OptiPass™

The Migratory Fish Passage Optimization Tool

Version 1.1.2 User Manual

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1. Overview

OptiPass^{TM} is a Microsoft Windows® based program for optimizing the mitigation of artificial barriers, which block or otherwise reduce the dispersal of diadromous (aka migratory) fish. The program integrates information on barrier passability (upstream and or downstream), mitigation cost, and potential river habitat gain for one or more target species in order to identify cost-efficient passage improvement strategies. Critically, OptiPass employs state-of-the-art optimization modeling and solution techniques, explicitly taking into consideration the spatial structure of barriers and the interactive effects of passage improvement on longitudinal connectivity. Optimization based methods provide a systematic and objective means of targeting barrier mitigation actions which maximize restoration gains given available resources. OptiPass represents a radical improvement over the ad-hoc methods commonly used in barrier prioritization planning.

OptiPass comes replete with a graphical user interface to quickly and easily generate optimized solutions. Additional functionalities have been built into OptiPass for performing batch runs across a range of budget values, varying the weights placed on different target species, and carrying out more detailed "what-if" type analyses such as changing the spatial focus (i.e., selecting subsets of watersheds for detailed study) and forcing specific barriers in or out of the final optimal solution. Besides being useful for strategically targeting high impact barriers within a given area that yield the "biggest bang for the buck," OptiPass can also be used in a variety of other ways such as in the short-listing of projects submitted for potential funding and helping to identify appropriate levels of investment in barrier mitigation that meet defined policy planning goals.

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3. Preliminaries

3.1 Barrier Mitigation

The effects of river infrastructure on fish and other aquatic organisms are well documented. In-stream structures often form physical barriers that prevent or otherwise reduce fish access to essential breeding and rearing habitat. The consequences of this include reduced fish productivity and abundance, restricted range size, and changes in aquatic community composition.

Given the significant problems associated with artificial barriers, mitigation actions designed to increase fish passage are increasingly being regarded as one of the most effective and cost-efficient means of watershed restoration (Bednarek 2001; Roni et al. 2002, 2008; OWEB 2004; Bernhardt et al. 2005; Fullerton et al. 2009). Barrier mitigation can take a number of different forms. Typical actions include: repair, retrofitting or replacement of culverts and other stream crossings (e.g., installation of baffles, slope realignment, boulder/substrate placement inside or at the outlet of a structure); placement of screens at diversion inlets; construction of rock ramps, fish ladders, lifts and other types of fish passes (usually on larger dams and weirs); modification (e.g., notching) or partial removal (e.g., leaving the abutment or base) of dams and weirs; and, in some cases, complete removal of legacy or high impact barriers.

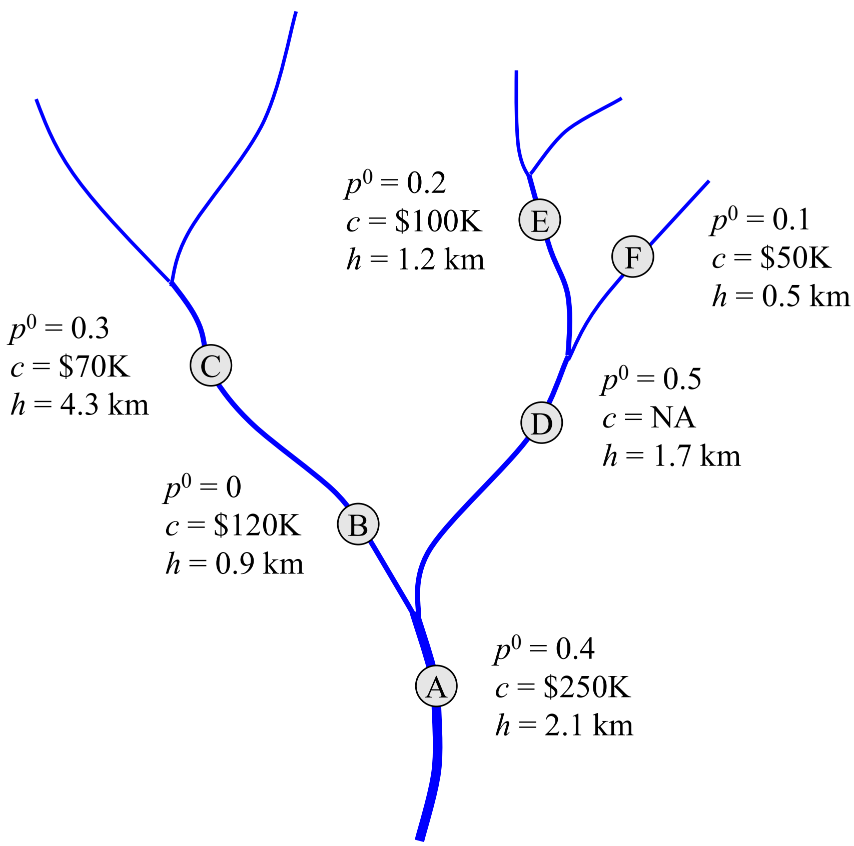
Importantly, the benefits afforded to fish can often be seen quite quickly following barrier. Catalano et al. (2007), for example, found that 10 out of 11 fish species, which had been entirely or mostly restricted below dams in the Baraboo River, Wisconsin, were able to recolonize upstream sections within one year after dam removal. Both Kanehl et al. (1997) and Burroughs et al. (2010) observed significant increases in native fish abundance within 4-5 years after dam removal along rivers in Wisconsin and Michigan, respectively. Another, more recent example is the removal of Elwah Dam in Olympic National Park, Washington State. Within just weeks of its removal in 2012, fish were observed in areas above the former dam (Klingsporn 2012). Coho and steelhead started to recolonize previously inaccessible upper tributary reaches within 7 months. Less than 5 months after the dam's removal, chinook began to naturally migrate back into the watershed, the first time since the Elhwa Dam was built in 1913.

3.2 Barrier Passability

The specific manner in which barriers impact fish dispersal can be highly variable, ranging from short delays to complete blockage, and are dependent on barrier type, river hydrology, and species (e.g., timing of migration and swimming capabilities). Complete barriers can reduce or fragment species distributions, resulting in dwindling populations that are increasingly genetically isolated and at greater risk of extinction. Partial or temporal barriers (e.g., many culverts) can block the movements of a proportion of fish populations and communities, usually weaker swimmers or early life-stages, or may reduce access at certain times (e.g., during high or low flows).

Barrier passability quantifies the degree to which a barrier inhibits the dispersal of fish. Upstream/downstream passability is taken as the fraction of fish (in the range 0-1) that are able to pass through, over or around a barrier while migrating upstream/downstream. Large hydropower dams often have 0 upstream passability, thus completely disconnecting all upstream habitat from the rest of the river network, but may allow partial downstream passability through the turbines or spillways. Culverts, weirs, and low-head dams, on the other hand, frequently have intermediate upstream passability values (e.g., 0.5 if moderately impassable) but downstream passabilities at or near 1. An example of 6 barriers with varying upstream passability values is shown below (Figure 1). Downstream passability for each barrier is assumed to be 1. Note that this figure will be used throughout for illustrative purposes.

Figure 1. Example barrier network with natural and artificial barriers represented as lettered nodes (A-F). Basic information pertaining to each barrier is listed next to each node, including current upstream passability (p^0), the cost (c) in thousands of dollars to fully repair/remove the barrier (i.e., increase upstream passability to 1), and the amount of river habitat (h) immediately above the barrier. Barrier D is a natural barrier with no mitigation option available (i.e., c = NA). Downstream passability is assumed to be 1 for all barriers.



There is a wide range of methods for assessing barrier passability. Some of the more common techniques, as described in Kemp and O'Hanley (2010), include:

- *Direct methods* like human observation, video filming, and telemetry studies.
- *Indirect methods* such as the use of abundance and density estimates (based on electro fishing surveys, redd counts, mark recapture studies), presence/absence data, and genetic profiling.

- *Rule-based and statistical methods* that relate physical and hydrodynamic characteristics of barriers with either (i) knowledge of fish swimming speed and jumping heights or (ii) empirical data on passability obtained from a sample of barriers.
- *Expert opinion* whereby passability is assigned (usually during a field visit) based on subjective assessment.

3.3 Cumulative Passability and Accessible Habitat

In situations where multiple barriers are present within a river network, *cumulative passability* describes the collective impact that multiple barriers have on fish passage. Cumulative passability, which is synonymous with longitudinal connectivity, can be evaluated empirically using telemetry methods (e.g., PIT tagging), but the high cost and labor involved generally makes this prohibitive, particularly when trying to assess a large number of barriers. More typically, passabilities at individual barriers are assumed to be independent, meaning that fish are neither more nor less likely to be able to pass a particular barrier given that they have successfully passed any number of barriers previously. If barrier passabilities are independent, then cumulative passability to/from an area immediately above a particular barrier can be evaluated by multiplying the passability of the barrier by the passability at each downstream barrier (if any are present). Note that this applies to either cumulative upstream passage or cumulative downstream passage. One simply needs to multiply the sequence of upstream barrier passabilities together to get cumulative upstream passability or the sequence of downstream passabilities together to get cumulative downstream passability.

For a demonstration, consider the example barrier network depicted in Figure 1. Barrier E is located above barriers D and A. Its cumulative upstream passability is 0.04, which can be found by multiplying the individual upstream passabilities of barriers E, D, and A together (i.e., $0.2 \times 0.5 \times 0.4 = 0.04$). For barrier C, meanwhile, cumulative passability is equal to the product of the passabilities at C, B, and A (since barriers B and A are downstream from C). Cumulative passability for C is 0 since B has 0 passability (i.e., $0.3 \times 0 \times 0.4 = 0$). A complete list of cumulative passability values for the set of example barriers depicted in Figure 1 is provided in the table below (Table 1).

Table 1. Current cumulative passability and accessible habitat for example barriers.

Barrier	Habitat (river km)	Passability	Downstream Barriers	Cumulative Passability	Accessible Habitat (river km)
A	2.1	0.4	-	0.40	0.840
B	0.9	0	A	0	0
C	4.3	0.3	B, A	0	0
D	1.7	0.5	A	0.20	0.340
E	1.2	0.2	D, A	0.04	0.048
F	0.5	0.1	D, A	0.02	0.010

When no barriers are located downstream, as in the case of barrier A, then cumulative passability is simply equal to the passability of the individual barrier. Consequently, cumulative passability is synonymous with the notion of *connectivity*, the capacity of migratory fish to reach a particular upstream area by successfully passing each and every intervening barrier starting from the mouth of the river.

Cumulative passability is especially important for determining the amount of *accessible habitat* (or connectivity-weighted habitat) above barriers. Accessible habitat is calculated as the net amount of habitat immediately above a barrier up to the next set of upstream barriers or the limits of diadromy multiplied by the cumulative passability of the barrier. Note that net habitat above a barrier is distinct from the total amount of habitat above a barrier (i.e., all habitat up to the limits of diadromy). The net amount of habitat for barrier D, for example, is 1.7 river km, whereas the total amount of habitat is 3.4 river km, which is equal to the sum of net habitats for barriers D, E, and F (1.7 + 1.2 + 0.5 = 3.4). Net habitat should be used when calculating accessible habitat since cumulative passability at upstream barriers may be different. Habitat between barriers (i.e., net habitat), on the other hand, will always have the same level of cumulative passability or connectivity.

Going back to the examples from Figure 1, barrier E with 0.12 cumulative passability and 1.2 (net) river km upstream has 0.048 km of accessible habitat (0.04 × 1.2 = 0.048). Barrier C with 4.3 upstream river km nonetheless has 0 km of accessible habitat since its cumulative passability is 0 (0 × 4.3 = 0). Table 1 shows the amount of accessible habitat for all barriers in Figure 1.

4. Barrier Prioritization Methods

An underlying goal of most barrier mitigation programs is to maximize increases in reconnected habitat given available resources. Unfortunately, resources available for carrying out barrier mitigation work are normally quite limited. Because of this, some sort of prioritization process is invariably required for efficiently targeting mitigation actions. In the broadest terms, prioritization methods can be classified as being *informal* or *formal*. Informal methods are distinguished by the fact that they rely exclusively on expert judgment. Formal methods, in contrast, employ some sort of structured, quantitative analysis. Furthermore, unlike informal methods, the criteria used for prioritizing barriers must be explicitly defined and measurable. There are 4 main categories of formal methods (in more or less increasing order of complexity): *scoring-and-ranking*, *graph theory models*, *greedy heuristics*, and *optimization models*.

4.1 Informal Methods

Informal methods are perhaps the most common approach, particularly outside North America. The process usually involves gathering together a variety of experts (predominately biologists) whose aim is to produce a short-list of barriers that are deemed to be most adversely impacting fish dispersal or general population status within some area of focus. Criteria taken into consideration vary but often include the potential amount of habitat gained from mitigation, the type and relative quality of habitat made available for different species and or life-stages (e.g., rearing for juveniles versus breading habitat for adults), the potential spread of invasive species, and the presence/absence of downstream barriers.

Although a fairly straightforward and commonsense approach, informal methods do suffer from a number of important drawbacks. For one, they lack rigor – recommendations are based entirely on subjective opinion with assessment criteria generally being only vaguely defined and or inconsistently applied. For example, certain criteria may be used to justify why one particular barrier is important (e.g., the barrier is impassable and located furthest downstream) while other criteria may be applied to a different barrier (e.g., there is a large amount of inaccessible spawning habitat upstream). Oftentimes costs are not factored in at all, thus calling into serious question how cost-efficient proposed mitigation actions are. Moreover, the lack of explicit, quantitative metrics makes it generally difficult to understand and weigh potential tradeoffs. Without a common measure for assessing benefits, for example, the value of partial versus full restoration of fish passage is problematic.

Nonetheless, informal methods are usually acceptable for identifying within a specific watershed the first few set of barriers to repair or remove that yield the greatest gains (however ill-defined that may be). Where they really fail is when applied to large spatial scales. Looking at multiple watersheds simultaneously is generally far too difficult a task. Even when the problem is broken down by watershed, the question still remains: How do you compare priorities across watersheds and, in turn, allocate funding? In some cases, it may be better to concentrate efforts on one or a few watersheds, while in others it may be far more beneficial to spread resources across many watersheds. The best course of action will be context dependent so there are no general rules that apply for resolving this issue.

A good example of the difficulty of employing informal methods comes from the UK. The Environment Agency, which has statutory responsibility for maintaining environmental quality of English and Welch freshwater bodies including free passage for migratory fish, employs a “divide-and-conquer” approach when it comes to barrier prioritization. The strategy relies on delegating responsibility to each region (7 in total) to come up with a list of high priority barriers for its jurisdiction. The manner in which priorities are arrived at are left to the individual regions and do not conform to a common set of criteria. To compound the problem, there are multiple species of interest across the different regions with each region focusing, to a greater or less extent, on a particular species or group of species. National level priorities are ultimately derived by “filtering” the various regional priorities using an ad-hoc process. The example here clearly illustrates why informal methods should generally be avoided in the context of wide-area barrier mitigation planning.

4.2 Scoring-and-Ranking

Scoring-and-ranking, without a doubt, is the most common type of formal method used for prioritizing barrier mitigation decisions (e.g., Taylor and Love 2003, Karle 2005; Kocovsky et al. 2009; WDFW 2009; Lawson et al. 2010; Martin and Apse 2011; Nunn and Cowx 2012). As the name implies, barriers are scored according to a set of assessment criteria, ranked in order of score, and then selected for repair/removal based on rank until the budget is exhausted. Scoring systems typically account for one or more of the following: (i) habitat quantity, (ii) habitat quality, (iii) degree of improvement in fish passage as a result of mitigation, and (iv) cost of mitigation. More sophisticated ones (e.g., Martin and Apse 2011; Nunn and Cowx 2012) further account for the number and or passability of downstream barriers.

The appeal of scoring-and-ranking lies in its simplicity.[1] As a number of studies have shown (e.g., O'Hanley and Tomberlin 2005; O'Hanley et al. 2013b), however, scoring-and-ranking can and often does produce especially poor quality solutions. As an illustration, consider the following scoring-and-ranking system, which uses benefit-cost ratios to rank mitigation projects. For simplicity, we only consider a single mitigation project per barrier.

$$S_j = \frac{\Delta p_j \times h_j}{c_j}$$

Here, Δp_j represent the change in passability given mitigation of barrier j, h_j the net amount of habitat above barrier j, and c_j the cost of mitigating barrier j. The score S_j assigned to any barrier j is the benefit of mitigation ($\Delta p_j \times h_j$) divided by cost (c_j). Note that more typically, total upstream habitat is used for h_j, but the basic analysis and conclusions remain the same regardless.

For the barriers shown in Figure 1, it is assumed that mitigation restores passability to 1. With habitat (h) measured in meters and cost (c) given in thousands of dollars, the score for barrier B would be computed as: $(1 - 0) \times 0.9 / 120 = 7.5$. Barrier C, meanwhile, would come out with a score of: $(1 - 0.3) \times 4.3 / 70 = 43$. Barrier C would be ranked above barrier B given its higher score. The full set of scores (in rank order) for each artificial barrier in Figure 1 is provided in the table below (Table 2).

Table 2. Simple scoring-and-ranking list. Note barrier D does not appear on list because it is a natural barrier.

Barrier	Δp	h	c	S
C	0.7	4300	70	43.00
E	0.8	1200	100	9.60
F	0.9	500	50	9.00
B	1.0	900	120	7.50
A	0.6	2100	250	5.04

With barriers having been ordered according score, the selection of barriers would then proceed by moving down from the top of the list until there are no more barrier repair/removal options. Given a budget of \$200k, for example, barriers C and E would be prioritized for mitigation. Accessible habitat would increase from its present amount of 1.238 km to 1.430 km. This is substantially less than the *maximum* amount of accessible habitat of 3.318 km given a \$200k budget, which is achieved by mitigating barriers B and C. Scoring-and-ranking thus produces just 9% of the maximum possible net gain: 0.192 km versus 3.318 km.

For a budget of \$100k, the performance of scoring-and-ranking is comparatively worse. The optimal decision would be to repair/remove barrier E, for a net increase of 0.192 km of accessible river habitat.

[1] To quote Hugh Possingham, the famous conservation planning scientist, "Somewhere right now, someone is thinking up a scoring-and-ranking method."

With scoring-and-ranking, however, C would be selected, resulting in no gain in accessible habitat (i.e., 0% of the maximum) since barrier B downstream has passability 0.

The examples above clearly show how scoring-and-ranking can yield costly and ineffective solutions. One reason for this is that scoring-and-ranking systems usually do not consider the underlying spatial structure of barrier networks. Passage barriers within the same watershed are, in fact, spatially interconnected. Cumulative passability at a given barrier is directly affected by the passability of each downstream barrier. Ignoring this can result in proposals to mitigate barriers located above impassable downstream barriers even thought this would produce no habitat gain whatsoever (e.g., mitigating barrier C but not B).

To try to overcome this to some extent, consideration of downstream barriers can be incorporated into scoring-and-ranking (Martin and Apse 2011; Nunn and Cowx 2012). A slightly more elaborate scoring system, for example, would replace Δp_j with ΔP_j, the change in cumulative passability given mitigation of barrier j. Doing so, the following ranking of barriers would be produced (Table 3).

With this revised scoring-and-ranking system, barriers located above any impassable barriers (e.g., barrier C) drop to the bottom of the list. Illogical proposals to mitigate barriers that deliver no net habitat gain are thus precluded. The results for our two hypothetical budgets of \$100k and \$200k bear this out. With \$100k, barrier E would be repaired, resulting in a 0.192 km gain. As mentioned previously, this is indeed the optimal decision at this budget level. With \$200k, barriers B and F would be mitigated, producing a net gain of 0.966 km. This is considerably better than the 0.192 km gain with the original scoring-and-ranking systems but still only 46% or the maximum gain (3.318 km).

Table 3. Revised scoring-and-ranking list incorporating downstream barrier impacts. Note barrier D does not appear on list because it is a natural barrier.

Barrier	ΔP	h	c	S
A	0.60	2100	250	5.04
B	0.40	900	120	3.00
E	0.16	1200	100	1.92
F	0.18	500	50	1.80
C	0	4300	70	0.00

Regardless of whether downstream impacts are considered or not, scoring-and-ranking suffers from an even more fundamental shortcoming, which is that decisions are made independently rather than in an adaptive or coordinated manner. Scores are calculated assuming that passabilities at other barriers are held constant. Mitigation of multiple barriers, however, produces interactive changes in cumulative passability. Put another way, the gain produced by mitigating a particular barrier is not fixed; it depends on if and to what degree other barriers downstream or upstream have already been mitigated or are provisionally slated for mitigation.

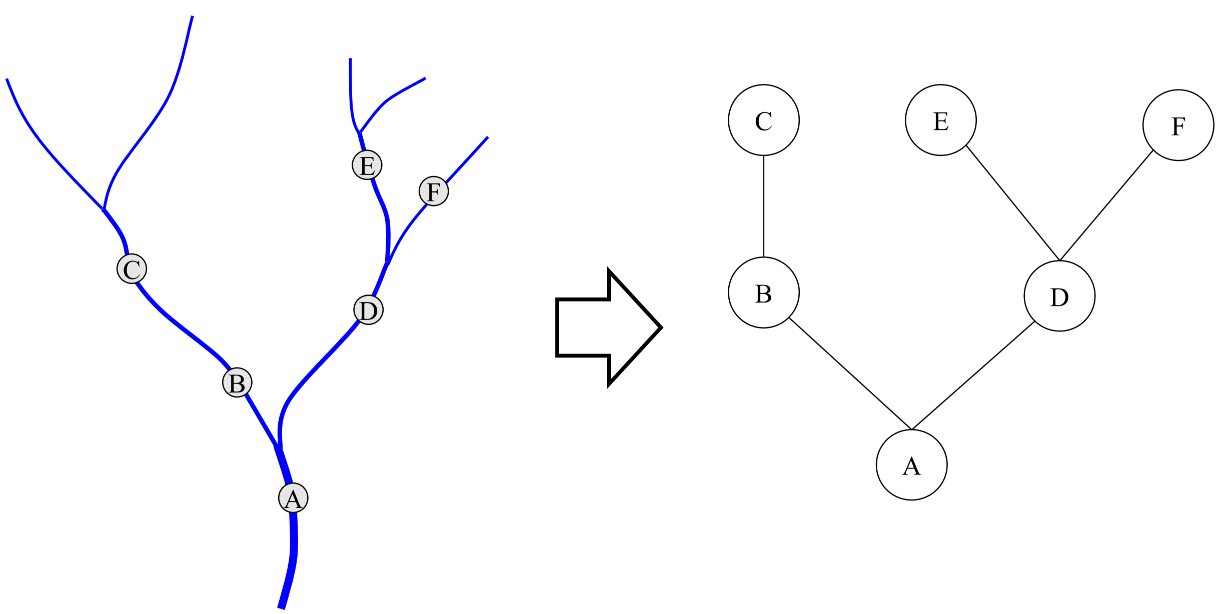
As a case in point, consider the solution produced under the revised scoring-and-ranking system for a budget of \$200k. Here, barrier B (the 2nd ranked barrier) would be selected initially, since it is the highest ranked and affordable option. Given the mitigation of B, the best decision would be to choose barrier C (the 5th ranked barrier) for a net gain of 3.318 km but instead barrier F (the 4th ranked barrier) is chosen, resulting in a gain of only 0.966 km. As the results clearly show, even spatially explicit scoring-and-ranking systems can produce extremely poor solutions because of the static, one-shot manner for deriving scores.

4.3 Graph Theory Models

Graph theory type models are noteworthy in that they are designed to capture the spatial structure of river and barrier networks. This allows them, unlike with scoring-and-ranking, to account for the interactive effects of barrier mitigation on cumulative passability. The application of graph theory involves two, interlinked steps. First, a *graph* composed of nodes and arcs is created to represent a particular barrier network. Second, a quantifiable index of some kind is used to describe the degree of longitudinal connectivity within the river network.

Although not properly described as such, one of the first and most well-known graph theory models within the context of barrier mitigation planning is the Dendritic Connectivity Index proposed by Cote et al. (2009). Based on this approach, a graph is constructed with barriers represented by nodes and arcs connecting adjacent barriers (Figure 2). The same representation is used by McKay et al. (2013) in their graph theory analysis, as well as by O'Hanley and Tomberlin (2005) who further embed this type of graph model into an optimization framework.

Figure 2. Graph theory representation of the example barrier network (Figure 1) according to Cote et al. (2009) and McKay et al. (2013). For the graph on the right, nodes (circles) represent barriers while arcs (lines) delineate spatial connections among barriers.



For diadromous species, the index is given by the equation:

$$\text{DCI} = \sum_{j=1}^{n} \frac{h_j}{H} \left(\prod_{k \in D_j} p_k^u p_k^d \right) \cdot 100$$

where H denotes the total amount of habitat within a particular watershed, p_j^u the upstream passability of a given barrier j, p_j^d the downstream passability of a given barrier j, and D_j the set of barriers downstream from j. The index varies from 0, indicating no river habitat is accessible, to 100, indicating all river habitat is fully accessible. It is worth noting that DCI accounts for both cumulative upstream and cumulative downstream passability of barriers. The use of a normalization factor (H), however, effectively only makes the index suitable for use within a single, self-contained watershed.

For the example barrier network (Figure 1), DCI under current passability conditions is 11.6, assuming downstream passability (p_j^d) is equal to 1 for each barrier j. This value simply represents a rescaling of the 1.238 km of currently accessible habitat. Different combinations of barrier mitigation actions produce different DCI values. Mitigating barriers B and C results in a DCI of 31.0 (3.318 km), while mitigating barriers A, B, and C results in a DCI of 77.5 (8.295 km).

Other graph theoretic approaches include work by Erős et al. (2011, 2012) and Segurado et al. (2013). The graph representation used by these authors (Figure 3) is distinctly different from the one previously mentioned in that nodes represent stream segments, while arcs designate whether or not stream segments are confluent with one another.

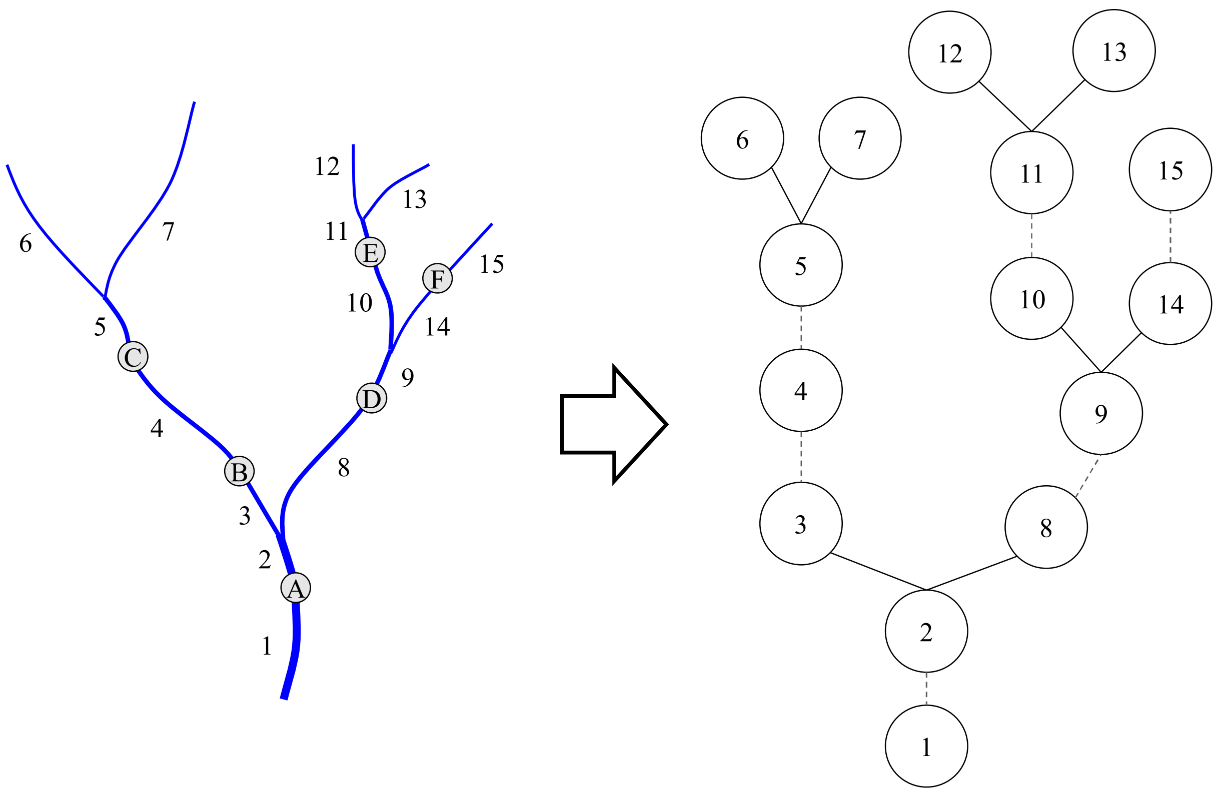
For this representation, two different indices have been proposed: the Betweenness Centrality (BC) index and the Index of Connectivity (IIC). BC measures the frequency with which a node (stream segment) falls within the shortest path between pairs of nodes (stream segments) in a network. It quantifies the role of steam segment to serve as "stepping stones." ICC, in contrast, provides an overall measure of longitudinal connectivity and quantifies the importance of both habitat availability and connectivity. For both BC and ICC, it is assumed that barriers are either complete passable or completely impassable. This makes these indices much more limited than DCI in that they do not allow for partial barrier passability.

Graph theory models are noteworthy for taking holistic view of river connectivity. Unlike with scoring-and-ranking, they are specifically designed to incorporate the interactive effects of barrier mitigation, thus allowing decisions to be made in a fully coordinated manner. Nonetheless, graph theory models by themselves are merely *descriptive* – they do not provide any guidance as to how barriers can be mitigated in a cost-efficient manner. This makes them only useful for carrying out very simple "what-if" type analyses involving questions like: How would longitudinal connectivity be affected by the mitigation of this particular barrier or this set of barriers? For a given budget, it is entirely up to the end-user to come up with a feasible portfolio of mitigation actions that maximizes overall connectivity. *Prescriptive* models, on the other hand, greedy heuristics and optimization models being prime examples,[2] produce a

[2] Scoring-and-ranking is also prescriptive but a rather poor example.

recommended best course of action. These solutions, in turn, can be implemented *in toto* or form the basis for more detailed modeling and fine-tuning later on.

Figure 3. Graph representation of the example barrier network (Figure 1) according to Erős et al. (2011, 2012) and Segurado et al. (2013). For the example barrier network on the left, numbers denote individual confluence and barrier bounded stream segments (15 in total). For the graph on the right, nodes (circles) represent stream segments while arcs (lines) show whether or not segments are confluent with one another. Solid arcs denote a barrier-free connection between river segments, dashed arcs denote an intervening barrier is present between two river segments.



4.4 Greedy Heuristics

The application of more sophisticated, greedy-type heuristics (O'Hanley and Tomberlin 2005; Diebel et al. 2014) offers a far better approach to barrier mitigation planning compared to scoring-and-ranking or standalone graph theory models. As with graph theory models, greedy heuristics incorporate the spatial structure of barrier networks.[3] Moreover, they are prescriptive in that they produce a single, actionable solution.

A greedy solution is made up of a ranked list but unlike in scoring-and-ranking, rankings are created in an *iterative* fashion. In brief, greedy methods work by first computing benefit-cost ratios for each barrier based on net changes in accessible habitat across an entire river network. Consequently, rather than looking at barriers in isolation, system-wide changes in cumulative passability (due to proposed mitigation

[3] Greedy heuristics either implicitly or explicitly define a graph structure.

actions) are taken into account. The barrier with the highest ratio is selected for mitigation, its passability updated, and then removed from further consideration. The whole process is subsequently repeated for all barriers still under consideration until a complete ranking has been produced.

Besides being extremely fast and easy to implement, the main advantage of greedy heuristics is that they are highly cost-efficient in most cases. Solutions found using greedy heuristics, in fact, are often optimal or near optimal. In O'Hanley and Tomberlin (2005), for example, net gains for greedy solutions were only 0-5% below the maximum on 4 test culvert networks across a range of potential mitigation budgets.

Nonetheless, greedy heuristics are still not full-proof, particularly with small budgets. Applying a greedy heuristic to our example network (Figure 1), the barriers would be ranked: A → B → C → E → F. With a budget of $200k, barriers B and C would be selected for a net gain of 3.318 km (100% of the maximum). At a budget of $100k, however, barrier C would be chosen, resulting in no net gain (0% of the maximum). In relative terms, this solution is extremely poor. On the other hand, given that maximum gain is only 0.192 km at this budget level, the greedy heuristic is not far off in absolute terms.

Greedy heuristics ultimately fail because lists are static by their very nature. The optimal set of barriers selected for mitigation, however, can vary considerably depending on the available budget. For example, at $100k, the optimal choice is to mitigate barrier E. At $200k, the optimal set of barriers is B and C, which does not include E. Formally, optimal solutions may not be perfectly *nested* (O'Hanley 2011), meaning that the set of barriers targeted for mitigation at one budget level may not all be chosen at a higher budget. Previously unaffordable or costly mitigation actions may suddenly become much more attractive given sufficient financial resources. Indeed, barriers may drop out as the budget increases only to come back in again at even higher budgets. Barrier E, for example, forms part of the optimal set for budgets in the range $100-110k, $290-360k, and $540k or more but does not appear in the ranges $120-280k and $370-530k. In practical terms, this implies that an optimal solution cannot be constructed by adding barriers one after the other as done using a greedy heuristic. Making optimal decisions requires moving away from the concept of static lists entirely.

4.5 Optimization Models

As the proceeding should make abundantly clear, effective barrier mitigation planning at basin-wide scales is an exceedingly challenging problem. Scoring-and-ranking has severe limitations and so should be strictly avoided.[4] Even graph theory models and greedy heuristics leave room for improvement. The question then arises, are there methods out there for making decisions in a fully coordinated manner that maximize habitat gains every time and in every situation? The answer is yes, by using advanced optimization modeling and solution techniques.

Optimization based methods like OptiPass provide a systematic and objective means of targeting barrier mitigation actions. The importance of spatial structure and accounting for the interactive effects of barrier mitigation on longitudinal connectivity are directly imbedded into the decision making framework.

[4] As an adaptation of a well-known US public service message against drunk driving: "Friends don't let friends use scoring-and-ranking."

Furthermore, optimization models guarantee that one will find *the most efficient* use of limited resources to maximize restoration gains, regardless of the specific study area one is looking at or what the budget happens to be. Put another way, optimization models share the same advantage as graph theory models in being spatially aware but are also prescriptive. In comparison to greedy heuristics, they invariably produce optimal solutions and so are more efficient.

The use of optimization has other advantages as well (Kemp and O'Hanley 2010). For one, their flexibility enables decision makers to effectively balance multiple, possibly competing, environmental and socio-economic goals (e.g., Kuby et al. 2005; Zheng et al. 2009; Zheng and Hobbs 2013). Even uncertainty can be incorporated into an optimization model in a coherent fashion, allowing planners to effectively hedge against risk. At the very least, optimization models are useful for identifying potentially cost-efficient solutions that can form the basis for more detailed modeling and fine-tuning later on. Taken together, optimization truly sets the gold standard for effective and robust barrier mitigation planning.

5. Optimizing Barrier Mitigation Actions with OptiPass

5.1 OptiPass in Nutshell

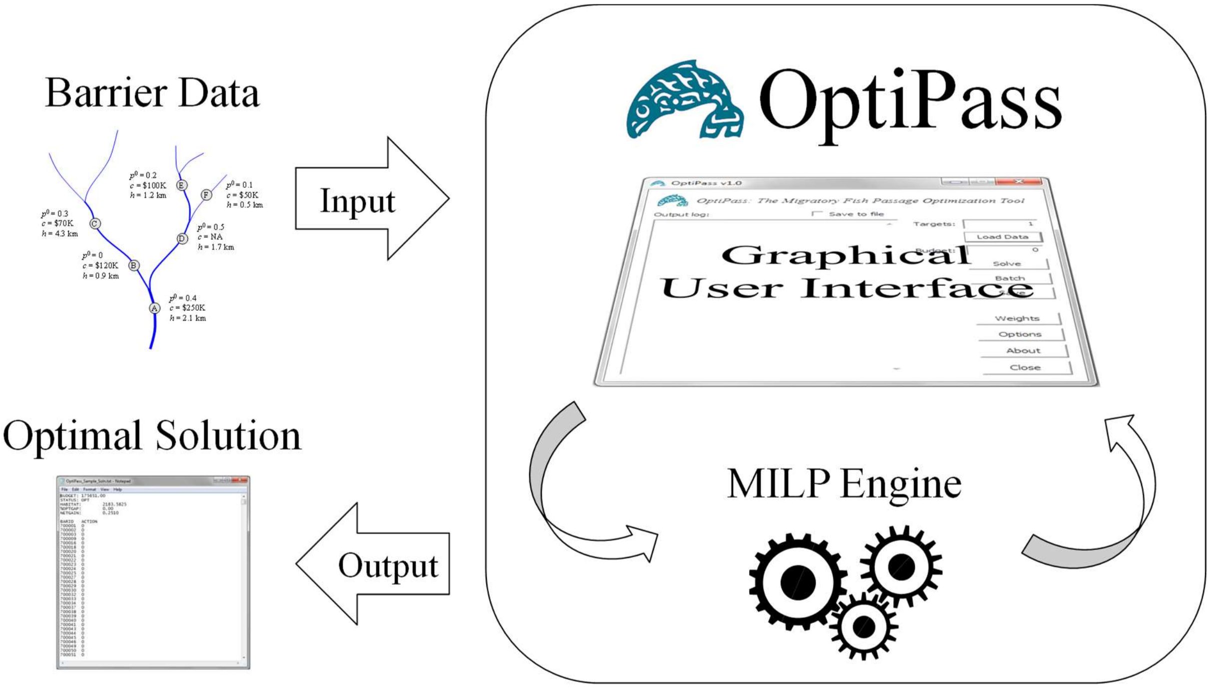
OptiPass provides an optimization based platform for carrying out barrier mitigation planning and analysis. It is designed to select barrier mitigation actions in the most cost-efficient way possible, taking into account barrier passability (upstream and or downstream), mitigation cost, and available upstream habitat. Critically, OptiPass incorporates the spatial structure of barrier networks and, in turn, the interactive effects that barrier mitigation decisions have on both cumulative passage and accessible habitat.

At the core of OptiPass is what is known as a mixed integer linear program (MILP). Specifically, for any given budget, the MILP determines an optimal portfolio of mitigation actions which maximizes the amount of accessible, possibly quality-adjusted, habitat above existing fish passage barriers. A mathematical formulation and detailed description of the MILP used within OptiPass are provided in the appendix.

When a barrier dataset is loaded into OptiPass, an MILP model is first created in the background (Figure 4). Once the user has inputted a budget value and hits the "Solve" button, the MILP model is solved *exactly* using a "branch and cut" algorithm (Winston 2004). Exact methods like branch and cut ensure that a verified optimal solution will be obtained. This stands in contrasts to *heuristic* methods more commonly employed in optimization based conservation planning software (e.g., MARXAN, Ball et al. 2009; Zonation, Moilanen et al. 2012), which have no guarantee of optimally though are usually capable of finding near-optimal solutions.

While exact methods invariably outperform heuristics in terms of solution quality, one potential issue for concern is speed. Solutions times for exact methods can sometimes be slow, even arduously slow, particularly for large sized problems. OptiPass, however, is extremely fast for most standard sized problems involving 100s to 1000s of barriers and is fully capable of solving very large-scale problems containing several 10,000s of barriers.

Figure 4. Diagrammatic overview of OptiPass.



OptiPass was originally designed for the *California Fish Passage Forum*[5] (one of 19 US National Fish Habitat Partnerships) and has been extensively tested using data contained in the California *Passage Assessment Database* (PAD).[6] For problems involving 100s of barriers, OptiPass generally solves in factions of a second. When run on the entire PAD dataset, which includes more than 6,000 barriers, OptiPass solves in a matter of seconds. OptiPass has also been successfully run on significantly larger datasets obtained from the Great Lakes basin with up 50,000+ barriers. Even on these extremely large problems, OptiPass manages to produce optimal solutions in only a few minutes.

There are a few other key features of OptiPass that are worth pointing out. First, *multiple mitigation projects* can be defined for any given barrier and included in an OptiPass input file (formatting details provided in Section 6.2). In many planning situations, only one mitigation project will be available at each barrier. The decision then is either to repair/remove the barrier or not. A common assumption is that mitigation will restore passability to 1, though this need not necessarily be the case (i.e., the user can specify any post-mitigation passability value).

In the more general case, one may need to choose among two or more mitigation options at a particular barrier. Naturally, the different mitigation projects should differ in terms of cost and the resulting increase in barrier passability afforded. For example, at a low-head dam one might be considering (i) carrying out

[5] URL: http://www.cafishpassageforum.org/
[6] URL: http://www.calfish.org/Programs/CaliforniaFishPassageAssessmentDatabase/tabid/189/Default.aspx

low-cost, remedial repairs to an existing fish ladder to improve passability; (ii) installing an entirely new fish ladder that would increase passability further for a considerably higher cost; or (iii) opting to completely remove the dam, which would fully restore passability, but require a substantial investment (i.e., option (iii) is the most costly followed by (ii) then (i)). OptiPass can decide which, if any, of these to choose, taking into consideration the budget and the set of mitigation alternatives available at other barriers.

A second key feature of OptiPass is that it is possible to handle *multiple species, taxa, guilds, etc.*, collectively referred to as *restoration targets*. In most cases, a decision maker will be focusing either explicitly or implicitly on one restoration target. This might be because there is indeed only one species or taxa of concern (e.g., steelhead) or, more commonly, because there is only a single estimated barrier passability value available for each barrier (e.g., a composite passability value for all migratory fish and life-stages present within the watershed). As such, by default only a single restoration target needs to be included in a basic OptiPass input file (formatting details provided in Section 6.3).

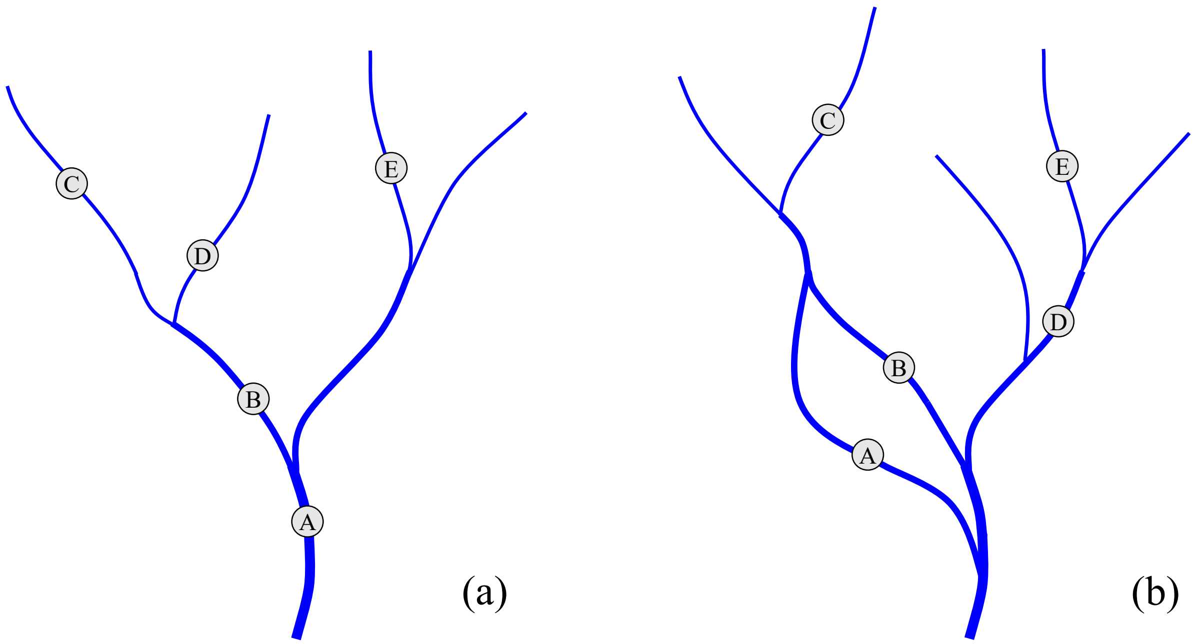
Occasionally though, there may be a need to look at multiple restoration targets simultaneously (e.g., steelhead, coho, and chinook), in which case it is possible to include and weight each target separately within OptiPass. The basic requirement for including multiple targets is that at every barrier, individual estimates for net upstream habitat and passability must be available for each target and represented separately in an OptiPass input file (though the values are permitted to be the same). Given sufficient data of this kind, the user can then weight each restoration target as desired in order to put more or less emphasis on any particular target. Invasive species can even be factored into an analysis by putting negative weights on these “anti-restoration” targets.

Lastly, OptiPass is fully capable of incorporating both *upstream* and *downstream passability* in an integrated manner. Downstream passability, particularly for small barriers (e.g., culverts, weirs, and low-head dams), is often assumed to be at or near 1 and so can be effectively ignored. In certain situations, however, this assumption may not hold, thereby making downstream passability a key planning consideration. For example, it might be known within a particular study area that downstream passability for salmon smolts is limited at certain barriers. Failure to incorporate smolt passage into the decision making process would inevitably result in inferior solutions that focus only on upstream passage for spawning adults. By simply multiplying the upstream (i.e., adult) and downstream (i.e., juvenile) passabilities together and then using these *bi-directional* passabilities in an OptiPass input file (details provided in Section 6.4), one can produce balanced solutions that optimize for the complete fish life-cycle.

5.2 Main Assumptions

To run OptiPass, a properly formatted input file, referred to as a “barrier file,” needs to be supplied. A barrier file contains essential information about each passage barrier within the defined study area. Basic file formatting requirements are detailed in Section 6.1. One key thing to note about a barrier file is that the barriers need to be arranged into what is known as a *tree network*. With a tree structure, it is assumed that streams never diverge as they flow downstream, thus excluding any system with braided rivers or delta areas that allow multiple dispersal paths to the same upstream location. In practice, what this means is that barriers can have at most one downstream barrier. Figure 5 below shows examples of tree and non-tree barrier networks.

Figure 5. Example tree (a) and non-tree (b) networks. In (a), no barrier has more than one downstream barrier. In (b), barrier C has two downstream barriers, barriers A and B. Note that in (b), the area located above barrier C can be reached either by passing barriers A and C or by passing barriers B and C.



A second main assumption of OptiPass is that barrier passabilities are *independent*. As mentioned previously, this means that the chances of fish passing a particular barrier are neither more nor less likely given that the fish have successfully passed other barriers. Coin tosses are a good analogy. Given that a fair coin lands heads on the first flip (or tails for that matter), the chance of it landing heads on the second flip remains the same (i.e., 50%). Consequently, the chances of two heads in a row is 0.5 × 0.5 or 25%. OptiPass applies the same principal to fish successfully passing multiple barriers.

The assumption of barrier independence is common in barrier assessment and planning (Kemp and O'Hanley 2010). In reality, there is probably some degree of conditionality among passability values. For example, the high energetic cost associated with passing an especially difficult barrier might make it less likely for a fish to pass the next barrier it encounters. If this were the case, then mitigation of a barrier could affect the passabilities of other barriers thereby making calculation of cumulative passability much more complex. Developing a planning tool capable of handling conditional passage does not pose any theoretical or major technical issues. The real issue involved is the considerable data requirements for specifying conditional passabilities. Rarely are sufficient amounts of data available to do this.

At the other end of the spectrum from barrier independence, one could postulate that fish which can pass a barrier with a given level of passability should be able to pass any subsequent barriers with the same or lower passability based on the notion that barriers select for threshold swimming and jumping abilities. If this were the case, cumulative passability for a series of barriers would simply be equal to the minimum passability value. Going back to the example barrier network (Figure 1), the cumulative passability for barrier D would be 0.4 (the minimum of passabilities 0.4 for A and 0.5 for D), while cumulative passability for barrier E would be 0.2 (the minimum of 0.4, 0.5, and 0.2 for A, D, and E, respectively). Assuming barrier independence is not only supported empirically (REF) but also results in more conservative estimates for cumulative passability.

At a much more basic level, it is an inherent assumption of OptiPass that increasing habitat accessibility equates to increases in overall fish population numbers and viability. Improving the population status of target fish populations is usually the underlying goal of any barrier mitigation planning exercise. It needs to be clearly stated, however, that OptiPass does not explicitly consider fish population dynamics in any way. The associated link between population size/viability and habitat amount is a cornerstone of ecological theory, something to which OptiPass adheres. Nonetheless, the spatial structure imposed by barrier networks on fish populations due to variability in access to critical habitat at different life-stages and the way this mediates growth and dispersal dynamics is entirely beyond the scope of OptiPass.

Lastly, it needs to be stressed that the quality of the solutions produced by OptiPass is predicated on having complete and reliable input data. Changes to any of the key input parameters (i.e., passability, cost, or net habitat values) can result in different optimal solutions. It is especially important that every potential barrier within the study area be incorporated into the analysis. This includes all artificial (i.e., man-made) barriers as well as natural barriers (e.g., waterfalls, large woody debris, etc.). Failure to include all barriers will invariably lead to imprecision in cumulative passability calculations and, in turn, the potential habitat gain that can be realized from barrier mitigation. In short, inaccurate data and, in particular, missing barriers will invariably lead to erroneous results.

5.3 Technical Details and Installation

OptiPass is written in Visual C++ using Microsoft Foundation Classes (MFC) provided in Microsoft Visual Studio. MILP modeling and solution routines were implemented using Cbc (COIN-OR branch and cut) callable libraries (https://projects.coin-or.org/Cbc). This free, open-source software project has been invaluable in the development of OptiPass. The work of the Cbc team is greatly appreciated. Version 1.1.1 of OptiPass was compiled in Visual Studio 2015 and uses Cbc version 2.9.7 libraries.

OptiPass can be run on PCs running Windows XP, Windows Vista, Windows 7 or Windows 8 operating systems. It comes in two versions: one for 32-bit machines (x86) and another for 64-bit machines (x64).

Before running OptiPass, you will need to download and install the Visual C++ Redistributable Package:

http://www.microsoft.com/en-us/download/details.aspx?id=30679

Select either x86 or x64 depending on your machine. If in doubt, choose the x86 versions of both OptiPass and the Visual C++ Redistributable Package, which will work regardless of the type of machine you are using.

6. File Formatting

6.1 Basic Input File

Relevant barrier data that need to be supplied to OptiPass are contained in what is referred to as a "barrier file." Formatting requirements for a basic OptiPass barrier file are pretty straightforward. Essential data fields for each barrier are listed below.

- **BARID**: A barrier identification (ID) value unique to each barrier. Format: alphanumeric (spaces permitted but no commas).
- **REGION**: The name of the spatial region in which the barrier is located. In many situations, a region will correspond to a hydrological catchment area (e.g., basin, watershed, subwatershed, etc.), which forms the natural spatial organization of rivers and barriers. However, any arbitrary spatial categorization can be used, including administrative areas (e.g., counties) that cross multiple catchments. Delineating barriers into different spatial regions is not strictly required but is useful as part of a "what-if" analysis involving changes to the spatial focus where mitigation efforts are to be carried out (see Section 7.4). If there is no need to organize the barriers into spatial regions, one can simply use the name of the given study area as the REGION field. FORMAT: alphanumeric (spaces permitted but no commas).
- **DSID**: The barrier ID (BARID) of the immediate downstream barrier. Note that barriers can have at most *one* downstream barrier. If no downstream barrier exists, then "NA" should be specified. Accordingly, "NA" should never be used as a barrier ID. FORMAT: alphanumeric (spaces permitted but no commas).
- **USHAB**: The *net* amount of useable habitat above the barrier up to the next set of upstream barriers or the defined limits of diadromy for the restoration target in question. USHAB can be given in any relevant unit such as length (e.g., river miles/kilometers) or area (e.g., wetted area). USHAB values can even be quality-adjusted, if desired, by taking the raw amount of habitat and multiplying it by a habitat suitability score. Note that suitability scores must be restricted to be greater than or equal to zero. FORMAT: nonnegative decimal value.
- **PREPASS**: The current (pre-mitigation) passability (normally upstream) of the barrier in the range 0-1. Passability is defined as the fraction of fish which are able to pass through, over or around a barrier when attempting to navigate it. Ideally, current passability should correspond to typical hydrologic conditions of the migration period for an average year. Full barriers should be assigned a value of 0; partial barriers should have values strictly between 0 and 1. FORMAT: decimal value in the range [0, 1].
- **NPROJ**: The number of mitigation projects that can potentially be carried out at the barrier. Natural barriers will typically have a value 0. For artificial barriers, a value of 1 should be specified assuming there in only one mitigation option available (e.g., repair/remove versus do nothing). If multiple options are available (see Section 6.2), a number larger than 1 can be given. FORMAT: nonnegative integer value.
- **COST**: The cost of mitigating a barrier. Note any monetary unit can be used, however, the OptiPass will generally run quicker if costs are given in rounded values (e.g., to the nearest

thousands or tens of thousands of dollars). For barriers having no available mitigation option (i.e., NPROJ = 0), a value for COST is not required. In such cases, one can leave the field blank or type in any user-defined code (e.g., "-", "NA", or "-999") to indicate that the field is not applicable. FORMAT: nonnegative decimal value.

- **POSTPASS**: Expected passability (normally upstream) at the barrier following mitigation. Post-mitigation passability should be in the range 0-1 and be greater than or equal to current passability (PREPASS). Ideally, post-mitigation passability should correspond to typical hydrologic conditions of the migration period for an average year. For barriers having no available mitigation option (NPROJ = 0), a value for POSTPASS is not required. In such cases, one can leave the field blank or type in any user-defined code (e.g., "-", "NA", or "-999") to indicate that the field is not applicable. FORMAT: decimal value in the range [0, 1].

The data fields listed above should be included in tab or comma delimited text file and *must* include a header. The fields should be listed in columns with each row corresponding to a particular barrier within the defined study area. The row in which a barrier is listed within the file is entirely arbitrary. A barrier file for the example network shown in Figure 1 is provided in Box 1 below. Note that since barrier D has no mitigation option available (NPROJ = 0), the cost of mitigation (COST) and post-mitigation passability (POSTPASS) both have the entry "-", meaning that these fields are not applicable.

Box 1. Barrier file for the example barrier network (Figure 1).

```
BARID    REGION   DSID   USHAB   PREPASS   NPROJ   COST   POSTPASS
    A  Example1     NA     2.1       0.4       1    250          1
    B  Example1      A     0.9         0       1    120          1
    C  Example1      B     4.3       0.3       1     70          1
    D  Example1      A     1.7       0.5       0      -          -
    E  Example1      D     1.2       0.2       1    100          1
    F  Example1      D     0.5       0.1       1     50          1
```

When reading in a barrier file, OptiPass performs basic error checking to ensure that the data have been provided in the correct format. This includes simple things like verifying that passability values (PREPASS and POSTPASS) are in the range 0-1 and that cost (COST) and upstream habitat values (USHAB) are greater than or equal to 0. More importantly, it will also check that the spatial geometry of the barriers is consistent. For example, OptiPass confirms that all downstream IDs exist and that there are no *cyclic paths* among the barriers. A cyclic path is one in which it is possible to start from a particular barrier and eventually return to the same barrier by following the sequence of downstream barrier IDs. Cyclic paths should not be present in a properly formatted barrier file.

If OptiPass does find an error in the barrier file, such as an invalid passability value or a cyclic path, it will throw out the line number of where the error was encountered. The user should then make appropriate fixes and verify that the rest of the data are correct. In any case, it is important to point out here that OptiPass only checks for obvious formatting errors. It is unable to verify that the data are an accurate representation of reality. It is **strongly recommended**, therefore, that the user always perform a thorough validation of the data *before* passing them into OptiPass.[7]

It is important to point out (as mentioned previously in Section 5.1) that OptiPass maximizes the amount of accessible habitat above *existing* barriers. It does not, by default, take into consideration habitat below the first set of barriers (e.g., below barrier A for our example barrier network). If the amount of habitat below barriers is considerable, the results reported by OptiPass can give an incomplete picture of both the amount of currently accessible habitat and the relative gain achievable from barrier mitigation.

If the user is interested in determining the *total* amount of available habitat within the study region, then additional "dummy" barriers need to be included at the river outlet of each self-contained watershed. By definition, a dummy barrier has current passability (PREPASS) equal to 1 and so does not impact connectivity in any way. Dummy barrier are used solely as a means of accounting for habitat between the mouth of the river and the first set of barriers that migratory fish would encounter.

Returning to our example barrier network (Figure 1), habitat below barrier A would not be included in OptiPass's calculations if it were given the data shown in Box 1. Let us assume that there is 0.7 km of river habitat between the river mouth and barrier A. To account for this, we need to make a few minor changes to the barrier file. We start by adding a dummy barrier with ID = "Dummy", USHAB = 0.7, PREPASS = 1, and NPROJ = 0. We then need to point barrier A to the dummy by changing its downstream ID from "NA" to "Dummy". The rest of the barrier file remains the same. The first 3 lines of our modified barrier file with a dummy barrier at the mouth of the river is shown in Box 2 below.

Box 2. Barrier file for the example barrier network (Figure 1) with an additional dummy barrier located at the mouth of the river to account for habitat below barrier A.

BARID	REGION	DSID	USHAB	PREPASS	NPROJ	COST	POSTPASS
Dummy	Example2	NA	0.7	1	0	-	-
A	Example2	Dummy	2.1	0.4	1	250	1
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Note that in our example, we only add one dummy barrier since there is a single river outlet for all of the barriers. For study areas encompassing multiple, self-contained watersheds, however, dummies would need to be placed at the mouth of each watershed and be assigned *different* barrier IDs (e.g., "Dummy1" for the first watershed, "Dummy2" for the second watershed, etc.).

6.2 Incorporating Multiple Mitigation Options

Incorporating two or more mitigation options requires only simple modification to a basic OptiPass input file. For each barrier in question, the user must first set the NPROJ field to the correct number of available mitigation projects. A pair of COST and POSTPASS fields then needs to be supplied for each mitigation option. For example, if a particular barrier had 2 alternative mitigation options, the value of NPROJ would

[7] It is worth remembering the old adage: "garbage in, garbage out."

be 2. This would be followed by four columns: a pair of COST and POSTPASS fields for option 1 and then another pair of COST and POST fields for option 2. Note that fields have to be given in this precise order (i.e., do not group by field type, say by putting the two COST fields together followed by two POSTPASS fields together).

As a more concrete example, imagine that barriers A, B, and E for the example barrier network (Figure 1) each had two alternative mitigation projects. Besides each of the currently defined projects for barriers A, B, and E that would restore passability to 1 and cost $250k, $120k, and $100k, respectively, suppose that there was a less costly alternative in each case that would increase passability to 0.75. The cost of these projects is given as $150k, $80k, and $60k, respectively. A properly formatted barrier file with this expanded set of options is shown in Box 3 below.

Box 3. Barrier file for the example barrier network (Figure 1) assuming there are 2 mitigation options available at barriers A, B, and E.

BARID	REGION	DSID	USHAB	PREPASS	NPROJ	COST1	POSTPASS1	COST2	POSTPASS2
A	Ex3	NA	2.1	0.4	2	150	0.75	250	1
B	Ex3	A	0.9	0	2	80	0.75	120	1
C	Ex3	B	4.3	0.3	1	70	1	-	-
D	Ex3	A	1.7	0.5	0	-	-	-	-
E	Ex3	D	1.2	0.2	2	60	0.75	100	1
F	Ex3	D	0.5	0.1	1	50	1	-	-

Note that due to the addition of 2 extra columns in the barrier file, the header has been expanded and the names of the COST and POSTPASS fields modified appropriately. Specifically, COST1 and COST2 refer to the cost of the first and second mitigation options, while POSTPASS1 and POSTPASS2 refer to the post-mitigation passability of the first and second options. This sort of convention does not need to be adhered to in any way. The header of an OptiPass barrier file is included simply to identify each column in an easy way. Accordingly, the user can assign the column names to be anything he/she finds appropriate.

6.3 Incorporating Multiple Restoration Targets

If there are multiple restoration targets under consideration instead of just one, the barrier file needs to include USHAB, PREPASS, and POSTPASS fields that are specific to each restoration target. As an example, imagine that there were an additional restoration target for the example barrier network (Figure 1). This second target is assumed to be a somewhat better swimmer than the first target such that current passability (PREPASS) for the target is 50% higher at each barrier (still 0 for full barrier B). For the purposes of illustration, it is also assumed that habitat suitability for target 2 is somewhat less, specifically 80%, compared to target 1. Accordingly, the net amount of habitat for target 2 above any particular barrier is computed as 0.8 times the net amount of habitat for target 1. At barrier A, for example, passability for target 2 would be $1.5 \times 0.4 = 0.6$, while the net amount of habitat would be $0.8 \times 2.1 = 1.68$ river km. A correctly formatted barrier file for our hypothetical scenario involving two restoration targets is shown in Box 4 below.

Box 4. Barrier file for the example barrier network (Figure 1) assuming there are 2 restoration targets.

ID	REGION	DSID	HAB1	HAB2	PRE1	PRE2	NPROJ	COST	POST1	POST2
A	Ex4	NA	2.1	1.68	0.4	0.6	1	250	1	1
B	Ex4	A	0.9	0.72	0	0	1	120	1	1
C	Ex4	B	4.3	3.44	0.3	0.45	1	70	1	1
D	Ex4	A	1.7	1.36	0.5	0.75	0	-	-	-
E	Ex4	D	1.2	0.96	0.2	0.3	1	100	1	1
F	Ex4	D	0.5	0.4	0.1	0.15	1	50	1	1

Note that in order for Box 4 fit horizontally on the page, some of the standard field names have been truncated in the header (i.e., BARID, USHAB, PREPASS, and POSTPASS have been changed to ID, HAB1/HAB2, PRE1/PRE2, and POST1/POST2, respectively).

As a more elaborate example, we could consider multiple restoration targets combined with multiple mitigation options. Suppose, in addition to having two restorations targets, we wanted to consider the availability of the less costly mitigation options at barriers A, B, and E discussed previously (see Section 6.2). As before, the cost of these projects is $150k, $80k, and $60k, respectively. For each of these, it is assumed that post-mitigation passability would increase to 0.75 for target 1 and to 0.9 for target 2.

A properly formatted barrier file with a total of 14 columns would need to be supplied to OptiPass as shown in Box 5 below. This would include two net upstream habitat amounts (H1 and H2 for targets 1 and 2, respectively), two current passability values (P0.1 and P0.2 for targets 1 and 2, respectively), a cost field for the first mitigation option (C1) followed by two post-mitigation passability values (P1.1 and P1.2 for targets 1 and 2, respectively), and a cost field for the second mitigation option (C2) followed by two post-mitigation passability values (P2.1 and P2.2 for targets 1 and 2, respectively).

Box 5. Barrier file for the example barrier network (Figure 1) assuming there are 2 restoration targets and 2 mitigation options available at barriers A, B, and E.

ID	REG	DS	H1	H2	P0.1	P0.2	N	C1	P1.1	P1.2	C2	P2.1	P2.2
A	Ex5	NA	2.1	1.68	0.4	0.6	2	150	0.75	0.9	250	1	1
B	Ex5	A	0.9	0.72	0	0	2	80	0.75	0.9	120	1	1
C	Ex5	B	4.3	3.44	0.3	0.45	1	70	1	1	-	-	-
D	Ex5	A	1.7	1.36	0.5	0.75	0	-	-	-	-	-	-
E	Ex5	D	1.2	0.96	0.2	0.3	2	60	0.75	0.9	100	1	1
F	Ex5	D	0.5	0.4	0.1	0.15	1	50	1	1	-	-	-

Yet more complex problems involving additional restoration targets and or mitigation options could be considered. OptiPass can accommodate up to 10 mitigation options per barrier and up to 20 restoration targets.

6.4 Incorporating Downstream Passability

In many practical planning situations, it can be safely assumed that downstream passability for migratory fish is at or near 1. This is typically the case with the majority of small in-stream barriers such as culverts, weirs, and low-head dams that permit high rates of passage in the downstream direction. In cases where passability downstream is a key concern for some or possibly all barriers (e.g., at hydropower dams where fish often suffer mortality as they the pass through turbines), downstream passability can be factored into OptiPass in a straightforward manner. By simply multiplying upstream passability by downstream passability, one can determine a barrier's *bi-directional* passability before and after mitigation. In this way, OptiPass can be easily parameterized to account for overall cumulative passability by considering the difficulty required to reach a particular upstream habitat area (upstream passability) as well as any impediments when heading back to sea (downstream passability).

As an example, suppose for our example problem that instead of current downstream passability being 1 for each barrier it were set to 0.7, indicating that most but not all fish can successfully navigate barriers moving in the downstream direction. Suppose further that barrier mitigation can restore full upstream and downstream passability, except at barrier B, where downstream passability tops out at 0.9 (it is a difficult barrier to mitigate). In this situation, current bi-directional passability would be calculated as $0.4 \times 0.7 = 0.28$ for barrier A, $0 \times 0.7 = 0$ for barrier B, and $0.3 \times 0.7 = 0.21$ for barrier C. In a similar manner, bi-directional passability following mitigation work would be $1 \times 1 = 1$ for barriers A and C and $1 \times 0.9 = 0.9$ for barrier B. Box 6 below shows how a barrier file can be updated to incorporate downstream passability by substituting bi-directional passability estimates into the relevant PREPASS and POSTPASS fields.

Box 6. Barrier file for the example barrier network (Figure 1) with bi-directional passability used in place of upstream passability estimates.

BARID	REGION	DSID	USHAB	PREPASS	NPROJ	COST	POSTPASS
A	Example6	NA	2.1	0.28	1	250	1
B	Example6	A	0.9	0	1	120	0.9
C	Example6	B	4.3	0.21	1	70	1
D	Example6	A	1.7	0.35	0	-	-
E	Example6	D	1.2	0.14	1	100	1
F	Example6	D	0.5	0.07	1	50	1

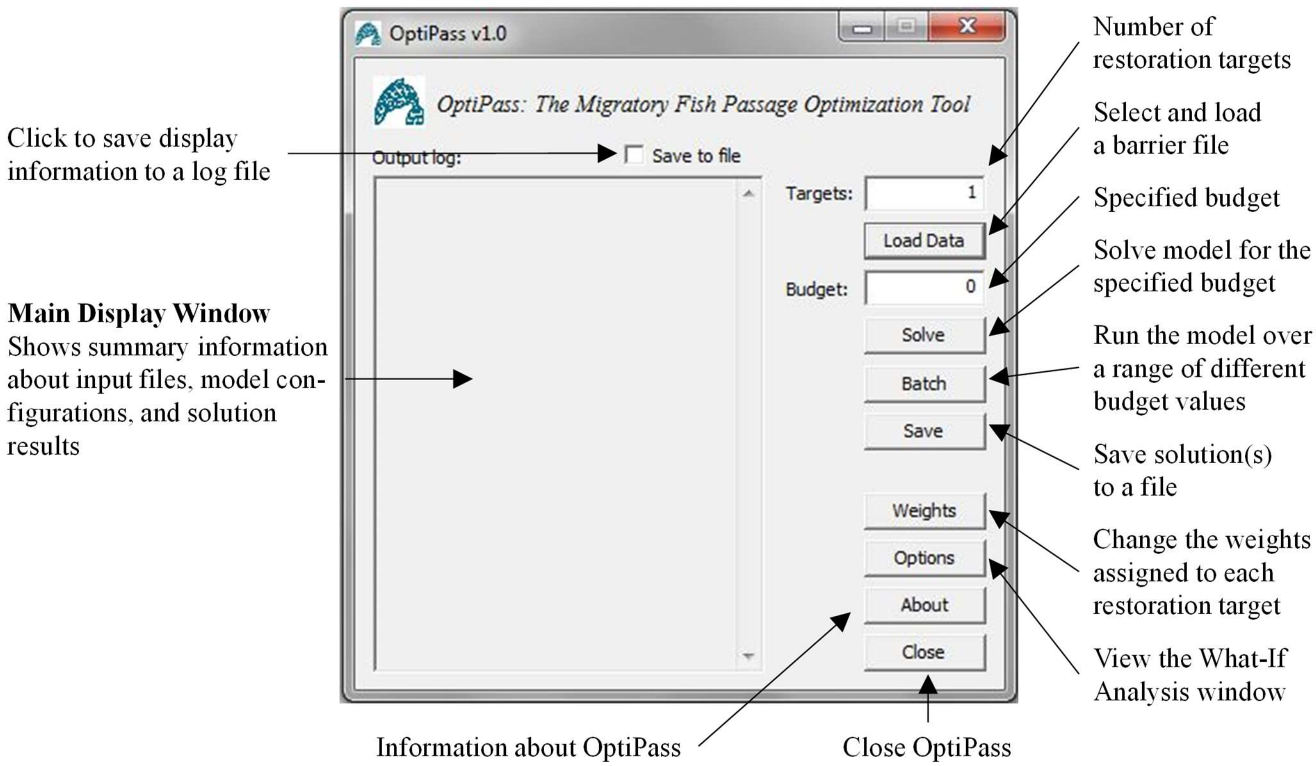
The really important question one needs to address upfront when deciding whether to incorporate downstream passability is to determine which life-stage downstream passability is relevant for. In the case of semelparous salmon, for example, upstream passage for adults trying to reach spawning grounds is essential, while downstream passage is only important for juvenile smolts returning to sea. With eels, on the other hand, the reverse is true. For migratory species that can reproduce multiple times (e.g., iteroparous species like alewife), one needs to decide whether downstream passability for adults or for juveniles is more important. Regardless of how they are differentiated according to life-stage, both upstream and downstream passage rates can be bundled together in OptiPass to capture the critical points in a species life-cycle that limit migration success.

7. Graphical User Interface

7.1 Main Window

The main window of the OptiPass graphical user interface (GUI), including an overview of its organization and primary controls, is shown in Figure 6 below. The GUI's main window has been designed with the goal of simplicity and ease-of-use in mind.

Figure 6. Overview of OptiPass's main window.



Basic steps for loading a barrier file, running an optimization, and saving a solution are given below.

Step 1. Enter the number of restoration targets for the barrier file of interest into the 'Targets' edit box. The default number of targets is 1. Note that if you enter an incorrect number of targets, OptiPass will be unable to read the selected barrier file correctly and throw out an error message.

Step 2. Click 'Load Data' to select a barrier file. A standard file search window will appear. By default, only text files with a '.txt' file extension will appear in the search window. To view and select other file types, change the file filter to 'All Files (*.*).' Navigate to the location of the desired barrier file and click 'Open.' Basic information about the barrier file, including the file name, the number of planning regions, the total number of barriers, and the number of *adjustable* versus *non-adjustable* barriers will be reported in the main display window. Adjustable barriers have at least one available mitigation project (NPROJ ≥ 1). Non-adjustable barriers cannot be mitigated (NPROJ = 0).

Step 3. Enter a budget amount into the ‘Budget’ edit box. Only values greater than or equal to 0 will be accepted.

Step 4. To run the optimization model, click the ‘Solve’ button. A command prompt window (aka DOS window) will appear indicating that the optimization model has begun solving. Detailed information about the status of the solution process will appear on the command prompt. When the solution routine has completed its run, the command prompt will close and summary information will be reported in the main display window. This includes confirmation that the solution found by OptiPass is optimal (Status), the total amount of potentially accessible habitat (Ptnl. habitat) that can be achieved for the given budget, the net gain in accessible habitat relative to baseline (Net gain), and the amount of time in seconds the optimization model took to solve. Baseline accessible habitat is determined assuming all barriers have their current passabilities (i.e., no mitigation occurs) and can be computed directly by entering a budget of 0. When dealing with multiple targets, the tag “wt.’ is appended before “habitat” to indicate that total habitat and net habitat gain are *weighted* amounts. Additionally, the unweighted amount of habitat for each target will be reported. See Section 8 for more detail about how to interpret the results. In very rare cases where OptiPass finds a feasible solution that cannot be proven optimal or no feasible solution can be found within a 6-hour time limit, an appropriate message is reported for Status.

Step 5 (optional). Click the ‘Save’ button to save the solution of the last run to an output file. The user will be prompted to enter a file name. Enter something appropriate, ideally using some sort of file naming convention that allows one to easily understand what the associated barrier dataset and budget amount are. The solution file will contain the same results summary information mentioned in Step 4 above along with a complete solution vector indicating the optimal mitigation action for each barrier. See Section 8 for more detail about the solution file.

Step 6 (optional). If desired, repeat Steps 3-5 for a different budget amount.

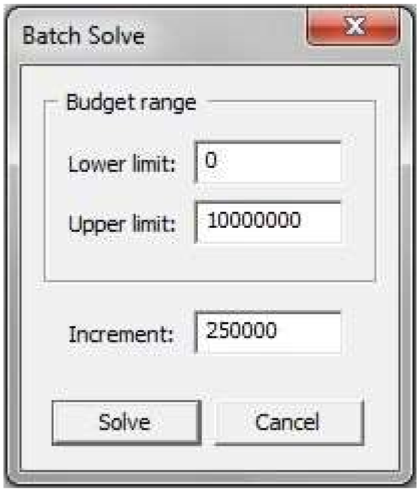
Step 7. When the analysis is complete, click ‘Close’ to exit OptiPass.

Additional functionalities provided in OptiPass include the possibility of performing batch runs for multiple, incrementally increasing budget values (accessed via the ‘Batch’ button), changing the weights assigned to each restoration target if and when multiple targets are present (accessed via the ‘Weights’ button), and conducting more detailed “what-if” type analyses (accessed via the ‘Options’ button) such as selecting regions to focus on for barrier mitigation and even forcing specific barriers in or out of the final optimal solution. These are discussed in turn in the following sections.

7.2 Batch Runs

OptiPass provides a special functionality for doing batch runs. Not infrequently, a user will want to run an optimization analysis for series of incremental budget values, say from \$0 to \$10M in steps of \$250k. This sort of thing occurs when one wants to generate a return-on-investment curve (aka Pareto curve or efficiency frontier) showing how total or net accessible habitat varies with budget. By performing a batch run, the user can avoid the need of repeatedly carrying out the multiple steps involved with generating and saving results for each budget value and instead instruct OptiPass to generate a full set of results all in one go.

Figure 7. OptiPass's batch window.



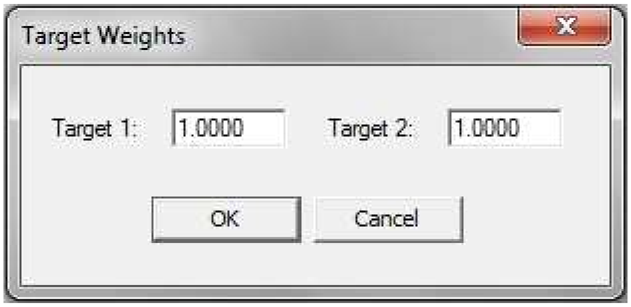
A figure of OptiPass's batch window is shown in Figure 7. The batch window can be accessed by clicking the 'Batch' button on the main window. Once the window appears, the user needs to enter 3 values: the lower value of the budget range (Lower limit), the upper value of the budget range (Upper limit), and a budget step size (Increment). OptiPass will check that sensible values have been entered, for example that none of the values are negative and that the upper value is greater than or equal to the lower value. An error message will be thrown out if an incorrect value has been entered. If the user hits 'Solve,' the window will close and OptiPass will proceed to solve each budget value in turn, reporting summary results of each individual run in the main display window as it proceeds. When the batch run is complete, if the user clicks the 'Save' button, all solutions for the batch run will be saved. Solution information stored in the results file is organized horizontally (left-to-right) starting with the first budget value and ending with the last budget value.

7.3 Assigning Target Weights

When dealing with multiple restoration targets, OptiPass assigns a default weight of 1 to each target, meaning that targets are weighted equally and all targets are "beneficial" in the sense that OptiPass should maximize the amount of reconnected habitat made available to each target. To change the default target weights, the user should click the 'Weights' button on the main window. A window showing the currently assigned weights, as displayed in Figure 8, will appear. The targets are numbered based on the order given the barrier file (i.e., target 1 refers to the first USHAB value, target 2 to the next USHAB value, etc.)

Enter an appropriate weight for each target. Assuming one wishes to maximize accessible habitat for a particular target (i.e., the target is considered "beneficial"), a positive value should be assigned. A higher (lower) weight indicates the target is valued more (less). A zero weight can be assigned to remove the target from consideration entirely. A negative weight indicates that a target is undesirable and that accessible habitat gain for the target should be minimized. If, for example, there are two targets (both beneficial) and target 1 is considered three times as important as target 2, then enter a 3 for target 1 and leave target 2's weight at 1. If on the other hand, the second target were an invasive species, then one could enter a negative weight of say -0.5 for target 2 and 1 for target 1 to indicate that limiting habitat gains for target 2 is important but that gains for target 1 are the primary concern.

Figure 8. OptiPass's target weights window.



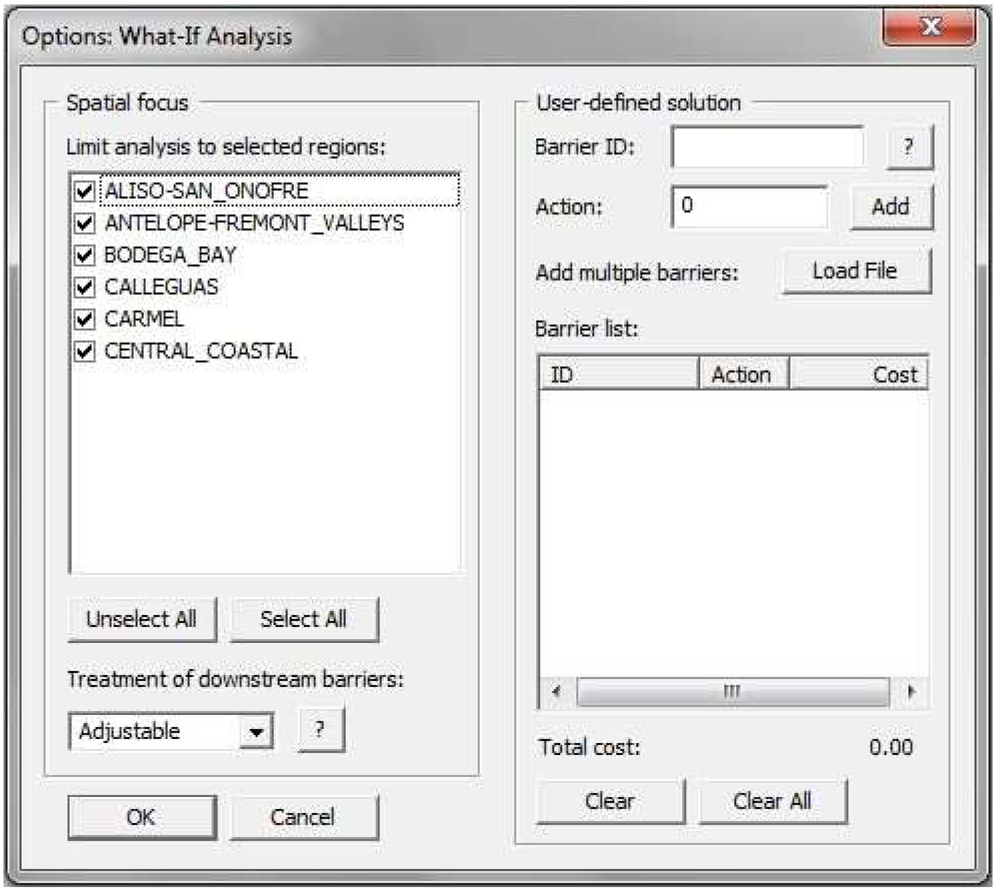
Note that there is no need to *normalize* the weights (e.g., so that they sum up to 1). Using the default assignment, in fact, the sum of weights will equal the number of targets. If preferred, however, one is free to normalize the weights in any suitable fashion. Going back to the example involving two beneficial targets, instead of assigning weights of 3 and 1 to targets 1 and 2, respectively, one could just well use weights of 0.75 and 0.25, respectively.[8] Note that the same optimal solution would be found regardless of which set of weights (unnormalized or normalized) were used.

7.4 What-If Analysis

Various "what-if" analyses can be performed in OptiPass by clicking the 'Options' button on the main window. A figure depicting the layout of the options window is shown in Figure 9. The options window is split into two main categories. Within the 'Spatial focus' section on the left, the user can select/unselect which regions to be the "focus" of barrier mitigation efforts. One of three options can be chosen for how to handle barriers within non-focus regions under the 'Treatment of downstream barriers' dropdown box. By selecting 'Adjustable,' any barriers that are directly downstream from selected focus regions (i.e., lying along the path to the river outlet) will be considered as candidates for potential mitigation. This option allows the user to consider the possibility of repairing/removing barriers which impact connectivity but are technically outside the area of focus. If the 'Non-adjustable' option is chosen, downstream barriers within non-focus regions will be considered vis-à-vis their impact on cumulative barrier passability within focus regions but otherwise excluded from consideration as candidates for mitigation action. This is the default option and forces passability at each non-focus downstream barrier to be set to its current PREPASS level. Although not recommended, the user can choose to treat focus regions in isolation by selecting the 'Excluded' option. This forces the optimization to completely ignore non-focus barriers and any potential impact they may have on cumulative barrier passability within focus regions.

[8] The normalization given here involves taking a target's initial weight and then dividing it by the sum of weights (i.e.., 3 / (3 + 1) = 0.75 for target 1 and 1 / (3 + 1) = 0.25 for target 2).

Figure 9. OptiPass's options window.



Under the 'User-defined solution' section on the right of the OptiPass options window, the user can specify that certain barrier actions be carried out or not. This is option is particularly useful when trying to assess how much habitat gain is affected by forcing specific mitigation actions into or out of the optimal solution. For example, while a certain barrier mitigation action might be technically possible, for practical/logistical reasons it might be difficult to implement (e.g., it is located on private land) and so should be excluded from consideration. Alternatively, there are often situations where it is required (e.g., based on legal obligations or policy directives) or simply desirable that a particular barrier be brought to a certain level of passability. In the former case, one needs to prevent the optimization model from choosing any mitigation option associated with the barrier (i.e., the barrier must be forced *out* of the solution), in the latter, mitigation of some kind is simply mandatory (i.e., the barrier must be forced *into* the solution).

To force a particular barrier action into/out of the solution, begin by typing the selected barrier ID (BARID) into the 'Barrier ID' edit box located in the top right. Be sure that the barrier ID is typed exactly as it appears in the barrier file. If the ID cannot be found within the currently loaded barrier file, a warning message will appear. Next, enter the number designating which action should be carried out. Only whole numbers from 0 up to the available number of mitigation projects (NPROJ) are accepted. By default, a 0 indicates that no mitigation action should be carried out. A value of 1 specifies that the first mitigation action should be implemented, a 2 specifies that the second mitigation action should be implemented, and so on. The mitigation actions are numbered based on the order given the barrier file (i.e., action 1 refers to the first COST value, action 2 to the next COST value, etc.) Accordingly, if only one mitigation option is available (NPROJ = 1), then either a 1 or 0 should be entered to indicate, respectively, that mitigation should or should not be carried out.

After providing the barrier ID and chosen mitigation action, hit the 'Add' button. The barrier ID, the chosen action, and the cost of the action will then appear in the list below. Underneath the list, the total cost required to mitigate all barriers being forced into the optimal solution will be shown. Note that this value sets a minimum threshold on the mitigation budget (i.e., the budget provided on the main window or in the batch window must be greater than or equal to the total cost of barriers being forced-in).

Box 7. Input file of a hypothetical user-defined solution for the example barrier network (Figure 1) in which barriers A and C are forced out and barrier E is forced into the optimal solution.

```
 BARID   ACTION
     A        0
     C        0
     E        1
```

As an alternative to manually entering multiple barrier IDs and mitigation action numbers, one can input this information into a tab or comma delimited text file and click the 'Load File' button. The file should contain two columns and *must* include a header. The first column should be a list of barrier IDs, the second a list of numbers indicating which barrier action should be implemented. A file containing a hypothetical user-defined solution for the example barrier network (Figure 1) is provided in Box 7.

8. Interpreting OptiPass Results

When an OptiPass solution is saved, a tab delimited text file, referred to as a "solution file," is created containing various pieces of information about the current solution. In the upper part of the file, summary information is provided, including the budget as well as total habitat and net habitat gain. Below this, the optimal mitigation action for each barrier is recorded.

A representative solution file for the example barrier network (Box 1) given a budget of $400k is shown in Box 8. The first line in the file (BUDGET) gives the budget at which the solution was obtained. The next line (STATUS) indicates whether the solution is optimal or not. A value of OPT indicates that the solution is a verified optimum, while FEAS indicates that solution is feasible but could not be proven optimal within the defined 6-hour time limit. In the third line, the percent optimality gap (%OPTGAP) is reported. Optimality gap refers to the percentage difference in accessible habitat between the solution and the theoretical upper bound.[9] This gives an indication of how far off the solution is from optimality. If the solution found is optimal (STATUS = OPT), then the optimality gap will be 0. In lines four and five, the total amount of potentially accessible habitat (PTNL_HABITAT) and the net gain in accessible habitat

[9] The upper bound is based on the linear programing relaxation to the MILP model.

(NETGAIN) relative to baseline are provided, respectively. Lastly, there is a solution table listing for each barrier ID (BARID) its optimal mitigation action (ACTION).

Box 8. Solution file for the example barrier network (Box 1) given a budget of $400k.

```
BUDGET:         400.00
STATUS:         OPT
%OPTGAP:        0.00
PTNL_HABITAT:   5.2850
NETGAIN:        4.0470

        BARID    ACTION
            A         1
            B         1
            C         0
            D         0
            E         0
            F         0
```

Looking at the solution in Box 8, we can see that for a budget of $400k, barriers A and B should be mitigated since they both have 1 for ACTION. The other barriers have a value of 0 for ACTION, indicating they should not be mitigated.

Box 9. Solution file for the example barrier network (Box 1) based on a batch run with a lower limit $0, upper limit $500k, and increment $100k.

```
BUDGET:         0.00      100.00    200.00    300.00    400.00    500.00
STATUS:         OPT       OPT       OPT       OPT       OPT       OPT
%OPTGAP:        0.00      0.00      0.00      0.00      0.00      0.00
PTNL_HABITAT:   1.2380    1.4300    3.3180    3.5100    5.2850    8.5200
NETGAIN:        0.0000    0.1920    2.0800    2.2720    4.0470    7.2820

        BARID    ACTION    ACTION    ACTION    ACTION    ACTION    ACTION
            A         0         0         0         0         1         1
            B         0         0         1         1         1         1
            C         0         0         1         1         0         1
            D         0         0         0         0         0         0
            E         0         1         0         1         0         0
            F         0         0         0         0         0         1
```

Unless one has done a batch run, only information pertaining to the last solution (i.e., to the most recent optimization run) is saved when writing to a solution file. Saving after a batch run will result in all solutions making up the batch run being exported. The solution file shown in Box 9 corresponds to a batch run performed over the range $0 to $500k with a step size of $100k. Note that since the solution file is tab delimited, it can be easily imported into spreadsheet software (e.g., Microsoft Excel®) or some other graphical/computing application (e.g., the R statistical package). In the case of batch runs, this allows one to quickly produce x-y type graphs showing how total or net accessible habitat (y-axis) varies with budget (x-axis). These are commonly referred to as return-on-investment, Pareto, or efficiency frontier curves.

If only one mitigation project is available (NPROJ = 1), then either a 1 or 0 will appear for ACTION to indicate that mitigation should or should not be carried out, respectively. For barriers having no mitigation option (NPROJ = 0), a 0 will invariably appear for ACTION. In cases where multiple mitigation actions are available, any whole number between 0 and the number of mitigation projects (NPROJ) may be given for ACTION. As an example, if the barrier file shown in Box 3 were run through OptiPass using a budget of $400k, the solution file shown in Box 10 would be produced. This barrier file, to remind you, has an additional, cheaper mitigation option available at barriers A, B, and E. Looking at the resulting solution, you can see that the second mitigation action is chosen for barrier A and the first mitigation option for barriers B and C (for the others, no mitigation should be performed). Interestingly, the total amount of accessible habitat has gone up from 5.285 km to 6.995 km as a result of including additional mitigation options in the optimization analysis. This has increased the flexibility given to the model in terms of how the budget can be allocated.

Box 10. Solution output file for the modified example barrier network with 2 mitigation options available at barriers A, B, and E (Box 3) and a budget of $400k.

```
BUDGET:        400.00
STATUS:        OPT
%OPTGAP:       0.00
PTNL_HABITAT:  6.9950
NETGAIN:       5.7570

        BARID    ACTION
            A         2
            B         1
            C         1
            D         0
            E         0
            F         0
```

One thing that needs careful attention is how to interpret total/net accessible habitat when multiple targets are present. As mentioned previously, when dealing with multiple targets, one has the option of assigning target specific weights. Total habitat and net habitat gain, in this case, represent weighted combinations of the total/net gain for each target. In the solution file, this is signified by appending "WT_" in front of HABITAT and NETGAIN. Additionally, extra rows are included in the top portion of the solution file reporting both the weight and the amount of accessible habitat for each target when dealing with multiple restoration targets.

Box 11. Solution output file for the modified example barrier network with 2 restoration targets (Box 4) and a budget of $400k.

```
BUDGET:              400.00
STATUS:              OPT
%OPTGAP:             0.00
WEIGHTS
TARGET1:             3.0000
```



```
TARGET2:           1.0000
PTNL_HABITAT
TARGET1:           5.2850
TARGET2:           5.2290
WT_PTNL_HABITAT:  21.0840
WT_NETGAIN:       15.5934

           BARID    ACTION
               A         1
               B         1
               C         0
               D         0
               E         0
               F         0
```

Returning to the modified example problem with two restoration targets described in Section 7.3, the solution file corresponding to a $400k budget is shown in Box 11 above. The problem was solved with a weight of 3 assigned to target 1 and a weight of 1 given to target 2. This can be seen from a quick inspection of the solution file. Total weighted habitat (WT_HABITAT) is reported as 21.084 km. This figure is based on the 5.285 km of accessible habitat made available for target 1 and the 5.229 km of accessible habitat for target 2.

9. Uses of OptiPass

OptiPass can potentially be used in a wide variety of ways to help inform planning and policy decisions. These include (but are not limited to) the following:

- Strategic planning tool
- Baseline setting tool
- Project screening tool
- Budgeting tool

As a *strategic planning tool*, OptiPass can determine which set of barriers to target for mitigation within a given planning region that yield the "biggest bang for the buck." This is what OptiPass does by default. Here, one simply runs OptiPass at a given budget amount, without using any special options settings. OptiPass will subsequently ensure that the barriers selected for mitigation maximize restoration gains for the specified budget. The set of barriers making up the optimal solution will invariably be problem specific. Selected barriers may be low-, mid- or high-order barriers (i.e., with few, medium, or many downstream barriers). They may be concentrated in certain areas or spread throughout the study area. They may involve mostly low-cost or high-cost projects, or some combination thereof. OptiPass will sort through all the possible combinations and choose the barriers that collectively provide maximum benefit relative to cost.

While certainly guaranteed to be optimal, the solutions produced by OptiPass may, in some cases, be less than ideal from a practical standpoint – they might be contentious politically or simply difficult to put into operation. Moreover, OptiPass is designed specifically to meet only one planning goal, the maximization of accessible habitat. Secondary environmental and socio-economic objectives associated with barrier mitigation like structural safety concerns and impacts on river hydrology and geomorphology are beyond scope.

Regardless, OptiPass can still find usefulness as a *baseline setting tool*. The solutions produced by OptiPass can be used as yardsticks with to compare against other, more politically acceptable or operationally feasible alternatives. Alternatively, OptiPass solutions can form the starting point for more detailed modeling and refinement in order to account for secondary planning goals. To compare how any alternative/modified solution stacks up against solutions derived from OptiPass in terms of accessible habitat, one simply needs to create a user-defined solution using the options window in which the barriers associated with the alternative/modified solution are forced into the optimal solution. OptiPass will then determine what the associated amount of accessible habitat is for this particular solution, thereby facilitating cross comparison with the OptiPass baseline solution. In short, OptiPass provides a mechanism for evaluating alternatives and facilitating negotiation among experts, decision makers, and key stakeholders.

Another important role of OptiPass is that of *project screening tool*. Often times, one is limited as to the set of mitigation options under consideration. A case in point is the selection of proposals that have been submitted to some governmental or NGO funding body. Here, the funding body will have a limited pot of money available to support restoration efforts and its task is to determine which projects to fund. Assuming the goal is to maximize accessible habitat gain, one simply needs to do the following. First, use the options window to forces all barriers not under consideration out of the optimal solution. Only candidate projects will have the possibility of being chosen. Next, run OptiPass to see which candidate projects should be selected given the amount of funding available. It really is as simple as that.

Lastly, OptiPass provides value as a *budgeting tool*. In many situations, budgets are not set in stone. There is instead flexibility with regard to the level of investment in barrier mitigation actions. The question then arises: What should the budget be that best achieves defined policy goals? The first step in addressing this question is determine how total or net accessible habitat varies with budget in order to see if there are certain thresholds, below which gains may be modest or above which gains begin to level off. Here, the batch facilities of OptiPass come into play. By performing a batch run and plotting the results of total (or net) habitat versus budget, one can identify exactly where the budget thresholds are. With this in hand, one can gain a clear understanding of the tradeoffs involved between increases in accessible habitat on the one hand and cost on the other. This, in turn, can feed directly into the program budgeting processes and the setting of a cost-efficient level of investment in barrier mitigation.

10. Limitations and Other Provisos

OptiPass has been thoroughly tested. However, it cannot be guaranteed that it will operate correctly under all operating systems and environments. Anticipating all potential combinations of erroneous input has not been possible.

Please read the sections covering main assumptions (Section 5.2), formatting requirements (Section 6) and how to interpret OptiPass results (Section 8) carefully. In particular, try to ensure that the input data are as accurate as possible and that all potential barriers (artificial and natural) within the defined study area are included in the analysis.

Even if it is presumed that the input data are complete and accurate, the demands of real-world watershed restoration planning are such that any proposed barrier repair/removal actions generated by OptiPass should be carefully reviewed by experts, ideally from multiple disciplines. The OptiPass modeling framework does not account for a whole host of key environmental and socio-economic issues besides accessible habitat, including impacts on river hydrology and geomorphology, the wider aquatic and riparian ecosystem, recreation, sport fishing, hydropower, water supply, flood control, likelihood of structural failure, and the consequences of failure with regard to property loss, disruption of transportation, and general public safety (just to name a few).

It is also strongly recommended that a sensitivity analysis be carried out in which the input data are systematically varied in order to assess the degree of robustness of any proposed OptiPass solution. This could include simple things like adjusting the upstream habitat, passability, and cost parameters to see if the optimal solution changes. One might also want to examine the potential impact on accessible habitat from forcing one or more barriers provisionally selected by OptiPass out of the optimal solution. This helps to determine how dependent the anticipated outcomes are with regard to any unforeseen changes that might occur when implementing proposed solutions.

11. User Support

Limited user support may be provided by contacting the developer via email (see contact info below). When doing so, please include in your request the following information:

- The word “OptiPass” in the subject line.
- The current version of OptiPass you are using.
- A detailed description of what you are trying to do or the specific problem you are having.

Reporting a Bug
If you find a bug please contact the developer via email (see contact info below). When reporting a bug, it is important to provide as much information as possible regarding the problem. At a minimum, be sure to include the following information:

- The word “OptiPass” in the subject line.
- The current version of OptiPass you are using.
- A detailed description of the problem, including a full list of setting you are using and a full account of the steps that led up to the problem.
- An attachment of input files if the problem seems to be specific to a particular set of data.

Contact Information

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Appendix: Problem Formulation

The optimization model employed by OptiPass, known formally as the Fish Passage Barrier Removal Problem (FPBRP), identifies for a given budget the set of barrier mitigation projects providing the largest amount of accessible habitat available for diadromous fish. The model as originally presented in O'Hanley and Tomberlin (2005) only considers a single species (aka restoration target) of interest. The model is extended here to account for multiple restoration targets.

Table 4. Notation used in FPBRP.

Symbol	Description
T	The set of restoration targets, indexed by t
J	The set of all artificial and natural barriers, indexed by j and k
D_j	The set of all barriers downstream from and including barrier j
A_j	The set of mitigation projects available at barrier j, indexed by i
w_t	Objective weight for restoration target t
v_{jt}	The net amount of habitat above barrier j for restoration target t
p_{jt}^0	Current passability of barrier j for restoration target t
p_{jti}	Increase in passability at barrier j for target t given implementation of mitigation project i
c_{ji}	Cost of implementing mitigation project i at barrier j
b	Available budget for carrying out mitigation actions

Given the notation in Table 4, along with the following decision variables:

$$x_{ji} = \begin{cases} 1 & \text{if barrier mitigation option } i \text{ is chosen for barrier } j \\ 0 & \text{otherwise} \end{cases}$$

$$z_{jt} = \text{cumulative passability of barrier } j \text{ for target } t$$

a mathematical formulation of FPBRP is provided below.

$$\max \sum_{t \in T} w_t \sum_{j \in J} v_{jt} z_{jt} \tag{1}$$

$s.t.$

$$z_{jt} = \prod_{k \in D_j} \left(p_{kt}^0 + \sum_{i \in A_k} p_{kti} x_{ki} \right) \qquad \forall j \in J, t \in T \tag{2}$$

$$\sum_{i \in A_j} x_{ji} \le 1 \qquad j \in J \tag{3}$$

$$\sum_{j\in J}\sum_{i\in A_j} c_{ji}x_{ji} \le b \qquad (4)$$

$$x_{ji} \in \{0,1\} \qquad j \in J, i \in A_j \qquad (5)$$

The objective function (1) maximizes the weighted sum of accessible habitat $v_{jt}z_{jt}$ over all barriers j and restoration targets t. The objective weights w_t allow certain targets to be prioritized over others. Invasive species, for which increased habitat is undesirable, can be assigned negative weights. Equations (2) determine the cumulative passability z_{jt} of barrier j for target t. For any barrier j, this is equal to the product of the passabilities at j and all barriers downstream from j (i.e., for barriers in the set D_j). Passability for target t at any barrier k in set D_j is equal to the current passability p^0_{kt} for target t (i.e., the PREPASS field in a barrier input file) plus the potential increase in passability $p_{kti}x_{ki}$ for target t given implementation of mitigation project i at barrier k (i.e., the difference between the POSTPASS and PREPASS fields in a barrier input file). If mitigation project i is selected for barrier k ($x_{ji} = 1$), then its passability is equal to $p^0_{kt} + p_{kti}$. If no mitigation project is selected ($x_{ji} = 0$ for all $i \in A_j$), then passability is simply equal to the current passability p^0_{kt}. Inequalities (3) specify that only one mitigation project i can be carried out at any given barrier. Constraints (4) stipulate that the total cost of mitigation actions cannot exceed the available budget. Lastly, constraints (5) impose binary restriction on all of x_{ji} barrier mitigation decision variables.

Note that the above model is nonlinear. An equivalent *linear* formulation of the problem can be devised by converting (2) into a probability chain (O'Hanley et al. 2013a). Probability chains, which come from the operations research literature, are useful for linearizing certain classes of high-order polynomial terms such as (2).

Specifically, if we introduce the following auxiliary variables:

y_{jti} = change in cumulative passability at barrier j for restoration target t given implementation of project i

and let d_j denote the barrier immediately downstream from barrier j, equations (2) can, in the case of positive weight targets ($w_t > 0$), be replaced with the following set of linear constraints.

$$z_{jt} = p^0_{jt} + \sum_{i\in A_j} y_{jti} \qquad \forall j \in J | d_j = \emptyset, t \in T \qquad (5)$$

$$z_{jt} = p^0_{jt} z_{d_j t} + \sum_{i\in A_j} y_{jti} \qquad \forall j \in J | d_j \neq \emptyset, t \in T \qquad (6)$$

$$y_{jti} \le p_{jti}x_{ji} \qquad \forall j \in J, t \in T \qquad (7)$$

$$y_{jti} \le p_{jti}z_{d_j t} \qquad \forall j \in J | d_j \neq \emptyset, t \in T \qquad (8)$$

Equations (5) and (6) determine, respectively, the cumulative passability for barriers having no downstream barrier versus at least one downstream barrier. Inequalities (7) and (8), meanwhile, place bounds on the allowable increase in cumulative passability y_{jti} for target t given implementation of mitigation project i at barrier j. Collectively, (5)-(8) allow both cumulative passability z_{jt} and increases in cumulative passability y_{jti} for any given barrier j to be determined in a recursive manner by taking into account the cumulative passability at barrier j's downstream barrier $z_{d_j t}$.

In the case of negative weight targets ($w_t > 0$), one simply needs to substitute (7)-(8) with the following in order to force variables y_{jti} to take on their correct values.

$$y_{jti} \geq p_{jti} x_{ji} \qquad \forall j \in J | d_j = \emptyset, t \in T \tag{9}$$

$$y_{jti} \geq p_{jti} \left(z_{d_j t} + x_{ji} - 1 \right) \qquad \forall j \in J | d_j \neq \emptyset, t \in T \tag{10}$$

