Water Diversion Selection Tool

User Manual and Reference

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TROUT UNLIMITED

Cover photo: Pentz-Smith Diversion, Weber River, UT (Jason Carey).

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Preface

Diversion structures have been used for millennia to withdraw water from rivers and streams. Human users of diversion structures face a range of challenges owing to the dynamic nature of rivers. Rivers and the fishes therein face a number of challenges owing to the constraints placed up them by man-made diversion structures.

The **Water Diversion Selection Tool** was developed to help resource professionals identify river- and site-compatible diversion mechanisms and the ecological and logistical tradeoffs of each site-compatible mechanism. The Tool development team included GIS analyst, fisheries biologists and scientists, fluvial geomorphologists, and engineers with deep, collective experience designing and constructing diversion structures. The Tool was not developed to make or prescribe a choice in diversion mechanism, rather to assist the user as they navigate through the decision-making process.

Use of the Water Diversion Selection Tool involves an interactive, multi-step process. First, the user provides and submits inputs regarding conditions in and around the intended diversion site. Then, the Tool yields a compatibility chart—a visual illustration of the relative compatibility (or lack thereof) between the conditions at the intended diversion site and 16 different diversion mechanisms. From there, the user can select for further exploration one or more site-compatible diversion mechanisms. The Tool displays River Impact, Operational and Complexity, and Total (combined) scores for each of the selected mechanisms.

The Scores generated by the Water Diversion Selection Tool reflect the collective, professional judgment of the development team and cannot necessarily account for all aspects of all sites and projects. Users are still encouraged to consult with the appropriate professional (e.g., engineer, geomorphologist, aquatic biologist) before advancing with a specific design concept.

This User Manual and Reference serves two purposes. First, it provides instructions for use of the Water Diversion Selection Tool. Second, and just as importantly, it provides background information and context regarding common diversion mechanisms in the Mountain West. Considered herein are impacts of diversion structures on river processes and fish passage, as well as relative constructions costs, operational and maintenance requirements, and legal complexities of diversion mechanisms.

The Appendix at the back of this User Manual includes descriptions of all the diversion mechanisms considered by the Diversion Selection Tool. A companion map, which illustrates real-world application of each mechanism, is **available at this link**.

Acknowledgements

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Compatibility Between Diversion Site and Diversion Mechanism

Mechanisms for diverting water from streams and rivers vary according to a host of factors, including region, stream size and type, diversion requirements, fish passage needs, and cost and maintenance capabilities. Diversion mechanisms have varying degrees of compatibility with physical and ecological river processes. A diversion mechanism's compatibility refers to the degree of negative impacts it might have on river processes and vice-versa. How much water, sediment, and wood a diversion impedes or the degree to which it alters channel migration and connectivity influence a diversion's compatibility. Selecting a diversion mechanism that is, for example, relatively compatible with anticipated sediment or wood loads can improve the diversion's performance, reduce operational and maintenance needs, and minimize negative impacts on the river.

The Water Diversion Selection Tool evaluates the relative compatibility between a site or suite of site-specific conditions and each of 16 different diversion mechanisms. The user defines the site conditions by answering a number of categorical and binary questions (Figure 1). The compatibility of each diversion mechanism is then considered relative to all of these stream site factors.

Users can inform the following attributes with respect to diversion site (the default response is *Unspecified*):

- **Stream Size** as determined by channel width (headwater tributary: < 10 ft, main stem tributary: 10-25 ft, main stem river: 25-200 feet, large river: > 200 ft)
- **Diversion Rate** to satisfy user needs (≤ 5 cfs, 5-100 cfs, ≥ 100 cfs).
- **Channel Planform** at and around the site (anabranch [multiple threads with vegetated islands], braided [multiple threads with non-vegetated islands], canyon, or single-thread alluvial).
- **Stream Gradient** within and around the site (low: < 1%, moderate: 1-3%, high: > 3%).
- **Impoundment Height** or required height of the water surface elevation (head) above the stream channel for proper diversion (≤ 2 ft, 2-8 ft, ≥ 8 ft). Note that for retrofitted structures, the required head may be less than the existing head.
- **Proximity to Infrastructure** as a binary choice (near or not near). This factor accounts for access to maintain and operate the diversion structure (think: roads and power supply) as well as proximity to other nearby infrastructure.

Users are also asked to consider and answer a series of binary (i.e., yes/no) questions about the intended diversion site (the default response is *No)*.

- **Fish passage desired for jumping fish**? Examples of jumping fishes include members of the salmon and trout family.
- **Fish passage desired for non-jumping fish?** Examples of non-jumping fishes include sculpin (*Cottus* sp) and lamprey (*Lampetra* spp.).
- **Coarse Sediment Loading?** Course sediment is defined here as gravel and larger bed material.
- **Fine Sediment Loading?** Fine sediment is defined here as sand and smaller particles.
- **Large Wood Loading**? Large wood is defined by pieces >10 cm in diameter and >1 m in length.
- **Fine Wood Loading**? Fine wood is defined by pieces <10 cm in diameter and <1 m in length.
- **Major Ice Flows?** Major ice flows are defined here as flows or jams with the potential to affect or damage infrastructure.
- **Water Recreation**? Water recreation is defined here as tubers and boaters.
- **Aquatic Macrophyte Loading**? Macrophyte loading is defined here as growth or downstream movement of plants at a level sufficient to foul an intake structure.

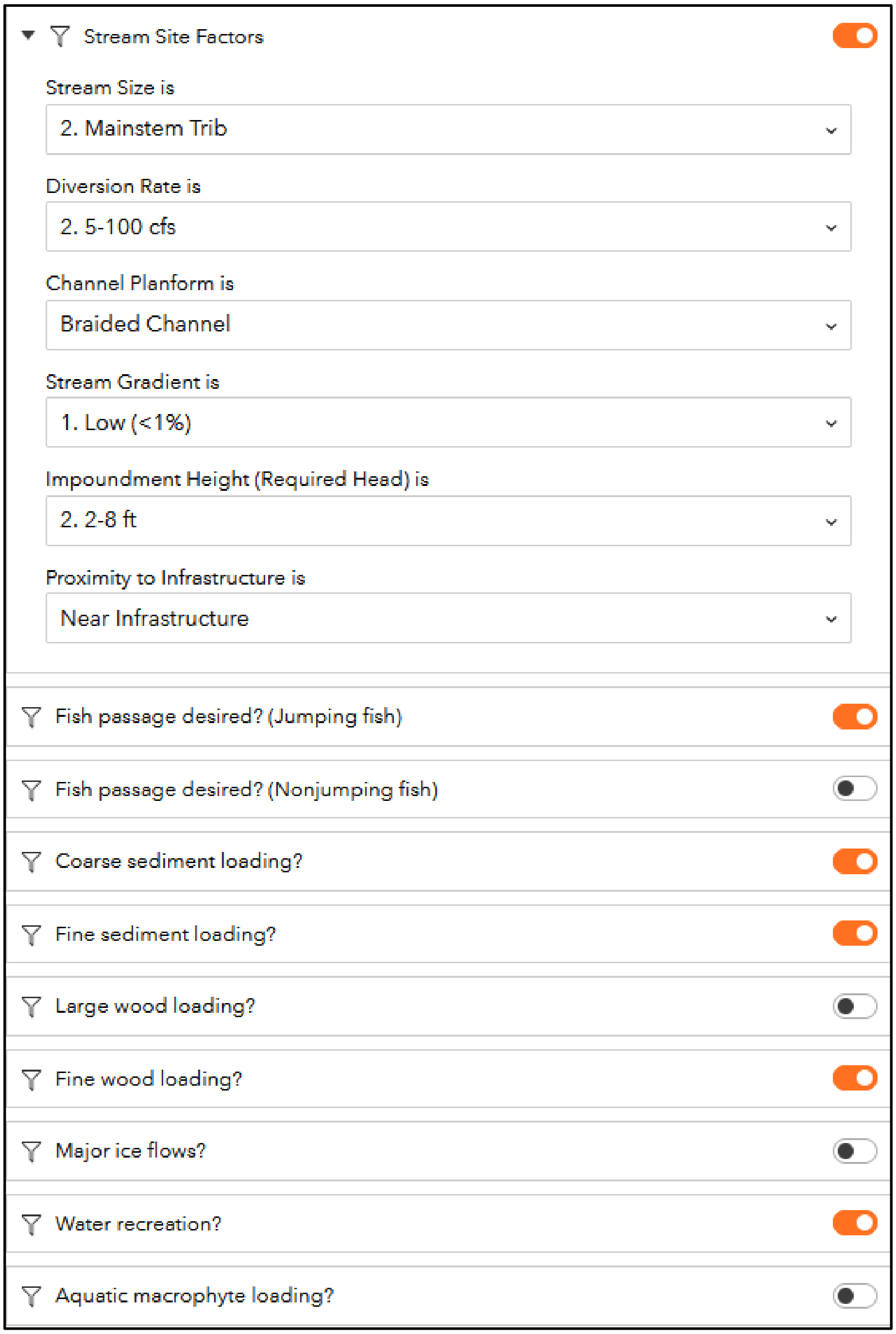

FIGURE 1. INPUT MODULE WHERE THE USER SELECTS THE APPROPRIATE SITE-SPECIFIC CONDITIONS.

Once the user submits answers to the site factor questions, they can proceed to a graphical representation of the predicted fit between diversion site and diversion mechanism.

The output or response in the Chart (Figure 2) is Relative Compatibility, with larger positive numbers indicating greater compatibility between site and mechanism and negative numbers indicating incompatibility between site and mechanism. Structures or mechanisms with similar relative compatibility might work equally well at the same or different sites. Note, however, that the most compatible structures in concept might not be the best or most feasible choice for a specific site. The user must determine which diversion mechanism best suits their site requirements, budget, and operational capacity. Moreover, the intent of the exercise is only to inform or support a decision. By selecting one or more blue bars, the user can create a subset of diversion mechanism for further exploration.

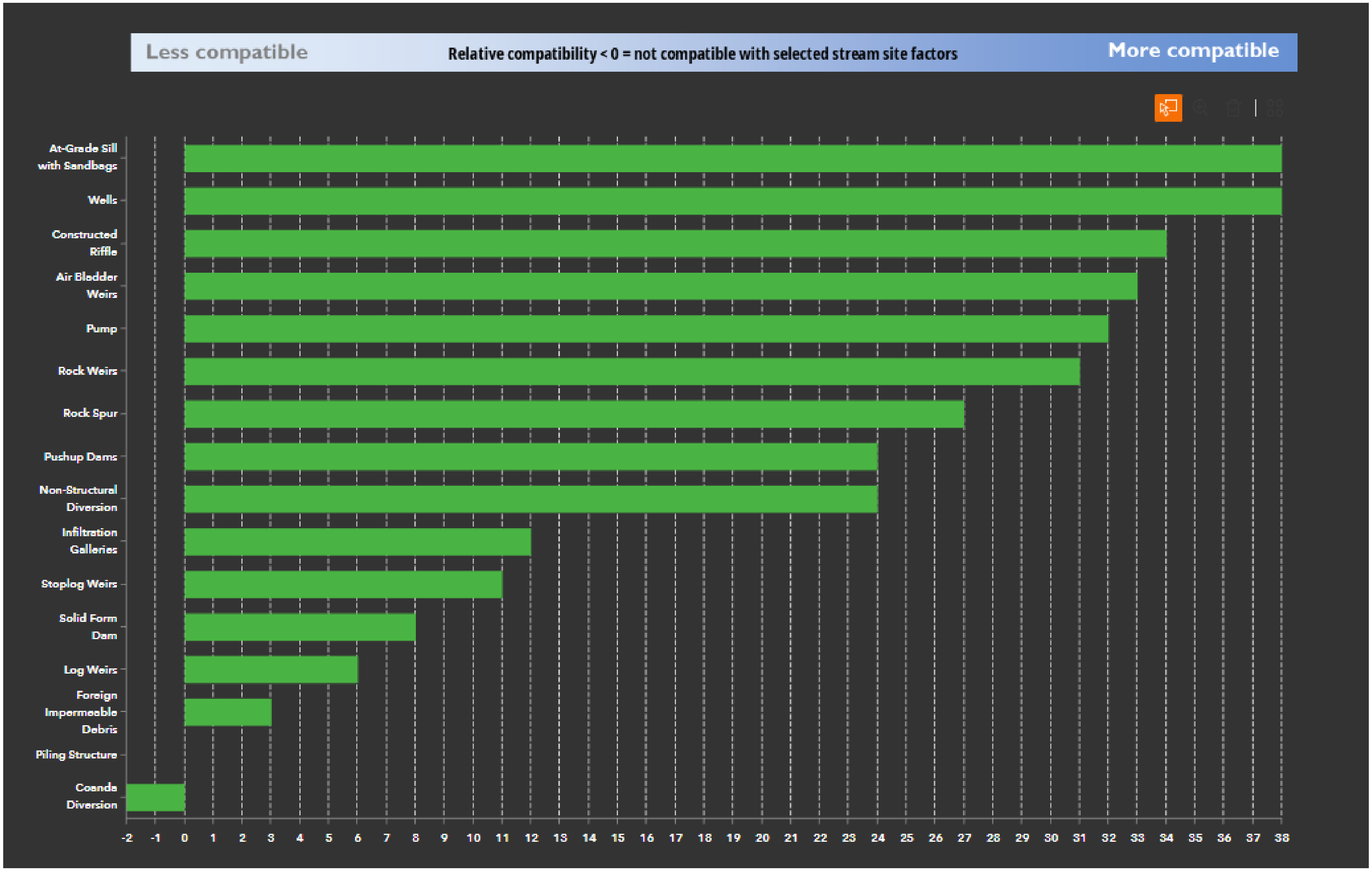

FIGURE 2. TOOL OUTPUT DISPLAYING RELATIVE COMPATIBILITY BETWEEN THE EXAMPLE SITE (SEE FIGURE 1) AND16 DIFFERENT DIVERSION MECHANISMS.

Impacts of Diversion Structures on Rivers and Streams

An effective diversion structure will be not only compatible with the river or stream setting (as discussed above), but also robust and resilient. A robust structure will resist change and divert the decreed flow under a range of streamflow conditions. A resilient structure will tend to return to its designed performance following flood or disturbance. Moreover, an effective diversion structure will reliably divert the decreed flow, require little maintenance, and be compatible with river processes, including flooding, material (e.g., wood, sediment) transport, and fish passage. A number of resources cover these topics in great detail (e.g., Axness and Clarkin 2013; Sholtes et al. 2017). For purposes of this document, we include here a short introduction to some of the natural processes and systems within which diversion structures reside.

River Processes and Diversion Infrastructure

River corridors are comprised of the channel(s), fluvial deposits, floodplain, and adjacent riparian zone (Harvey and Goosef 2015). Within river corridors, water, sediment, wood, and organisms travel downstream and laterally during floods as water carries them out across floodplains (Wohl 2017). Aquatic organisms might also travel upstream to fulfill life history requirements (see next section). Both lateral and longitudinal (upstream-downstream) connectivity of river corridors are therefore an important aspect of healthy rivers and the ecosystems they support.

Diversion infrastructure can disrupt longitudinal connectivity by blocking upstream and downstream migration of aquatic organisms, and by disrupting the natural downstream flow of water, sediment, and wood. Diversions can impound or trap water, sediment, and wood; increase or reduce local slope; and altering hydraulic conditions for swimming organisms. Additionally, diversion structures can create hydraulic conditions that accelerate scour and result in negative geomorphic and habitat outcomes (Sholtes et al. 2017).

Stream channel(s) within an alluvial river corridor typically naturally migrate across and down their floodplains as outer banks are eroded and points bars and islands are constructed. This channel migration supports the formation and evolution of side channels and floodplain wetlands, which can play a critical role in the life cycle of many aquatic species (Trush et al. 2000; Florsheim et al. 2008; Kondolf 2011). Channel migration also supports the natural succession of many native riparian plants that are dependent on disturbances (Scott et al. 1996). As such, channel migration helps create the complex riparian and floodplain habitat that is integral for healthy riverine ecosystems.

Not all reaches or channel segments within a river exhibit the same tendency for lateral migration, as this tendency is influenced by valley width, slope, and upstream sediment supply. Following the river corridor "strings and beads" concept, reaches that behave more like strings (e.g., relatively narrow, steep valleys) tend to exhibit less lateral migration than reaches that behave like beads (e.g., relatively wide, flat valleys; Wohl et al. 2018). Nevertheless, all river corridors exhibit some level of dynamism.

Channel spanning features like a diversion structure can impede natural channel migration processes by artificially inserting a hard point within a river corridor. Though this hard point may be necessary for water diversion, it can disrupt incremental channel migration and force a channel to remain static. By reducing flow downstream, diversion structures can also influence channel morphology and riparian ecology. For example, diversions in small mountain streams were found to create deeper, slower flowing channel conditions downstream with greater fine sediment in the bed (Baker et al. 2011; Caskey et al. 2014). Alternatively, a diversion structure might trigger sediment accumulation (i.e., aggradation) and give rise to an artificially wide and shallow condition upstream by reducing sediment transport (Stamp and Schmidt 2006).

Fish Passage Considerations

Fish require different habitats throughout their life and will travel considerable distances, both upstream and downstream, to access those habitats (Brown and Mackay 1995; Schoby and Keeley 2011; Hodge et al. 2017). Fish passage is the ability of fish and other aquatic organisms to move volitionally between different habitats.

Physical instream features, including water diversion structures, can inhibit or altogether block fish passage (Schmetterling 2003; Gibson et al. 2005; Richer et al. 2020a). Different fish species have different swimming and jumping abilities and when the height of a structure (e.g., a water diversion) exceeds the jumping performance of fish and/or velocities over the structure exceed the swimming performance of fish, an obstacle to upstream migration exists (Castro-Santos 2006; Kondratieff and Myrick 2006). Entrainment of fishes into irrigation ditches and canals can be a significant impediment to downstream fish passage. For example, a water conveyance system can become a population sink when fish are capable of making it into, but not out of, a ditch or canal (Roberts and Rahel 2008; but see Carlson and Rahel 2007). Fish screens and behavioral guidance systems (e.g., electric barriers) can be effective tools for reducing rates of entrainment (Gale et al. 2008; Kowalski et al. 2022). Because maintenance of fish passage requires technical, species-specific considerations, aquatic biologists should be consulted during the early planning stages of a project (Richer et al. 2020b).

During the design of new or retrofitted diversion structures, consideration of the type of fish for which upstream and downstream passage could be improved can increase the likelihood of facilitating fish passage. One strategy is to divide the overall height of one structure into multiple structures with smaller heights. Example diversion structures that use this strategy include rock and log weirs. Fishways or other engineered devices might also be incorporated into taller diversion structures, such as solid form dams.

Another successful strategy, especially with non-jumping fish, is to extend the length of the diversion structure, thereby reducing slope and water velocity. Typical diversion structures create a singular distinct elevation change within the river channel like a waterfall. However, the same effect of raising a body of water's elevation can be achieved by creating a ramp. Factors such as length, slope and width of the ramp can create hydraulic conditions that are more favorable to up- and downstream passage. Example diversion structures to create this ramp effect are constructed riffles.

Diversion structures that do not span the channel can be more compatible with fish passage objectives. Year-round fish passage can be achieved with infiltration galleries, wells, pumps, rock spurs, and non-structural diversions. Fish passage might also be achieved on a seasonal basis by using air bladder weirs, at-grade sills with sandbags, stoplog weirs, and pushup dams.

River Impact Scores

The Diversion Selection Tool considers all diversion mechanisms of interest (i.e., all user-selected mechanisms) in light of river processes. Each mechanism is evaluated based on the predicted relative impact on the processes of water, sediment, and wood transport; channel migration; and fish passage (upstream and downstream). Also considered are relative risks of dewatering and relative hazard to recreational boaters. The individual scores from each of five categories are summed into a single River Impact Score (Figure 3; Table 1). Higher scores (out of 25) correspond with more desirable conditions: fewer relative impacts on physical and biological river processes.

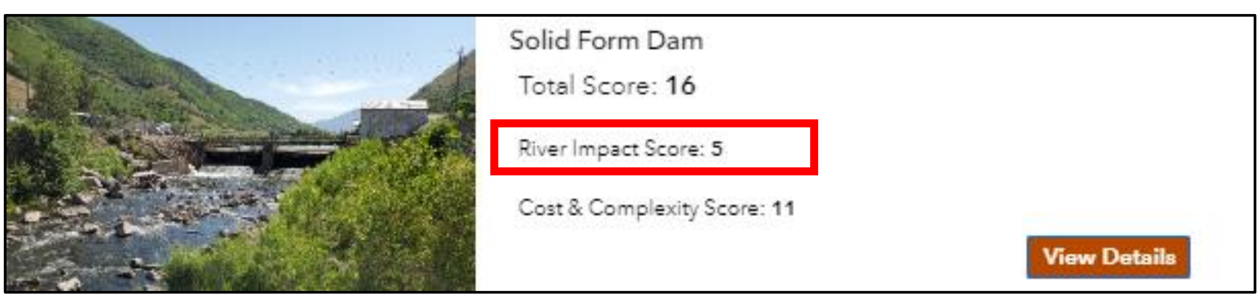

FIGURE 3. AN EXAMPLE OF THE RIVER IMPACT SCORE REPORTED FOR EACH INDIVIDUAL DIVERSION MECHANISM.

Table 1. Diversion impacts on river processes

Diversion Mechanism	Water Surface	Channel Spanning	Engineered	Permanent Footprint	Impact on River Process	Impact on Fish Passage	Dewatering Risk	Entrainment Potential	Recreation Risk	River Impact Score
Wells	Off-Channel	Off-Channel	Yes	Yes	5	5	5	5	5	**25**
Infiltration Galleries	Variable	No	Yes	Yes	5	5	4	5	5	**24**
Non-Structural Diversion	Permanent	Yes	No	No	5	5	4	3	5	**22**
In-Channel Pump	Variable	No	Yes	No	5	5	3	3	5	**21**
Rock Spur	Permanent	No	Yes	Yes	4	3	4	4	4	**19**
Coanda Diversion	Permanent	Sometimes	Yes	Yes	3	4	3	5	3	**18**
At-Grade Sill with Sandbags	Adjustable	Sometimes	Sometimes	No	4	3	2	3	5	**17**
Constructed Riffle	Permanent	Yes	Yes	Yes	3	4	3	3	4	**17**
Pushup Dams	Adjustable	Sometimes	No	No	4	3	2	3	3	**15**
Log Weirs	Permanent	Yes	Sometimes	Yes	2	3	3	3	3	**14**
Rock Weirs	Permanent	Yes	Yes	Yes	2	3	3	3	3	**14**
Air Bladder Weirs	Adjustable	Yes	Yes	Yes	4	3	1	2	2	**12**
Stoplog Weirs	Adjustable	Yes	Yes	Yes	3	3	1	2	2	**11**
Foreign Impermeable Debris	Adjustable	Sometimes	No	No	3	3	2	1	1	**10**
Piling Structure	Permanent	Yes	Yes	Yes	1	1	1	1	1	**5**
Solid Form Dam	Permanent	Yes	Yes	Yes	1	1	1	1	1	**5**

NOTE: 5 = Low negative impact, 1= High negative impact. Higher river impact scores correspond with more favorable conditions (i.e., fewer negative impacts on river processes).

Cost and Complexity of Diversion Structures

For the owner and operator of a diversion structure, cost and complexity are necessary considerations. Cost considerations include not only the one-time expense of construction, but also the long-term expense of operation and maintenance. Complexity factors can include, among other things, the number of moving or moveable parts in a diversion, permitting processes, and legal implications of a particular diversion mechanism.

Operation, Maintenance, Repair, Replacement, and Rehabilitation

Water diversion structures are subjected to floods, wood and sediment transport, ice jams, and/or other environmental forces that can impact function and trigger necessary action. Once constructed, a diversion structure requires operation, maintenance, repair, rehabilitation, and replacement (OMRR&R), the collective goal of which is to maintain a structure at “as-built” or acceptable conditions and performance over the structures’ lifespan.

The following items might be considered in evaluating the OMRR&R needs of a particular diversion project:

- Operation.— Human control of adjustable or changing features, including power consumption and network and utilities fees. Operation also includes regular monitoring, inspection, data collection, and reporting.
- Maintenance.—Routine, planned, and scheduled upkeep of project features, equipment, and/or supplies.
- Repair.—Unscheduled correction of damage resulting from environmental events, vandalism, or other unforeseen circumstances.
- Rehabilitation.—Corrections to un-anticipated hydraulics, shifting, wear and tear, weathering, or material degradation, all with an aim towards improving project performance. Rehabilitation includes resetting features, augmenting features with additional materials, and/or refurbishing features and components.
- Replacement.— Removal, demolition, disposal, and exchange of project features or components that cannot be repaired or rehabilitated.

In general, water diversion structures are designed to minimize long-term requirements for OMRR&R, and structures that are compatible with the natural environment typically incur the lowest OMRR&R costs and efforts. Moreover, accounting for natural processes and the dynamic nature of rivers on the front end can reduce OMRR&R requirements over the long run. Further, understanding the natural processes that result in long-term OMRR&R can help to optimize the up-front capital costs of a project (Figure 4). Because upkeep is required for the duration of a diversion structures’ lifespan, OMRR&R cost estimates typically account for this same time horizon (often 50 years).

Accordingly, the Water Diversion Selection Tool accounts for anticipated OMRR&R requirements across a structures' expected lifetime.

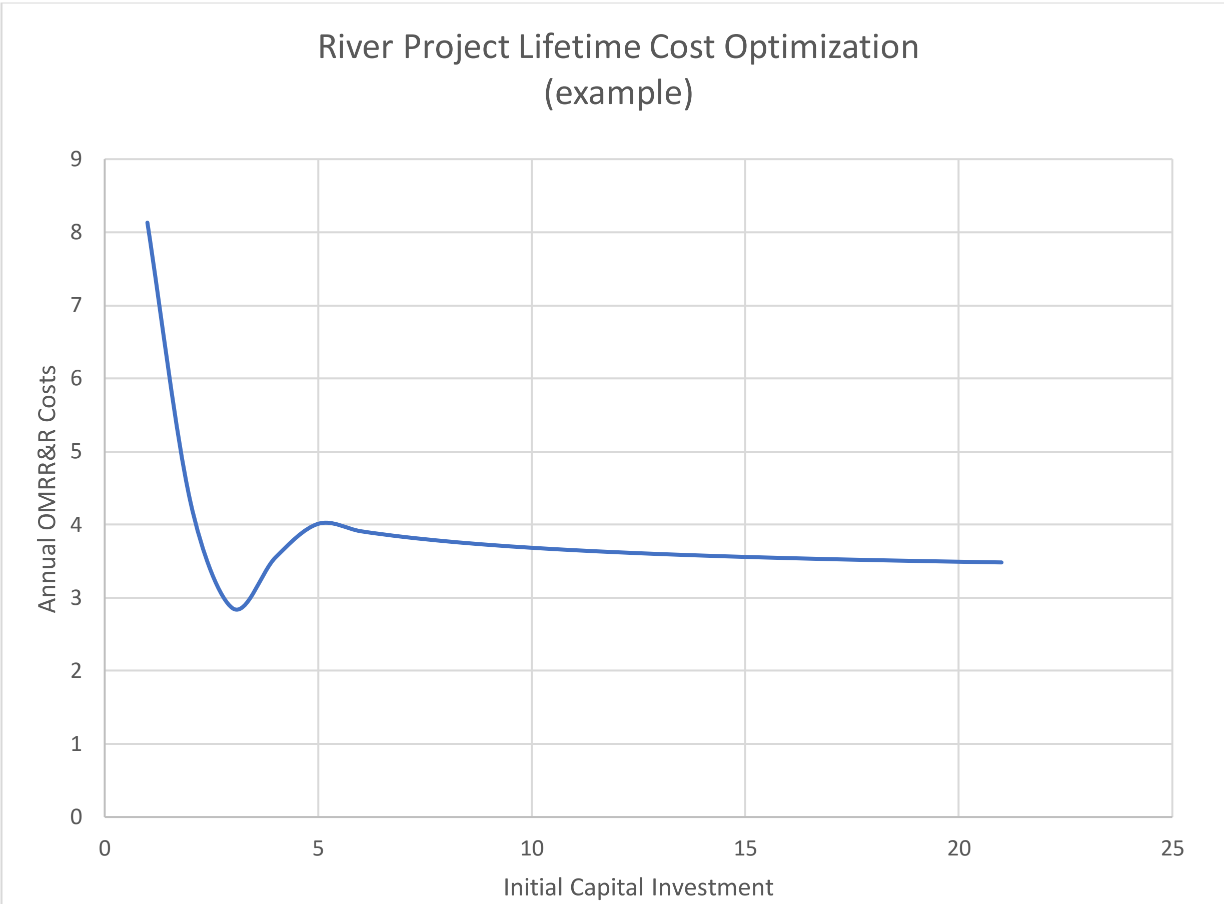

FIGURE 4. RIVER DIVERSION PROJECT LIFETIME COST OPTIMIZATION EXAMPLE (J. CAREY).

Legal complexity

Western water law is far beyond the scope of the Water Diversion Selection Tool and this User Manual. Suffice it to say that choice in diversion structure can have significant legal implications and that legal implications might influence choice in diversion structure. For example, in the State of Colorado, a water right owner cannot convert from diverting surface water to diverting groundwater without entering into the Water Court process (Colorado Revised Statute 37-92-302[1][a]; *Orr vs. Arapahoe Water & Sanitation District 1988)*. The prospect alone of going to Water Court would be a non-starter for the vast majority of diverters in the State. Another potential consideration is water administration, including both the ability of a senior water user to place a call and the ability of a junior user to bypass water during a call. Water administrators in the State of Colorado are typically unwilling to honor calls for water when the requesting water right owner lacks the ability to sweep the river. Consequently, to construct a partially-spanning diversion structure in Colorado is to risk the opportunity to place a call, an implication that may or may not concern an individual water user. The Diversion Selection Tool was designed to work across state and county lines and thus accounts for legal complexity, including permitting constraints, at only a coarse scale.

Cost and Complexity Scores

The Water Diversion Selection Tool considers all diversion mechanisms of interest (i.e., all user-selected mechanisms) in light of cost and complexity. Each mechanism is evaluated based on the predicted relative costs of construction and maintenance and operational and legal complexities (including permitting). Also considered is risk of flood-related damage, both to the structure and surrounding area. The individual scores from each of five categories are summed into a single Cost and Complexity Score (Figure 5; Table 2). Higher scores (out of 25) correspond with more favorable conditions—namely, lower risk, cost, and complexity. Nevertheless, individual cost and complexity components might be more or less pertinent to a particular project.

FIGURE 5. AN EXAMPLE OF THE COST AND COMPLEXITY SCORE REPORTED FOR EACH INDIVIDUAL DIVERSION MECHANISM.

TABLE 2. DIVERSION MECHANISM COST AND COMPLEXITY EVALUATION

Diversion Mechanism	Construction Cost	O & M Costs	Operational Complexity	Legal Complexity	Flood Damage Risk	Cost and Complexity Score
Non-Structural Diversion	5	3	5	4	4	**21**
Rock Spur	4	4	5	4	3	**20**
Pushup Dams	5	2	4	5	4	**20**
Log Weirs	3	4	5	4	3	**19**
Foreign Impermeable Debris	5	3	5	5	1	**19**
Rock Weirs	3	3	5	4	3	**18**
Constructed Riffle	2	4	5	3	3	**17**
Stoplog Weirs	3	3	4	3	3	**16**
At-Grade Sill with Sandbags	4	2	1	5	4	**16**
Piling Structure	1	5	5	1	3	**15**
Wells	2	1	4	1	5	**13**
In-Channel Pump	2	1	3	4	3	**13**
Infiltration Galleries	1	2	1	2	5	**11**
Coanda Diversion	2	1	3	2	3	**11**
Solid Form Dam	1	2	3	1	4	**11**
Air Bladder Weirs	1	1	1	2	4	**9**

NOTE: 1 = High cost and complexity, 5 = Low cost and complexity. Higher scores correspond with preferred conditions (i.e., little cost and complexity in terms of permitting, construction, operation, and maintenance).

All Things Considered

The final output of the Water Diversion Selection Tool is a Total Score comprised of both River Impact and Cost and Complexity scores (Figure 6).

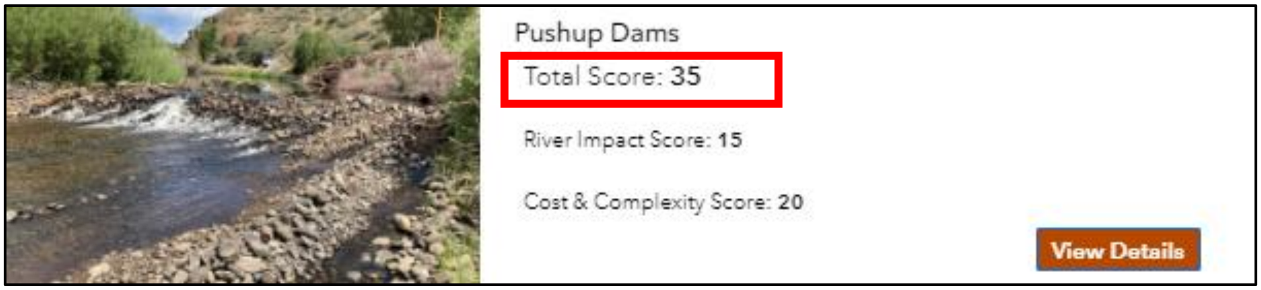

FIGURE 6. EXAMPLE OF A TOTAL SCORE FOR A DIVERSION MECHANISM.

The Total Score reflects an equally weighted sum of the two scores and thus represents a balance between considerations of river processes, cost, and complexity (Table 3).

TABLE 3. SUMMARY OF SCORES BY DIVERSION MECHANISM.

	Score		
Diversion mechanism	River Impact	Cost and Complexity	Total
Non-Structural Diversion	22	21	43
Rock Spur	19	20	39
Well	25	13	38
Pushup Dam	15	20	35
Infiltration Gallery	24	11	35
Constructed Riffle	17	17	34
In-Channel Pump	21	13	34
Log Weir	14	19	33
At-Grade Sill with Sandbags	17	16	33
Rock Weir	14	18	32
Foreign Impermeable Debris	10	19	29
Coanda Diversion	18	11	29
Stoplog Weir	11	16	27
Air Bladder Weir	12	9	21
Piling Structure	5	15	20
Solid Form Dam	5	11	16

References

Axness, D.S. and K. Clarkin. 2013. Planning and Layout of Small Stream Diversions. USDA Forest Service, National Technology & Development Program. 188p.

Baker, D. W., B. P. Bledsoe, C. M. Albano, and N. L. Poff. 2011. Downstream effects of diversion dams on sediment and hydraulic conditions of Rocky Mountain streams. River Research and Applications 27:388-401.

Brown, R. S., and W. C. Mackay. 1995. Fall and winter movements of and habitat use by Cutthroat Trout in the Ram River, Alberta. Transactions of the American Fisheries Society 14:873-885.

Carlson, A. J, and F. J. Rahel. 2007. A Basinwide Perspective on Entrainment of Fish in Irrigation Canals. Transactions of the American Fisheries Society 136:1335-1343.

Caskey, S. T., T. S. Blaschak, E. Wohl, E. Schnakenburg, D. M. Merrit, and K. A. Dwire. 2015. Downstream effects of stream flow diversion on channel characteristics and riparian vegetation in the Colorado Rocky Mountains, USA. Earth Surface Processes and Landforms 40:586-598.

Castro-Santos, T. 2006. Modeling the Effect of Varying Swim Speeds on Fish Passage through Velocity Barriers. Transactions of the American Fisheries Society 135(5):1230-1237.

Florsheim, J. L., J. F. Mount, and A. Chin. 2008. Bank erosion as a desirable attribute of rivers. Bioscience 58:519-529.

Gale, S. B., A. V. Zale, and C. G. Clancy. 2008. Effectiveness of Fish Screens to Prevent Entrainment of Westslope Cutthroat Trout into Irrigation Canals. North American Journal of Fisheries Management 28(5):1541-1553.

Gibson, R. J., R. L. Haedrich, and C. M. Wernerheim. 2005. Loss of fish habitat as a consequence of inappropriately constructed stream crossings. Fisheries 30(1):10-17.

Harvey, J, and M. Goosef. 2015. River corridor science: Hydrologic exchange and ecological consequences from bedforms to basins. Water Resources Research 51:6893-6922.

Hodge, B. W., K. D. Battige, and K. B. Rogers. 2017. Seasonal and temperature-related movement of Colorado River cutthroat trout in a low-elevation, Rocky Mountain Stream. Ecology and Evolution 7:2346-2356.

Kondolf, G. M. 2011. Setting goals in river restoration: when and where can the river ‘heal itself’? Pages 29-43 in A. Simon, S. J. Bennett, and J. M. Castro, editors.

Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools. Geophysical Monograph Series 194, American Geophysical Union, Washington D.C.

Kondratieff, M. C., and C. A. Myrick. 2006. How High Can Brook Trout Jump? A Laboratory Evaluation of Brook Trout Jumping Performance. Transactions of the American Fisheries Society 135:361-370.

Kowalski, D. A., E. I. Gardunio, and C. A. Garvey. 2022. Evaluating the effects of an electric barrier on fish entrainment in an irrigation canal in Colorado. River Research and Applications 38:539-547.

Richer, E. E., E. R. Fetherman, E. A. Krone, F. B. Wright III, and M. C. Kondratieff. 2020a. Multispecies Fish Passage Evaluation at a Rock-Ramp Fishway in a Colorado Transition Zone Stream. North American Journal of Fisheries Management 40:1510-1522.

Richer, E. E., M. C. Kondratieff, B. F. Atkinson, and K. R. Bakich. 2002b. Stream Restoration, Fish Passage, and Stream Stabilization Projects: Guidance for Reviewing 4040 Projects. Colorado Parks and Wildlife Aquatic Research Section, Fort Collins. CO.

Roberts, J. J., and F. J. Rahel. 2008. Irrigation Canals an Sink Habitat for Trout and Other Fishes in a Wyoming Drainage. Transactions of the American Fisheries Society 137:951-961.

Schmetterling, D. A. 2003. Reconnecting a fragmented river: movements of Westslope Cutthroat Trout and Bull Trout after transport upstream of Milltown Dam, Montana. North American Journal of Fisheries Management 23:721-731.

Schoby, G. P., and E. R. Keely. 2011. Home range and foraging ecology of Bull Trout and Westslope Cutthroat Trout in the upper Salmon River basin, Idaho. Transactions of the American Fisheries Society 140:636-645.

Scott, M. L., J. M. Friedman, and G. T. Auble. 1996. Fluvial process and establishment of bottomland trees. Geomorphology 14:327-339.

Sholtes J. S., C. Ubing, T. J. Randle, J. Fripp, D. A. Cenderelli, and D. C. Baird. 2017. Managing Infrastructure in the Stream Environment. Advisory Committee on Water Information, Subcommittee on Sedimentation. 65p.

Stamp, M. L., and J. C. Schmidt. 2006. Predicting channel response to flow diversions. Stream Notes. Rocky Mountain Research Station, Fort Collins, CO. Available: https://www.fs.usda.gov/biology/nsaec/assets/sn_10_06.pdf

Trush, W. J., S. M. McBain, and L.B. Leopold. 2000. Attributes of an alluvial river and their relation to water policy and management. Proceedings of the National Academy of Sciences, 97(22):11858-11863.

Wohl, E. 2017. Connectivity in rivers. Progress in Physical Geography: Earth and Environment 41(3):345-362.

Wohl, E., K. B. Lininger, and D. N. Scott. 2018. River beads as a conceptual framework for building carbon storage and resilience to extreme climate events into river management. Biogeochemistry, 141(3):365-383.

Appendix A: Channel-Spanning Diversion Structures

Channel spanning diversions are suitable when moderately high head is needed to gravity feed water to a headgate and ditch system. The requirement for a high-head diversion is sometimes owing to channel incision or inefficient headworks. The headgate and ditch should be evaluated for efficiency, which might help reduce the head requirement. The following pages include examples of diversion structures that span the width of the channel and raise the upstream water elevation to provide head for diverting water to a nearby ditch or canal.

Air Bladder Weir

An air bladder weir consists of a pneumatically-actuated gate, which is typically supported by a channel spanning at-grade concrete sill with abutments and cut-off walls to provide structure stability. Air bladder weirs provide a feasible option for required diversion head ranging from approximately 3 feet to up to 8 feet with span lengths of 300 feet or more. Multiple bladders can be installed end to end to increase the maximum practical span length or to increase river level control.

Air bladder weirs require mechanical equipment to provide large, compressed air volumes to allow for the inflation and deflation of the rubber bladder. The mechanical equipment will typically require grid power for operation but solar power with battery arrays could be an option for smaller installations.

Air bladder weirs should be expected to create a significant barrier to upstream fish passage when closed (raised). A dedicated constructed fishway may be prudent to provide passage. Air bladder weirs are typically raised (closed) at low flow and lowered (open) at high flow and set intermediate at average flows. These work well in streams with high bed load, icing, and debris potential. Air bladder height can be adjusted relatively quickly or can be automated to respond to continuous changing flow events.

Initial project costs are high due to the amount of infrastructure involved, but in comparison to structures of a similar size magnitude, project costs are comparable to or lower than other infrastructure intensive options, such as solid form dams. Implementation costs will exceed $500K for a small installation. Air bladder weir operation and maintenance requires a relatively high level of training due to the presence of electrical and mechanical systems. The air bladder portion of the structure has a normal expected life span of approximately 30 years and may need replacement over the diversion lifetime.

At-Grade Sill with Sandbags

A rock or concrete sill spanning the channel serves as a platform for a temporary dam constructed with sandbags (place by hand or with heavy equipment) installed seasonally to divert flow. After the irrigation season ends, the sandbags are removed until they are needed in the subsequent irrigation season.

This relatively simple diversion mechanism requires some engineering design for the sill placement and construction. It also requires seasonal maintenance in placing and removing the sandbags as well as weekly to monthly inspections to ensure the sandbags remain in place. If “big bags” (1 cubic yard) are used, then access for heavy equipment is required.

This diversion mechanism can be compatible with river processes and fish passage as the sandbags are only placed seasonally, which may be timed to coincide with certain fish migration and spawning periods. The upstream head or impoundment height they create may be limited by the number of rows of sandbags feasibly stacked at a given site and will almost certainly be less than five feet, ranging from the one to three feet head height most typically.

Constructed Riffle

These types of diversions use natural materials to create grade control that mimics natural features and processes in a riffle pool morphology providing a specified water surface elevation at the upstream end that allows water users to divert.

Constructed riffles are best applied at sites where the diversion height is less than 6 feet and in streams with existing gravel cobble substrate and limited or controlled lateral migration. The longitudinal slope of the riffle is typically 40:1 or flatter. Boulder-sized material may be used as grade control at the riffle crest and within the downstream ramp portion of the riffle with native material sized to mobilize at a certain flood frequency used as fill. In streams with gradients in excess of 4% it becomes challenging to utilize constructed riffles as drops become more prevalent, increasing the material size, length and cost of the constructed riffle. Seepage flow through the constructed riffle may also be a design consideration, especially for low flows.

When designed properly, the maintenance costs of a constructed riffle should be relatively small. Post flooding, the riffle may shift and inspection should occur to verify that the basic head, shape, grade and materials are as designed. As these are typically not grouted, adjustments to the structure may be made over time, potentially requiring the use of a heavy equipment.

Constructed riffles are compatible with fish passage and sediment transport, and generally resilient to impacts of flooding. Channel migration can present a challenge to use of constructed riffles, but risk of migration might be reduced by stabilizing streambanks and/or installing cutoff sills.

Foreign Impermeable Debris

Un-designed diversions constructed out of foreign impermeable debris are commonly used check structures that utilize available material to divert water; usually for moderate head loss less than 6 feet. These materials can include tarps, poles, broken concrete, plastic, or other miscellaneous materials not naturally found in streams. Sometimes these diversions are created by pushing up native substrate in combination with foreign impermeable debris. They can be temporary structures that are only used during the diversion season.

These types of diversions are simple to construct but very unfavorable for a variety of reasons. Foreign impermeable debris can prevent fish passage both upstream and downstream. Materials can easily become dislodged, causing structure failure while also allowing the unnatural materials to wash downstream. An impermeable structure does not allow sediment transfer which can lead to structure failure when too much sediment builds up. Additionally, foreign impermeable debris diversions are typically not designed to withstand flood flows. Due to all these factors, continuous maintenance can be expected and typically requires equipment entering and disturbing the stream channel.

Initial project costs can be very low when materials are on hand, but maintenance costs can be significant. These costs can include regular repair and purchasing of new materials that may wash downstream.

Log Weirs

Log weir diversions are grade control structures constructed out of logs or timbers partially or fully buried in the stream substrate and banks at a fixed elevation; usually for low head (< 4 feet). Ballast is sometimes necessary as well as anchoring including pinning, cables, or chains. Branches and rootwads are removed from the logs prior to installation. Typically log weirs are constructed in a V-shape with the point of the V oriented upstream to concentrate flows in the center of the channel. A notch can be added to log weirs for fish passage during low flows.

This type of diversion is practical where logs can be harvested locally or where hauling other materials to site, like large rock, is unfeasible. Log weirs are appropriate for small streams where the bankfull width is narrow enough for the logs to extend into the banks to prevent outflanking at high flows. Streams with fine-grained soils are not suitable for log weirs as the substrate can leak between and around logs, causing piping, although this may be prevented by using filter fabric. Finding straight, uniform logs can also be a challenge.

Maintenance costs should be low if log weirs are designed and installed properly and if logs are fully submerged at all times. Logs that are exposed out of water for periods of time are prone to decay and will need to be replaced. If filter fabric is used, it can break down over time and lead to erosion. After high flow events log weirs should be inspected for bank erosion, accumulated debris, and scour below or behind the logs. Compromised log weirs are susceptible to washing out during high flow events, causing risk to downstream infrastructure.

Depending on the size of the logs and drop over the structure, log weirs might provide fish passage, sediment transport, and resilience across a large range of flows, but elevations cannot be adjusted once logs are installed. Initial project costs can be low, less than $100k, due to its application in small streams and if materials are available locally, but remote locations may drive prices higher.

Piling Structure

A piling structure is typically installed where groundwater cutoff is needed to push extreme low flows to the surface. These may be constructed of interlocking steel sheet piles or H-piles with steel plates or wood boards spanning between the H-piles or concrete to form a continuous wall. This type of diversion would normally be used in a small cobble/gravel or sand bed system where the individual piles can be mechanically driven into the stream bed. Stream systems with large cobble or boulder sized bed material or bedrock dominated systems require excavation and placement of the pile.

Piling structures are efficient water diversion systems and can be designed to allow for maximum water withdrawals at very low in-stream flow conditions. A piling diversion structure could be utilized for diversions as low as 2 feet high and up to approximately 15 feet high. However, cost factors would be expected to limit the practical application of this type of diversion at either end of the height range.

Piling structures are typically significant fish passage barriers and would be expected to require a dedicated constructed fishway to allow for upstream passage. These types of structures are also highly impactive to river processes as they tend to capture bed load, debris, and ice. Also, as the crest height is typically non-adjustable, they can present an upstream flooding risk unless a spillway or other flood management measures are implemented. Capital costs are high, but annual operation and maintenance costs would be anticipated to be relatively low with most maintenance related to removal of accumulated sediment and debris, and potentially, repairs due to flood impacts.

Pushup Dam

These types of diversions are constructed seasonally by using heavy equipment to push up native stream materials to create a dam. They are often covered in tarps to prevent leakage through the material. This protects the dam and creates the desired water surface elevation upstream of the dam. Generally, at the end of the diversion season, the tarps are removed and natural river processes or flooding remove the dam structure. This type of dam has low capital construction costs.

Pushup dams can be used in most types of shallow streams, limited primarily by heavy equipment access. This type of diversion is also limited to smaller head height differentials, typically less than 4 feet.

The maintenance costs of a pushup dam are directly related to operational costs of the heavy equipment necessary for constructing the pushup dam. Tarps are relatively inexpensive, but do require replacement on a regular basis.

Pushup dams are primarily incompatible with aquatic organism passage and sediment transport when in use. After the irrigation season, pushup dams are typically left in place to be washed out under later flow events. As such, they can pose a barrier to fish passage beyond the irrigation season. Additionally, the annual operation of heavy equipment in the channel to construct these may also impact aquatic life. There is evidence that some fish passage through the structure is possible if the structure is not well sealed by tarps. However, they can provide full aquatic organism passage and sediment transport when they are removed.

Rock Weirs

Rock weirs are grade control structures constructed of large rock installed at a fixed elevation. They can be applied as a single structure or a series of steps to meet the desired diversion elevation with total head differentials generally less than 6 feet. Rocks are sized large enough to remain immobile during high flow events and are typically larger than the natural substrate in the stream. Weirs are oriented in an upstream arch shape to prevent outflanking and bank erosion. Because rock weir structures are naturally permeable, the structure elevation may need to be installed higher than anticipated in order to account for water flowing through the substrate.

Rock weir diversions are practical in streams with step-pool or pool-riffle morphology, gravel and cobble substrate, and stable banks. Locations with sandy soils or streams prone to avulsion are not suitable for rock weirs. Availability of rock can be a factor in cost.

These structures should be inspected for accumulated debris, scour, bank erosion, and shifted rocks after flood events. Expected maintenance can include replacing or resetting shifted rocks to ensure the water surface elevation continues to match the diversion elevation.

Rock weirs are limited to their fixed elevation and may need maintenance after high flow events. They allow for fish and other aquatic species passage at a range of flows due to the multiple flow pathways through the rocks, as well as sediment transport. Initial project costs can vary depending on the size of the stream, from less than $100k to over $500k for large rivers. Continual maintenance can be expected if subjected to flood events since even large, oversized rocks can shift and settle.

Solid Form Dam

These types of diversions typically use concrete or steel to permanently span a channel and create a water surface elevation that allows water diversion. This type of dam has one of the highest capital costs and is typically only cost effective where head differentials greater than 7 feet are required.

This type of diversion can be used in all types of streams and is best applied at sites where diversion of the entire river is needed.

When designed properly, the maintenance costs of a solid form dam are related to debris removal. Depending on the configuration and debris loading, debris removal in front of the diversion can be required daily. No special skills are required for this maintenance. Post flood, the dam should be inspected to verify that undercutting and loss of material around the abutments has not occurred. Repair of solid form dams can be expensive, but solid form dams rarely require repairs.

Solid form dams are incompatible with aquatic organism passage and sediment transport. Permanent fish passage structures or bypass channels are required to facilitate fish passage. They can also create a water fouling scenario due to the stagnant water pooled at the upstream side.

Stoplog Weir

These types of diversions typically use a concrete base located at the riverbed elevation to permanently span a channel. Vertical concrete abutments are located on both sides of the base and include slots for stoplog installation. Stoplogs are typically only used where head differentials are less than 4 feet and the channels are very narrow. Depending on the width of the river, either permanent or removable stanchions are used. Between the abutments or stanchions, stoplogs can be installed to create an upstream water surface elevation that allows water diversion. This type of dam falls mid-pack in terms of capital construction costs.

This type of diversion can be used in most types of streams, but due to the need for manual placement of stoplogs it is best applied at sites where the stream is not prohibitively wide.

The maintenance costs of a stoplog weir are mostly related to debris removal, stoplog installation and stoplog replacement. Depending on the configuration and debris loading, debris removal in front of the diversion can be required daily. No special skills are required for this maintenance. Stoplogs should be adjusted throughout the diversion season and removed post diversion season. No special skills are required for this operation; however, it can be difficult if not impossible to remove stoplogs under high flows. Generally, stoplogs are made from wood that requires replacement every few years.

Stoplog dams are incompatible with aquatic organism passage and sediment transport when stoplogs are in use. However, this diversion mechanism can be designed to provide full aquatic organism passage and sediment transport when the stoplogs are removed.

Appendix B: Partially-Spanning and Subsurface Diversion Structures

Partially-spanning and subsurface diversion structures might involve some in-channel infrastructure to assist in surface flow diversion, but do not span the entire stream channel and/or are installed below or adjacent to the channel. This type of diversion is practical in low-head scenarios (e.g., < 2 feet), where water velocity alone can supply the diversion and where low-flow conditions are infrequent during the irrigation season. Partially-spanning and subsurface diversions can be more compatible with river processes and other stream uses, such as fish passage and boater recreation. However, they come with their own limitations and maintenance requirements; application should be evaluated on a case-by-case basis.

Coanda Diversion

A Coanda diversion is generally a static, self-cleaning intake screen installed in the bottom of a stream channel or constructed side channel to facilitate water diversion. Typically, a curved screen is installed on the downstream side of a fixed concrete weir followed by a sloped acceleration plate. Water flows over the concrete weir and acceleration plate onto the curved screen, which is typically constructed from tilted wedge-shaped wires oriented perpendicular to stream flow. The shape of the screen combined with the wedge wire construction creates a downward force on the water column (Coanda effect) and a shearing effect to force water through the screen and into the diversion.

A Coanda diversion is most effective in stream systems where the diversion is a relatively small percentage of the overall in-stream flow to ensure adequate bypass flow which cleans the screen. This type of diversion also requires a relatively high level of analysis and understanding related to stream hydrology, stream gradient, localized channel hydraulics, diversion rate, bedload mobility potential, icing potential, and debris loading potential to determine if this option is suitable for a given diversion site.

This type of diversion can impede upstream fish migration, particularly at low in-stream flows as the curved screen requires up to several feet of head differential to operate. Fish passage issues can be mitigated by installing the Coanda diversion in a constructed side channel or by installing a fishway at the diversion site. Significant bed load movement, ice jams, and large debris can all present operational and maintenance issues for Coanda diversions. Capital costs can vary widely depending upon the size of the diversion and stream but are comparable to other diversion types requiring concrete and steel infrastructure. Design costs as a percentage of the overall project budget will tend to be higher than other diversion types due to the level of analysis required to ensure a successful project.

Infiltration Gallery

Infiltration galleries function in a similar fashion to a well except that the perforated intake pipe or pipes are oriented horizontally to the ground surface instead of vertically. The intake pipes can be located directly below the stream or off-channel below the local water table. This type of diversion only works well with sites that have coarse subsurface materials that readily allow water to flow through the interstitial spaces between individual particles. Infiltration galleries installed in low permeability soils or in well graded materials that include a silty fraction are prone to failure. Infiltration galleries are also prone to plugging over time due to moss or algae buildup, or other biofouling.

Infiltration galleries can be equipped with backwash systems to reduce the risk of plugging induced failure, but these systems add infrastructure cost and complexity. For an infiltration gallery to be effective over the long term, a significant understanding of the native subsurface materials and groundwater hydrology is required, and they should only be installed where these conditions are nearly ideal.

Design and implementation costs are typically high in comparison to other diversion types, and combined with a relatively high risk of failure, this type of diversion is often only suitable for owners willing to accept the operational risks and high overhead and maintenance requirements.

As infiltration galleries are installed below the stream bed with no in-stream infrastructure (post construction), they will typically have no adverse impact on fish passage, stream function, debris movement, or flood risk.

Rock Spur

Rock spurs or vanes provide velocity heading on the diversion side of a stream using large rock installed at a fixed elevation. They are constructed with rock sized large enough to remain immobile during high flow events and are oriented at an angle pointed upstream. The crest elevation of a rock spur is lower toward the center of the stream than at the bank to prevent bank erosion. Since rock spurs span only part of the channel, they accommodate fish passage and debris and sediment transport well.

This type of diversion is practical where the amount of water being diverted is only a small portion of the overall stream flow and must be placed to take advantage of stream flow lines that encourage water diversion but not sediment diversion. They should also be used where an impounded head differential is necessary to divert the required flow rate.

Rock spurs are limited to their fixed elevation and may need maintenance after high flow events. They should be inspected for scour, bank erosion, and shifted rocks after flood events. Expected maintenance can include replacing or resetting shifted rocks to ensure the water surface elevation continues to match the diversion elevation.

Initial project costs can vary depending on the size of the stream and availability of rock but will be lower than channel spanning structures like constructed riffles and rock vanes. Continual maintenance can be expected if subjected to flood events since large, oversized rocks can shift and settle over time.

Non-Structural Diversion

Under certain circumstances, a structure elevating the head of stream flow to facilitate diversion into a canal may not be required. A non-structural diversion involves an off-channel intake, typically with a headgate, drawing water into a canal. The velocity head of flow (1.5 feet of head for every 10 feet per second of velocity) drives the flow diversion. Geomorphic features such as islands, side channels, oxbows, or anabranching streams can facilitate such flow diversion as pictured here. Headgates or other flow control structures within the off-channel intake may be required to control the diverted flow rate. Rock spurs may also be installed in conjunction with a non-structural diversion to enhance flow withdrawal.

Because no formal diversion structure is involved, non-structural diversions are relatively compatible with rivers and can be low maintenance in many circumstances. Without proper screening, they may entrain fish (like any diversion structure). However, these diversions may be more susceptible to evolving stream conditions including channel migration and side channels or oxbows silting in over time. Therefore, non-structural diversion face many of the same challenges that structural diversions face given the desire to maintain a reliable flow rate from a certain location along a dynamic river.

Pumps

Pumps may be installed on the side of a river to divert flow into irrigation conveyance structures. They may be designed to provide a range of pressures or head to overcome elevation differences as well as flow rates.

Pump diversions often require a secondary form of diversion structure to maintain sufficient water depth for the pump intake to remain submerged, particularly at low in-stream flows. The need for a secondary diversion structure can be reduced or eliminated by moving the pump intake to an off-channel location constructed at an elevation below the bottom of the stream channel in the form of a constructed basin. Also, when pumping from a larger river or reservoir, floating intakes can be used or minimum stream flows may be sufficient such that a secondary diversion structure or off-channel intake may be unnecessary.

Pump systems will typically require an intake screen to prevent debris from entering the pump intake. When fisheries impacts are a concern, the pump intake needs to be designed to minimize or eliminate fish mortality through entrainment or impingement on the fish screen.

On-channel pump diversions are susceptible to damage from high flows, debris, and icing issues, potentially requiring that the pump intake be temporarily removed from the waterway seasonally or during high-risk events. Off-channel pump installation will greatly reduce or mitigate these risks.

Unless a secondary diversion structure is required, pump systems typically do not adversely affect fish passage, and have the added benefit that diversion rates are typically independent from in-stream flow and relatively constant regardless of in-stream water depth. Diversion rates can also be readily measured for monitoring purposes.

Pump systems will require either grid power or a generator for operation, leading to relatively high ongoing operating costs. Pumps can also require complex maintenance that the end user is not qualified to perform. Design and implementation costs are all typically relatively high. When grid power is not readily available, the cost to extend grid power to a remote site is often prohibitive while generator driven systems are expensive to operate and require a high level of maintenance.

Wells

Wells utilize pumps to create the head differential and are typically constructed off-channel to allow for the abandonment of an existing in-channel diversion. By removing the in-channel diversion, fish passage and river processes can often be largely returned to a natural, unmanaged state. Wells installed near rivers typically interface with the surficial water table or alluvial aquifer and can impact stream flow. A single well or series of wells can be installed with well screen diameters, depths, and pumps sized to produce a wide range of flow rates. However, a single well is typically limited to less than 1 ft^3/s or 450 gallons per minute (up to 800 GPM) depending on aquifer and well properties as well as the pump size.

A significant challenge of replacing an on-channel diversion with an off-channel well relates to Western water law. Often, it is legally very difficult to transfer the priority date for a senior on-channel water right to a new off-channel well. The water right for a new well might be assigned a priority date based on the timing of when the well is put into service. Few water right holders are open to exchanging a senior priority date for a significantly more junior priority date. However, the legal complexity of transferring an in-channel diversion to an off-channel diversion will vary depending on the water district and state.

Wells are also likely to increase operation and maintenance costs, particularly if the well is replacing a gravity irrigation diversion, due to the addition of power costs for pumping. Design and implementation costs should be similar to any other system that utilizes pumping.

As grid power is required to operate this type of system, it is imperative that grid power already be near the project site as the cost to extend grid power long distances is often prohibitive for a given project size. It is also important to have a good understanding of the local geology and groundwater hydrology characteristics to ensure project success. An inherent risk of drilling a new well is that a significant portion of the overall project budget can be expended only to discover that the well will not produce sufficient flow to meet the needs of the project.