Pools: Examining the Flow Resistance and Stability of Artificial Step Pools in Comparison with their Natural Counterparts

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Abstract

This study looked at step pool stream studies, reports, and field data in five catchment areas. The areas of interest include the Rio Cordon catchment area in Italy, the Cascade Mountain Range in Washington, the Siuslaw National Forest in Oregon, various areas in California, the University of Richmond in Virginia, and the Arkansas River Basin in Colorado. The purpose of this study was to compare the flow resistance and stability after large flooding events of artificial and natural step pool sequences to potentially provide information to improve monitoring of newly installed step pools and the design of future step pool structures. To measure flow resistance, a ratio of average height of the steps divided by the average length of the pools divided by the slope (H/L/S) was used, which was determined from a previous study by Abrahams et al. (1995) to correlate with maximum flow resistance. To compare stability of the steps following flood events, observational data was collected from studies and reports on the steps used. The average H/L/S values for the artificial and natural steps were calculated to be 3.23 and 1.22, respectively. According to the ideal maximum flow resistance range of 1-2, found by Abrahams et al., the natural step pools were found to maximize flow resistance more effectively than the artificial step pools. In analyzing the observational data, 7 out of 8 artificial and 8 out of 8 natural showed signs of instability following flood events. So, while natural step pools were better at maximizing flow resistance, they were not necessarily more stable than artificial step pools. This provides evidence that there are potentially other factors that contribute to the instability of step pools including the size of the flooding and increased sediment transport from upstream.

Introduction

In recent decades, the prevalence and popularity of stream restorations has really grown in places all over the world. As the negative impacts of humans on the surrounding environments is being increasingly recognized, towns, cities and other organizations are seeing the ecological and economic opportunity provided by stream restorations. Benefits include improved water quality, habitat for aquatic species, and flood and erosion control (Bernhardt et al., 2007). The City of Richmond is participating in this trend by restoring a small stream on the campus of the University of Richmond called Little Westham Creek. One of the stated goals of the restoration is to improve storm water management and prevent scouring of the stream banks that was observed prior to restoration.

To help with this task, step pool structures were installed in two tributaries of Little Westham Creek, with the idea that they will help dissipate the energy of water coming into the stream, specifically during high flow events, which will in turn prevent erosion and scouring. But, even though the main objective of the step pools is to help stabilize the stream banks, how do we know whether artificial step pools are as effective at doing so compared to step pools found in natural stream environments? This study will look to answer that question.

From the early 1900s to the present, there has been a significant amount of research into step pools, specifically natural step pools, and their role and value in ecosystems as a way to dissipate the energy of rushing water. Up until the late 1980s, step pools were mainly examined from an engineering perspective and not an ecological perspective. But, in recent decades research into step pools has focused more on the step pools as features in their environments. Studies have looked at how natural step pools form, the ecological benefits they provide to ecosystems, and more recently how these benefits can be applied in stream restoration projects where artificial step pool structures are installed.

Natural step pools are mainly found in high altitude, mountainous areas where streams have less room to maneuver compared to low altitude streams (Hayward, 1980). They are found in all types of environments including humid streams and arid deserts, and are usually only observed in locations that have a gradient of 4% or greater (Hayward, 1980) (Clarke, 1988) (Grant, 1990). The reason for formation of step pools within these systems is to allow for energy dissipation vertically rather than horizontally, like what is found in streams and rivers closer to sea level (Clarke, 1988). As the water cascades over the steps, its horizontal kinetic energy is turned into vertical energy and absorbed as turbulence in the pool below (Clarke, 1988).

Step pools have been shown to form during high magnitude, infrequent flooding events and then stay around during low flow periods (Chin et al, 1989). High flows pick up large rocks and logs and carry them down river. Once the water level drops, the debris is deposited in the stream (Chin et al, 1989). When these objects are great relative to the size of the channel, pools form behind them, and a step-pool-step pattern develops (Hayward, 1980). Based on this theory, research has shown that one of the main roles of natural step-pools in stream channels is to stabilize stream beds and reduce erosion during heavy flooding events (Church et al, 2007).

Since the 1950s, hydraulic engineers have been interested in understanding the flow mechanics behind step pool systems and how they could be applied in an industrial setting to irrigation systems in agriculture, drainage ditches, and other places where water needs to be transported over long distances and in steep areas (Rouse et al., 1965). Engineers wanted to understand the role of debris, such as logs and boulders, in providing flow resistance in these high altitude, natural streams, so it could then be applied in the real world (Chin, 1989). Flow experiments were carried out in lab environments to see whether relationships could be seen between flow resistance and channel debris within streams and to try and develop a formula that would encapsulate this relationship (Powell, 1946) (Peterson and Mohanty, 1960).

The authors used metal, concrete, and other hard materials to try and mimic natural obstacles found in streams, and found a relationship between the flow resistance ability of these “roughness elements” and their overall size, spacing, and density within streams (Peterson and Mohanty, 1960). However, they struggled to develop a formula to characterize the relationship they were observing. Part of the reason why they struggled was due to the fact that they did not treat step pools as a feature of the environment in which they are found. They focused on the processes performed by the step pools and less on the formation of the steps themselves and their role in ecosystems.

Kellerhals et al. (1970) was the first to look at step pools from a hydrological perspective rather than solely from a hydraulic perspective. Instead of trying to understand the flow characteristics of the step pools, the team looked at the interaction and role of the steps in their stream environment as a whole. They found that there was a relationship between the dimensions and structure of the steps and the upstream flow characteristics of the stream (Kellerhals et al.). Greater velocity upstream correlated with more steps downstream to counteract the energy of the water flowing down (Kellerhals et al.) This provided evidence to support the theory that step pools help to stabilize stream banks by dissipating the energy of the water flowing over them.

Abrahams et al. (1995) conducted a laboratory flume study to further understand the relationship between the geometry of step pool sequences and their ability to maximize flow resistance. The authors found a clear correlation between the length of the step pools, the average height of the steps, the slope that they are located on, and the step pool's ability to maximize flow resistance during high flooding events (Abrahams, 1995). A ratio of the height of the steps divided by the length of the pools divided by the gradient of the steps (H/L/S) was developed (Abrahams et al., 1995). The results of the study showed that step pools with H/L/S ratios between 1-2 were able to maximize flow resistance, which corresponds to greater stability of the stream banks and decreased erosion. This finding was supported by field measurements of natural step pool structures carried out by Lenzi (1997).

Based on this discovered relationship by Abrahams et al., over the past 20 years, researchers have focused on the potential viability of using step pools in stream restoration projects. The impacts of humans on stream ecosystems is increasingly being recognized and research into restoring streams to a more natural state is becoming more popular (James et al., 2006). Over the past century, the world has seen rapid urban growth. As more land was bought for development, streams were converted from natural, meandering channels to straight, narrow channels (Chin and Gregory, 2010). Roadways were expanded and streams were diverted underneath them (James et al., 2006).

The conditions created by rapid urbanization have forced streams into straight, narrow channels where they have less room to meander horizontally and have to deal with high magnitude water discharges from storm water infrastructure (Chin and Gregory, 2010). The stream ecosystems in these areas cannot behave naturally, and so they have become severely degraded over time. Step pools are seen as one way to potentially stabilize the banks and decrease scouring and erosion, especially during high flow events due to the role they have been found to have in mountain streams (Chin et al, 2008).

While there has been a lot of promise shown in using step pools in stream restoration projects for the purpose of stabilizing stream channels, limited analysis has been done to see whether artificial step pools are affective in providing the same ecosystem benefits as natural step pools do.

This study will look to compare artificial and natural step pool systems to see whether artificial step pools maximize flow resistance and stabilize stream banks like their natural counterparts. The purpose of this analysis will be to understand the effectiveness of artificial step pools in reducing erosion and stabilizing the stream banks during flooding. This study will look to give greater insight into the role of artificial step pools in erosion prevention, their overall viability in stream restoration projects, and potentially provide valuable information to improve on-going step pool monitoring and maintenance as well as their integration in future projects.

My research looks to answer the question: How do artificial step pool structures compare to natural step pool structures at stabilizing stream channels and maximizing flow resistance during high flood events? I believe that artificial step pool structures are not as good at maximizing flow resistance an stabilizing the stream channels during flood events relative to natural step pools.

Methodology

To carry out this research, a total of 34 step pool structures were analyzed from five scientific studies, restoration reports, and field measurements in the Little Westham Creek at the University of Richmond. 19 of the step pools were naturally formed structures and 15 were artificial structures installed during stream restoration projects. There was variability in their total length, slope, and number of steps, however, they all fell into the category of "step pools" as defined by the literature they were found in.

The step pools were located in six areas: the Rio Cordon catchment area in the Italian Alps, the Cascade Mountain Range in Washington, the Siuslaw National Forest in Oregon, Contra Costa, Monterrey, and Los Angeles Counties in California, University of Richmond in Virginia, and the Arkansas River Basin in Colorado.

Eight of the natural step pools were located in streams in the Rio Cordon river basin in the Dolomites of Northern Italy. The streams were located at an elevation of about 2200m, and the land around them is actively used for grazing (Lenzi, 2003). The climate is an alpine environment, with most of the precipitation occurring as snowfall (Lenzi, 2003). Annual flooding usually occurs during May and June and is caused by snowmelt, but flooding also occurs in the late summer and early fall (Lenzi, 2000). Major flooding had occurred in the past including a large flood in 1994 which was estimated to be a 30-50 year flood (Lenzi, 2001).

The eleven other natural step pools studied were located on the western side of the Cascade Mountain Range in Washington. The elevations of the streams ranged from 355 m to 1244 m (MacFarlane and Wohl, 2003). The step pool reaches ranged in length from 40.6 m to 71.4 m and contained between 13 and 30 steps (MacFarlane and Wohl). The areas in which these streams were found are relatively remote and heavily forested with little to no human impact (MacFarlane and Wohl).

Five of the artificial step pools were located in Colorado's Arkansas River Basin. The steps are located in mountain channels. The mean drainage basin elevation was 3,450 m (Thomas et al., 2000). These step pools were installed in 1989 for the purpose of habitat enhancement (Thomas et al.). The steps experienced several large floods in the years following installation.

Five artificial step pool sequences were located in the Baxter, Alamo, and East Alamo Creeks in Contra Costa County California. Baxter Creek was restored in 1996 as part of a city wide storm drainage improvement project. Many of the creeks in the area had been culverted in the 1940s due to population and growth pressures (Purcell, 2002). Instead of repairing the culverted stream, the city decided to recreate an above-ground stream and return it to a more natural state. A flood event with a recurrence interval of 14 years occurred in the area following the installation and between post construction monitoring surveys in 1999 and 2005 (Chin, 2008). The four step pool structures installed in the reaches of Alamo and East Alamo Creeks were part of a plan to restore the creeks after 150 years of overgrazing and significant incision of the banks had occurred. (Chin, 2008).

Three other step pools located in Karnowsky Creek, Dry Canyon Creek, and the Carmel River were analyzed. Karnowsky Creek, located in the Siuslaw National Forest in Oregon, was part of a large meadow restoration project. The creek had been channelized to make room for agriculture in the area. In some places, the banks were 3 meters high surrounding the creek. The US Forest Service started to restore the stream in 2004 to help with groundwater storage within the valley (Chin, 2008). Step pools were added to provide grade control because the gradient was very steep in some places and prevent erosion like was seen prior to the restoration (Chin et al., 2008). Logs were used to create the steps and boulders were placed just below each step to try and prevent scouring of the stream banks (Chin et al., 2008). The area sees large flooding especially during the winter season.

Dry Canyon Creek, located in the Calabasas, CA, was restored in 2006 because it had become severely eroded and invaded by non-native species. The channel had narrowed, and trash and concreate rubble had accumulated in the stream from attempts to stabilize the banks by building retaining walls (Chin et al., 2008). The goals of the restoration and implementation of steps was to improve the stream habitat and stabilize the banks.

The Carmel River was restored in 2015 following the removal of the San Clemente Dam that had been there since 1921 (Marson et al. 2016). The river is located in a Mediterranean climate and has historically experienced droughts as well as major flooding caused by El Niño (Marson et al.). Step pools were installed with the goal of helping to stabilize the sides of the stream. In 2016, the river experienced a two flooding events with reoccurrence measurements of approximately two and three years (Marson et al.).

Finally, two artificial step pool structures were located on the University of Richmond campus. They are located in two small tributaries that flow into Little Westham Creek on the edge of the University campus. Over hundreds of years of human usage, the creek was straightened and significant erosion of the banks had occurred. Complete restoration of the creek was completed in 2019 and step pools were installed to reduce erosion from storm water runoff.

To measure the maximum flow resistance of each of the step pools, the H/L/S ratio described by Abrahams et al. (1995) was used. From each of the streams investigated, three dimensional measurements of the step pool structures were collected. The dimensions co the average height of the steps (H), the average length of the pools (L), and the average slope (S) of each entire step pool sequence. The measurements used were standard across the step pool studies and are shown in Figure 1. The average height of the steps was defined as the average distance from the top of a step to the surface of the water in the pool below. The average length of the pool was defined as the distance measured from the top of an up-stream step to the top of the next downstream step. The slope was measured by taking the change in elevation from the top step to the bottom step and the length of the step and finding the gradient change between them. From these measurements, the flow resistance H/L/S ratio was calculated for each step pool for comparison and analysis between the step pools and also against the ideal maximum flow resistance range found by Abrahams et al (1995).

Additionally, to analyze how the H/L/S ratio correlates with the overall stability of the steps during flood events and see whether there is a noticeable relationship between the two factors, observational survey data and notes from the case studies, scientific articles, and reports were aggregated. Not all of the streams had notes on changes to the step pools, though. Out of the 31 streams examined, seven artificial streams and eight natural streams had detailed observations and data of changes that could be used. Some studies included longitudinal profiles of the streams taken before and after the flooding events. The observed changes to the step pools were placed into five distinct categories: erosion and scouring of the banks, water flowing through the steps, step pool reorganization, destruction of steps, and no observed changes.

Following the collection of data, analysis and comparison of the artificial and natural step pools was done to conclude whether artificial step pools are less stable than natural step pools during flooding events.

Results

The dimensional and geometric analysis as well as the H/L/S flow resistance ratio for all of the artificial and natural step pools are shown in Table 1 and Table 2. The height of the artificial step pools was found to average around .76 meters. The average pool length was 7.6 meters, and the average slope gradient was calculated to be .042 m/m. The average H/L/S ratio for all of the artificial step pools was found to be 3.23.

The Alamo Creek and East Alamo Creek restorations were shown to have the tallest steps and the longest pool lengths at about 1.2 meters in height and 10 meters in length (Table 1). The largest H/L/S ratio was San Miguel Creek at 13.26, however, that value was significantly higher than the next closest, Halfmoon Creek, which was found to have a ratio of 5.71 (Table 1).

Additionally, 8 out of the 15 artificial step pools analyzed had an H/L/S ratio of 2 or above. Two streams were found to have an H/L/S value that was less than one at .95 and .63 (Table 1). Karnowsky Creek, Baxter Creek, Horn Creek, and the two step pools measured at the University of Richmond had flow resistance values between 1 and 2 (Table 1).

For the natural step pool sites, the average height of the steps was found to be .55 meters, and the average pool length was 3.65 meters (Table 2). The average gradient of the steps was calculated at .11 and the average H/L/S ratio was measured to be 1.32 (Table 2). All of the step pool sequences were found to have H/L/S flow resistance ratios between 1 and 2.

The flow resistance ratio differences between natural and artificial step pools are shown in Figure 2. The average slope of each step pool sequence was plotted on the x-axis, and the calculated H/L/S value was plotted on the y-axis (Figure 2). A black line at a ratio of 1.5 represents the average max flow resistance value measured by Abrahams et al (1995) (Figure 2). In looking at the graph, the natural step pools are found at a range of different slopes from .05 to .22, however, they all were found to have similar flow resistance ratios (Figure 2). The artificial step pools, on the other hand, are found at gradients that are no higher than .1, and their H/LS ratios were found to range from values less than 1 all the way up to 13.26 (Figure 2).

Moreover, analysis of observational and physical data collected from the step pools following flooding events was completed. 7 out of the 8 artificial step pools that were observed showed noticeable changes in stability, and 4 out of 6 natural step pools showed changes after flooding.

The artificial step pool streams inspected in California showed a wide range of changes. Baxter Creek experienced a significant flood in 2005 that led to significant reorganization of the steps (Chin et al., 2008). The number of steps went from 5 originally to 14 in 2005 (Chin et al., 2008). The longitudinal profile pictures of the steps in 1999 and 2005 show the reorganization of the steps and the addition of more steps (Figure 4).

During an assessment in 2006 at East Alamo Creek, the steps showed no signs of erosion or changes following a 9-year flood event in 2003 (Chin et al., 2008). Observational assessment of Karnowsky Creek showed scouring and erosion of the banks following a 5-year flood. The pools became significantly deeper, there was erosion observed on the channel sides, and there was formation of additional steps (Chin et al., 2008). A longitudinal profile of the steps show the deepening of the pools and increase in the number of steps over the same distance (Figure 5).

More significantly, the step sequence in Codornices Creek was shown to have been completely destroyed by a 25-year flood (Chin et al., 2008) There was local erosion of the banks around the steps and water flowing through the steps rather than over top of them (Chin et al., 2008).

A survey of the Carmel River steps one year after installation showed shifting of many of the anchoring boulders of the steps. One boulder moved 4 meters downstream from where it was originally placed, and the left bank near the step pool showed signs of erosion. In certain places, the water had eroded the banks down to the bed rock, as well (Marston et al., 2016).

The observational assessment completed for the natural steps in the Italian alps following severe flooding in 1994 showed complete destabilization of 8 out of 8 step sequences. In 5 out of 8, the step reaches were shortened by an average of 42% (Lenzi, 2001) 3 out of 8 step series were changed completely from step pool systems to being defined as “pool-riffle” structures due to a large deposit of sediment in the steps (Lenzi 2001) For the 5 step pools that survived, the pool spacing between steps decreased by approximately 25-30% (Lenzi, 2001)

Discussion

The results of this research do provide support for part of my thesis that artificial step pool sequences are not as effective at maximizing flow resistance compared to natural step pools. However, the results do not show whether they are less effective at stabilizing channels compared to natural step pool sequences.

The majority of artificial step pools that had observational data and did not fall within the maximum flow resistance (H/L/S) ratio of 1-2, proposed by Abrahams et al. (1995), showed instability during large flooding events that occurred after they were installed. Similarly, though, 66% of the natural step pools examined after flooding were unstable, as well.

It is also important to point out that even though the flow resistance of the artificial step pools in Baxter Creek (1.1) was found to fall within the range corresponding with maximum flow resistance, the steps still showed signs of changing and reorganization following the flood event.

Similarly to Baxter Creek, the majority of the natural step pools that were analyzed for changes were found to be unstable following large flooding events, as well. Even though most of the natural step pools were found to have a H/L/S ratio within the ideal range for flow resistance, 8 out of 8 step series showed signs of restructuring following flooding in the Italian Alps. So, while studies have shown that steps with a ratio of 1-2 is shown to maximize flow resistance during high-energy flow events and stabilize the stream banks, the evidence provided here shows that steps measured as having “maximum flow resistance” are not necessarily more stable than

Based on the results, there is not a clear difference between the abilities of artificial and natural step pools at providing stability in streams during high-flow periods. Although previous research showed that step pools with dimensions that maximum flow resistance tend to be stable during biennial flooding or longer, these findings seem to contradict it. Therefore, there must be some other variable or variables at play to explain what was found.

One potential explanation for why restructuring of these steps was seen could be that the scale and discharge of water during the flooding events was much larger than what the area had seen in the recent past. The flood that hit the Rio Cordon area in 1994 had a measured reoccurrence rate of 30-50 years (Lenzi et al., 2003). The reoccurrence rate of the flood that happened in Baxter Creek was 14 years (Boucher, 2005). So, while the natural steps may have developed over time to withstand smaller flooding events, when the large event occurred, the steps were not formed to withstand it, so they became destabilized.

Evidence to back up this explanation was presented in a study looking into the formation of natural step pool series. In a lab experiment, Whittaker et al. (1982) found that during regular flooding events occurring between 1-25 years, step pools will behave as stable structures. However, flooding events with occurrence rates of 30 years or more can completely destabilize the steps and lead to complete destruction or reorganization of the steps as was seen in the Lenzi et al. study. So, this shows that the overall scale of a flood can impact step pools greatly.

Additionally, research into the movement of sediment through step pool features has also shown that increased sediment from upstream can cause harm and potentially destroy steps downstream (Keller and Swanson, 1979). The sediment gets carried downstream and due to the geometry of the steps, the sediment can build up and create instability or dislodge parts of the steps (Marion and Weirich, 1999). The build-up of sediment could have been a potential contributor to the instability seen within the natural and artificial step pools.

Furthermore, a more recent study into the behavior and architecture of step pools has provided evidence that contradicts the findings of Abrahams et al. (1995). The study proposes that the relationship between flow dynamics and stability in the stream is better encapsulated by a new term called the “aspect ratio”, which is calculated as the active stream width divided by the step drop height (Chartrand, 2011). The aspect ratio was tested with data from three mountain streams and was observed to be inversely related to the mean slope. (Chartrand, 2011). The results communicate that the maximum flow resistance ratio determined by Abrahams et al. does not necessarily capture the full behavior of step pools, which is why the findings in this study do not match with the conclusions of Abrahams et al.

The insight that this research has provided into the differences between artificial and natural step pools is valuable, however it is important to realize that there are some limitations to this study and more research needs to be done in comparing the effectiveness of artificial and natural step pools at protecting streams against erosion and scouring. One of the limitations of this study were the number of step pools analyzed for both their dimensions and observable changes to their structure. Only 19 natural and 15 artificial streams were captured in this study, and out of those only 14 total had observational data following flooding events.

While step pools have been studied for a long time, their use in stream restoration projects is still fairly new. There is a good amount of literature on understanding the role of step pools in ecosystems, but there is not a lot of on-going monitoring of step sequences succeeding restoration. Two exceptions are authors Lenzi who has studied step pools for over 20 years and continually assess the same steps located in the Italian Alps (Lenzi, 1997, 2000, 2001, 2002, 2003). Chin et al. has looked at step pools and analyzed restoration projects in California over a long period of time, which has allowed for detailed accounting and analysis of changes to the artificial step pools. Few other restoration projects involving step pool structures have had detailed long-term monitoring and assessment after original implementation.

There are many more questions to be answered that would be useful in understanding the differences and similarities in performance between artificial and natural step pools. I think one of the most intriguing questions that came out of the research is what level of flooding should the steps be designed to withstand? Additionally, should artificial step pool structures be given room to readjust naturally instead of designing them based on theoretical maximum flow resistance ratios? Research has shown that step pools in nature do not immediately start out having maximum flow resistance (Chin and Phillips, 2007). Periodic flooding events over time help to restructure the step pools to make them better able to dissipate the energy associated with the flowing water (Chin and Phillips, 2007). So, by possibly designing the steps in a way that allows them to stabilize naturally, less overall maintenance would need to be done.

For future installations of step pools to be successful, additional variables need to be taken into account. While many projects have designed step pool sequences with the reoccurrence rate of flooding for the area in mind, many have not. In order to ensure effectiveness of the steps over time, it is recommended that they should be designed to withstand flooding with reoccurrence rates of 30 years or more. Detailed assessment of the banks and land upstream from the proposed location of the steps should also be completed prior to installation. By doing so, it will help to understand whether there is a threat of severe sediment load transport and deposit in the steps.

In addition, when designing artificial step pools, it is recommended to use both the Abrahams et al. (1995) ratio and the “aspect ratio” put forth by Chartrand et al. (2011). The reasoning for using both is because more research needs to be done to see whether one is better than the other. This will ensure that the steps are stable from the beginning and can withstand high-energy flooding.

The step pools in Little Westham Creek at the University of Richmond are very new and not enough time has passed to be able to tell how well the steps will be able to provide stability to the tributaries and stream in which they are located. However, these findings show that even though the ratio calculated from the geometry of the steps fall within the ideal range for maximum flow resistance, there are still many other factors that can contribute to instability of the steps and the stream as a whole.

To make sure that the steps in Little Westham Creek are able to provide the benefits they were implemented to provide, assessment is recommended after every severe flooding events that are determined to have a reoccurrence rate of 2 years or more. Additionally, on-going annual monitoring annually to see whether significant changes, such as reorganization of the steps, movement of the materials within the steps, and erosion of the banks should be carried out in order to guarantee the steps last long into the future and the stream does not become degraded over time like it was prior to the restoration. This will allow people visiting the area well into the future to experience the same benefits that the newly restored stream ecosystem provides now.

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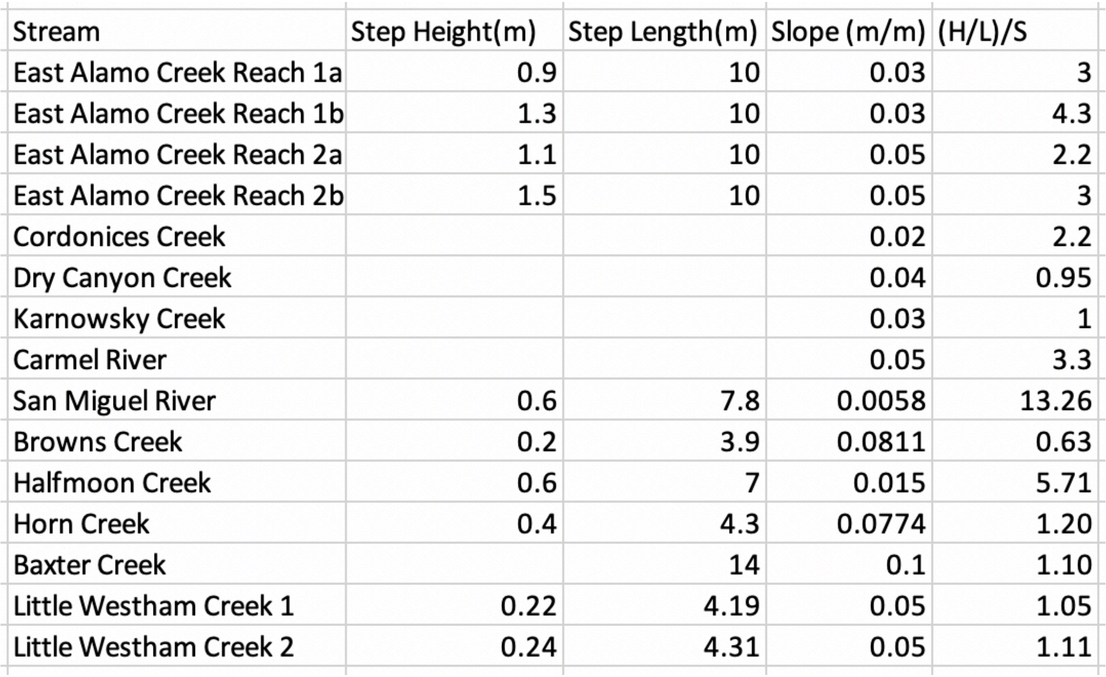
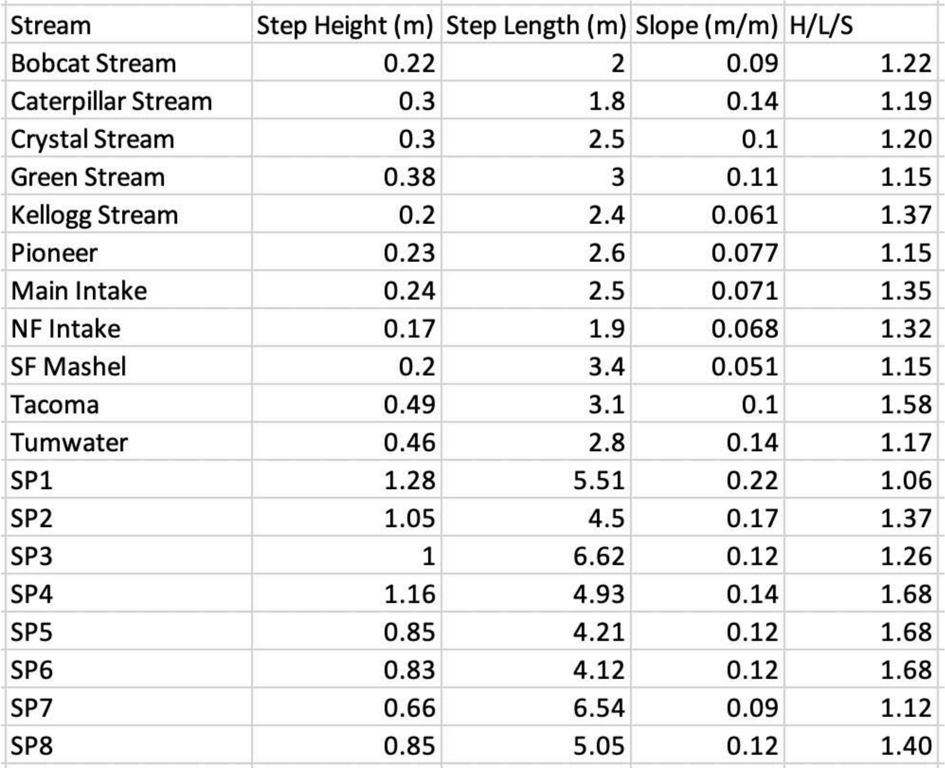
Tables and Figures



Stream	Step Height(m)	Step Length(m)	Slope (m/m)	(H/L)/S
East Alamo Creek Reach 1a	0.9	10	0.03	3
East Alamo Creek Reach 1b	1.3	10	0.03	4.3
East Alamo Creek Reach 2a	1.1	10	0.05	2.2
East Alamo Creek Reach 2b	1.5	10	0.05	3
Cordonices Creek			0.02	2.2
Dry Canyon Creek			0.04	0.95
Karnowsky Creek			0.03	1
Carmel River			0.05	3.3
San Miguel River	0.6	7.8	0.0058	13.26
Browns Creek	0.2	3.9	0.0811	0.63
Halfmoon Creek	0.6	7	0.015	5.71
Horn Creek	0.4	4.3	0.0774	1.20
Baxter Creek		14	0.1	1.10
Little Westham Creek 1	0.22	4.19	0.05	1.05
Little Westham Creek 2	0.24	4.31	0.05	1.11

Table 1: Average dimensions and flow resistance ratios for each of the artificial streams used in the study.



Stream	Step Height (m)	Step Length (m)	Slope (m/m)	H/L/S
Bobcat Stream	0.22	2	0.09	1.22
Caterpillar Stream	0.3	1.8	0.14	1.19
Crystal Stream	0.3	2.5	0.1	1.20
Green Stream	0.38	3	0.11	1.15
Kellogg Stream	0.2	2.4	0.061	1.37
Pioneer	0.23	2.6	0.077	1.15
Main Intake	0.24	2.5	0.071	1.35
NF Intake	0.17	1.9	0.068	1.32
SF Mashel	0.2	3.4	0.051	1.15
Tacoma	0.49	3.1	0.1	1.58
Tumwater	0.46	2.8	0.14	1.17
SP1	1.28	5.51	0.22	1.06
SP2	1.05	4.5	0.17	1.37
SP3	1	6.62	0.12	1.26
SP4	1.16	4.93	0.14	1.68
SP5	0.85	4.21	0.12	1.68
SP6	0.83	4.12	0.12	1.68
SP7	0.66	6.54	0.09	1.12
SP8	0.85	5.05	0.12	1.40

Table 2: Average dimensions and flow resistance ratios of each of the natural step pools used in the study.

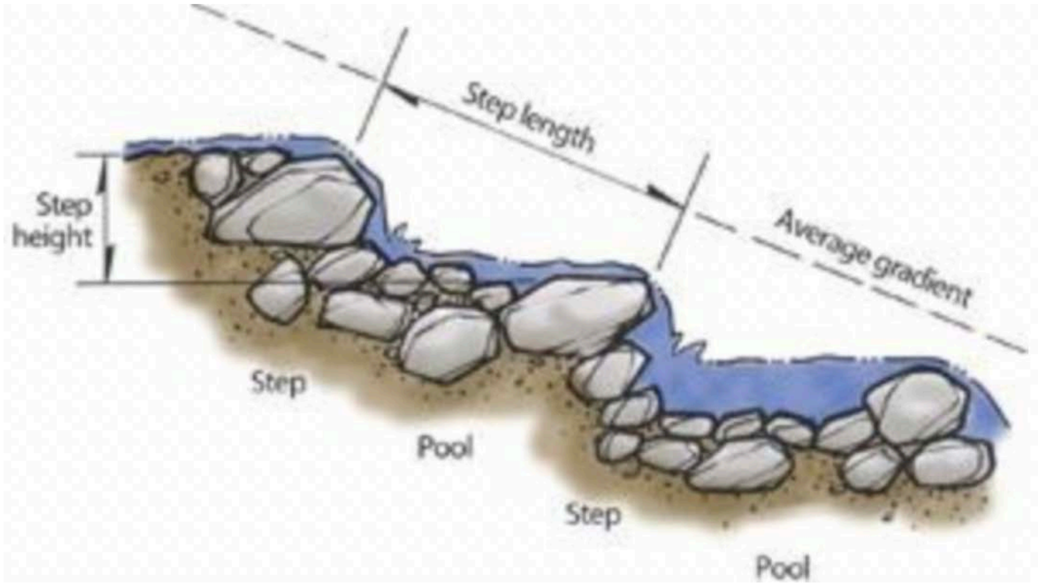


Figure 1: Step pool dimensions as measured in the studies used as well as in the field (Moses, 2010).

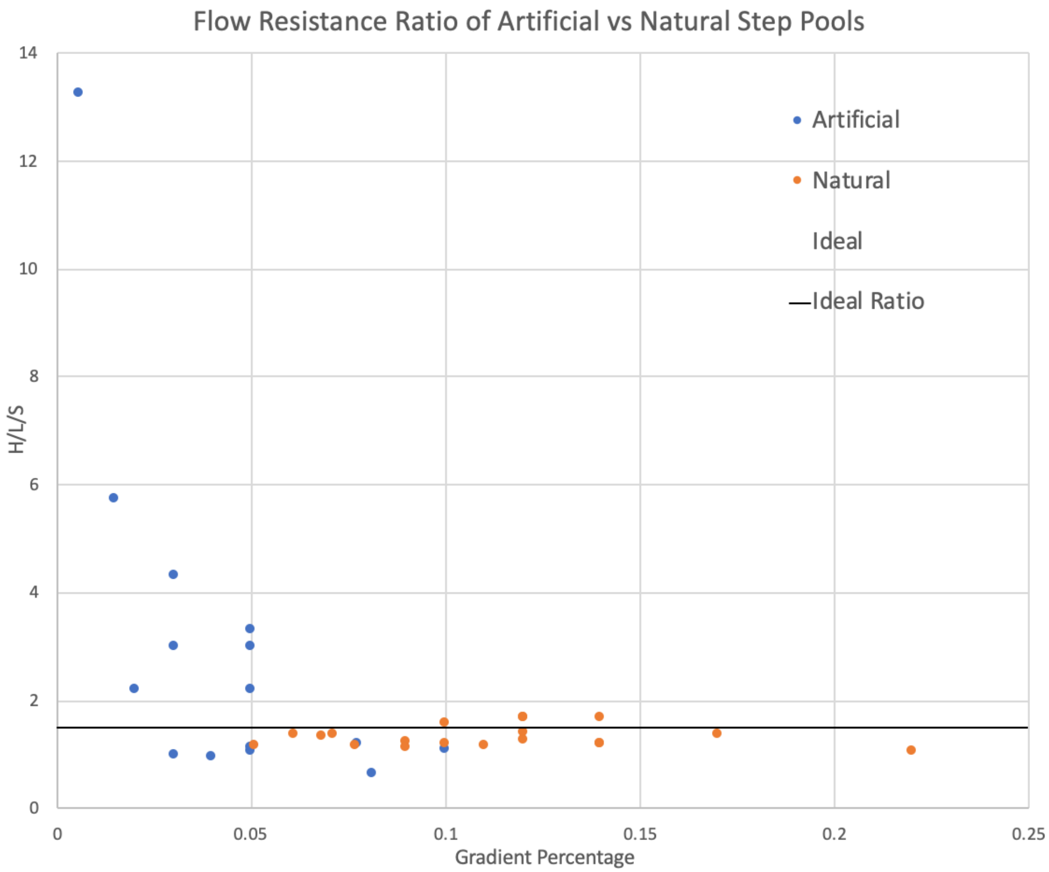


Figure 2: This graph compares the H/L/S flow resistance ratios between the artificial and natural step pools. The H/L/S ratio is placed on the y-axis, and the average slope is placed on the x-axis.

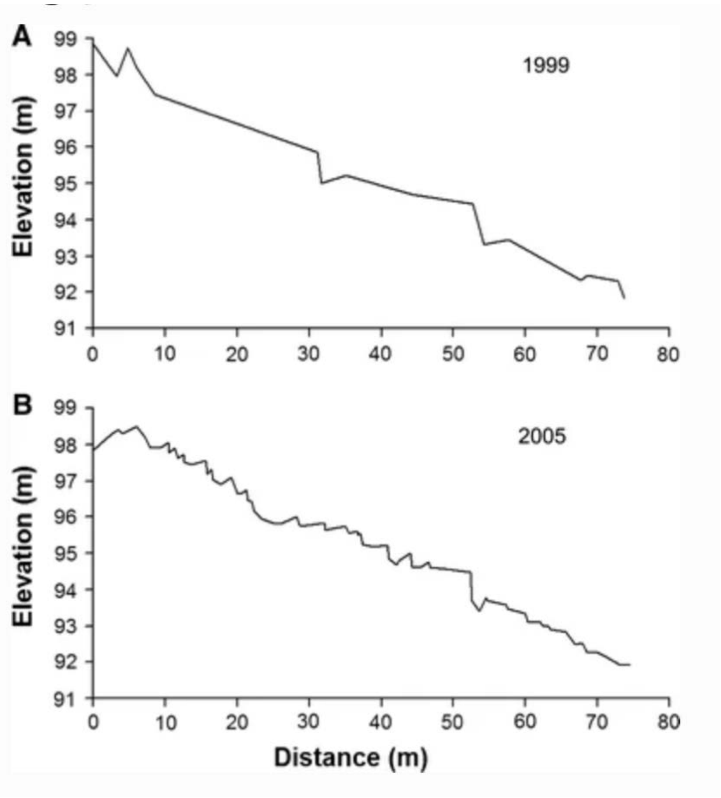


Figure 3: Longitudinal profile of Baxter Creek right after installation in 1999 and after flooding in 2005 (Chin, 2008).

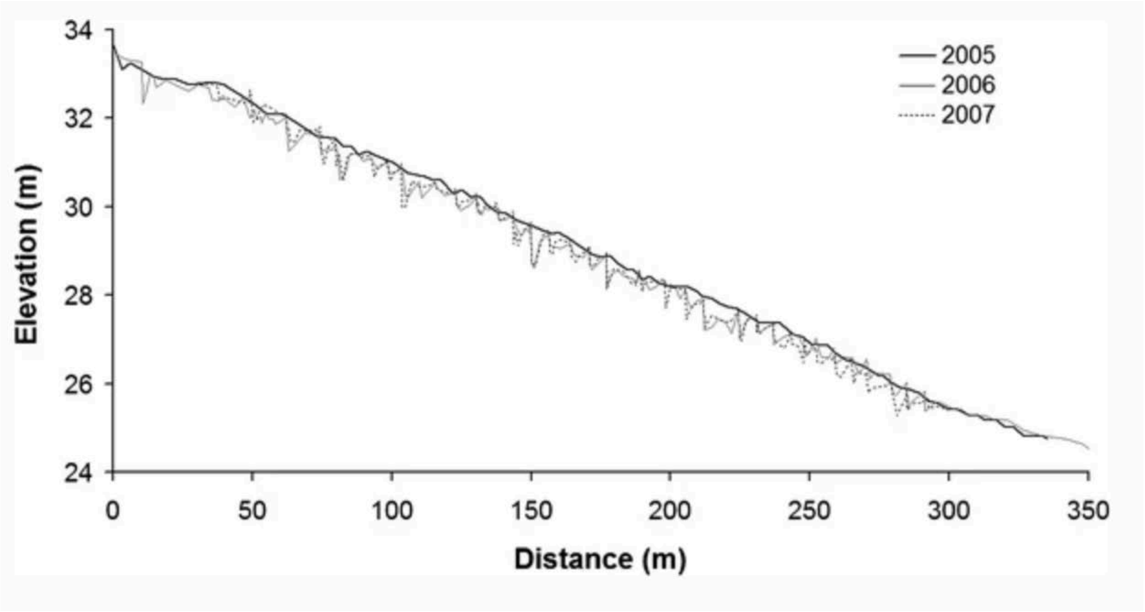


Figure 4: Longitudinal profile of Karnowsky Creek right after installation in 2005 and after flooding events in 2006 and 2007 (Chin, 2008).