Thesis Portfolio

2025 UVA ASCE Steel Bridge Competition
(Technical Report)

Navigating Barriers: Evaluating the Effectiveness of Rock Arch Rapids for Anadromous Fish Passage in comparison to Dam Removal
(STS Research Paper)

An Undergraduate Thesis

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Fulfillment of the Requirements for the Degree
Bachelor of Science, School of Engineering

Bear Matheson
Spring, 2025

Department of Civil Engineering

Table of Contents

Sociotechnical Synthesis

Restoring Rivers and Rebuilding Systems

The following thesis portfolio contains my technical paper on the revitalization of the UVA ASCE Student Steel Bridge team and my sociotechnical paper on the success of nature-like fishway design in restoring diadromous fish populations in American Rivers. Throughout my research of fishway designs it has become more and more apparent on the need to address environmental repercussions of aging infrastructure throughout the United States.

Our capstone team designed and fabricated a steel bridge to compete in the 2025 ASCE Student Steel Bridge Competition. The bridge was designed to fit competition requirements and to model improvements for the Skunk River Trail. The team optimized structural performance, constructability, and aesthetics through iterative modeling and analysis in Revit and RAM Elements. After completing the model, steel was ordered, and the bridge was fabricated by the team. The fabrication process included welding, cutting, bolt-hole drilling, grinding, and painting. The bridge was tested under an oscillating 2500lb load in the UVA structures laboratory. Alongside technical objectives, the team prioritized reviving the UVA Steel Bridge Team by recruiting undergraduates, structuring leadership roles, and holding workshops. The report includes detailed drawings, design evolution, and compliance documentation with AISC and ASCE competition standards. Our team was successful in constructing the bridge and competing in the ASCE Regional Symposium at the end of March 2025. Although the bridge was disqualified due to slightly overtime construction, the bridge performed well under load tests, and the competition provided valuable insights for future years. Future teams will look to build a lighter bridge with fewer connections and smaller members. Our team satisfied its goals of constructing the bridge, attending competition, and building a solid foundation of the UVA Steel Bridge Club for the future.

Dam infrastructure is the number one disruptor of diadromous fish migration, as a result, innovative solutions like the *Rock Arch Rapids*, a nature-like fishway on the Cape Fear River in North Carolina, have been designed to assist migratory fish in traversing these barriers, while still preserving existing dam function. This research evaluates whether such fishways can be as effective in restoring fish populations as complete dam removal, by analyzing fish migration data, ecological studies, and comparing the *Rock Arch Rapids* to similar nature-like fishways in the Red River Basin, Mn, to the dam removal project of the Quaker Neck Dam on the Neuse River, NC. Initial telemetry studies from 2013-2015 revealed upstream passage efficiencies below the targeted 80% for American shad (53-65%), striped bass (19-25%). Following design modifications completed in 2021, passage efficiencies improved for the American shad (71 ± 14%) and striped bass (32 ± 8%), falling short of the Neus River's post-removal spawning success (~90% for American shad). Although the Red River Basim fishways demonstrate ecosystem reconnection, their data is not quantitative enough to outweigh the Cape Fear studies. Despite advancements in design, the *Rock Arch Rapids* does not achieve the ecological restoration potential of dam removal, proving only to be a temporary solution to when full removal is constrained by economic, political, or logistical factors.

2025 UVA ASCE Steel Bridge Competition

A Technical Report submitted to the Department of Civil Engineering

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science, School of Engineering

Bear Matheson
Spring, 2025

Capstone Project Team Members
Zoe DeGuzman
Cooper Davenport
Wren Sadler
Benjamin Van Zandt

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Advisor

Jose Pantaleon Gomez III, Department of Civil and Environmental Engineering

Design Report

Davenport, DeGuzman, Matheson, Sadler, Van Zandt, Venner

Introduction

Design Problem Statement

Our 4th year Civil Engineering Capstone group is tasked with reviving the dormant UVA ASCE Steel Bridge Competition team. The ASCE Steel Bridge Competition provides a fictional problem statement for which the bridge model is meant to be a solution. For 2025, the ASCE has provided details about bridging the Skunk River Water Trail.

The Skunk River Water Trail was initially formed by a glacial melt, which provides a river corridor that runs through Story County, Iowa. It has historical uses since the late 1800's of powering saw and grist mills and is now managed by the Story County Conservation. The river runs through Peterson Park, which has unique and longstanding natural habitats and aquatic wildlife in the river and on a river island sandbar. The park wants to better connect trails while appealing to Story County Conservation environmental standards. Thus, our technical problem is: “How do we improve the trail connections in Peterson Park while navigating the South Skunk River and leaving its wildlife undisturbed?”

Design Objectives

The main constraint of the problem is that the solution must be a steel bridge. Our team has designed and will construct a steel bridge that adheres to the following constraints: The maximum height of the bridge is 3’-0” above the ground. The height of the stringer must be 1’-7” to 1’-11” excluding the height of the footing. The width of the bridge must be between 3’-6” and 5’-0”. The minimum vertical clearance must be 0’-7” above the ground. The span length of the North side stringer must be between 15’-6” and 16’-6”. The span length of the South side stringer must be between 20’-0” and 21’-0”. Each individual member cannot exceed the dimensions of 3’-6” x 0’-6” x 0’-4”. The maximum horizontal separation between stringer members is ¼". The maximum elevation difference along a stringer is 1/8”.

Within these constraints, the team has iteratively worked through our design to optimize structural efficiency, constructability, cost, and aesthetics of the bridge. Through analysis using structural design software (Revit, RAM), the team has minimized the deflection of the bridge by increasing its load capacity while limiting the weight, cost, and speed of construction of the bridge. By testing different member types and configurations, the best member options were selected. Aesthetics were considered by selecting the best member shapes, configurations, and paint designs to make the bridge visibly pleasing without impacting efficiency.

The team has purchased the material to be used for the final construction of the bridge and is awaiting delivery. The team will ensure an efficient connection method through practice in Lacy Hall. The team has been practicing the welding and other fabrication equipment before fabrication of the final construction material takes place. In preparation for the competition, the team will plan and execute multiple runs of construction to improve the method and efficiency of construction at the competition.

Holistic Goals

The primary goal of our capstone was to fabricate the bridge to be built based on our model and within the constraints of the competition to carry the required load. With this, we hope to have a tangible display that can represent the work of Civil Engineers at UVA. Completion of this goal is determined if the group can construct and present the bridge at the capstone presentation at the end of the Spring 2025 semester.

The secondary goal was to compete at the ASCE Steel Bridge Competition. This was a lofty goal based on the time constraints of the project, which is why this was our secondary goal. This goal will be achieved if the team attends and competes at the March ASCE Symposium.

The final goal of this capstone is to leave the legacy of a Steel Bridge club at UVA. We worked to recruit new members and establish a club structure to last beyond our time at UVA. Completion of this goal is determined by the active membership at the end of the Spring 2025 semester. Moreover, this goal will be measured based on the involvement of underclassmen in leadership roles at the end of the Spring 2025 Semester.

Design Constraints

Our final design prioritized the strength of the bridge we would be disqualified if the horizontal sway exceeds ¾", and vertical deflection is a significant factor in our team's standing in the competition. Since the total weight of the bridge is also a competition category, we aimed to use the smallest members that kept both the horizontal and vertical displacement under ½" according to the analysis model. We decided to change the truss members to L1-1/2X1-1/2X1/8 and placed three beams for everything chord section instead of two. Since the horizontal sway was significant in the earlier design iterations, we added four sets of cross bracing between the middle chord connections and increased the member size to 2”X1/8” flat bars. We also removed all vertical members since they barely contributed to the stiffness of the bridge.

In the analysis model we assumed simple support conditions, fixed connections between all perpendicular members, and hinged connections between the truss members. There were two possible load cases for the lateral load test as established by the competition rules: 7’0” or 8’6” from one end of the span. Both cases were analyzed and produced similar results. Since the vertical loads are placed on two 3’0” long decking units, it was modeled as four separate 3’0” distributed loads along the north & south top stringers. The total force was 1400 pounds on decking unit #1 and 1100 pounds on decking unit #2, totaling 2500 pounds as the rules dictate. With every iteration of design, we first modeled it in Revit then ran the analysis software to make sure it was stable. After finalizing the structure, we drafted detailed drawings in Revit of the bolted connections. Finally, we created a spreadsheet outlining the amount of each member we need, which was given to Liphart Steel to provide us with a cost estimate.

Conclusion and Discussion

In progressing towards the team’s primary goal of fabricating a bridge within the constraints of the ASCE Steel Bridge Competition, the team has completed the design phase of our project and is in the early stages of the fabrication phase. The material for the bridge has been ordered, and we are planning to begin fabricating within the next two weeks. We plan to construct our bridge according to the modeled design. This design has been iteratively analyzed to ensure its strength and stiffness capabilities.

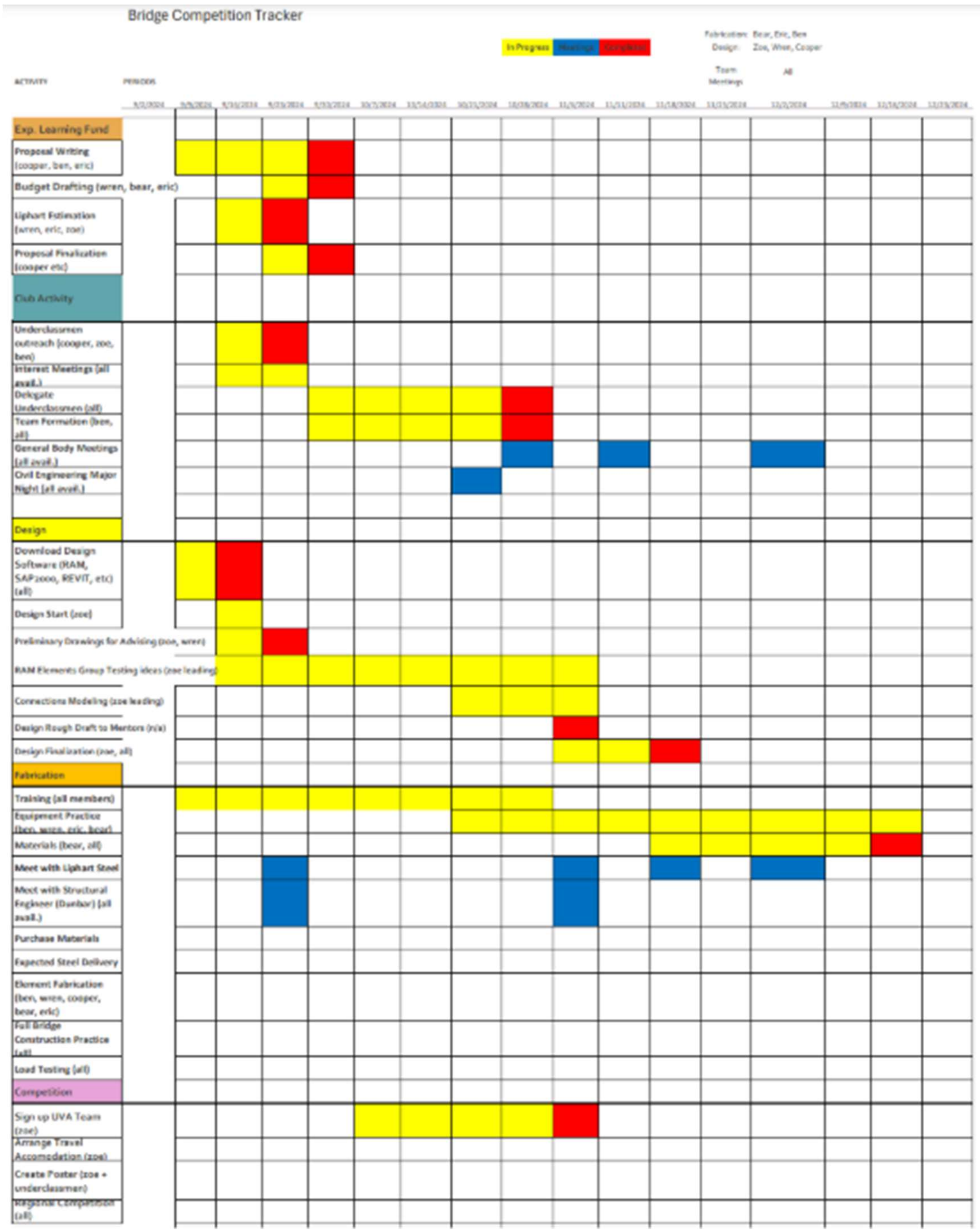
Due to delays with the acquisition of steel, the beginning of the semester focused on working towards achievement of the final goal of leaving a legacy of a sound Steel Bridge Team organization. We have continued to encourage recruitment of new members along with establishing leadership positions for future generations of the team. In combination with fostering a structured group dynamic, the team has been working towards establishing the team as an official CIO according to UVA guidelines. The team has done this by holding modeling and mechanics workshops, encouraging members to obtain safety certification to aid in the fabrication process, and hosting elections to establish future leaders of the organization. The team has been organized into modeling, fabrication, and presentation sub teams. A draft of the club constitution has been created and ratified. Attendance at club meetings and workshops has been growing, so the team is optimistic that a sound foundation for the Steel Bridge Team will lead to the future development of a thriving organization.

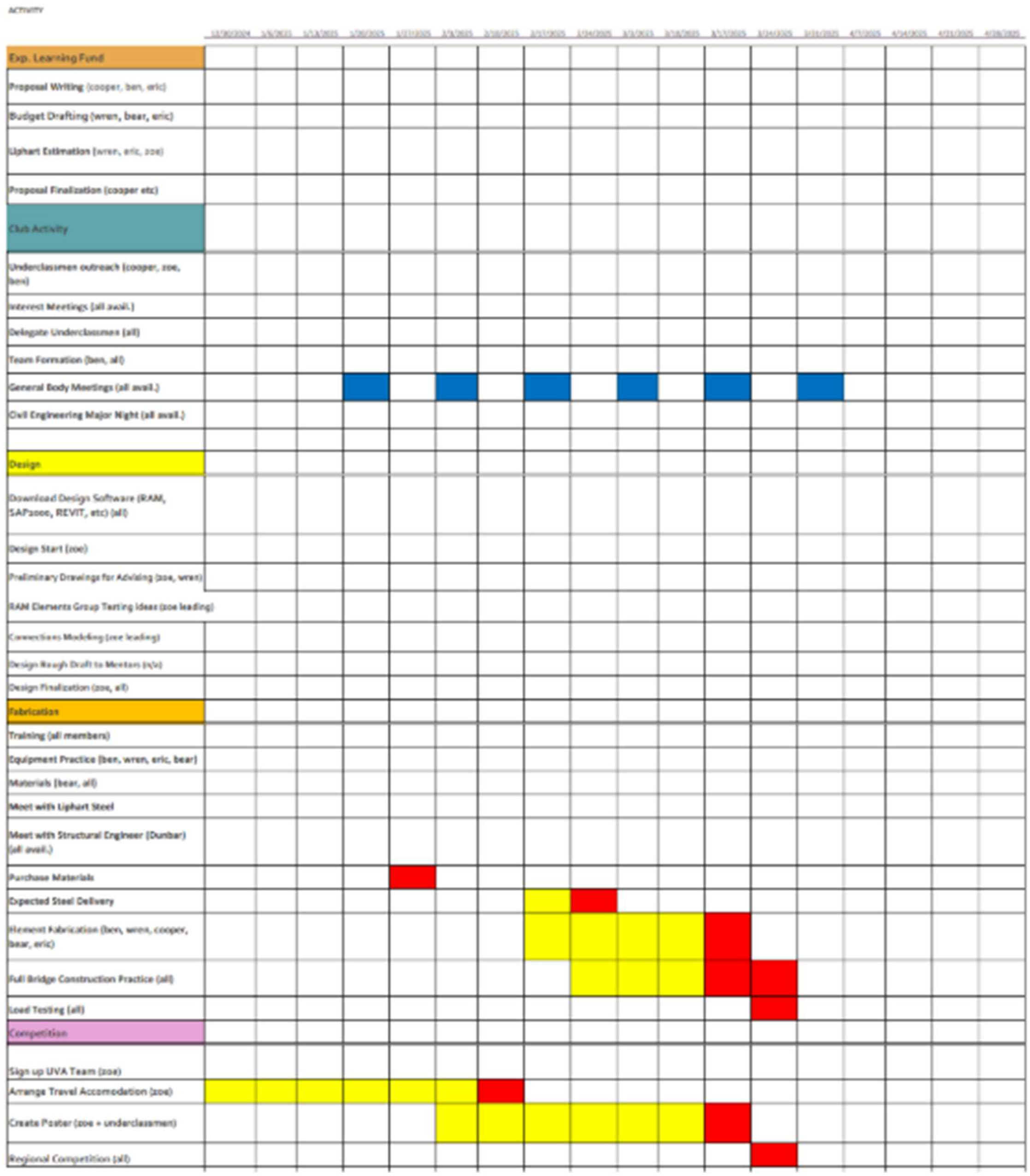
When the steel finally arrived at the end of February, the team completed fabrication and construction practice in the short window of time left before the ASCE/AISC Steel Bridge competition March 28/29th. First, the team completed all safety training and has become acquainted with the equipment to be used for the fabrication of the bridge. After the steel was delivered, the next steps were to measure and count the members to ensure there weren't any errors from the supplier. Next, the team de-rusted the members and removed burrs, established the name and location of the stringer members, and marked all plates, WTs, & angles for bolt holes that were later drilled. The following step was to construct a test section of the bridge without plates or channels welded on, then welded all plates to the WTs and pedestals. Then the team constructed the entire bridge and measured it to make sure it matched the structural drawings. Finally, the channels were welded to the top of the stringers and all members were painted. Before the competition, the bridge was load-tested in the civil engineering lab and deflected approximately 1 inch under a weight of 2500 pounds.

On March 28th and 29th the team traveled and competed in the competition hosted by West Virgina State University in Beckley West Virginia. There, we competed against 7 other Virginia/West Virginia steel bridge teams. This was a significant milestone as it was the first time in 7 years that UVA had competed in the competition. Unfortunately, we were not able to construct the bridge in the required 45-minute period and as a result were disqualified. Although we did not get scored the judges, our results from the horizontal and vertical load tests were competitive with the other teams, giving us confidence in our overall bridge strength. The disqualification was in no way seen as a failure, in fact, competing in the competition alone was our most ambitious goal and getting there was the team's largest success. Now, the 2025 Steel Bridge Team's work is displayed on Engineer's Way representing the hard work of the team and the UVA Civil Engineering department, just as we had hoped.

Appendices

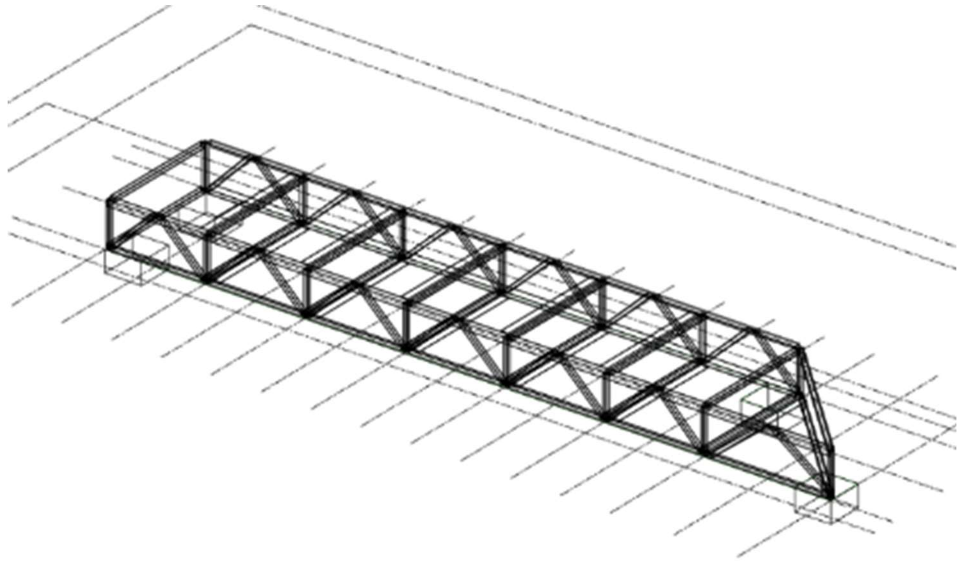
Appendix A – Detailed Schedule


Bridge Competition Tracker
In Progress
Fabrication: Bear, Eric, Ben
Design: Zoe, Wren, Cooper
Team Meetings: All
ACTIVITY
PERIODS
Exp. Learning Fund
Proposal Writing (cooper, ben, eric)
Budget Drafting (wren, bear, eric)
Liphart Estimation (wren, eric, zoe)
Proposal Finalization (cooper etc)
Club Activity
Underclassmen outreach (cooper, zoe, ben)
Interest Meetings (all avail.)
Delegate Underclassmen (all)
Team Formation (ben, all)
General Body Meetings (all avail.)
Civil Engineering Major Night (all avail.)
Design
Download Design Software (RAM, SAP2000, REVIT, etc) (all)
Design Start (zoe)
Preliminary Drawings for Advising (zoe, wren)
RAM Elements Group Testing ideas (zoe leading)
Connections Modeling (zoe leading)
Design Rough Draft to Mentors (n/a)
Design Finalization (zoe, all)
Fabrication
Training (all members)
Equipment Practice (ben, wren, eric, bear)
Materials (bear, all)
Meet with Liphart Steel
Meet with Structural Engineer (Dunbar) (all avail.)
Purchase Materials
Expected Steel Delivery
Element Fabrication (ben, wren, cooper, bear, eric)
Full Bridge Construction Practice (all)
Load Testing (all)
Competition
Sign up UVA Team (zoe)
Arrange Travel Accomodation (zoe)
Create Poster (zoe + underclassmen)
Regional Competition (all)

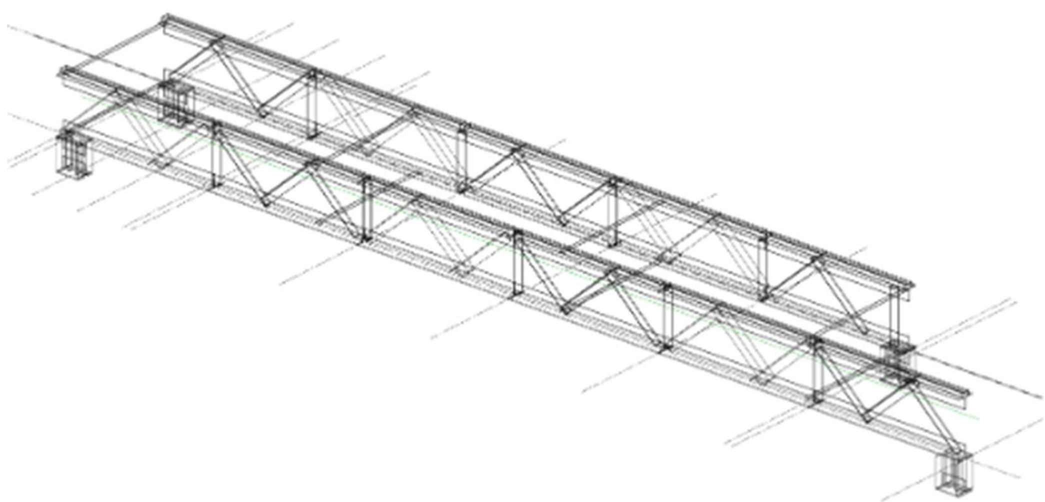


Appendix B – Design Evolution

All iterations of our design followed the dimensional constraints given in the rules and contained top & bottom chords, lateral braces, and truss members along the north and south side. Our first bridge design, pictured below, spanned 16’6” on the north side and 20’0” on the south side. The chords were a combination of 2’9” long L2X2X1/4 members and the truss members were HSS1-1/4X1-1/4X1/8. There were two lateral and two vertical HSS1-1/4X1-1/4X1/8 sections between each angle connection along the span. We decided to abandon this design because it had too much steel, which made it unnecessarily heavy and would take too long to construct.



Our second set of structural plans used a 3’4” long WT3X6 members for chords. We also added a 2” wide channel along the top chord so it can follow the stringer template provided at the competition. The truss members were changed to L2X2X1/8, and the lateral braces were changed to 1”X1/8” flat bars. Instead of adding lateral members at every WT connection, we placed two horizontal members at four locations equally spaced along the span. We ultimately had to update this design because the analysis model failed the steel design code checks and deflected more than the competition rules allowed.



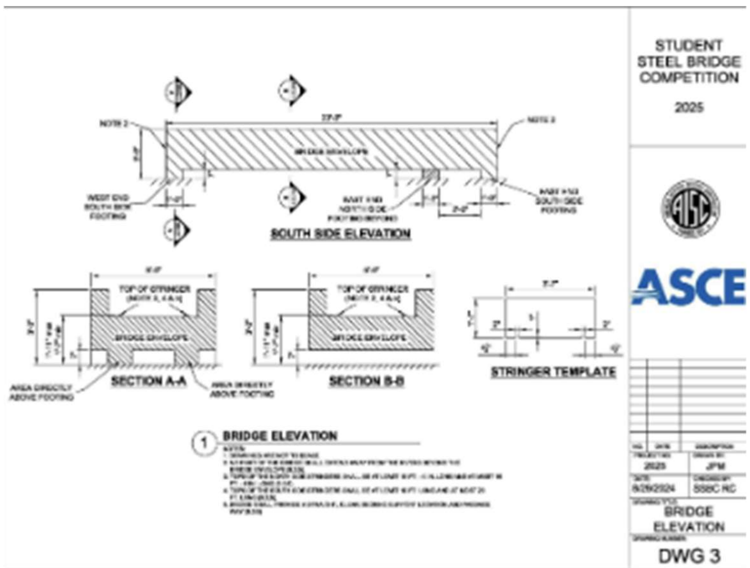
Details for our final bridge design are provided in the main report. We ultimately chose members that provided adequate strength without being too heavy or too difficult to construct.

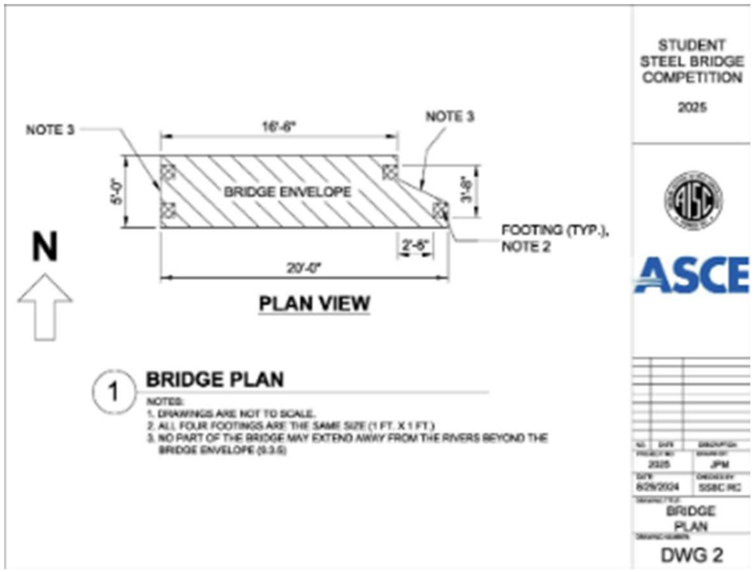
Appendix C – Engineering Standards

The ASCE & AISC Student Steel Bridge Competition (SSBC) requires specific bridge dimensions and constraints outlined in their 2025 Official Student Steel Bridge Competition Rules. Section 9 of this specification states that bridge must comply with the following dimensions, additionally outlined by images taken from the SSBC Rules.

Dimensions (Section 9 of SSBC Rules) -

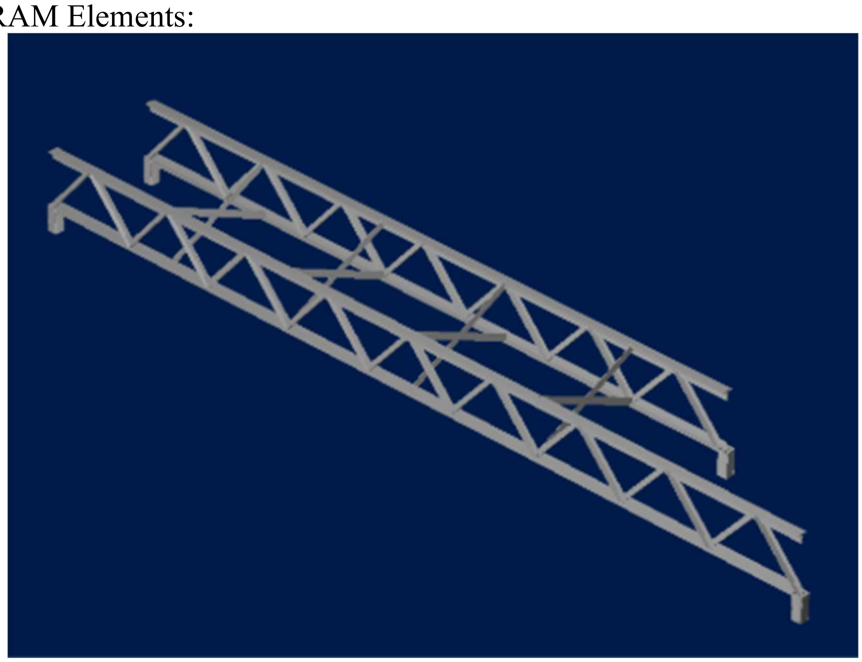
- Maximum height – 3'0" above ground/river
- Height of stringer – 1'7" to 1'11" (measured at T/STL)
- Width – 3'6" to 5'0"
- Minimum vertical clearance – 0'7" (i.e. minimum footing height)
- Span length of north side stringer – 15'6" to 16'6"
- Span length of south side stringer – 19'0" to 20'0"
- Stringer members must be straight across and fully connected
- Maximum horizontal separation between stringer members – 0' ¼"
- Maximum elevation difference along stringer – 0' 1/8"
- Each member fits into 3'6" X 0'6" X 0'4" box
- No cables



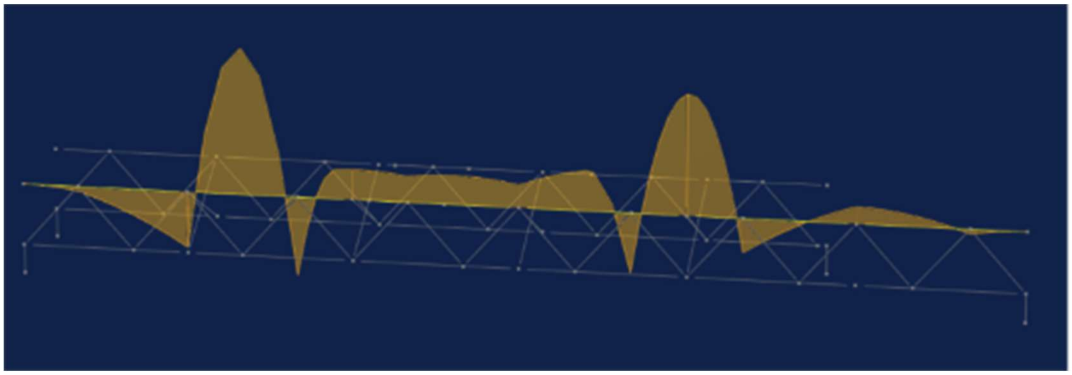


Additionally, the rules state that the bridge must be built entirely built from steel, and it must be stable, or else the bridge is disqualified from competition. Our bridge is demonstrated to comply with these guidelines, as illustrated by our final design drawings shown in the report and in Appendix B & D.

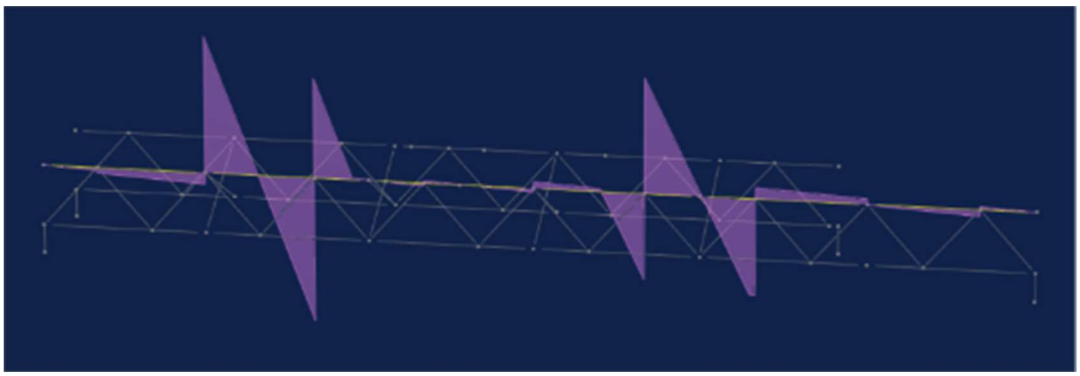
The bridge was designed using typical AISC-specified A992 and A36 steel, using load combinations and LRFD methodology outlined in Specification B of AISC 360-16 Specification for Structural Steel Buildings. This compliance is reflected in our structural analysis diagrams created from RAM Elements:



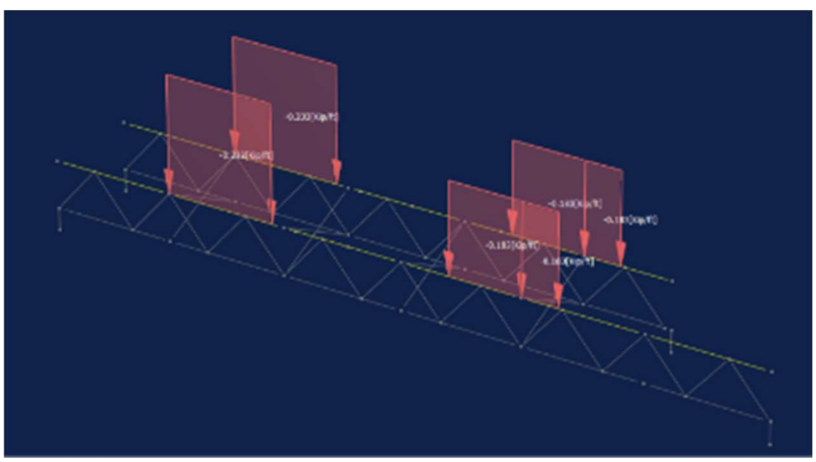
Rendered Model



Moment Diagram



Shear Diagram



Load Diagram

Appendix D – Technical Deliverables
Attached with this report is a copy of structural drawings drafted in Revit, the displacement results from the analysis software, and the steel code checks for each member.
Link to supporting files:
https://myuva-my.sharepoint.com/:f:/g/personal/ywn7rq_virginia_edu/EjTuGe5e6TlPg09sQ9hh6mkBAjL_tcJXE6UYFIRdnX-7Og?e=S4C514

Navigating Barriers: Evaluating the Effectiveness of Rock Arch Rapids for Anadromous Fish Passage in comparison to Dam Removal

A Research Paper submitted to the Department of Engineering and Society

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements of the Degree
Bachelor of Science, School of Engineering

Bear Matheson

Spring, 2025

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Thesis Advisor

Venkataraman Lakshmi, Department of Civil and Environmental Engineering

STS Advisor

Richard Jacques, Department of Engineering and Society

"If the barrier still exists. The problem still exists." Laura Wildman, Vice President of Ecological Action at Save the Sound (Kessler, 2014)

The construction of dams and barriers to control and supply water has significantly changed the river ecosystems worldwide, disrupting migration patterns for anadromous fish and damaging the overall ecological nature. Dams are the largest disruptor to these migratory patterns, inhibiting fish's abilities to reach their native spawning grounds and increasing predation. In an attempt to allow fish to pass these barriers, fish passage systems were introduced. While fish ladders have been somewhat successful for strong swimming fish, like salmon, their effectiveness across all species remains inconsistent. Even with decades of development in fish ladder design, some argue that the only way to return fish to their native spawning grounds is to completely remove the barrier (Kessler, 2014). However, full dam removals are not always possible due to economic, political, and logistical constraints. Over the last 30 years, engineers and environmental scientists have teamed up to change their approach from conventional fish ladder design and create a fish ladder that mimics nature and allows more than one fish species to pass at a time; these are referred to as nature-like fishways (Katopodis et al.,2001). One such example is the *Rock Arch Rapids* on the Cape Fear River in North Carolina, USA. *The Rock Arch Rapids* uses a rock ramp design to mimic natural river conditions, while keeping the original dam structure (NOAA, 2022). While the *Rock Arch Rapids* offer an innovative design, the long-term ecological effectiveness of the fishway is still uncertain. This paper examines the Cape Fear River *Rock Arch Rapids* to assess whether nature-like fishways can be as effective as full dam removal in restoring fish populations or if it is merely a temporary solution that prolongs the impacts of dam infrastructure. By analyzing ecological studies, fish migration data, and comparing similar fishways, this research will evaluate whether nature-like fishways can function as a viable alternative to dam removal.

Literature Review

River restoration through fish passageways and dam removal has been a highly debated topic over the last 30 years. Before diving into this debate in further detail, the differences, and implications of these two restoration strategies must be explained. Simply understood, in a dam removal, the dam that is currently in place is completely removed. This causes an immediate change in hydraulic head, returning the river to its natural flow and gradient. It may seem like an easy fix, but without careful consideration of the river's sediment distribution and downstream conditions, these operations can have damaging effects on the river and surrounding communities. Issues like reservoir sedimentation, channel incision, riverbank erosion, habitat degradation, and loss of vegetation can recover over an extended period but often need restorative measures to overcome. (Aadland, L., 2010). On the other hand, nature-like fishways can be implemented while keeping the underlying structure of the dam in place. This reduces the need for aggressive upstream and downstream restoration, hence the practicality of fishways. These structures bridge the upstream and downstream ecosystem and offset the losses from inundation. The challenges here lie in the specific dam conditions. If the slope of the fishway is too steep, it is difficult for fish and other species to traverse and make the habitat of the structure (Aadland, L. 2010).

The Cape Fear River in North Carolina is home to many anadromous fish species like the American shad, striped bass, and Atlantic sturgeon. Their migrations are blocked by 3 separate locks and dams that no longer serve their original commercial purposes. As part of the Sustainable Rivers Program backed by the US Army Corps of Engineers. A nature-like fish passage was installed at lock and dam #1 (LD-1) in 2012 (USACE, 2020). This fish passage, called the *Rock Arch Rapids*, is the largest nature-like fishway of its kind, crossing a dam with a 10ft crest and 275ft perpendicular length (USACE, 2020). When originally constructed, the goal was to have a fish passage efficiency of 80% for the following three fish: American Shad, Striped Bass, and Flathead Catfish. In a study published in 2019 in the *Transactions of the American Fisheries Society* researchers analyzed the effectiveness of the *Rock Arch Rapids* 3 years before modifications were completed (2013-15). The study focused on the span of the river between LD-1 (*Rock Arch Rapids*) to LD-3 as seen in *Figure 1*. There, they installed telemetry receivers below, in the lock chamber (LD-2, LD-3), and above each dam structure to detect the 3 different tagged fish (the American shad, striped bass, and flathead catfish). As well as note environmental factors in the river such as flow rate and temperature (Raabe, J, et al., 2019). The results from the 3-year study showed that there is more work to be done. The American Shad efficiency was above 50% throughout all four years, with the adjusted maximum efficiency ranging from 53-65%. The striped bass struggled to cross at a rate above 50%, with an adjusted max. of 19-25%. Lastly, the flathead catfish was much more erratic with a rate between 13-83%. Although the upstream passage efficiency was disappointing, the downstream passage results were promising. The American shad and striped bass passage efficiency was recorded as 100% and 93-100% respectively over the 3 years (Raabe, J. et al., 2019). With numbers like this, it is difficult to argue whether nature-like fishways have the potential to match the effectiveness of dam removal in fish passage. Believers in the rock arch rapid design and the Cape Fear River Watch would not back down at the result of this study. However, it was clear that alterations to the fishway had to be made to increase the upstream passage efficiency.

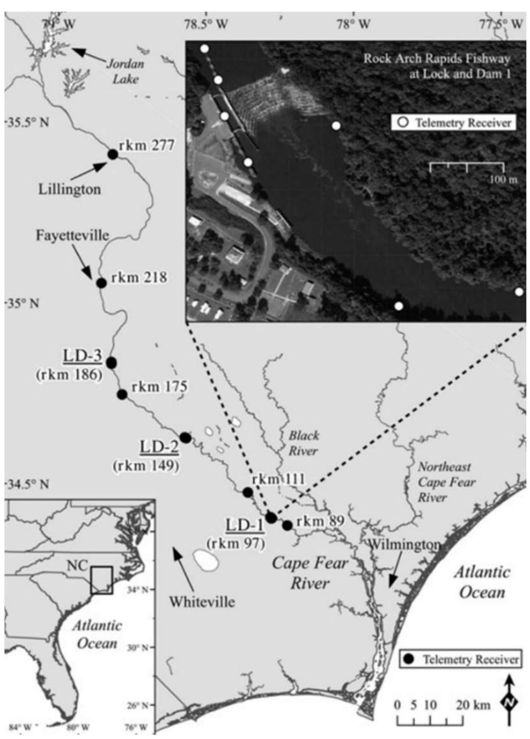


Figure 1: *Map of Lock and Dams on Cape Fear River*

Starting in 2018, plans to adjust the design of the R*ock Arch Rapids* began. Shown in *figure 2*, the new design would aid larger fish like the striped bass and sturgeon by further staggering the pools, increasing pool size, and reducing the overall gradient (Sargent, D., 2022). Throughout this report, the modifications to the Cape Fear fishway and other similar designs will be further discussed and put up against similar dam removal projects to decide if they can stand on their own as a workable solution to the loss of fish habitat.

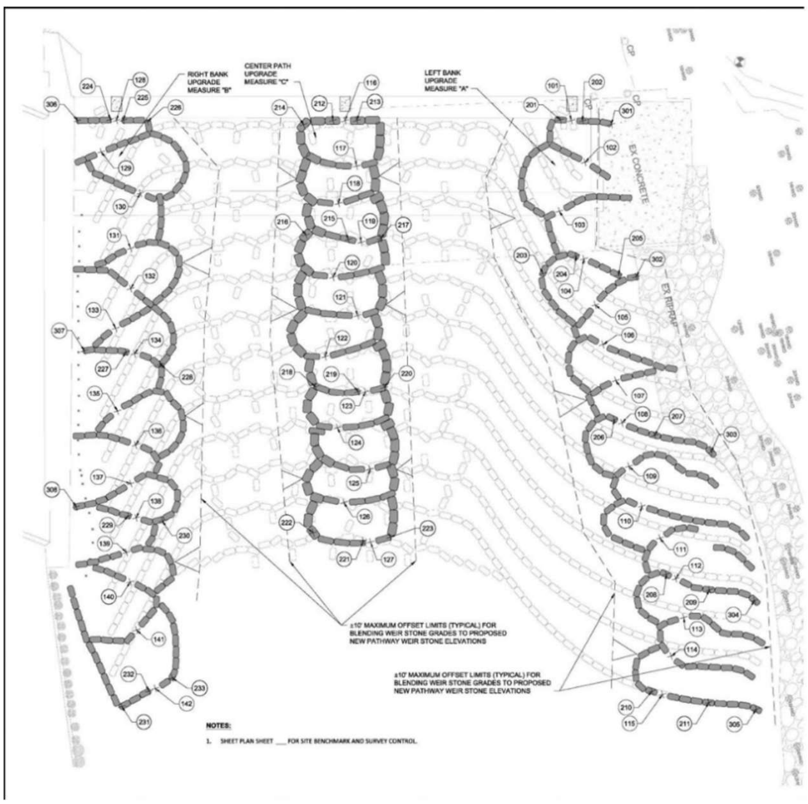


Figure 2: Proposed design for the remodeling of the Rock Arch Rapids

Methodology

To determine whether nature-like fishways like the *Rock Arch Rapids* on the Cape Fear River, can have the same productivity and long-term ecological value as full dam removal and restoration, two research goals need to be addressed. First, quantitative fish migration data over rock arch fishways should be collected on the Cape Fear River and other similar rivers like those in the Red River Basin, MN.

Second, the long-term ecological impact of the fishway on the fish population and river environment should be analyzed to show improvement from typical low-head dams. Comparing these goals to those of a dam removal project of similar scale will decide whether Rock Arch Rapids can be a workable solution for fish passage and river restoration.

Quantitative fish passage data will be primarily focused on the *Rock Arch Rapids* on the Cape Fear River. Since the passage was installed in 2012, there have been a series of improvements that have taken place and completed in 2021 (Cape Fear River Watch). Previously mentioned, the study published in the *Transactions of the American Fisheries Society*, said that the effectiveness of the fishway was not to the standard they were expecting, 80% passage rate. Modifications to the spacing and depth of the pools as well as slope of the rapids were done in hopes of meeting the passage goal of 80% (Sargent, D., 2022). Similar data will be investigated to find the new success rate of the three fish (American shad, striped bass, and flathead catfish, as well as the Atlantic sturgeon, which many of the new alterations are accommodating for (NOAA, 2022). With limited public access to data, the NOAA and Cape Fear River Watch should give insight into the effects of the recent modifications. There have been many other similar-sized rock arch rapid fishways that have been constructed in Minnesota. In fact, 48 of the 72 fish barriers within the Red River Basin have been modified or removed in massive restoration effort by the Minnesota DNR to recover native spawning grounds for lake sturgeons (Minnesota DNR, 2025). Two dam modifications worth investigating are the Riverside Dam, and the Crookston Dam, on the Red River and Red Lake River, which have been replaced by rock arch rapid fishways of comparable size to the one on the Cape Fear LD-1. However, it is important to note that the Red River and Red Lake River do not have the same anadromous fish species. Instead, these fish passages are built primarily for large potamodromous fish like lake sturgeons (Aadland, 2010).

As discussed previously, the ecological damage that dams cause to river environments reach far beyond the fish migration. In comparison to full dam removal, river restoration and long-term impacts must be understood to decide if nature-like fishways are just a temporary solution. Using angler surveys and reports from the N.C. Division of Marine Fisheries, the population trends of the fish species can be understood (NCDEQ, 2025). If migration numbers do not improve despite the fishway upgrades, it may be a sign that the *Rock Arch Rapid* is delaying a larger issue of dam-induced habitat degradation. Finally, these results can be compared to the Quaker Neck Dam removal on the Neuse River, NC. This similar low-head dam, removed in 1998, disrupted the migration patterns of similar anadromous fish like the Atlantic sturgeon, American shad, and striped bass (Hightower, J. E., & Beasley, C. A., 2006). Comparing the ecological response of fish populations on the Neuse River to the current conditions upstream on the Cape Fear River, will set the benchmark for what nature-like fishways must achieve to be on par with dam removal projects.

<u>Results</u>

After receiving the results of the first telemetry study at LD-1 and failing to meet the 80% passage efficiency, the USACE, Cape Fear River Watch, and other partners believed there was still room for improvement in the design. Using deeper, wider, and staggered pools and increasing flows through sections, the new *Rock Arch Rapids* design further mimics natural rapid features. Two studies on the passage efficiency of striped bass and American shad, and adult Atlantic sturgeon were conducted to see the success of the new design (NOAA, 2022). Using similar acoustic telemetry methods as the 2013-15 study, researchers from The Nature Conservancy gathered results on the modified structure from 2022-24. Both the American shad and striped bass crossed the fishway at a greater efficiency, however the numbers still fell short of the 80% efficiency goal. The American shad efficiency increased to from 56 ± 8% to 71 ± 14%. The striped bass also increased from 22 ± 2% to 32 ± 8%. Lastly, no tagged Atlantic sturgeons passed during the spring studies (Bunch, A., Unpublished). The improvement in numbers is a testament to the hard work put in and clearly demonstrates the rock arch rapid design to be an effective fishway. However, failure to reach the 80% goal indicates this design for key anadromous fish species does not hold up against the efficiency of complete dam removal.

In comparison to the LD1 on the Cape Fear River, the Crookston Dam on the Red Lake River in Crookston, MN has a crest height, width, and average flow of 15ft, 192ft, and 1,200 cuffs. A similar rock arch rapid design was used as seen in *Figure 3.* To understand the effectiveness of the fish passage, the Minnesota Section of Fisheries Staff conducted fish surveys before and after construction of the fishway (Aadland, 2010). The channel catfish and sauger were two of the fish that were investigated. Before the fishway there were zero recordings of sauger and only one channel catfish. Following construction, a later survey reported 222 channel catfish upstream (Huberty, 2005). Anglers even reported sauger catches 75 miles above the passage and eyewitnesses viewed large species like freshwater drum spawning and moving through the rock arch rapids (Aadland, 2010). Although fish passage data is not as comprehensive as the Cape Fear study, angler surveys and eyewitness accounts prove the rock arch rapids effectively fuse upstream and downstream environments but do not prove the structure is as efficient as dam removal itself. The project also improved downstream habitat by filling a previously eroded right bank and creating a new floodplain with the release of sediment (Aadland, 2010). The recovery of riparian vegetation in the new floodplain indicates the beginning of long-term improvements to the habitat because of the new structure.

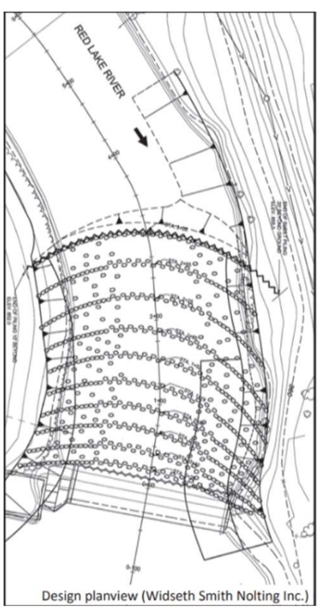


Figure 3: Crookston Dam Rock Arch Rapid Design

The Riverside Dam on the Red River, MN is also worth comparing to the LD-1 on the Cape Fear River. With a crest height of 13ft, width of 320ft, and mean flow of 3,029 cfs, it stacks up close to the size and flow rate at LD-1. Again, the USACE used the rock arch rapid design to provide new spawning habitat and reconnect the river (Aadland, 2010). Over the last decade, researchers from the University of Nebraska have been studying the movement of channel catfish, bigmouth buffalo, walleye, freshwater drum, and the lake sturgeon on the Red River (Note: this study was not specifically on the passage efficiency at the Riverside Dam). Over the three-year study, the bigmouth buffalo was recorded passing upstream and downstream at the Riverside Dam, but the channel catfish was not (Enders, E., et al., 2019). More recent data is revealing larger lake sturgeons to be moving throughout the entire Red River system (Bunch, K., 2023). Shown in *Figure:4* is a map of the Red River Basin indicating telemetry receiver sites for the study. Although the data does not specifically analyze passage through the Riverside Dam fishway, movement of fish and population growth confirms the rock arch rapid as an effective connector of upstream and downstream environments. In 2023, the Drayton Dam was the last on the Red River to be converted to a rock arch rapid in hopes of further enhancing integration of the river. The next release of the telemetry study is expected to come out in June 2025 with new data on the Drayton Dam rock arch rapids (Bunch, K., 2024). Converting the Drayton Dam structure will open the entire Red River and its tributaries. The upcoming research should continue to show an upward trend in movement throughout the entire basin, a decrease in movement may indicate inefficiencies in rock arch rapid designs.

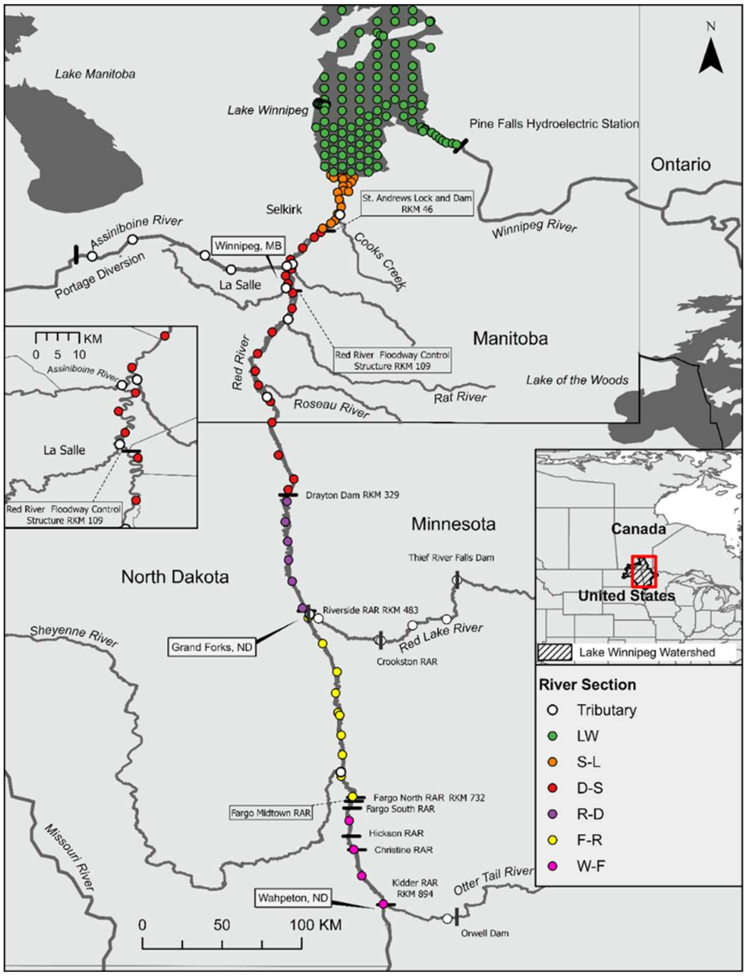


Figure 4: Red River Basin Barrier map indicating locations of rock arch rapids ("RAR"), dams and telemetry receivers.

Approximately 80 miles north of the tailwaters to the Cape Fear River is the tailwaters to the Neus River. The Neus River in North Carolina is home to the same anadromous fish species: American shad, and striped bass. In 1998, the Quaker Neck Dam was removed from the river, allowing for free flow, and unlocking the upper reaches of the river for anadromous fish species (Hightower, J. E., 2006). During his time at the USGS, Joseph Hightower of N.C. State University, conducted a survey of 25 striped bass and 25 American shad before the dam was removed to identify spawning habits and the effect of the low-head weir. He found that only 13 striped bass and 8 American shad reached the dam and only 3 striped bass were able to pass over the dam, which was completely submerged by high water flows. Secondly, he figured out that the preferred spawning conditions were upstream of the dam, proving the need for these fish to continue their migration (Hightower, J. E., 2000). After removal in 1998, the USGS conducted surveys on the eggs and larvae from the American shad and striped bass above the dam. The results showed that in 2003, 93.9% of American Shad and 77.01% of striped bass eggs were found above the earlier site of the Quaker Neck Dam in the main stem of the river or in tributaries. In 2004, the percentages of striped bass eggs dropped to 18.9%, but that can be attributed to low flows (Hightower, J. E., 2006). *Figure 5* exemplifies this with a map of egg/larvae connections before and after the dam removal (Hightower, J. E., 2006). The data makes it clear how dam removal plays a role in expanding the environment of these fish and enhancing their migration. These numbers should set the standard for nature-like fish ladders that need to be achieved to be on par with dam removals.

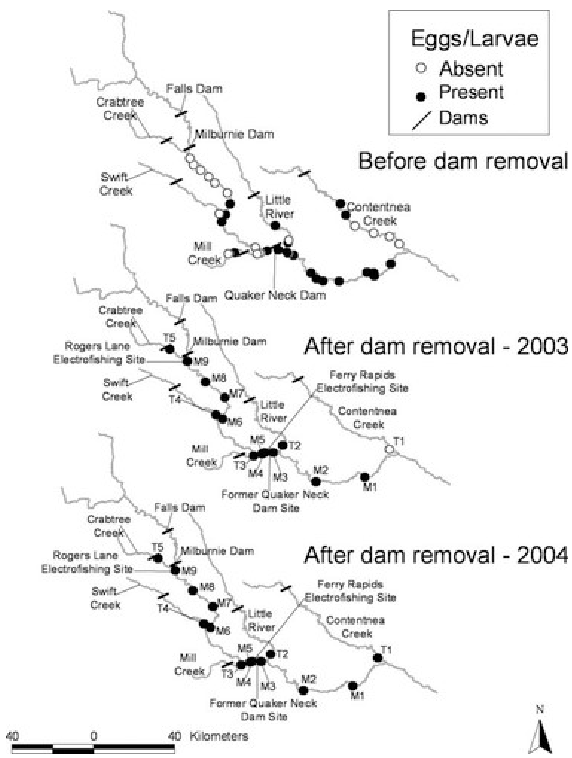


Figure 5: Spawning Reaches of American Shad on Neus River

Discussion:

The Neus River is a role model for the work being done on the Cape Fear River. With the same species of anadromous fish, a direct comparison of fish migration in the two rivers is the best way to understand nature-like fishway's effectiveness. The USGS surveys on the Neus River indicated a strong egg/larvae presence upstream of the Quaker Neck Dam location. Both years the American Shad had a ~90% spawn rate and the striped bass ~77% (Hightower, J. E., 2006). For the sake of the data consumed, it is best to assume that if fish are migrating past a barrier, they are doing so to spawn. Holding this assumption, the project goal for the Rock Arch Rapids of 80% passage efficiency is reasonable. Fish behavior is key to understanding the efficiency of the passage. Like the Neuse River study, the American shad outperformed the striped bass in passage upriver in the first study of the *Rock Arch Rapids* (Raabe, J, et al., 2019). On the Neus, striped bass numbers were lower in the 2nd year due to lower flow. The smaller, American shad pushes for the upper reaches regardless the river flow, while the larger striped bass does not need to travel as far (Hightower, J. E., 2006). This is important to note as it could be a reason the striped bass passage efficiency is lower than expected at *The Rock Arch Rapids.* In the second study on the Cape Fear River, conducted by *The Nature Conservancy*, passage rates for the American shad and striped bass both increased because of the modifications to the rock arch rapid design. The numbers for each fish 71 ± 14% and 32 ± 8%, respectively, fall short of the spawning rates recorded on the Neus River (Bunch, A., Unpublished).

The efforts put forth by the USACE and the Minnesota DNR in the Red River Basin show confidence in the rock arch rapid design. Specifically, aiding larger fish like the lake sturgeon. With limited data on statistical passage efficiency, angler surveys and eyewitness recordings indicate large improvements in fish populations in previously blocked reaches of the river. The work done in the Red River Basin is less about fish migration and more about reconnection a massive ecosystem of rivers. Improvements in fish numbers throughout the basin have been recorded and the Lake Sturgeon Restoration Plan has been successful (Minnesota DNR, 2025). The rock arch rapid fishways have gone a long way in contributing to the interconnection of the Red River Basin and their effectiveness as a fishway to many different species of fish should be recognized.

Conclusion:

Nature-like fishways are designed to accommodate all fish species and be indistinguishable from natural river conditions. The evidence from the Minnesota DNR shows that varied species of fish can successfully traverse these barriers through nature-like fishways, proving that rock arch rapid can restore a blocked ecosystem. The migration of anadromous fish in North Carolina is a different challenge and the annual fish passage of thousands of fish is imperative to the growth of these species. The main difference between the Red River Basin and the Cape Fear River is the need for every fish to successfully pass the fishway. If nature-like fishways cannot be at least 80% efficient, then they are not showing the same success as dam removal. The re-design of the *Rock Arch Rapids* on the Cape Fear River is one of the most impressive nature-like fishways in the United States, however, after 13 years trying to improve its performance, the fishway still falls short of dam removal. As a result of this, it can be concluded that although rock arch rapids may offer a path – but not a solution – falling short of and delaying the restoration only dam removal can deliver.

Works Cited

Kessler, R. (2014, May). *Mimicking Nature, New Designs Ease Fish Passage Around Dams*. Yale School of Environment. https://e360.yale.edu/features/mimicking_nature_new_designs_ease_fish_passage_around_dams

Katopodis, C., Kells, J.A., Acharya, M. (2001) *Nature-Like and Conventional Fishways: Alternative Concepts?*. Canadian Water Resources Journal Vol. 26, No. 2. https://www.tandfonline.com/doi/epdf/10.4296/cwrj2602211?needAccess=true

NOAA. (2022, May). *Fish Passage Inspired by Nature on the Cape Fear River, North Carolina*. https://www.fisheries.noaa.gov/feature-story/fish-passage-inspired-nature-cape-fear-river-north-carolina

Raabe, J., Hightower, J., Ellis, T., Facendola, J. (2019). *Evaluation of Fish Passage at a Nature-Like Rock Ramp Fishway on a Large Coastal River,* Transactions of the American Fisheries Society, 148(4), 798-816. https://academic.oup.com/tafs/article/148/4/798/7819366

Aadland, L. (2010) *Reconnecting Rivers: Natural Channel Design in Dam Removals and Fish Passage*, Minnesota Department of Natural Resources, Intro. https://files.dnr.state.mn.us/eco/streamhab/reconnecting_rivers_intro.pdf

Aadland, L. (2010*) Reconnecting Rivers: Natural Channel Design in Dam Removals and Fish Passage,* Minnesota Department of Natural Resources, Ch1. https://files.dnr.state.mn.us/eco/streamhab/reconnecting_rivers_chap1.pdf

Aadland, L. (2010) *Reconnecting Rivers: Natural Channel Design in Dam Removals and Fish Passage,* Minnesota Department of Natural Resources, Ch2. https://files.dnr.state.mn.us/eco/streamhab/reconnecting_rivers_chap2.pdf

Aadland, L. (2010) *Reconnecting Rivers: Natural Channel Design in Dam Removals and Fish Passage,* Minnesota Department of Natural Resources, Appendix. https://files.dnr.state.mn.us/eco/streamhab/reconnecting_rivers_appendix.pdf

Cape Fear River Watch. (n.d.). *Fishery Restoration,* Cape Fear River Watch. https://capefearriverwatch.org/fish-restoration/

Kaelke, M. (2025*) Rock Arch Rapids: Restoring Fish and Rewriting the Story of the Red River Basin.* West Central Initiative. https://wcif.org/blog/environment/rock-arch-rapids/

Bunch, A. (2025) *LD1 Data,* [Unpublished Data]. The Nature Conservancy North Carolina Chapter

Hightower, J. E., & Beasley, C. A. (2000). *Effects of a Low-Head Dam on the Distribution and Characteristics of Spawning Habitat Used by Striped Bass and American Shad*, Transactions of the American Fish Society, 129(6) ,1316-1330. https://onlinelibrary-wiley-com.proxy1.library.virginia.edu/doi/full/10.1577/1548-8659%282000%29129%3C1316%3AEOALHD%3E2.0.CO%3B2

Hightower, J. E., & Burdick, S. M. (2006). *Distribution of Spawning Activity by Anadromous Fishes in an Atlantic Slope Drainage after Removal of a Low-Head Dam*. Transactions of the American Fisheries Society, 135(5), 1290-1300. https://onlinelibrary-wiley-com.proxy1.library.virginia.edu/doi/full/10.1577/T05-190.1

USACE, (2020). *Cape Fear River Locks and Dams Bladen County, North Carolina.* U.S. Army Corps of Engineers Wilmington District. https://eft.usace.army.mil/saw-nav/FILES/Public_Notice/PUBLIC_CFRLD_Sec_216_Disposition_Study_Draft_Integrated_Report_and_EA_(clean,_with_appendices)_-_8Jan2020.pdf

Sargent, D. (2022). *Lock and Dam 1 Fish Passage*. Cape Fear River Watch. Slideshow. https://capefearriverwatch.org/fish-restoration/

Huberty, G.L. (2005). *Red Lake River fisheries population assessment, summer 2005, reaches one and two report, river mile 0.0 to 125.7.* Minnesota Department of Natural Resources. Section of Fisheries. Study 3. St. Paul, Minnesota

Minnesota DNR, (2025). *Red River of the North Sturgeon Restoration*. Minnesota Department of Natural Resources https://www.dnr.state.mn.us/fisheries/red-river-sturgeon.html

Enders, E., Watkinson, D., Charles, C., Pegg, M., Wendel, J., Caspers, T., (2019). *Red River Telemetry Study 2018/19 Final Report.* International Joint Commission. https://www.ijc.org/sites/default/files/migrate_default_content_files/201819_YearEnd_Report_Red_River_Telemetry_Study.pdf

Bunch, K., 2023. *Study Finds Fish Passing Dams, Moving Across Red River System.* International Joint Commission. https://www.ijc.org/en/study-finds-fish-passing-dams-moving-across-red-river-system

Bunch, K., 2024. *Study Finds Fish Traveling Across Much of Red River Watershed.* International Joint Commission. https://www.ijc.org/en/study-finds-fish-traveling-across-much-red-river-watershed

Engineering Fish Ladders: Challenges and Innovations in Addressing Anadromous Migration Barriers

Technical Paper

From Concrete to Nature: The Evolution of Fish Ladder Design and Ecosystem Sustainability

STS Paper

A Thesis Prospectus Submitted to the Faculty of the
School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements of the Degree
Bachelor of Science, School of Engineering

Bear Matheson

Fall 2024

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Prospectus Advisor

Venkataraman Lakshmi, Department of Civil and Environmental Engineering

STS Advisor

Richard Jacques, Department of Engineering and Society

Introduction

Since the implementation of modern infrastructure to control and supply water required by State, regional and local government agencies, the decline of migratory and anadromous fish species has become a critical environmental concern throughout the world. The word anadromous comes from the Greek term *ana-dromos* meaning "running-up." It describes the fish species such as salmon, who migrate up freshwater rivers from sea to spawn. Dams are one of the largest disruptors of these natural migratory patterns, blocking essential spawning grounds and damaging reproductive rates. In response, fish passages have been introduced allowing for species like salmon to traverse these barriers. There are more than 80,000 dams in the U.S. and many of them have some kind of fish pass. The implementation of fish passages throughout the United States has been a major effort to help restore native fish populations. The fish ladder is one of the most used fish passages designs, however, its effectiveness is inconsistent. One study documented that only three percent of American Shad make it through all the fish ladders on the way to their spawning ground. Throughout my research I will be examining the current fish ladder designs, where they are and are not being used, and the kind of innovations that are taking place. In my technical essay, I will assess the challenges surrounding the design and implementation of fish ladders and provide an explanation as to how the decisions have been made. My STS essay will address innovation in technologies and strategies that can increase the effectiveness of fish ladders.

Technical Discussion

There are many ways to transport fish across a barrier such as a dam. These vary from ladders, to elevators, to "trap and transport." This research will focus specifically on the different ladder designs that are the most frequently used across all types of barriers. The basic design is a series of ascending pools where a fish can swim against the current and move its way to the top (NOAA, 2013). The three "man-made" types that will be explored are Pool and Weir, Denil, and Vertical slot. Each one has its own respective advantages and disadvantages for different rivers and species. Before explaining the components and characteristics of each design, it is important to understand why there is not a one-size fits all ladder.

There are many species of fish that require the assistance of fish ladders to move through rivers and the capabilities of each of each species can vary greatly within the same water. Understanding the target fish and when they are moving upriver is key to choosing a design. At the same time, the flows of rivers are constantly changing, and the infrastructure design must be accommodating. If the water traveling through the system is too fast or the fish do not get any chances to rest, they will become fatigued and stressed. There is also a certain amount of water a fish needs to climb the structure, which can be difficult to attain at certain times of the year. Understanding the specific river is the first step to creating a successful fish passage. With respect to the site, the engineer must fully understand the location and its environment to make the optimal decision on how fish will want to move upstream.

Entrance is the most critical part of the design. If fish refuse to climb the ladder, it is a failure. Typically, entrances have a high velocity flow pouring out to mimic natural rivers and attract fish to the passage. However, this method cannot be used for all. For example, what happens if water is washing over a spillway? Once the fish makes their way into the ladder, channel design needs to be considered. Again, the design should try to mimic natural conditions to minimize stress. This can be done by adding obstacles that stir up the flow and providing natural lighting conditions. Lastly, the exit should be designed so that every other aspect of the ladder operates effectively. The exit should control flows through the system, block debris, and be in a location that reduces the risk of fish falling back over the dam. With so many variables, no two structures are the same. (CivilGeo, 2024)

Of the three design types previously mentioned (Pool and Weir, Denil, and Vertical Slot), each one has its own respective advantages and disadvantages for different flow rates and fish species. The Pool and Weir (*Figure 1)* is one of the most used fish ladders and has been in existence the longest. This design consists of a staircase of plunge pools, separated by walls that span the width of the channels called “weirs”. The pools function as resting/queuing periods for fish to reduce stress while they leap from one pool to the next. If the flow gets too high, a phenomenon called streaming occurs and the water flows as a surface jet over the weirs, inhibiting the fish’s ability to cross. Overall, this design caters to leaping fish, that includes trout and salmon, requires predictable or managed flow to prevent streaming. The Denil fish passage design (*Figure 2*) features a ramp-like structure with continuous flow through a series of chutes from top to bottom. This requires fish to continuously swim until they reach the top. Denil ladders are more suitable for fish that are not adept to leaping but require increased strength to reach the top of each span given that there are no resting areas between chutes. They also accommodate a greater range of flow rates and can be effective at steeper slopes. This design is commonly used in short and steep instances. Vertical slot ladders (*Figure 3*) are a combination of multiple fishway designs. Instead of weirs that water flows over, it has vertically oriented slots between pools that allow fish to pass from pool to pool and rest behind baffles. The non-turbulent, deep pools can accommodate many different fish species and water levels. This design is best suited for rivers that have a large and diverse range of

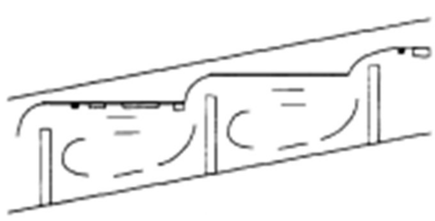


Figure 6: Pool and Weir Fish Ladder

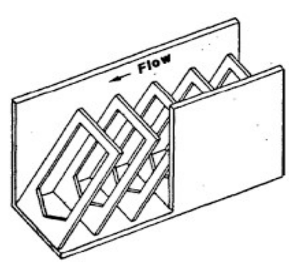


Figure 2: Denil Fish Ladder

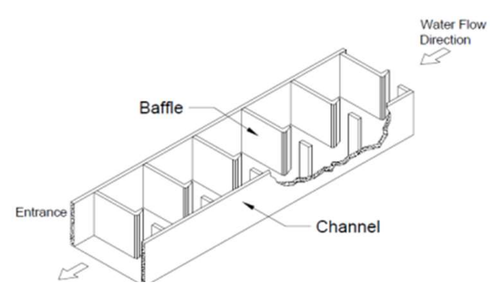


Figure 3: Vertical Slot Fish Ladder

species migrating. (*Fish Passage Technologies: Protection at Hydropower Facilities*, 1995).

STS Discussion

There have been thousands of fish ladders implemented across the world; each one different than the others. Despite years of development and advancement in fish ladder design, there are still more failures than successes. The evaluations reveal that the designs are not recovering the fish species to a level they were before the dams were constructed. Many professionals and environmentalists think that the only viable solution is complete dam removals, "The barrier still exists. The problem still exists" – Laura Wildman (Kessler, R. 2013). "There is no such thing, I have been told by men who were in the business of making them, as a good or even adequate fishway" – John Hay 1959 (Goldfarb, B. 2018). Although the quotes from Laura Wildman and John Hay are grim, there is still a need to explore potential new innovations that could further enhance the effectiveness of anadromous fish migration. Specifically, evaluating the potential of making nature-like fish ladders an effective alternative.

Civil engineers are re-evaluating the earlier fish ladder designs to understand why the current manufactured fish ladders continue to fail. Instead of overengineering the structures with concrete baffles, weirs and slots, nature-like fish passages using logs, rocks and gravel to separate pools that provide a traversable rapid. This method creates a considerably better habitat for fish and accommodates a wide range of species and not just the athletic and commercialized fish species. Often, these designs require upstream flow control, and the slope requirements can make them up to five times longer than typical fish ladders (Thomas & Mann, 2018)**.**

Rock ramps are another similar natural imitator that have gained considerable attention globally. This design is also convenient for low barriers and can be constructed at a steeper slope without requiring up-stream flow control. Unlike the narrow and smooth concrete chute of traditional fish ladders, this design can span the entire river and create turbulent flow through pools of rocks. The realistic environment of the rock ramp design allows small fish and invertebrates to live within the rapids as well as providing spawning fish a place to bed and lay eggs (FISHBIO). This is a major enhancement to the habitat that affects more than just migrating fish. *Figure 4* shows resting pools where salmon or trout would preferably spawn. Unquestionably, nature like fish ladders and rock ramps have many advantages over the typical designs. Most importantly they are a low-cost option that can benefit the entire river ecosystem. Although they do not accommodate all fish passages, there are many passages that can be reverted to this method. Notably, in North Carolina, on the Cape Fear River, there is a large nature-like rock-ramp fishway. The nationally recognized fish passage known as the *Rock Arch Rapids*, has recently been modified to be more appealing for the traversing fish. Specifically, the American shad, blueback herring, striped bass, and Atlantic Sturgeon. Shown in *Figure* 4, this fishway uses the rock ramp technique. Instead of a typical weir and spillway, the rock ramp slopes to the peak of the weir maintaining the same dam level. Originally constructed in 2012, the Cape Fear River Watch has just completed a renovation that aims specifically to aid traversing striped bass and Atlantic sturgeon (Cape Fear River Watch). Currently, researchers are conducting two consecutive studies on the movement of these fish to determine if large scale nature-like fish ladders can make a notable difference. (NOAA, 2022).

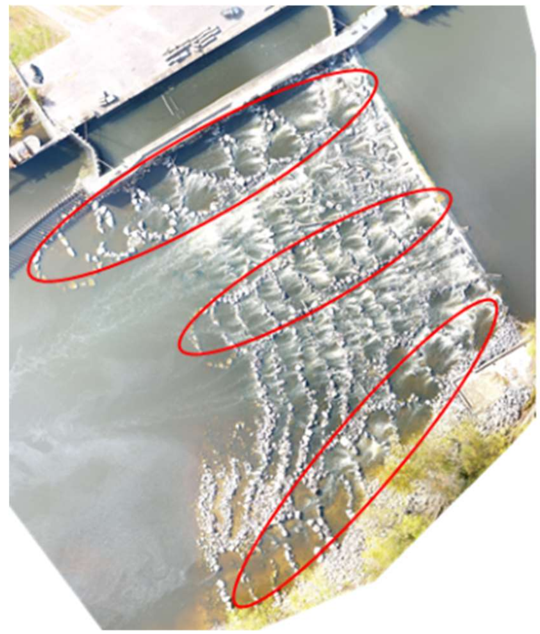


Figure 4: Rock Arch Rapids

Conclusion

The widespread implementation of fish ladders has been a proactive response to restoring anadromous fish populations throughout the United States. Still, many challenges persist, and continued innovation and refinements are needed. Each fish passage design has its own unique advantage. Through my technical research, I expect to gain a practical and detailed understanding of how engineers address the complexities of fish ladder design. Next semester I will be taking an independent research class with Dr. Lakshmi, the John L Newcomb Professor of Engineering in the Department of Civil and Environmental Engineering at the University of Virginia. This course will enable me to take a deeper dive into my findings and the hands-on research will allow me to speak with professionals, visit active fish ladders, evaluate new concepts, and enable me to design and fabricate a scaled model of my design by the end of the Spring semester. By comparing traditional fish ladders to nature inspired structures, I expect to gain insights that can enhance fish ladder efficacy and promote engineering solutions and designs that mimic natural river conditions and address the specific needs of various fish species across different river environments.

References

NOAA. (2024). *What is a fish ladder?* NOAA's National Ocean Service. https://oceanservice.noaa.gov/facts/fish-ladder.html

United States (1995). Fish Passage Technologies: Protection at Hydropower Facilities. Washington, DC: Congress of the U.S., Office of Technology Assessment.
Thomas, S., & Mann, J. (2018, May 30). FISH PASSAGE DEVICES. PG&E's Potter Valley Project.

CivilGEO. (2024). *Design of fish passages & ladders with HEC-RAS.* CivilGEO. https://www.civilgeo.com/es/design-of-fish-passages-ladders-with-hec-ras/

The Constructor. (n.d.). *7 Types of Fish Ladders or Fishways*. The Constructor. https://theconstructor.org/water-resources/types-fish-ladders-fishways/33911/

Slatik, E. (1975). *Laboratory Evaluation of a Denil-Type Steeppass Fishway with Various Entrance and Exit Conditions for Passage of Adult Salmonids and American Shad.* Marine Fisheries Review. https://spo.nmfs.noaa.gov/sites/default/files/pdf-content/MFR/mfr379/mfr3783.pdf

Nordlund, B. (June, 2009). *Design of Upstream Fish Passage Systems*. National Marine Fisheries Service, NWR. https://www.fishscreensoc.com/wp-content/uploads/2010/09/Section-1-Background-Material.pdf

Kessler, R. (2014, May). *Mimicking Nature, New Designs Ease Fish Passage Around Dams*. Yale School of Environment. https://e360.yale.edu/features/mimicking_nature_new_designs_ease_fish_passage_around_dams

Goldfarb, B. (2018, January). *What's the Future of Fishways?* Hakai Magazine. https://hakaimagazine.com/news/whats-the-future-of-fishways/

FISHBIO. (2023, July). *Nature-Inspired Fish Passage*. https://fishbio.com/nature-inspired-fish-passage/.

NOAA. (2022, May). *Fish Passage Inspired by Nature on the Cape Fear River, North Carolina*. https://www.fisheries.noaa.gov/feature-story/fish-passage-inspired-nature-cape-fear-river-north-carolina

Cape Fear River Watch. (n.d.). *Fishery Restoration*. https://capefearriverwatch.org/fish-restoration/#

NSW Government. (2023). *Fishway - Rock Ramp*. NSW Department of Primary Industries. https://www.dpi.nsw.gov.au/dpi/fishing/fish-passage-nsw/improving-fish-passage/fishways/precast-rock-ramp

Murray Darling Basin Authority. (2024). *Fishways of the River Murray*. https://www.mdba.gov.au/water-management/infrastructure/fishways-river-murray