A Bayesian Network to Prioritize Restoration of Aquatic Connectivity in the Santiam River Basin, OR

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Introduction

This study was initiated to develop a flexible tool for evaluating and prioritizing fish passage restoration as accomplished by replacement of road culverts in streams that may act as passage barriers. The issue of prioritization is critical, as the cost of restoration is very high, estimated at over $375 million on public lands in Oregon and Washington alone (GAO 2001; http://www.gao.gov/new.items/d02136.pdf). This does not include thousands of potential culvert barriers that exist on other lands. In Oregon, the Oregon Watershed Enhancement Board has invested $28 million to restore passage at 313 barriers over the last ten years. Clearly there are many more barriers in place than can be restored in a short time frame with limited resources available.

The question of prioritization is driven in part by limited resources, but also by the great variability among barriers in terms of 1) the degree to which fish passage is impaired, 2) the benefit to fish of removing the barrier, and 3) the cost of the project. Each of these key considerations can be a deciding factor in terms of identifying passage restoration priorities, or the decision to restore passage in a case study.

The degree to which fish passage can be impaired can be determined in theory. However, in practice there is much uncertainty in terms of whether a structure, like a stream culvert, is a barrier in reality. Available tools for assessing the degree of passage impairment, such as FishXing (http://www.stream.fs.fed.us/fishxing/) are not designed to fully account for certainty of the probability that fish of different species or life stages will be able to swim through a culvert under different environmental conditions. Consequently FishXing is conservative in that it tends to overestimate the degree to which culverts pose barriers to fish passage (bias), and due to the numerous differences among species, life stages, and stream flows, estimates of passage impairment are likely uncertain or imprecise (e.g., Burford 2005; http://etd.lib.montana.edu/etd/view/item.php?id=18). In the context of prioritization, these uncertainties can lead to undesirable outcomes including replacement of structures that did not initially impair fish passage and limited ability to identify priorities because all structures appear to be barriers (e.g., limited “decision space”). Accordingly, if uncertainty can be addressed, the value of information from FishXing for prioritizing restoration is greatly improved.

Whereas much effort has been invested in protocols for assessing passage impairment, the problem of “thinking outside of the pipe” has received less attention. In addition to allowing passage, the benefit to fish of removing a barrier depends on 1) the suitability of habitat that may be accessed if the barrier is removed, and 2) the probability that fish will use the habitat. If habitat suitability is low, then barrier removal may not be warranted because fish will not use the newly accessible habitat, or worse yet, a case of an "ecological trap" may result. The latter refers to attracting fish to habitats that may not be beneficial to individuals or populations. Even if habitat suitability is optimal, existing populations of fish may be too far away or other factors may act to limit the probability that they will actually colonize the habitat (e.g., established populations of nonnative species, other barriers downstream). Informally phrased, this would represent the "field of dreams" hypothesis after the movie of the same name: if habitat is restored, will the fish come?

Finally as mentioned above, cost is an obvious but critical consideration to weigh in relation to the potential benefits to fish. This, combined with other uncertainties (e.g., Fausch et al. 2009; http://www.fs.fed.us/rm/boise/publications/invasive_fish.shtml) can lead to complex decisions that are difficult to make without use of a decision support system (see Peterson et al. 2008; cited in Fausch et al. 2009). Current schemes for prioritization do not account for uncertainty, including lack of information, lack of precision in measurements, or incorporation of local expert opinion, or variability in the opinion of experts.

To address the limitations of current prioritization methods, I have been working to develop a decision support tool for prioritizing restoration of passage in the case of threatened steelhead trout (*Oncorhynchus mykiss*) in the Santiam River basin. This specific case and lessons learned will produce a procedure that can be generalized and applied to other species and locations. Following work by (Peterson et al. 2008) I am using a Bayesian network to incorporate diverse sources of information into a prioritization procedure that explicitly accounts for uncertainty.

Methods

This Bayesian network combines empirical evidence and expert opinion, depicting relationships between factors affecting the decision to replace a barrier. Netica software was used to construct the model. Measures of habitat suitability consist of the rearing capacity of a stream to support juvenile steelhead (e.g., Burnett et al. 2007), underlying geology and whether a culvert is in an Oregon State designated cold core habitat or spawning area. Potential colonization of reconnected habitat is based on the presence of redds and redd distance from the barrier. The status of a barrier is depicted as whether the culvert is an unconditional barrier to adults or juveniles. Cost to replace the culvert is broken down into three categories based on analysis of OWRI data. Degree of passage impairment, habitat suitability, potential colonization, and cost all influence the decision to replace a culvert. Finally because Bayesian networks are well suited to working with uncertainty, it is not necessary to have complete information for decision making. The cost of incomplete information is increased uncertainty about the value of a particular restoration opportunity. This uncertainty can be reduced with additional information, but it may not be necessary in many cases to know everything to make a decision.

Outcome

This model can assist decision making when assessing a culvert for replacement using complete or partial information. A culvert can be assessed under different hypothetical levels of information. For example, information can be entered into requisite nodes and the decision to repair recorded. Then, a parameter can be changed to assess the difference of the finding to that parameter (e.g., a sensitivity analysis). In this way different information scenarios can be applied and assessed, assisting decision makers. This allows users to assess the value of additional information in helping to arrive at a decision. Restoration can be costly, but the information needed to inform restoration may also carry a significant cost. Considering both can lead to a more efficient solution.

This model is not to be used without considering other factors, such as opportunity for restoration versus priority. The final decision to restore passage is obviously not up to the model. Our hope is that this simple and useable tool can be used to more effectively incorporate existing information (including uncertainty) into more cost-effective prioritization of fish passage restoration projects, and to provide a clear and transparent means of documenting the basis for decisions to fund restoration. An existing Bayesian network (Peterson et al. 2008) is already being used by practitioners to assess fish passage restoration opportunities in the inland western US (isolation vs. invasion; D. Peterson, USFWS, personal communication).

In addition to assessing priorities, restoration of passage can be monitored in relation to priorities given to individual projects (implementation monitoring) and success can be evaluated (effectiveness monitoring) in relation to hypotheses that this model generates. For example, if a project is conducted on a reach of stream with high habitat suitability, strong connectivity to existing populations, and the barrier removed is known to prevent all passage, we would predict a strong probability of fish response. If this was not realized through subsequent monitoring, we would have to question our initial assumptions in our prioritization process (validation monitoring).

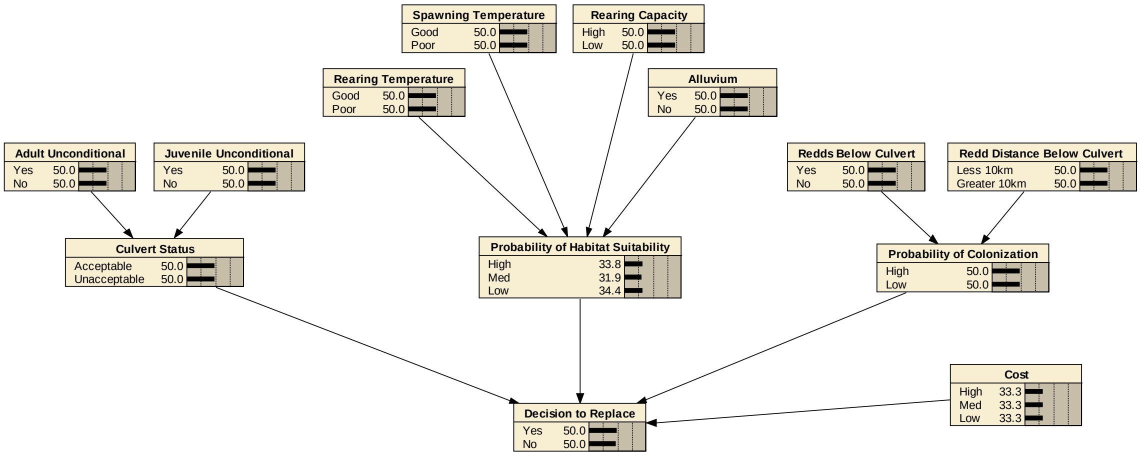

Figure 1. DRAFT Bayesian network model to be used in prioritizing fish passage restoration for steelhead trout in the Santiam basin. This model incorporates habitat suitability, probability of colonization, culvert status, and cost, as outlined above. Each of the nodes in this model represents a series of discrete states (e.g., “Yes or No,” “High Medium Low”) that are linked via conditional probability tables using Netica. Values for these tables are drawn from the scientific literature or expert opinion (see Appendix for details).

Appendix: Bayesian Network Definition and Node Descriptions

Bayesian networks (BN) are common statistical tools used to aid decision making in resource management and numerous other fields. The BN can combine empirical evidence, expert opinion or both, depicting relationships between factors affecting a potential outcome. A BN consists of nodes (variables) that can be discrete (e.g. yes/no) or continuous (e.g. range of values). Parent nodes have no nodes feeding into them while child nodes have nodes feeding into them. A child node can act as a parent node. A node can be represented with different states; i.e. yes/no or low/medium/high. Nodes are connected with arrows, indicating a cause and effect relationship. The relationship is depicted as a probability in a conditional probability table (CPT), which depicts every possible combination of parent states. The CPT values can be from expert opinion or empirical data, and can be weighted to represent the importance of different parent nodes.

There are different types of uncertainty that can be accounted for within the model. Uncertainty in the source data can be reflected as probabilities in the CPT (e.g. the degree of yes or no) to determine the node states. The final node (decision to replace) has two states, but is represented through a probability (e.g. 80% yes, 20% no). This depicts the probability that for given inputs the output will be not just "yes or no", but a range of yes or no. By running the model uncertainty is carried through to the final node. Uncertainty can also be accounted for in the mean standard deviation of individual nodes.

Additional information on Bayesian networks can be found at:
www.spiritone.com/~brucem/bbns.htm site maintained by Bruce Marcot, and documentation for Netica at www.norsys.com

Nodes

Rearing Capacity:
Rearing capacity (intrinsic potential) consists of habitat suitability curves for stream gradient, mean annual flow and calibrated valley width which depict the inherent ability of a stream to support juvenile steelhead under pristine conditions. It is derived from empirical studies and expert opinion.

Source: Burnett et al 2007, NOAA for GIS layers

Potential Sources of Uncertainty: Habitat suitability curves that establish intrinsic potential values.

Alluvium:
The proportion of basin in alluvium can be used as a predictor of redd abundance in the Santiam basin. Underlying geology of the area affects location of alluvium deposits.

Source: USGS, Walker and Macleod Geology map of OR 1991, Steel et al. 2003.

Potential Sources of Uncertainty: Data layer is coarse 1:500,000.

Spawning Temperature:
Node indicates if the stream is identified as an OR DEQ designated spawning use stream. These are streams or sections of streams that are designated salmon and steelhead spawning use.

Source: OR DEQ Fig 340B, Salmon and Steelhead Spawning Use Designations map

Potential Sources of Uncertainty: Does not include all potential spawning locations.

Rearing Temperature:
Stream temperature is determined whether stream is located within an OR DEQ cold core water habitat. Streams within the cold core water habitat (good) should be cooler temperatures than streams not within the designated habitat (poor).

Source: OR DEQ Standards

Potential Sources of Uncertainty: Streams can exceed desired temperatures in the cold core habitat, location of temperature gages can influence temperature recordings.

Redds Below Culvert:
A measure of fish abundance below the culvert to answer the question; Are there steelhead below the culvert? Neighborhood effect, work in areas with higher fish populations.

Source: ODFW online data

Potential Sources of Uncertainty: Not all streams surveyed, surveyor bias, extrapolating redd counts from area to another, determining the distance to the nearest known redd.

Redd Distance Below Culvert:
The closer redds are to the culvert, the higher the chance of fish using the opened habitat. This node addresses the neighborhood effect.

Source: ODFW online data

Potential Sources of Uncertainty: Incomplete survey data.

Adult Unconditional:
Node depicts whether the culvert is a barrier to upstream migrating adult steelhead. The degree to which the culvert is a barrier is defined as a percent of the expected flow conditions at the culvert during the adult return period. Additional factors include physical characteristics of the stream immediately above and below the culvert. Determined using established protocols (e.g. FishXing) to identify barrier culverts to fish.

Source: ODFW, watershed councils.

Potential Sources of Uncertainty: Surveyor bias, protocol effectiveness, is it known whether the culvert is a barrier to particular species and life stages, what is the definition of barrier, is there a threshold for passability during a range of flows.

Juvenile Unconditional:
Node depicts whether the culvert is a barrier to upstream migrating juvenile steelhead. The degree to which the culvert is a barrier is defined as a percent of the expected flow conditions at the culvert during the adult return period. Additional factors include physical characteristics of the stream immediately above and below the culvert. Determined using established protocols (e.g. FishXing) to identify barrier culverts to fish.

Source: ODFW, watershed councils.

Potential Sources of Uncertainty: Surveyor bias, protocol effectiveness, is it known whether the culvert is a barrier to particular species and life stages, what is the definition of barrier, is there a threshold for passability during a range of flows.

Cost:
Node describes the estimated cost to repair a particular culvert. 1,448 fish passage projects from 1995 to 2005 were analyzed for cost. The average cost was $45,572 with a minimum of $100 and a maximum of $5,264,000. Costs were broken into three categories; low <$50k, $50k < med <$150k, and high >$150k.

Source: Oregon Watershed Enhancement Board's (OWEB) Oregon Watershed Restoration Inventory (OWRI) database.

Potential Sources of Uncertainty: Not all projects have costs, potential misidentified projects.

Probability of Habitat Suitability:
This combines prior nodes; rearing capacity, alluvium, spawning temperature and rearing temperature. Nodes are not equally weighted: Temperature>IP>Alluvium. Temperature should be considered more important than potential habitat. Because the alluvium layer is very coarse, it is the least weighted.

Source: IP, Alluvium, Spawning Temperature, Rearing Temperature nodes

Potential Sources of Uncertainty: Conditional probability table values, proper weighting of nodes.

Probability of Habitat Colonization:
Depicts the probability of whether the habitat will be colonized if aquatic connectivity is restored. This is a combination of redds below the culvert and redd distance below the culvert.

Source: Redds below culvert and redd distance below culvert nodes

Potential Sources of Uncertainty: Conditional probability table values, proper weighting of nodes, see also uncertainty in source nodes.

Culvert Status:
Node depicts whether the culvert has been established as a barrier to different life stages. It is assumed that if the culvert is a barrier to adults it is a barrier to juveniles as well. If the not a barrier to adults, it still may be a barrier to juveniles.

Source: Adult unconditional node.

Potential Sources of Uncertainty: Conditional probability table values, proper weighting of nodes, see also uncertainty in source nodes.

Decision to Replace: The probability that a culvert of interest should be replaced. This could be multiple pipes depending on site. High scores can translate into high ranking, although no threshold value has been determined.

Source: Culvert Status, Probability of Habitat Suitability, Probability of Colonization, Cost

Potential Uncertainty: Conditional probability table values, previous nodes, all previous uncertainty.