Thinking Inside the Box (Culvert): Developing a Low-Cost, Easy-to-Install Retrofit Prototype For Fish Passage

Final Report

Jessica Kozarek

St. Anthony Falls Laboratory

University of Minnesota

CTS 23-11

CENTER FOR TRANSPORTATION STUDIES
UNIVERSITY OF MINNESOTA

Technical Report Documentation Page

1. Report No. CTS 23-11	2.	3. Recipients Accession No.
4. Title and Subtitle Thinking inside the box (culvert): Developing a low-cost, easy-to-install retrofit prototype for fish passage		5. Report Date May 2024 6.
7. Author(s) Jessica Kozarek, Matt Hernick		8. Performing Organization Report No.
9. Performing Organization Name and Address St. Anthony Falls Laboratory University of Minnesota 2 SE 3rd Ave Minneapolis, MN 55414		10. Project/Task/Work Unit No. 2023018 11. Contract (C) or Grant (G) No.
12. Sponsoring Organization Name and Address Center for Transportation Studies University of Minnesota 440 University Office Plaza 2221 University Avenue SE Minneapolis, MN 55414		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes https://www.cts.umn.edu/publications/researchreports/		

16. Abstract (Limit: 250 words)

This project addresses a need to develop a low-cost, easy-to-install, and safe culvert retrofit for fish passage. Culverts can create barriers to fish movement due to fast-flowing water with no resting areas, shallow flow, and/or lack of cover. While new culvert design guidance addresses these concerns, many existing culverts have known fish passage issues that are not slated for replacement. We previously investigated a potential solution, using mussel spat rope, a fibrous plastic rope that has been demonstrated to facilitate fish passage in New Zealand. This design showed promise in laboratory, fish, and field trials. However, despite interest, concerns over the release of plastic into the environment have inhibited its use. Therefore, we leveraged this experience to investigate new solutions with benefits similar to the installation of mussel spat rope (i.e., low-flow resting areas, cover, and minimal impact to culvert capacity) but that are made with bio-based sustainable materials. The goals of this project were to 1) identify appropriate materials and 2) design and test protypes in flume experiments. We have several viable prototype designs ready for field-scale testing and/or deployment made with a range of non-plastic materials.

17. Document Analysis/Descriptors		18. Availability Statement	
Fishes, Fish ladders, Animal migrations, Culverts, Retrofitting, Biological materials		No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 20	22. Price

THINKING INSIDE THE BOX (CULVERT): DEVELOPING A LOW-COST, EASY-TO-INSTALL RETROFIT PROTOTYPE FOR FISH PASSAGE

FINAL REPORT

Prepared by:

Jessica Kozarek, Matt Hernick
St. Anthony Falls Laboratory
University of Minnesota

MAY 2024

Published by:

Center for Transportation Studies
University of Minnesota
440 University Office Plaza
2221 University Avenue SE
Minneapolis, MN 55414

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

RATIONALE FOR WORK

Road-stream crossings can create barriers to fish movement if the conditions at the crossing, such as fast-flowing water with few resting areas or very shallow depths, exceed swimming abilities. These flow conditions commonly occur in culvert barrels in Minnesota (Kozarek et al. 2021) and across the country. Multiple impassible culverts within a stream network can have cumulative effects on fish communities by limiting access to key habitat, such as that needed for spawning or refugia during extreme conditions like drought. Barriers to fish movement can also isolate and thus further risk endangered populations (Kozarek et al. 2017). Design strategies for new or replacement culverts can encourage fish passage (Hernick et al. 2019), but retrofit solutions are needed for existing culverts that are not scheduled for replacement. In larger culverts with high velocities, baffles and weir retrofits have been used for decades to create resting areas for fish, but these can be costly and difficult to install in tight culverts, can create maintenance issues, and can significantly alter culvert capacity. In addition, often culvert retrofits are designed with the largest (often game fish) passage in mind, but passage can also be critical for smaller fish species and weaker swimmers such as the endangered Topeka Shiner (Kozarek et al. 2017).

Figure 1. Testing plastic mussel spat rope in a Minnesota culvert during low and low-moderate flows. (Kozarek and Hernick 2018). This product functions as desired but is composed entirely of plastic fibers, easily shedding microplastics.

There remains an open gap for an inexpensive, easy-to-install culvert retrofit for problem culverts to address fish passage when culvert replacement or redesign is infeasible. The research team previously investigated the use of mussel spat rope to facilitate fish passage through culverts (Kozarek and Hernick 2018). Mussel spat rope is a polyethylene plastic rope with many filaments designed for mussel aquaculture (Figure 1). Repurposing this material as a culvert retrofit for fish passage has been shown to be highly effective in steep, perched, or high-velocity culverts in New Zealand (David et al. 2014), but it had not been tested elsewhere, in larger culverts, or for other fish species. MnDOT contracted the research team to investigate the potential for use in Minnesota box culverts focusing on 1) the hydrodynamic performance of the ropes, 2) use of these ropes by Minnesota fish species, and 3) evaluation of field installations in typical box culverts. These results showed that the installation of mussel spat ropes has promise, and the research team was approached by several counties, as well as practitioners in other states for information on this design. Ultimately, the use of mussel spat ropes was not promoted, however, due to its high potential to release microplastics into the environment because the fibers wear. Therefore, the goal of this project was to develop a novel prototype culvert retrofit for fish passage that is inexpensive, easy to install, scalable for different sizes and types of culverts, and made from a sustainable, non-plastic material.

FINAL PROJECT UPDATE

IDENTIFICATION OF MATERIALS AND CONFIGURATIONS FOR FLUME TESTING

The research team developed a matrix of potential materials including sisal, coir, cotton, and hemp and a matrix of potential configurations including a single rope (of various dimensions), multiple ropes, ropes with knots, and two potential modifications designed to replicate the mussel spat rope with natural fibers. Combined, the final research matrix had twelve different experimental runs with different material/configurations and a control run comparing natural fiber options to the mussel spat rope used in earlier experiments.

ROPE LONGEVITY

One large potential drawback of natural fiber ropes is longevity. All rope materials may experience degradation from ultraviolet light and/or abrasion. Additionally, natural fibers degrade by biological action and chemical breakdown. To test the longevity of natural fiber ropes we placed them in the outflow of the Outdoor StreamLab at SAFL for four months. The ropes were partially submerged in flowing water to simulate a difficult environment similar to the end of a culvert at low flow. The test was inspired and informed by a study of ropes placed in seawater in Plymouth, England in Atkins and Purser (1936).

Five types of rope were used: hemp, cotton, sisal, manila, and coir (see Figures 2-4). All were 19 mm (3/4”) diameter three-strand twisted except the coir, which was hand braided from three smaller strands. One rope of each type was treated with pine tar, a traditional rope preservative made from pine trees and stumps, and one rope of each type was left untreated. When ropes were removed from the water and dried, the ropes were covered with biological growth and fine sediment. Ropes were visually examined and twisted and flexed by hand to gauge degradation. In this testing environment, the coir rope survived the best both with and without treatment. The hemp rope began to break down treated and untreated. The addition of pine tar appeared to increase longevity of the cotton, sisal, and manila ropes.

Figure 2. Ropes before placement in the water. From left to right are untreated coir, manila, sisal, cotton, and hemp, then the same sequence treated with pine tar. The near side of the frame was placed downward in the water

Figure 3. Mid experiment. Biological growth visible on ropes.

Figure 4. Ropes after drying. From left to right, untreated hemp, cotton, sisal, manila, and coir, then the same sequence treated with pine tar. Ropes were evaluated by manually twisting at mid-length.

FABRIC LONGEVITY

Student researchers brainstormed other potential materials for culvert retrofits, and selected recycled t-shirts as a potential material. As it was unknown how long fabric would last in a flowing aquatic environment, t-shirt material was tested in conjunction with other fabric types. Eight fabric types were tested in several weaves and colors ranging from 100% hemp, hemp-cotton blends, and 100% cotton. Three replicate fabric rectangles of each type were attached to a frame with metal grommets and placed in the Outdoor StreamLab outflow.

By the time the cloth squares were removed from the water nearly all of the fabric was degraded (see Figures 5-7). Some fabric from each sample of the 55% Hemp, 45% Organic Cotton, black Fleece Weave, around the grommets, and one grommet held fibers of 100% Hemp canvas weave. The same properties of flexibility and high surface area that are helpful in creating a low-velocity zone for aquatic organism movement around a rope are likely responsible for the rapid deterioration of the t-shirt material. This material might be a low-cost option for a seasonal passage enhancement.

Figure 5. Fabric samples before deployment.

Figure 6. Fabric samples placed in water.

Figure 7. Remnants of fabric samples with the most fabric remaining.

FLUME TESTING OF MATERIALS AND CONFIGURATIONS

The research team utilized the tilting bed flume at SAFL to test the flow patterns created by different materials and configurations (see Figure 8). The goal of these experiments was to compare alternate materials (natural fiber) and configurations to the plastic-based mussel spat rope used in previous research (Kozarek and Hernick 2018). Specifically, we determined the cross-sectional area of velocity reduction using measurements collected with an acoustic Doppler velocimeter (ADV; Nortek Vectrino +) attached to the instrumentation carriage. To supplement these measurements, we observed performance, ease of handling and installation.

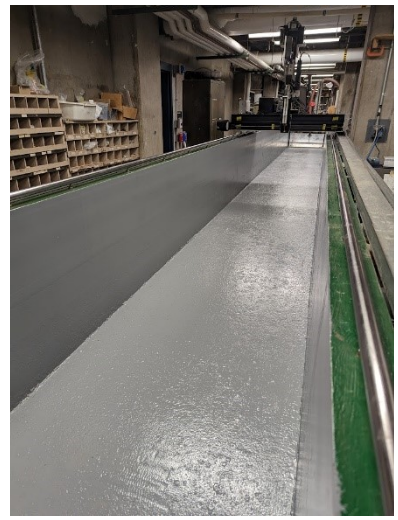

Figure 8. Tilting bed flume at

In addition to different rope types and diameters, different knot spacings and three different constructed shapes were tested to evaluate the potential for the creation of low flow (resting areas) for fish adjacent to the retrofit (Figure 9; Table 1). These constructed shapes were designed to provide flow through the fibers in a net format, with fibrous pom poms, or with fringe. The fringe material was constructed using discarded t-shirt material.

Figure 9. Examples of different prototype rope retrofit configurations tested in the flume.

Table 1. Summary of flume trials. Difficulty of construction was subjectively ranked. Usable low velocity area was defined aa the cross-sectional area less than 0.3 m/s minus the area of the rope. Note that the double rope scenarios cannot be directly compared as data were collected around the entire rope (not half).

Experiment	Description	Difficulty of construction (1-5, lower is easier)	Relative Usable Low Velocity Area (cm^2)
No Rope	Background data with no ropes	1	0
Single rope down middle of flume			
Plastic Rope	Mussel spat rope (similar to Kozarek and Hernick 2018)	1	28
19 mm Manila Rope	Manila rope diameter 19 mm	1	9
t-shirt Rope	rope made from t-shirt material with ~ 1 inch fringe	4	25
Manila Braided Rope	Three strand braid	2	14
38 mm Manila Rope	single rope with 38 mm diameter	2	17
Coir Net	coir net was rolled and tied with coir rope in ~30cm intervals	3	35
PomPom Rope	strips of frayed rope attached in pom pom shape to rope	4	38
Knotted Rope			
Manila Knot Rope (larger Spacing)	38 cm between knots	1	6
Manila Knot Rope (smaller spacing)	19 cm between knots	2	14
Manila Knot Rope (middle spacing)	28 cm between knots	2	16
Double Ropes			

Manila Double Rope	two 19 mm manila ropes	2	*
Manila Double Knot Rope	two 19 mm manila ropes with knots	3	*

The plastic furry rope tested in Kozarek and Hernick (2018) showed promise for facilitating fish passage in flume and fish trials. Fish were observed to utilize the low flow areas adjacent to and underneath the ropes to navigate upstream. Therefore, other rope materials and configurations were compared to this scenario. One thing to note, the plastic ropes stretch significantly and also float, creating a low flow area that iss relatively symmetric above and below the ropes. The natural fiber ropes stretched less and floated less during flume experiments (Figure 10). For performance, this may be a desirable characteristic as ropes that are not floating are less likely to capture debris. Of the configurations tested, the single, unmodified ropes provided the smallest flow refugia, while the materials that allowed the flow to interact with the fibers created much larger low flow areas (Table 1; Figure 10), at times exceeding the resting area created by the plastic furry rope. While the t-shirt rope performed similarly to the furry rope, he longevity test of the t-shirt material indicated that this option is a very short-term solution. Despite this, the solution is creative and creates potential volunteer opportunities for construction of temporary fish passage retrofits by interested community members. The options made out of coir fiber (net and pom pom) outperformed the plastic furry rope in terms of relative flow refugia area. The coir net, however, has a greater potential for trapping debris. The pom pom rope should not have the same debris trapping issues, but is likely the most difficult to manufacture.

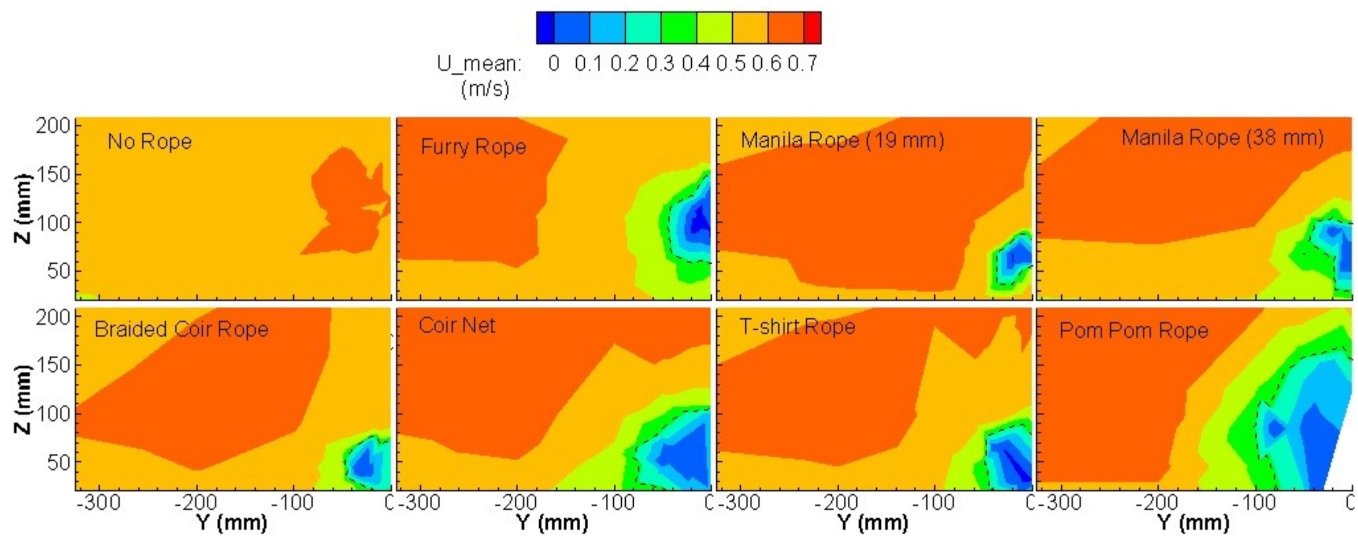

Figure 10. Velocity contours for all single rope tests. Dotted lines represent the 0.3 m/s (half of the background velocity contour). Note that data were collected over half of the flume width (0 = flume centerline).

To evaluate the potential for an off the shelf solution with minor modifications, ropes with knots of different spacing were tested (Figure 11). To be effective in these flow conditions, knots had to be placed at least ever 28 cm or closer. Because the relative flow refugia provided by a single rope with knots was relatively small, we tested unmodified ropes and ropes with knots in pairs (Figure 12). In pairs, knotted ropes show some promise for reducing flow between the ropes (although not to the 0.3 m/s threshold that was used for evaluation).

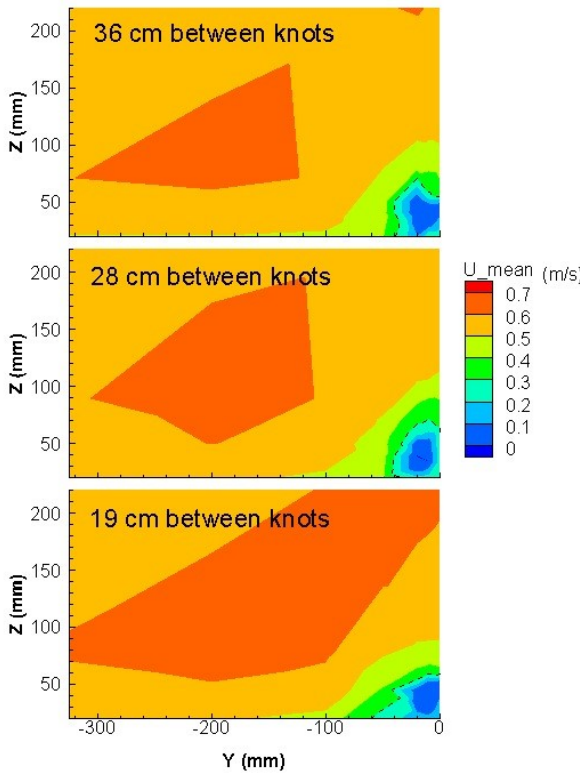

Figure 11. Velocity contours for all single knotted rope tests. Velocity cross sections were collected halfway between knots. Dotted lines represent the 0.3 m/s (half of the background velocity contour). Note that data were collected over half of the flume width (0 = flume centerline).

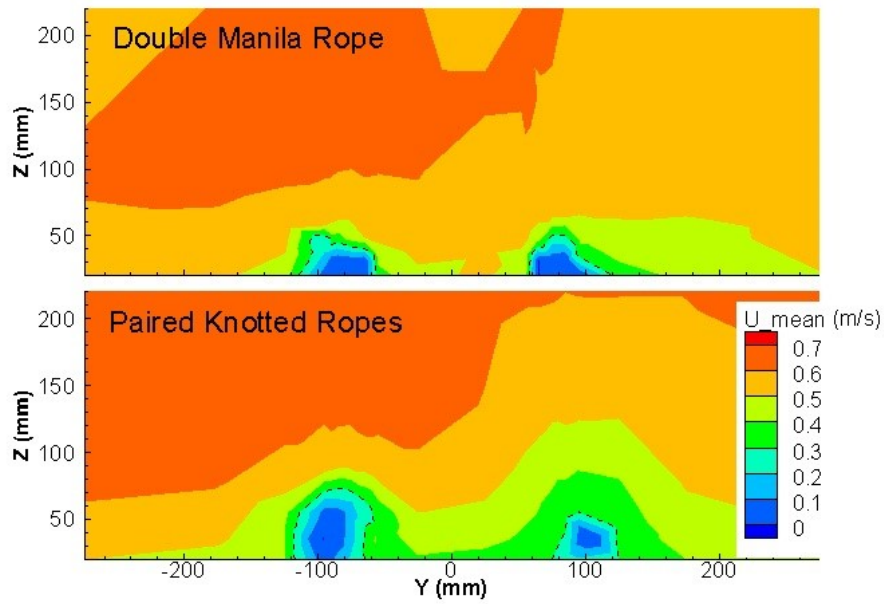

Figure 12. Velocity contours for all paired rope tests. Dotted lines represent the 0.3 m/s (half of the background velocity contour). Note that 0 = flume centerline.

SUMMARY

Culverts of all shapes and sizes are ubiquitous on the Minnesota landscape and can be considered an essential part of the transportation system. However, the environmental impacts of culverts that create barriers to fish and the movement of other aquatic organisms are well recognized. Culvert design guidance in Minnesota addresses these concerns, but it only applies to new or replacement culverts. The goal of this project is to find a solution to facilitate fish passage in culverts that are known barriers, but where funding does not allow for a fish-friendly reconstruction before the end of the existing culvert's service life. Since we are targeting a technology that can be deployed quickly and inexpensively in a large number of culverts, the potential impacts of improving fish movement are significant at the watershed and state level, as well as on an even larger scale.

Of the options tested in this project, the most difficult to construct, the pom pom rope, showed the most promise to provide benefits equal to or better than the plastic furry rope tested in Kozarek and Hernick (2018) and David et al. (2014). The t-shirt rope, designed by the students working on this project, has the benefits of using a waste product and functioned similarly to the furry rope but showed disappointingly fast degradation. Net-based options created low-flow areas but raised some concerns over the potential for debris trapping. Individual unaltered ropes provided little roughness and thus little refugia, but knotted ropes could provide an easy-to-construct solution if installed in pairs.

NEXT STEPS

In areas of the world where mussel aquaculture is prevalent, furry mussel spat ropes are being repurposed to facilitate fish passage, particularly in New Zealand. While these materials showed promise as a low-cost/easy-to-install culvert retrofit for Minnesota fish species, the difficulty in shipping these ropes internationally, plus the concerns over plastic release into the environment have limited their usefulness. Even for their intended purpose for mussel aquaculture, there are attempts to get away from the plastic impact, including biodegradable plastic (Arantzamendi et al. 2023) and biowaste (Paul-Burke et al. 2022) based ropes. The results of this study have reinforced the mechanism for turbulent energy dissipation created by the interaction of flowing water and fibers or knots to create low flow areas adjacent to the ropes. Within Minnesota and nationally, efforts are underway to reduce the amount of plastics used in erosion control materials and research is underway to define the functional longevity of non-plastic containing erosion control materials. This work, funded by MnDOT and led by the University of Minnesota's Bioproducts and Biosystems Engineering Department may help to better define material properties that are more resistant to degradation. The next steps toward further deploying this technology are to 1) investigate manufacturing options for complex rope configurations such as the pom pom rope and 2) better define the functional longevity of available bio-based materials based on ongoing research.

REFERENCES

Arantzamendi, L., Andrés, M., Basurko, O. C., Suárez, M. J. (2023). Circular and lower impact mussel and seaweed aquaculture by a shift towards bio-based ropes. *Rev Aquac.,* 1– 10. doi:10.1111/raq.12816

David, B. O., Tonkin, J. D., Taipeti, K. W. T., & Hokianga, H. T. (2014). Learning the ropes: Mussel spat ropes improve fish and shrimp passage through culverts. *Journal of Applied Ecology, 51*(1), 214–223

Hernick, M., Lenhart, C., Kozarek, J., & Neiber, J. (2019) *Minnesota guide for stream connectivity and aquatic organism passage through culverts.* St. Paul, MN: Minnesota Department of Transportation, Research Services & Library.

Kozarek, J. L., Herb, W., & Bentelspacher, N. (2021). *Assessing culverts in Minnesota: Fish passage and storm vulnerabilit*y (Final Report 2021-29). St. Paul, MN: Minnesota Department of Transportation, Research Services and Library, Office of Transportation System Management.

Kozarek, J., Hatch, J., & Mosey, B. (2017). *Culvert length and interior lighting impacts to Topeka Shiner passage* (Report MN/RC 2017-4). St. Paul, MN: Minnesota Department of Transportation.

Kozarek, J. & Hernick, M. (2018). *Use of mussel spat rope for fish passage in culverts* (Report MN/RC 2018-13). St. Paul, MN: Minnesota Department of Transportation.

Paul-Burke, K., Ngarimu-Cameron, R. H., Burke, J., Bulmer, R., Cameron, K., O'Brien, T., & … Ranapia, M. (2022). Taura kuku: Prioritizing Māori knowledge and resources to create biodegradable mussel spat settlement lines for shellfish restoration in Ōhiwa Harbour. *New Zealand Journal of Marine and Freshwater Research. 56*(3), 570–584.