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Re-establishing connectivity is a primary restoration activity for enhancing the recovery of migratory fishes, but actions are often limited by lack of funds and understanding of the benefits of individual projects. The objective of this study was to develop a Bayesian Network (BN) to assess priorities for restoration of aquatic connectivity as accomplished by replacement of culverts at road stream crossings that may act as passage barriers to winter run Steelhead (*Oncorhynchus mykiss*) in the North and South Santiam Rivers (state of Oregon). The model predicted the probability of biological benefit obtained by removal or replacement of a culvert. The degree of passage impairment, habitat suitability and probability of habitat use influenced the predicted biological benefit. This model structure was populated with conditional probability table values derived from expert opinion and a Bayesian learning algorithm to produce outcomes based on different model inputs. Both models were then used to assess 141 data scenarios land and fishery managers would likely encounter. Results of the BN indicate that culverts that 1) are barriers to adult and juvenile steelhead, 2) are located in Oregon Department of Environmental Quality

(DEQ) designated cold core water habitat, 3) have a high capacity for rearing juvenile fish, and 4) have a high probability of habitat use will provide the highest overall benefit. As anticipated, culverts that are not barriers to upstream migrating fish provided the lowest benefit, regardless of habitat suitability or habitat use. In addition to specific results for the Santiam basin, comparison between the two models and across information scenarios illustrated the sensitivity of such models to various conditions likely to be encountered by decision makers; in general, the two models agreed when all input nodes were engaged by having a state value entered, yet disagreed as fewer input nodes were engaged. The passage impairment of a culvert and the probability of habitat use exerted a strong influence on model output. Finally, this model may serve as a template for providing a coarse evaluation of culverts in other basins or may be a foundation upon which additional nodes may be added.

A Bayesian Network for Prioritizing Restoration of Aquatic Connectivity

by
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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My Signature below authorizes release of my thesis to any reader upon request.

Eric J. Andersen, Author

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Dr. Desiree D. Tullos provided editing of all sections of the manuscript. Dr. Jason B. Dunham provided assistance in model design.

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CHAPTER 1- GENERAL INTRODUCTION

Steelhead trout (*Oncorhynchus mykiss*) are listed under the Endangered Species Act (ESA) in the Pacific Northwest as a result of declining populations (Myers et al. 2006; Nehlsen et al. 1991; NOAA 2005). In order to support recovery of listed steelhead, reconnection of habitat by eliminating fish blocking culverts is a key goal (Oregon Plan 1997; Primozich and Bastasch 2004). Restoring access to habitat by removing barrier culverts is commonly undertaken and has a high rate of success as measured by the ability of fish to pass through a newly installed culvert (Dent et al. 2005; Paul et al. 2002; Roni et al. 2002). While prioritization systems are in place (Peterson et al. 2008), there is no consistent method in use in the Pacific Northwest to identify and prioritize problem culverts (Beechie et al. 2008). Common methods such as scoring and ranking of sites can be inefficient (O'Hanley and Tomberlin 2005) and choosing barrier removal on the basis of stream length only may result in overlooking high quality sites (Steel et al. 2004). In some instances, ad-hoc opportunistic restoration occurs as a systematic plan to address problem culverts is not in place and funding is often lacking (MB&G 2007). The issue of prioritization is critical and necessary, as the cost of restoration is very high (Bernhardt et al. 2005; US GAO 2001) and adequate resources do not exist for removing all barrier culverts.

The objective of this modeling effort was to produce a Bayesian Network model to predict the overall benefit to threatened winter run steelhead (*Oncorhynchus*

mykiss) in the Santiam River basin (Willamette River, Oregon) by removing a culvert under different information scenarios. The model was based on the main drivers of culvert removal: passage impairment at a culvert, habitat suitability of the upstream area and probability of habitat use. Two models of identical structure were populated with differing conditional probability table values and the results compared. In general, the models agreed when all input nodes were engaged, yet disagreed as fewer input nodes were engaged. In this paper, I 1) present the model, 2) evaluate decisions made within the model, and 3) discuss tradeoffs in model decisions.

CHAPTER 2 - A BAYESIAN NETWORK FOR PRIORITIZING RESTORATION OF AQUATIC CONNECTIVITY

Introduction

Several *Oncorhynchus* species are listed under the Endangered Species Act (ESA) in the Pacific Northwest as a result of declining populations (Myers et al. 2006; Nehlsen et al. 1991; NOAA 2005). Factors contributing to the reductions include over fishing, fluctuating ocean conditions, habitat degradation and restricted access to historical habitat (Nehlsen et al. 1991; NMFS 1996; Ricciardi and Rasmussen 1999). It is widely recognized that the disruption of aquatic connectivity by culverts at road stream crossings that block fish from historical habitats (Primozich and Bastasch 2004; Sheer and Steel 2006) is a major contributor to salmonid declines.

Fragmentation of streams by human activities is pervasive (Meixler et al. 2009; Park et al. 2008; US GAO 2001) and detrimental to stream fishes (Pringle 2003). A reduction in access to habitat (e.g. connectivity) can reduce the probability of a fish population's persistence (Morita and Yamamoto 2002; Rieman and McIntyre 1993; Young 1995) in addition to overall fish production (Beechie et al. 1994). Because stream habitat is dispersed and of differing quality (Schlosser 1991; Wiens 2002), many fishes must move through stream networks to access habitats required for different life stages (Fausch et al. 2006). In the Lower Columbia and Willamette River Basins in the Pacific Northwest, for example, there has been an estimated 40% loss of accessibility to spawning habitat for steelhead as a result of anthropogenic barriers (Sheer and Steel 2006). In the case of the state of Oregon, nearly all streams within the state have fish-blocking culverts on them (Mirati 1999).

In order to support steelhead recovery, reconnection of habitat by eliminating problem culverts is a key goal (Oregon Plan 1997; Primozich and Bastasch 2004). Restoring access of fish to habitat by removing barrier culverts has a high rate of success and is commonly undertaken (Dent et al. 2005; Paul et al. 2002; Roni et al. 2002). A study in Oregon found a 77% likelihood of replacement culverts and newly installed culverts of being able to pass fish, when fish passage was a goal (Paul et al. 2002). In addition, habitat reconnection has been shown to be effective at enhancing fish abundance (Roni et al. 2008). A 52% increase in steelhead parr was attributed to barrier removal in an Idaho basin (Roni et al. 2002). While the benefit of and need to restore aquatic connectivity in some streams is apparent; there is no consistent method to identify and prioritize problem culverts (Beechie et al. 2008).

The issue of prioritization is critical due, in part, to the high cost of restoration, estimated at over $375 million on public lands in Oregon and Washington (Bernhardt et al. 2005; US GAO 2001). The Oregon Watershed Enhancement Board (OWEB) reports that $17.1 million was invested on fish passage restoration at 269 sites during the biennium of 2007 to 2009 (OWEB 2008). It is estimated that up to 28,000 culverts occur solely on state and federal roads in Oregon (MB&G 2007). A tremendous amount of potential barriers exist and adequate resources do not exist for removing them all (MB&G 2007). Thus, some prioritization of barrier removals is necessary (Roni 2005).

The identification of which culverts to replace first and the methodology used to select them can be a challenging proposition (Hoffman and Dunham 2001; Peterson et al. 2008). Common methods such as scoring and ranking of sites can be inefficient if they do not directly consider spatial variability of the culverts (O'Hanley and Tomberlin 2005). Discounting the spatial arrangement of potential barriers may lead to culvert replacements with additional downstream barriers, negating project effectiveness. Additionally, choosing barrier removal on the basis of stream length only may result in overlooking high quality sites (Steel et al. 2004). In some instances, systematic planning or adequate funding is not in place to address problem culverts and ad hoc opportunistic restoration substitutes (MB&G 2007). Identifying barriers for removal based on model predictions of the density of steelhead redds has been proposed within the Santiam basin, although the models are not applicable to the entire basin (Steel et al. 2004). Furthermore, regardless of the prioritization methods in use decisions are often made with incomplete information, which increases the uncertainty in restoration outcomes (Pess et al. 2003). The limitations of current prioritization methods necessitate an innovative decision support approach to assist in prioritization.

One such approach is a Bayesian Network (BN); used to assist prioritization of culverts in the inland western United States (Peterson et al. 2008), although not previously utilized in the Pacific Northwest. BNs have several advantages over existing scoring and ranking methods. A BN is composed of an influence diagram thereby explicitly depicting the relationships amongst model variables (McCann et al. 2006; Pourret et al. 2008). In contrast to scoring and ranking methods, the model's transparency eliminates ambiguities between relationships of variables (Cain 2001). BNs can also provide valuable information under a wide range of data environments (e.g. data rich vs. data poor; McCann et al. 2006). Importantly, BNs are probability based and thus well suited to accounting for uncertainty (Arthington et al. 2007; Korb and Nicholson 2004; Marcot 2006).

The objective of this study and modeling effort was to produce a BN to predict the overall benefit to winter run steelhead (*Oncorhynchus mykiss*) in the Santiam River basin by removing a culvert under different information scenarios. The model was based on three main drivers of culvert removal: passage impairment at a culvert, habitat suitability of the upstream area, and the probability of habitat use. Two models of identical structure were populated with differing conditional probability table values and compared. In this paper, we 1) present the model structure, 2) explain decisions made within the model, 3) demonstrate results of the prioritization, and 4) discuss tradeoffs in model decisions.

Methods

Study Site

Oregon's Santiam River (Fig. 2.1) is a major tributary to the Willamette River and is composed of two fourth field hydrologic unit areas: the ~1,968 square kilometer North Santiam and the ~2,690 square kilometer South Santiam basins (PNW-ERC 2002). The Santiam basin originates in the western Cascade Mountains, a volcanic mountain range characterized by temperate coniferous forests of Douglas fir (*Pseudotsuga menziesii*), Western Hemlock (*Tsuga heterophylla*) and Western Red Cedar (*Thuja plicata*) in the lower and middle elevations. True fir (*Abies* sp.) and pine (*Pinus* sp.) are prominent in the upper elevations. Underlying bedrock is dominated by basalt and andesite, with steep mountain slopes and high stream densities (E&S Environmental Chemistry Inc. 2002; Franklin and Dyrness 1973). The basin terminates in the Willamette Valley, an alluvial plain with occasional outcrops of sedimentary and volcanic rock. The hydrology of the Santiam basin is snow dominated in the higher elevations (>915m) and rain dominated in the lower elevations (<915m; Nolin and Daly 2006). Precipitation occurs primarily in winter, with more accumulation in the upper elevations. The Santiam basin has an extensive and diverse road network. The upper portions of the basin are dominated by logging roads; while numerous state, county and private roads occur in the lower basin.

The Santiam River basin historically contained the highest proportion of returning adult winter steelhead in the Willamette basin, with an estimated return number of ~125,000 adults (Myers et al. 2006). Recent return estimates are below ~1,500 adults (Primozich and Bastasch 2004). Upper Willamette Valley steelhead trout, which includes the Santiam Basin population, are listed as threatened under the ESA (Myers et al. 2006). Native cold water fishes found in the Santiam Basin, in addition to steelhead trout, include Chinook salmon (*Oncorhynchus tshawytscha*), cutthroat trout (*Oncorhynchus clarki*). Summer-run steelhead and kokanee (*Oncorhynchus nerka*) have been introduced in the Santiam basin, in addition to several warm water species.

The Santiam follows a global pattern of major modifications occurring in the lower and middle portions of a river basin (Pringle 2001). There are four large dams constructed for flood control within the Santiam basin that disrupt aquatic connectivity, in addition to significantly altering the flow regime from historical conditions. As of 2009 the Big Cliff and Detroit Dams, located on the mainstem of the North Santiam, completely impede upstream passage by fishes. Foster and Green Peter Dams are constructed on the mainstem of the South Santiam River. Foster Dam has upstream passage of native Chinook salmon and winter run steelhead via trap and haul, while downstream passage of fish is through the dam’s spillway. Foster Dam is located below the fish blocking Green Peter Dam. The dams without fish passage eliminate access in the North and South Santiam basins to 69% and 46%, respectively, of prime habitat for steelhead within the basins (Sheer and Steel 2006)

Culvert Surveys

Eighty culverts in the lower Santiam River basin (Fig 2.1), below the aforementioned flood control projects, were identified for this study from the Oregon Department of Fish and Wildlife's (ODFW) culvert database (ODFW 2007). Only culverts listed by ODFW as being of "unknown passage status" were considered in this analysis. Culverts were surveyed during the summer low flow period of August and September in years 2008 and 2009 following guidelines outlined in the National Inventory and Assessment Procedure (Clarkin et al. 2005). FishXing software (FishXing 2006) was used to assess passage impairment at the culverts. FishXing determines passage impairment by comparing fish swimming and jumping abilities to modeled culvert hydraulics for a range of stream flows (FishXing 2006). Adult and juvenile fish considered for assessment were assumed to have a length of 60 cm and 15cm respectively. Swimming abilities for adults and juveniles were taken from the FishXing database (Jones et al. 1974; Weaver 1963). Because all sites were ungaged, the 5% and 95% exceedance values were calculated from USGS regression equations (Risley et al. 2008). We analyzed passability during the migration return period (December through June) for adults and the entire year for juveniles (Primozich and Bastasch 2004). The USGS website StreamStats, in addition to a Geographic Information System (GIS), were used to calculate all parameters for the regression equations (USGS 2009). A culvert was considered impassable if FishXing results indicated there was no passable flow range for the stream discharge values entered.

Model Structure and Conceptual Foundation

A Bayesian approach to statistics is different than a frequentist (e.g. Gaussian) approach (Dennis 1996; Korb and Nicholson 2004). Frequentist statistics do not incorporate prior information, assuming that data is random and could be represented by a normal distribution (e.g. bell shaped curve). In contrast, Bayesian statistics assume that data are not randomly distributed and allow the use of existing information to form prior probabilities (Ellison 1996). Using Bayesian statistics, model outcomes can be constrained based on information about the system. A Bayesian approach to removing culverts thus offers important advantages over a frequentist approach because recommendations for removing culverts are ideally not made randomly, but are based on specified criteria that can be described with prior probabilities.

Due in part to these advantages, BNs are commonly used to aid decision making in numerous disciplines, including natural resource management (Arthington et al. 2007; Pourret et al. 2008; Varis and Kuikka 1999). BNs are directed acyclic graphs that are based on an influence diagram (Charniak 1991; Marcot et al. 2001). The influence diagram is composed of nodes connected by linkages, illustrating the causal relationships amongst variables in a system (Fig. 2.2; Korb and Nicholson 2004; Marcot et al. 2001). Linkages are represented by an arrow and indicate a causal relationship between nodes (Charniak 1991). Each model node (e.g. variable) can express a discrete state (e.g. value). A parent node has no other nodes leading into it; while child nodes do have other nodes leading into them (Nyberg et al. 2006). A node can simultaneously be a parent node and a child node. Input nodes are parent nodes with no nodes leading to them. A node's influence on another node is diluted as the number of links increases between them (Peterson et al. 2008). Relationships between model variables are enumerated as probabilities within a node's Conditional Probability Table (CPT; Cain 2001; Marcot et al. 2006). CPT values may be created by expert opinion, learning algorithms or a combination of both (Stewart-Koster et al. 2010). The end result of a BN is to produce a posterior probability based on selected nodes (Korb and Nicholson 2004). Advantages of BNs include transparency, accounting of uncertainty, and the ability to incorporate empirical evidence, expert opinion or both (Korb and Nicholson 2004; Marcot et al. 2006; McCann et al. 2006). Disadvantages of using BNs include difficulties representing feedback loops and the use of faulty expert opinion (McCann et al. 2006; Nyberg et al. 2006). BNs are not self updating and prior probabilities may change over time causing difficulties in portraying time series (McCann et al. 2006; Nyberg et al. 2006).

General Process

This BN was created using Netica software (Norsys Software Corp. 2010) by (Fig 2.3): 1) developing a conceptual influence diagram based on the most concise factors driving the decision to replace a culvert: passage impairment, habitat suitability and habitat use (Fig. 2.4); 2) collecting and assimilating data to populate the nodes (Fig. 2.5; Table 2.1; see Appendix for methods and data sources); 3) generating conditional probability tables. For the third step, qualitative relationships (Table 2.2) between nodes designated in the first step were converted to quantitative relationships (Tables 2.3 and 2.4) in the CPT. For the analysis, I created two identical model structures with different CPT values, one based on Expert Opinion (EO) and the other generated by Netica's Counting Algorithm (CA), described in detail below. The two models were then used to assess multiple data scenarios land managers would likely encounter.

Model Branches

The predicted benefit ('high', 'medium' or 'low') was modeled as dependent on three branches (outlined in further detail below): Culvert Status, Habitat Suitability and Culverts Below. Each of the nodes represented assumptions about the drivers influencing decision making regarding a culvert. The *Culvert Status* node represented potential conditions encountered by fish at the actual culvert, as determined by FishXing calculations. The *Habitat Suitability* node, described below, represented the instream conditions above the culvert and is used to assess suitability for juveniles. It was assumed that if an area is suitable for juvenile rearing it would also be suitable for spawning (Steel and Sheer 2003). Finally, the *Culverts Below* node indicates the presence of culverts downstream of a culvert of interest and thus, as a proxy variable, represents the potential ability of a fish to reach and therefore use habitat.

The first branch of the model (Culvert Status) represented passage impairment at a culvert for adult and juvenile fish (see appendix A). The nodes *Adult Barrier* and

Juvenile Barrier indicated whether there was unconditional passage impairment at a culvert for each life stage. Unconditional passage impairment occurred when there was no flow condition at the culvert that permitted passage of fish. Each node had a state value of ‘yes’ or ‘no’, indicating FishXing’s evaluation of passability. Culverts that were barriers to adults were assumed to be barriers to juveniles. Both nodes were parents of the child node *Culvert Status* which represented the overall condition of the culvert. *Culvert Status* had three states (‘Barrier’, ‘Partial Barrier’ and ‘Not Barrier’) to reflect the severity of impairment at the site. A culvert was a ‘Barrier’ when no flow conditions at the culvert permitted passage of both life stages, a ‘Partial Barrier’ when flow conditions impeded passage of only juveniles and ‘Not Barrier’ when neither life stage was blocked by flow conditions at the culvert. The model assigned benefit according to impairment, which reflected the assumption that a higher benefit would result from replacing culverts that were barriers to both life stages as opposed to barriers to only juveniles or non-barriers to adults and juveniles.

The second branch of the model (Habitat Suitability) also consisted of three nodes and represented the biological benefit of the upstream habitat (see appendix A). Stream temperature is a regulating force on aquatic ecosystems and plays a major role in fish metabolism (Bjornn and Reiser 1991; Hynes 1970). This important element was captured in the *Rearing Temperature* node, where a culvert was assessed as to whether it was or was not (e.g. ‘yes’ or ‘no’) located in Oregon Department of Environmental Quality (OR DEQ) designated cold core water habitat (OR DEQ

2009). Cold core water habitat areas are not to exceed 16 degrees Celsius (60.8 degrees Fahrenheit) for the seven day average. For this model, I focused on rearing temperature because unsuitably warm water temperatures do not appear to be a limiting factor for adult steelhead during times of spawning, primarily April to May in the Santiam (Primozich and Bastasch 2004). To describe the ability of a stream reach to rear juvenile steelhead (e.g. *Rearing Capacity* node), the intrinsic potential (Burnett et al. 2007) of the upstream reach to the next culvert was calculated and assigned a state of ‘high’, ‘medium’ or ‘low’. Intrinsic potential values range from 0.0 to 1.00 and are calculated from the geometric mean of habitat suitability curves for gradient, mean annual flow and valley constraint. I only considered stream reaches with high intrinsic potential values, which are the upper quartile. Prior probabilities for *Rearing Capacity* states were obtained objectively by binning the calculated intrinsic potential values based on a logarithmic scale (see appendix A). Both habitat nodes (*Rearing Temperature* and *Rearing Capacity*) were parents to the child node *Habitat Suitability* (states ‘high’, ‘medium’ and ‘low’). The *Habitat Suitability* node represented the combined effect of both its parent nodes.

The third branch of the model (Culverts Below) consisted of one input node (*Culverts Below*) that considered the potential use of habitat (see appendix A). It was assumed that sites with a higher probability of fish use would have a higher benefit than sites with a low probability of use. A surrogate for potential habitat use by fish was the presence of culverts lower in the stream network. Additional downstream culverts were assumed to lower the probability that fish would use upstream habitat. Aerial photos and GIS road network layers were used to analyze stream networks to determine the presence of (‘yes’ or ‘no’) additional downstream culverts below surveyed sites.

Conditional Probability Tables

CPTs expressed the relationships between parent nodes and their states as a joint probability distribution (Cain 2001; Marcot et al. 2006). As previously noted, I generated CPTs based on expert opinion and through a Bayesian learning algorithm based on field data (Tables 2.3 and 2.4; Appendix B). Both models used collected data to inform the prior probabilities in all input nodes. I assumed that the prior probabilities based on surveyed culverts were an adequate representation of the study area.

CPT values in the EO model were a reflection of assumptions about the influence of model nodes on one another (Table 2.3) as well as uncertainties in input data. There were three nodes with CPT values: *Culvert Status, Habitat Suitability* and *Benefit*. The relationships within the *Culvert Status* node were based on FishXing’s tendency to overestimate passage impairment at culverts (Burford et al. 2009). FishXing tends to over estimate culverts as barriers, which introduced uncertainty when evaluating the culvert. The uncertainty in FishXing assessments was taken into account using subjective opinion when developing the CPT values. For example, when FishXing classified a culvert as a barrier to adult fish, the probability that it truly was a barrier would be less than 100% (Table 2.3). Values in the *Habitat Suitability* CPT were based on the author's expert opinion and published data (see appendix A). For example, the assumption that stream temperature should exert a stronger influence on young fish than rearing habitat was formalized in the CPT values (Table 2.3). CPT values for the *Benefit* node were a synthesis of the unique interactions between each of its parent nodes (*Culvert Status*, *Habitat Suitability* and *Culverts Below*) and combination of parent node states. Within the *Benefit* node CPT, replacing culverts that were barriers to two life stages (e.g. 'Barrier') provided more benefit than culverts that were barriers to one life stage (e.g. 'Partial Barrier') only. When considering only one life stage, passage of adults was assumed more important than juveniles. Culverts deemed 'Not Barriers' (e.g. impart no passage impairment) were assumed to always provide a low benefit if replaced; regardless of habitat suitability or habitat use. This reflected the professional judgment that replacing culverts that are not barriers to fish is contrary to management objectives. In this expert opinion model, sites with better habitat conditions were given preference over sites with lower quality habitat to indicate the importance of upstream habitat in culvert replacements. The presence of additional culverts lower in the stream network was a proxy for habitat use and greatly influenced the benefit.

The CA CPTs were based on the initial qualitative relationships (Table 2.2) between the nodes. Collected field data was then imported into Netica and CPT values were generated using Netica's 'counting algorithm', a Bayesian learning algorithm. The overall theoretical basis for establishing the node relationships was similar to that used in the EO model; however there were some differences in actual values (Table 2.4). Probabilities between EO and CA differed because of the method used to produce them. The counting algorithm structures the CPT values based on the field data. When there was an adequate amount of field data that represented a particular state; the counting algorithm clearly based the state value on the established qualitative relationship. For example, in the *Habitat Suitability* node the qualitative relationship for the combination of node states *Rearing Temperature* as ‘yes’ and *Rearing Capacity* as ‘medium’ would yield a *Habitat Suitability* of ‘high’ (Table 2.2). The actual probability generated by the counting algorithm to represent the qualitative value ‘high’ was distributed to the three states in the *Habitat Suitability* node (high, medium and low) and was influenced by the collected field data. When there were many instances of a particular node combination within the data; the counting algorithm generated a probability that reflected the qualitative relationship, such as 92% high, 4% medium and 4% low in the *Habitat Suitability* node. If there were very few instances in the field data, the probability would not emulate the qualitative relationship as strongly and the probabilities generated for the *Habitat Suitability* node states may be 50% high, 25% medium and 25% low. If the data set did not have the node combination, the algorithm assigned an equal probability for each state; 33% high, 33% medium and 33% low. In my model, there were four instances where the counting algorithm generated equal probabilities due to a lack of data and new probabilities were interpolated from probabilities in adjacent node states.

Data Scenarios

For each of the two CPT models (EO and CA), the difference in the probability of benefit was evaluated and recorded for 141 different individual data scenarios (see appendix B). Only input node state combinations were assessed in the data scenarios. Data scenarios represented typical levels of information a land manager may have for prioritizing culvert replacement, and were organized into three main groups: complete (48), partial (44) and limited (49). A complete data scenario was a situation when each input node in the model had a state value entered and represented a data rich environment. That is, the scenario represented an uncommon situation where the manager may have perfect knowledge about the value of all nodes. The partial data scenario represented a moderate lack of knowledge regarding the culverts, upstream habitat and potential habitat use in the basin, modeled in my BN as having state values for one or two input nodes not entered. Finally, a limited data scenario represented a data poor environment where little information was available on the input nodes, characterized in this model as having only one or two input node state values entered. Data scenarios were evaluated by systematically entering different combinations of nodes and node states and recording the model output.

Testing for Correlation among Variables

The data for the input variables was assessed to determine if variables were independent of one another (Zar 1996). Using correlated variables may lead to a less parsimonious model. Using a chi-square test, there was no correlation between *Adult*

Barrier and *Rearing Capacity* or *Culverts Below* nodes (all $p<0.05$); *Juvenile Barrier* and *Rearing Capacity* or *Culverts Below*; *Rearing Temperature* and *Rearing Capacity* or *Culverts Below* (all $p<0.05$); or between *Rearing Capacity* and *Culverts Below* ($p<0.05$). However, the *Adult Barrier* and *Juvenile Barrier* were not independent of each other. This is expected because it was assumed that any culvert that was a barrier to adult fish would also be a barrier to juvenile fish. The relationship was expressed in the model structure. There was a correlation between the *Rearing Temperature* data and the nodes *Adult Barrier* and *Juvenile Barrier*. This could possibly be explained by the fact that nearly 80% of all culverts surveyed were barriers to juveniles and 70% barriers to adults; if so many culverts were barriers this would increase the chance of a relationship with other data. The relationship between the data was assumed not a causal relationship and thus, the lack of independence between these variables did not cause a change in the structure of the model.

Sensitivity Analysis and Model Verification

Netica's entropy reduction (mutual information) was used to evaluate the influence of each individual node on the final node (*Benefit*) for the two models. Larger entropy reduction values indicate a reduction in the uncertainty regarding the influence of individual nodes on the final node and thus; those nodes with the largest entropy reduction values would be the most influential on the final node. Sensitivity values can be influenced by the number of links between nodes because an increasing number of links can dampen the importance of a node on a query node (McCann et al. 2006; Peterson et al. 2008). For example, it is expected that the *Culvert Status* node would exert more influence on the *Benefit* node than either the *Adult Barrier* or *Juvenile Barrier* nodes because there is only one link separating *Culvert Status* from *Benefit* as opposed to two links for *Adult Barrier* and *Juvenile Barrier* nodes.

The model was verified using Netica's 'test with cases' function to determine if field data were accurately being classified. An individual surveyed culvert and its associated field data were considered one 'case'. All field data (e.g. cases) were assigned a random number and divided into two groups (e.g. 1-40 and 41-80). The first half was used to build the model and inform the prior probabilities. CPT values were then generated using Netica's counting algorithm. No CPT values were altered. Subsequently, the second half of the field data was used to test the model predictions. A confusion matrix was produced showing the predicted classification of cases versus actual case classification (Marcot et al. 2006). The model's error rate was defined as the number of times the model predicted known cases (e.g. field data) incorrectly divided by the number of total classifications (e.g. total case number; Norsys Software Corp. 2010).

Results

Summary of Surveyed Culverts

Of the 80 culverts surveyed, 55 (68.7%) culverts were located in the South Santiam basin and 25 (31.3%) were in the North Santiam basin. Most (73%) of the sites surveyed were concrete culverts, with the remaining composed of corrugated metal (26%) or PVC (1%). In addition, culverts that were surveyed generally were less than 1.22 meters in diameter. FishXing results indicated that 56 (70%) of culverts were barriers to adults and juveniles, 10 (12.5%) were barriers to juveniles and not adults, while 14 (17.5%) were not barriers to adults or juveniles. Fifty six (70%) culverts were located within OR DEQ designated cold core water habitat and 24 (30%) were not located in designated cold core water habitat. Very few culverts were located on streams with high intrinsic potential for rearing juvenile steelhead trout. This was somewhat expected as many of the surveyed culverts were located lower in the basin in areas that can be marginal for steelhead trout. Seventy three (91%) culverts had a rearing capacity (e.g. intrinsic potential) score of low; all of which had zero meters of high intrinsic potential stream reaches above the surveyed culvert. Five (6%) culverts had a rearing capacity value of medium. The amount of stream reaches with medium ranked rearing capacity ranged from 124 m to 632 m, with an average length of 375 m. There were only 2 (2.5%) culverts in the high rearing capacity category, with a maximum length of high intrinsic potential stream reach of 3,101 m. Of the culverts surveyed 50 (63%) did not have any additional culverts located lower on the stream network, while 30 (37%) did have culverts lower on the stream.

Sensitivity Analysis and Model Verification

When comparing entropy reduction values, the models were not equally sensitive to the same nodes (Table 2.5). In the EO model the *Culverts Status* (0.304), *Culvert Below* (0.217) and *Juvenile Barrier* (0.154) nodes were the three most influential nodes. However, the *Culverts Status* node was about a third as influential as the *Culvert Below* node and about twice as sensitive as the *Juvenile Barrier* node. Within the CA model, the *Benefit* node was similarly the most sensitive to the *Culverts Below* (0.224) node and was at least two times as influential as the other top nodes. The *Habitat Suitability* (0.138) and *Rearing Temperature* (0.09) nodes were the second and third most influential nodes in the CA model. It was expected that the *Culverts Below* node would exert a major influence due to the node's proximity to the *Benefit* node and because both models were constructed to provide a reduced benefit with the presence of additional downstream culverts (e.g. predicted lack of habitat use). It was also expected that the *Culvert Status* node would be influential in both models, yet was not very influential in the CA model.

Node sensitivity values were influenced by the combined effect of node prior probabilities and CPT values. The discrepancy between the sensitivity values in our respective models was most likely attributed to the probabilities assigned within the CPTs. Thus, in addition to model structure; the method used to generate CPTs and actual CPT values influenced model sensitivity.

The model had an error rate of approximately 7.5% (Table 2.6). The model predicted some cases as being high, when they were actually medium or low (type 2 errors). The error in this model was most likely associated with CPT values in the *Benefit* node having an equal probability for some data combinations. That is, when building the model with half of the field data, there were some state combinations not represented because of the limited data set. These ‘missing cases’ were assigned an equal probability (e.g. 33-33-33) by the counting algorithm. In some instances the equal probabilities did not accurately reflect the case data. When constructing the model with half the data and changing the CPT values to those of the final EO or CA models, and then testing against the second half of data the error rate dropped to zero. This indicated that the models were classifying the field data correctly. This occurred because the CPT values were constructed to reflect the qualitative values. For example, when the field data had a qualitative value of medium for some combination of variables (e.g. node states) and that same combination of variables (e.g. node states) had its highest probability within the medium category in the quantitative CPT, the error rate is zero. If the highest probability was in the low category, there would be an error. Because the quantitative values were based on the qualitative values the error rate was always low. If the quantitative values deviate from the qualitative values, then the error rate would increase.

Data Scenarios

The probability of benefit was assessed for agreement between the two models for the complete, partial and limited data scenarios (see appendix B). This was performed to determine if the models would give the same result when identical information was entered and to evaluate the effect of limited information on predicted benefit. Agreement was defined as the condition when the highest probability was assigned to the same category within the benefit node. For example, if an identical data scenario was entered into both models and each model assigned the highest probability to the "medium" category within the *Benefit* node, the models agreed.

Overall, the models agreed for 106 out of 141 individual data scenarios (75%). Discrepancies in each model's assessment of individual data scenarios can be explained by differences in generating CPT values, as discussed in the methods section on CPTs.

When assessing agreement between the models for the three main groups of data scenarios, a mild trend emerged. There was less agreement amongst model outputs as the data scenarios progressed from complete to limited. There was 89% agreement (43 of 48) between complete data scenarios, 79% agreement (35 of 44) among partial data scenarios and 55% agreement (27 of 49) in limited data scenarios. However, the models strongly agreed (86%) across all groups of data scenarios when the *Adult Barrier* node had a state value of 'no' regardless of additional node state values (43 of 50 individual scenarios).

The models did not assign the probability of benefit to each category (e.g. high, medium or low) equally. Of all possible individual data scenarios considered, the EO model assigned 18.4% as high benefit probability, 28.4% as medium and 53.2% as low. In contrast, the CA model assigned 27% percent to the high benefit category, 21.3% to the medium category and 51.8% to the low category. This occurred because as the data scenarios progressed from complete to limited, the models agreed less. When the models didn’t agree, it was because the predicted benefit had been assigned to a different category for each model. Because the models didn’t always agree, the probability of benefit was not equally assigned to each category equally. The discrepancy can be related to the disagreement of models as the data scenarios progressed from complete to limited.

Despite the differences in predicting the probability of benefit across the three information scenarios, there were some commonalities between the EO and CA models. The models assessed the field surveyed culverts fairly equally. When using the EO model to assess each surveyed culvert, 32 (40%) were predicted to provide a high benefit, 9 (11%) as medium and 39 (49%) as providing a low benefit. When using the CA model 32 (40%) were predicted to provide a high benefit, 10 (12.5%) as medium and 38 (47.5%) as providing a low benefit. In all complete and partial data scenarios where the *Adult Barrier* and *Juvenile Barrier* nodes had a state value of ‘no’, the models agreed and placed the highest probability in the low category of the benefit node. While the exact probabilities were not the same, the assignment of node categories (e.g. high, medium, low) still agreed. This was expected because the CPTs were deliberately biased against placing benefit on culverts that are not barriers.

In another example, for both models the complete and partial data scenario where the *Adult Barrier* node and the *Juvenile Barrier* node both had a state value of ‘yes’ gave the same result as when the *Adult Barrier* node had a state value of ‘yes’ and the *Juvenile Barrier* node had a state value of ‘no’. This was due to the assumption, embedded in the CPTs, that it was not possible to have a culvert that was a barrier to adults but not juveniles.

Model output may be interpreted simultaneously as an absolute value (e.g. determining whether the models agree) and as a relative value (e.g. percent in each benefit category). Alternately, the probabilities for the high and medium categories or the probabilities of medium and low categories may be combined. In this way the models may be used to identify scenarios with a specified medium-high or medium-low probability value. Combining the final probabilities could provide an additional way to categorize individual sites.

For example, the complete data scenario where the nodes *Adult Barrier*, *Juvenile Barrier* and *Rearing Temperature* were ‘yes’, *Rearing Capacity* was ‘high’ and *Culverts Below* was ‘no’; both models agreed that the predicted benefit would be in the high category although the actual probabilities assigned to each category within the *Benefit* node were different. For example the EO model yielded an 85.3% probability of high benefit, 5.25% medium and 9.5% low, while the CA model gave 50% high, 33.5% medium and 16.5% low. This is important if the model output is interpreted as the relative benefit of a site. Even though the models agreed that the predicted benefit was high, the EO model classified this scenario as yielding a higher percent benefit than the CA model. If presented with a site that has this scenario, the model user would correctly interpret a high benefit. However, if only using the EO model, a very high probability of benefit would be interpreted. If using the CA model, there is the chance that a high-medium benefit may be realized.

In the individual complete data scenario where the *Adult Barrier* and the *Culverts Below* nodes had state values of ‘no’, the *Juvenile Barrier* and *Rearing Temperature* nodes had a state value of ‘yes’ and the *Rearing Capacity* node had a state value of ‘medium’ both models agreed that the predicted benefit would be high. For example, in the EO model, the predicted probability of benefit would be 45.9% high, 44.6% medium and 9.5% low, while the CA model predicted 37.5% high, 36.1% medium and 26.3% low. However, when examining the probabilities within the high and medium categories of both models there was little difference between the two categories. Therefore, the interpretation of the actual benefit derived in a situation was made by combining the categories and inferring that there was a medium-high benefit to be obtained. In situations such as this, the models leave some room for interpreting the final predicted benefit by the model user.

The flexibility of using expert opinion to define state probabilities allowed for a more appropriate representation of the predicted benefit in at least one critical data scenario; that of a partial barrier with high habitat suitability and potential use. Both models were established to predict a high benefit for this specific scenario, yet the CA model instead predicted a medium benefit. In this scenario the EO predicted an overall high benefit (81% high, 9.5% medium and 9.5% low), but the CA model predicted an overall medium benefit (35.1% high, 39% medium and 25.9% low). A limited data set most likely influenced the CA model's ability to generate adequate CPT values, which in turn influenced the model's ability to accurately predict benefit for this scenario.

Case Study

The North and South Santiam basins both provide opportunities to restore passage for steelhead. Two case studies are presented to illustrate strengths and weaknesses of the EO model.

Mad Creek

Mad Creek is located in the North Santiam River Basin and flows directly into the Mainstem North Santiam River (Fig. 2.6). The basin encompasses approximately 21 square kilometers and is mostly forested. Mad Creek has a culvert (labeled "downstream") at its mouth that is an impediment to adults and juvenile fish. Little Rock creek is a tributary to Mad Creek, which also has one culvert (labeled "upstream") that acts as a fish barrier. Both culverts are located on streams in cold core water habitat. The upstream habitat is composed of a large percentage of stream reaches with high intrinsic potential. The length of stream with high intrinsic potential between the downstream culvert and the next upstream culvert is 3,101 meters. The length of high intrinsic potential above the upstream culvert is 632 meters.

When assessing both culverts at Mad Creek with the EO model, the downstream culvert would provide an overall high benefit: 85.3% high 5.25% medium and 9.5% low, while the upstream culvert would provide only a low benefit (11.6% high, 36.6% medium and 51.7% low). However, by toggling the *Culverts Below* node through alternate states, it is shown that when no culverts are located lower on the stream network, the upstream culvert would provide a high benefit (69.5% high, 21% medium and 9.5% low) if replaced. In this way the predicted benefit of alternate scenarios can be evaluated and used to assist management decisions. Thus an appropriate strategy in this case would be to replace the downstream culvert first and then the upstream culvert for optimal benefit. One caveat is that if the downstream culvert is replaced with a bridge, the model will predict that a high benefit may be realized when replacing the upstream culvert. However, if downstream culvert is replaced with another culvert, the model will predict a low benefit when replacing the upstream culvert. This may be inaccurate if the replaced culvert downstream passes fish.

Hamilton Creek

The Hamilton Creek sixth field subbasin is a priority basin for the South Santiam Watershed Council. Hamilton Creek straddles the Willamette Valley and Cascades ecoregions. The upper portions of the basin are primarily private industrial, as well as some federal, forestland. The lower portions of the basin have been converted to agriculture with pasture, grass seed production and mint as the primary land uses.

Four culverts (labeled “A”, “B”, “C” and “D”) were surveyed on tributaries to Hamilton Creek (Fig. 2.7). All culverts had the following characteristics in common: located in cold core water habitat, low rearing capacity and no culverts lower on the stream network. The culverts “A”, “C” and “D” were all barriers to adults and juveniles. Each was predicted to provide a high probability of benefit (47.2% high, 42.9% medium and 9.9% low) but, the difference between high and medium benefit was only 4.3%. This small difference should be taken into consideration during evaluation of the three sites. Culvert “B” was a partial barrier (e.g. blocks juveniles only). Replacing culvert “B” was predicted to provide a benefit of 23.4% high, 59.9% medium and 16.7% low. While the model indicates a medium probability of benefit, there was still over a 20% chance that a high benefit could be realized. In addition, combining the probabilities also provides a method for comparing the sites. There was a combined probability of 90% that the three culverts would provide a medium-high benefit and an 83% chance of the single culvert providing a medium-high benefit. These values were similar and thus could be evaluated as a group.

When presented with a situation, as in Hamilton creek, additional knowledge not available to the model should be considered. For example, the model did not distinguish between each of the three culverts with the same predicted benefit. That is, each culvert had the same predicted benefit despite differences in reality. The ‘on the ground’ differences should be considered. In the case of culvert “C”, the upstream conditions include multiple stock ponds and additional culverts. The resources needed for additional surveys and habitat improvements could be cost prohibitive for this tributary. Culvert “D” was located on a creek that has had extensive channel modifications and scant riparian cover. Culvert “A” was on a tributary originating in a small basin with riparian modifications. Of the three culverts evaluated by the model as providing a high benefit, only “A” was located in a basin with the highest true potential for habitat benefit.

When comparing culverts “A” and “B”, it would appear that “A” is the best option. However, the purpose of the model is not to make the decision for the land manager, but to assist in organizing information for decision making. Culvert “B” drains a much larger basin and has more usable habitat, although not high intrinsic potential. Thus the land manager should draw on additional environmental variables, such as basin area, or local conditions when choosing an appropriate management strategy.

Discussion

General Comments

A critical and complex decision often confronting a land manager is the prioritization of barrier culverts for replacement (Fausch et al. 2009). Using winter run steelhead in the lower North and South Santiam River watersheds as a case study, I presented a BN to organize information surrounding the prioritization of culvert replacement within a basin. This model provides a clear framework for justifying the need to fund restoration opportunities. The BN allowed culverts to be quickly evaluated and a coarse catalogue of potential project sites produced. The models were derived from the main drivers of barrier removal, which were quantified and arranged in an influence diagram to depict conditional dependencies between variables. Two models of identical structure, but differing CPTs, were compared by evaluating a range of common data scenarios.

Considerations for Using BNs in Prioritizing Restoration

The model illustrated that three main drivers of culvert replacement, passage impairment, habitat suitability and habitat use, could be incorporated into a BN for prioritizing culverts. We constructed this model to emphasize the benefit of replacing culverts that were barriers to both adult and juvenile fish, as opposed to juveniles only. The model was structured such that culverts that were not barriers produced a low benefit, regardless of additional node values. Predicted habitat use (e.g. *Culverts Below* node) was very influential in the model. Low habitat use, predicted by the presence of additional downstream culverts, was shown to reduce the benefit obtained by removing a culvert. This reinforced the belief that sites with little use by fishes would provide a reduced benefit and that the spatial arrangement of culverts had an effect on the predicted benefit. Within the habitat suitability branch, temperature exerted more influence than instream habitat conditions.

Consistent with any modeling effort, the source data used to populate the model was an important and influential component in model development and thus, model predictions should be viewed cautiously. For example, the lack of empirical stream temperature data for the study area necessitated the use of a proxy variable (e.g. *Rearing Temperature*) to predict stream temperature. However, the proxy variable may not accurately predict temperature in all cases.

The model showed that by manipulating node states, the necessity of collecting additional data was not always warranted to make a management decision. In cases where only partial information was known about a site, the predicted benefit was recorded before and after alternate scenarios were evaluated by toggling state values. If the predicted benefit showed a small change, the advantage of collecting additional data was not substantial. This feature of the BN allows resource managers to evaluate where to devote resources in prioritization efforts.

Comparison to Existing Methods

Prioritizing the removal of barriers within the Santiam River basin using mixed models to predict the density of steelhead redds has been proposed (Steel et al. 2004). A major drawback of the mixed models stems from its limited applicability in the lower portions of the Santiam basin, where barrier removal may provide important benefits. When considering subbasins below Big Cliff and Green Peter Dams, the BN I presented can be applied to all subbasins as opposed to the redd density models.

Further, the mixed models were constructed by examining only the few basins where redd surveys occurred. The BN I presented is not constrained by examining only areas with redd surveys, but was constructed to represent the broader basin and to be transferrable across basins. In addition, the BN I presented utilizes data resources that can be found in online GIS sources (see Appendix A). Finally, the BN model clearly illustrated the relationships between factors driving the decision to replace culverts and the results can be quickly displayed graphically or spatially (e.g. GIS).

Condition Probability Tables

One of the benefits of using a BN is that professional judgment can be incorporated within a decision framework (McCann et al. 2006). Using expert opinion in crafting a model's CPT allowed for a distribution of probabilities among states that was not achievable using the counting algorithm alone. The counting algorithm strictly relied on field data; although interpolation of values occurred where data was lacking. Expert opinion based values allowed for a more nuanced approach to defining probabilities for combinations of node states. The flexibility of using expert opinion to define state probabilities allowed for a more appropriate representation of the predicted benefit in at least one critical data scenario; that of a partial barrier with high habitat suitability and potential use. In this instance because of a limited data set, the counting algorithm generated a probability that may not have adequately reflected the potential benefit to be gained. This was a critical point when using the counting algorithm, as it was strongly influenced by the dataset. Thus, the model was particularly vulnerable to incomplete datasets for representation of the prior probabilities.

Evaluating Culverts under Alternate Data Scenarios

This model can readily be used to evaluate culverts under alternate scenarios and assist decision making. If complete information is known about a culvert, it may be entered as evidence into the model and the probability of benefit recorded. Alternate data scenarios may then be applied by toggling different state values in order to evaluate the effect of specific nodes on the predicted benefit. Similarly, less than complete information may be entered into the model and the posterior probability of benefit recorded. Then all nodes may be engaged and the change in the final output assessed. Doing so allows the model user to determine if collecting additional field data is warranted for sites where only partial information is available. For example, if a culvert with partial information has a predicted low benefit and adding additional information does not change the predicted benefit; collecting more data may not be warranted. However, if the predicted benefit changes, it may be advantageous for the additional information to be actually collected. In this way a land manger can consider the potential benefits of further data collection. This is a useful application of the model as gathering and processing data can be time consuming and costly.

Based on my results, the EO model provides the most meaningful results with the complete data scenarios. When all prior nodes are engaged (e.g. complete information entered), it is expected that the uncertainty in model results would be the lowest. However, as fewer prior nodes are informed (e.g. less evidence entered), the uncertainty in the model output was found to increase because the model is calculating the posterior probability using limited evidence. Thus, I found that single node entries provided the result with the highest uncertainty. The model will generate a posterior probability indicating a level of benefit regardless of the number of nodes with evidence entered. Ultimately, however, the interpretation of the probabilities is the responsibility of the model user.

Influence of Scale and Binning Source Data

As with other modeling techniques, the reliability of the source data used to construct the model has a strong overall effect on the model's output. This is fundamental with a BN because the source data is used in creating prior probabilities, which in turn describes the system being modeled. If the prior probabilities of the nodes are not representative of the system, the model output may not be useful. This is always a key element when using a BN, as the source data may be influential in numerous ways.

The method of binning continuous (e.g. intrinsic potential) source data for the Rearing Capacity node has a direct influence on the node's prior probabilities. Had the intrinsic potential scores been binned using subjective breaks in the data as opposed to a logarithmic scale, the Rearing Capacity node's value (e.g. high, medium or low) for some culverts may have been different. For example, increasing the minimum length of stream reach needed to achieve a high value could have made it impossible to achieve a rearing capacity value of high, which in turn would have reduced the probability of the model predicting a high benefit. Had the length of stream reach needed to achieve a high value been reduced, more culverts could have been classified as having a high rearing capacity, which may have influenced the model's ability to assign a high probability of benefit for some sites. In our data set, an alternate binning approach would not have necessarily increased the number of culverts predicted as providing high benefit because a vast majority of surveyed culverts had zero meters of "high" intrinsic potential stream reaches. However, if a different group of culverts was surveyed, this lack of response to binning may not be the case.

This model was built using fourth-field hydrologic unit codes as the spatial extent for data collection. Like others (Levin 1992; Wiens 1989), the spatial scale at which this model was constructed influenced the final output. A different scale would likely have influenced the prior probabilities of the input nodes and resulted in a different model and predictions. Had a sixth field basin been chosen, such as with the Hamilton Creek case study, several complications would have occurred. All culverts would have been assumed to meet the Rearing Temperature requirements as the entire basin is located in cold core water habitat. This would have generated a 100% prior probability that culverts met rearing temperature, unlike the priors that resulted in the final models. All sites would have had a rearing capacity value of low because, when using the scale of Hamilton Creek, no surveyed culverts have upstream reaches with high intrinsic potential. No culverts would have been able to receive a habitat suitability score of greater than medium. While this may have been an accurate prediction; it could have prompted a reevaluation of CPT values or the addition of more habitat suitability variables.

Limitations

This model is not to be used without considering additional factors, such as additional environmental (e.g. water allocations) and logistical (e.g. landowner cooperation, funding priorities) factors. Stream channel morphology, riparian vegetation, and stream productivity all influence instream habitat for steelhead and could be taken into consideration (Raleigh 1984). Limitations of the model include processes and decision criteria that were omitted from the model. For example, this model does not consider the possible impacts of invasive and nonnative species on native populations, an important consideration in restoring connectivity (Jackson and Pringle 2010). In some situations a land manager may opt to keep a barrier culvert in place in order to avoid undesirable impacts from invasion of nonnative fish (Fausch et al. 2009). Further, a future BN could be updated as downstream barriers are removed or additional nodes added.

There can be potential problems when using proxy measures of variables, such as *Rearing Temperature* and *Culverts Below* nodes in our model. First, culverts that are in cold core water habitat were assumed to not exceed the seven day average of 16 degrees Celsius. However, there are instances of water courses exceeding the state specified temperature requirements within the cold core designated areas of the Santiam River basin (OR DEQ 2006). Determining the percentage of culverts in cold core water habitat that actually met temperature requirements was beyond the scope of this study due to a lack of monitoring data. Of the hundreds of water courses within the Santiam basin that were designated cold core water habitat, the Oregon DEQ only monitors 11 large rivers for temperature. Therefore, it is difficult to derive an accurate percentage of streams in cold core areas that actually met temperature criteria. Furthermore, not all streams outside of cold core water habitat have unsuitable water temperature. Additional stream temperature monitoring, especially of smaller tributaries, may be useful in developing a clearer picture of the source data used in the *Rearing Temperature* node.

Secondly, the *Culverts Below* node was a proxy for habitat use where the presence of additional culverts downstream of a surveyed culvert would indicate a lower probability of habitat use. The main assumption was that a culvert was most likely a barrier to fish, based on the results of our culvert surveys. However, it is unlikely that all downstream culverts are barriers, particularly those that are recently installed. Altering the influence of the *Culverts Below* node may be necessary in future versions of the model to better reflect the true passage status of downstream culverts.

Conclusions

Fragmentation of rivers and streams by culverts is a threat to aquatic ecosystems throughout North America. Restoration of aquatic connectivity by replacement of barrier culverts is part of a suite of management strategies undertaken to improve and maintain fish populations. BNs can be used to effectively incorporate existing information into cost-effective prioritization of fish passage restoration projects, and to provide a transparent means of documenting the basis for decisions to fund restoration. We demonstrated how BNs can be used to assist decision making under complete and less than complete data scenarios. Our primary findings were: First, BNs offer a valuable approach to culvert prioritization. Second, in our analyses, the Expert Opinion model was preferred due to the flexibility and ability to incorporate uncertainty directly into the model. Third, there was an increased level of uncertainty in model output in limited data scenarios as opposed to complete data scenarios. Finally, the models were useful in organizing information and evaluating the value of information in decision making about culvert replacement. Recommendations were made regarding model components to evaluate in using BN models for prioritizing restoration.

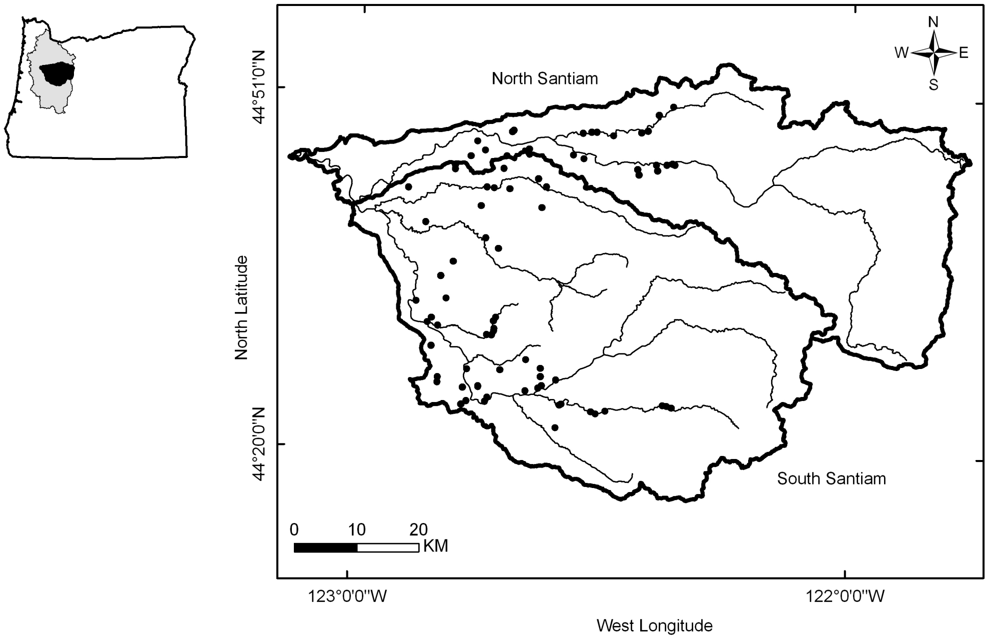


Figure 2.1 Map illustrating the location of the Santiam River basin (black) within the Willamette River Basin (grey), Oregon. The detail shows the North and South Santiam basins with major tributaries (thin black lines). Points represent surveyed sites included in the analysis.

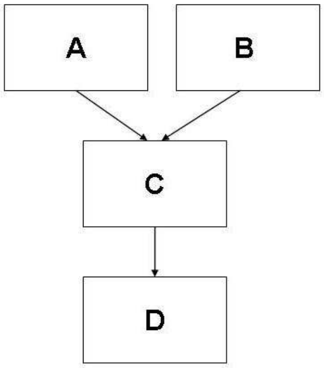


Figure 2.2. A hypothetical Bayesian network illustrating input nodes (*A* and *B*), parent nodes (*A*, *B* and *C*) and child nodes (*C* and *D*). Nodes *A* and *B* are input nodes and parents to child node *C*. Node *C* is simultaneously a parent of child node *D*.

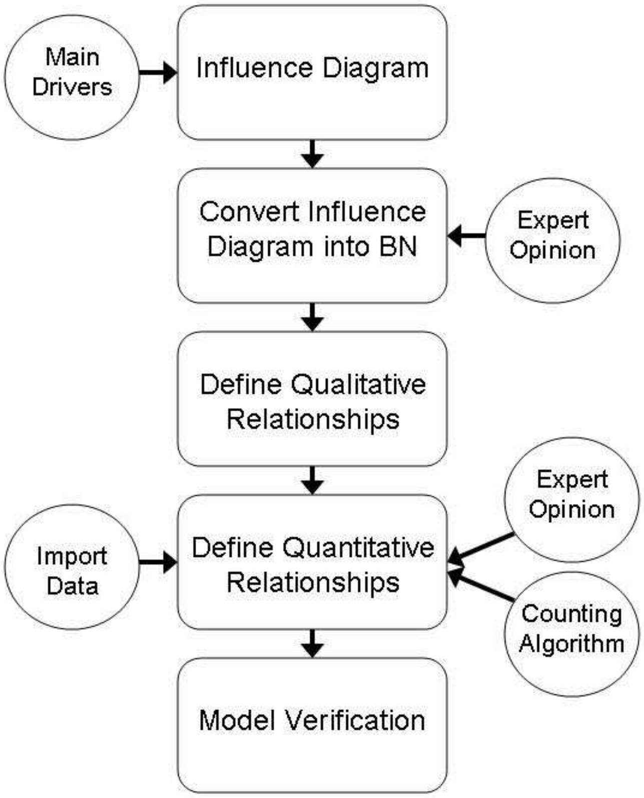


Figure 2.3. Flow chart of modeling process.

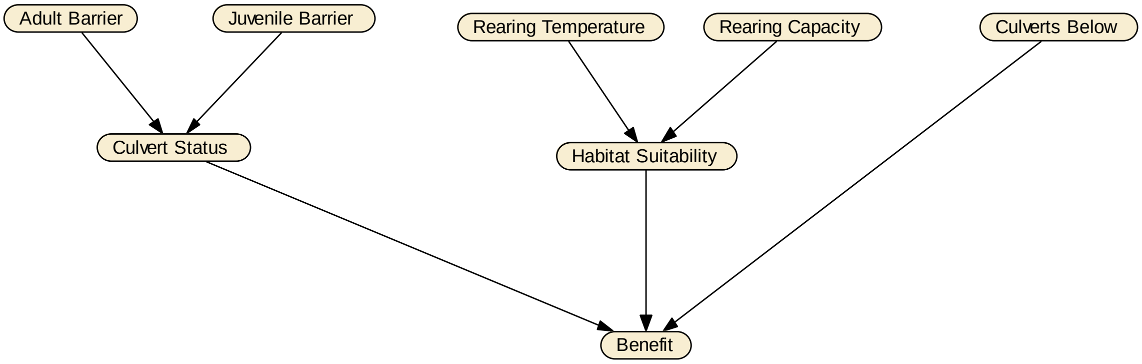
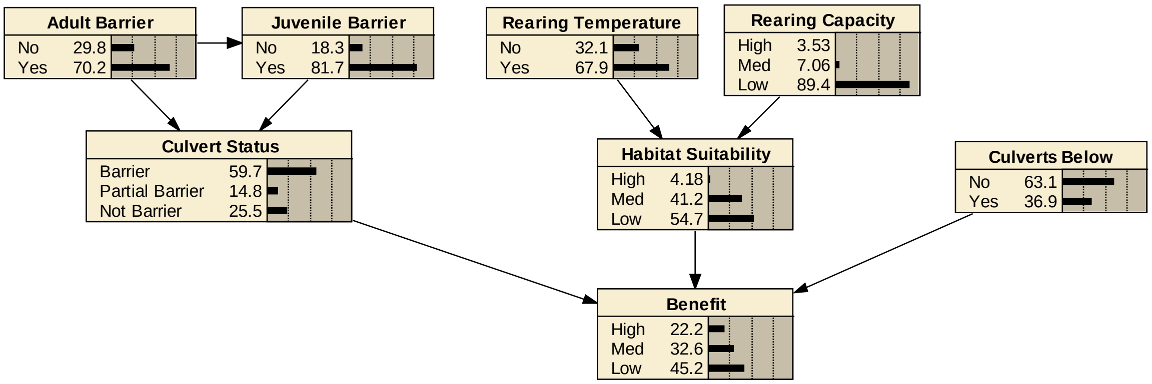


Figure 2.4. Conceptual model (e.g. Influence Diagram) used to construct final models.

(a) Expert Opinion



(b) Counting Algorithm

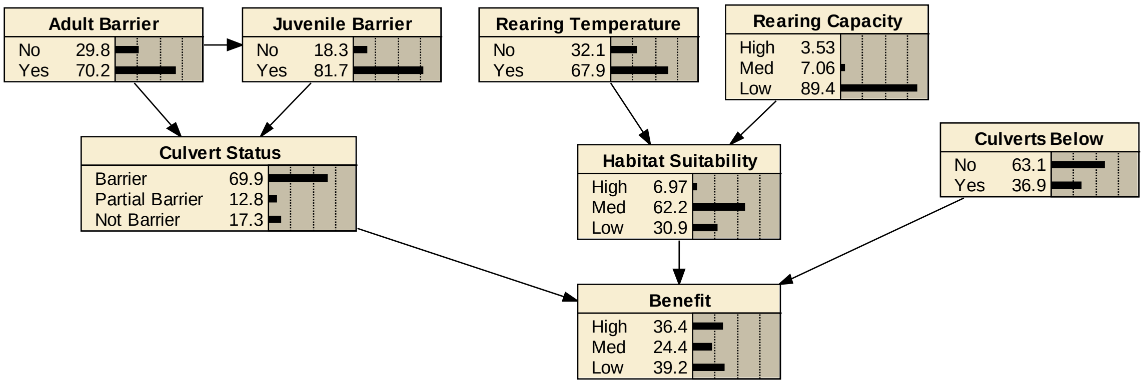


Figure 2.5. Both models exhibiting prior probabilities. The prior probabilities of the input nodes are the same in Expert Opinion (a) and the Counting Algorithm (b), but not in the child nodes. Variation in the child node prior probabilities results from differences in the conditional probability table (CPT) values.

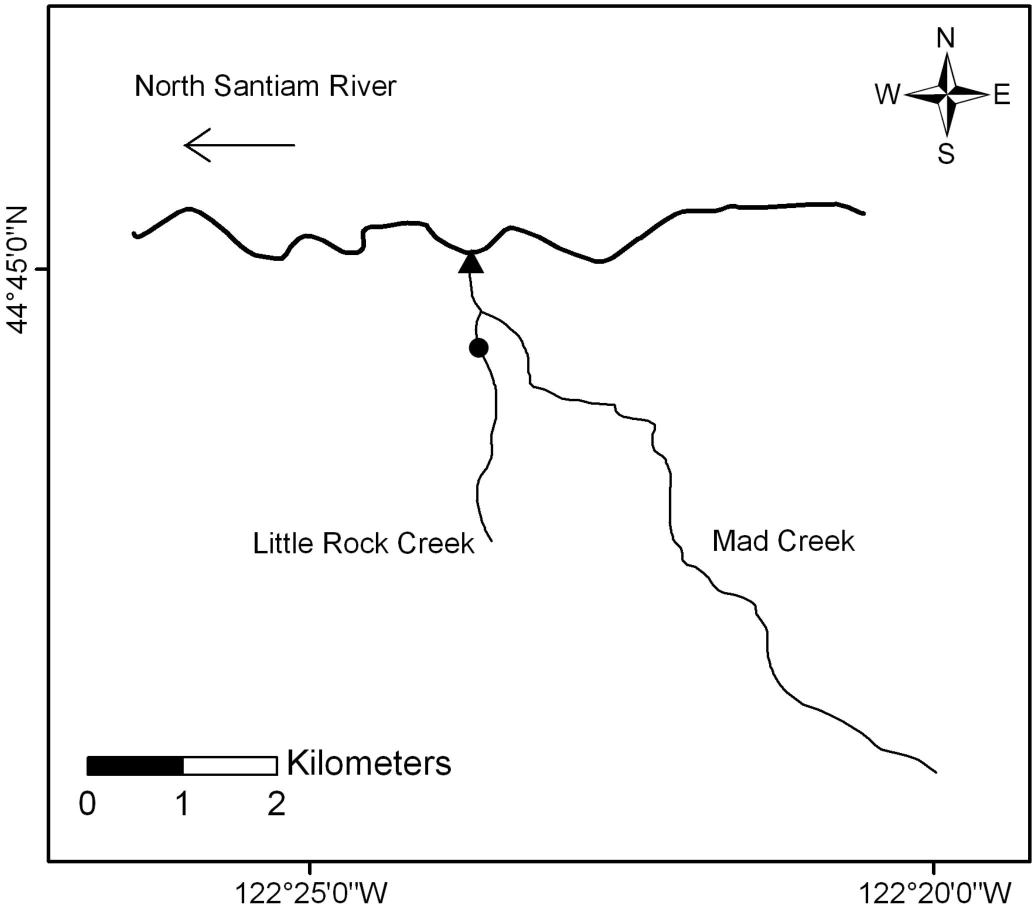


Figure 2.6. Mad Creek case study. Map illustrates the mainstem North Santiam River with the Mad Creek Tributary. Little Rock creek is a tributary to Mad Creek. The downstream culvert is identified as a triangle (▲), while the upstream culvert is identified as a circle (●).

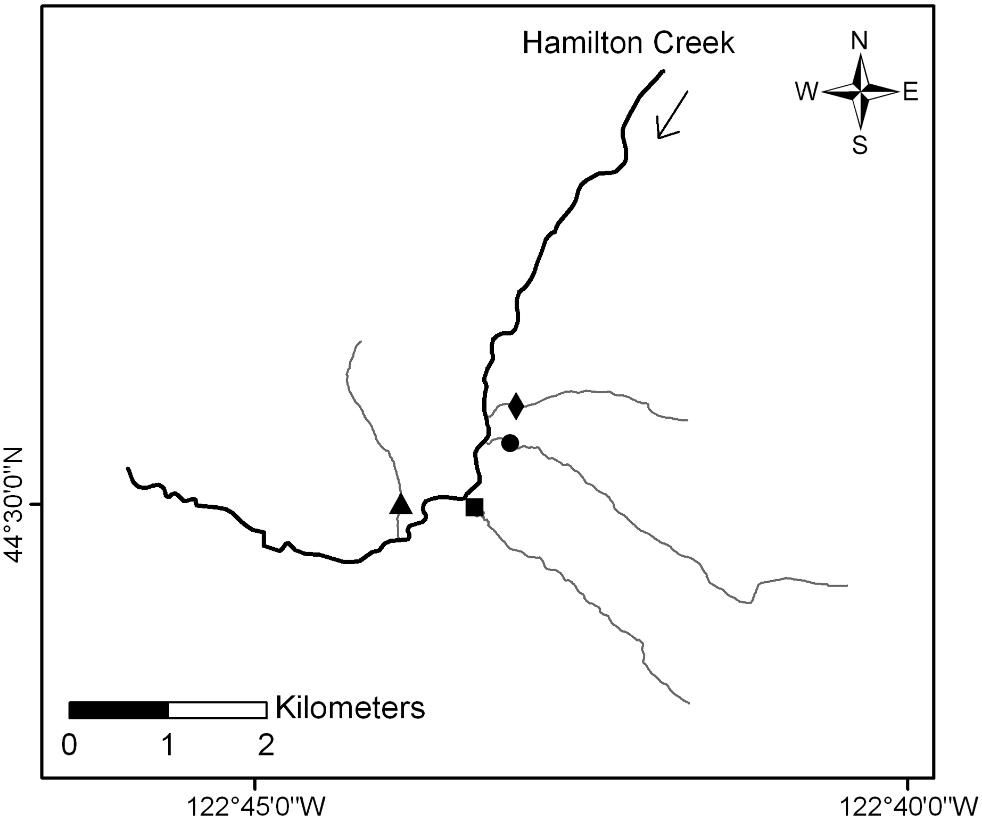


Figure 2.7. Hamilton Creek case study. Map illustrates Hamilton Creek and four tributaries, each with a culvert. Culvert “A” is represented with a diamond (♦), culvert “B” as a circle (●), culvert “C” as a square (■) and culvert D as a triangle (▲).

Table 2.1. Nodes, node definitions and node states used in both models.

Node	Definition	States
Adult Barrier	A culvert is an adult unconditional barrier if there are no flow conditions (within the 5%-95% exceedance values) at the culvert during the return period (Dec-May) that enable adult fish to pass through the culvert. Depicts whether the culvert is an unconditional barrier to upstream migrating adult winter run steelhead during the period of December to May.	Yes No
Juvenile Barrier	A culvert is a juvenile unconditional barrier if there are no flow conditions (within the 5%-95% exceedance values) at the culvert during the return period (Dec-May) that enable adult fish to pass through the culvert. Depicts whether the culvert is an unconditional barrier to upstream migrating juvenile winter run steelhead during the entire year.	Yes No
Culvert Status	Depicts whether the culvert has been established as an unconditional barrier to adults, juveniles, both adults and juveniles or neither.	Barrier Not Barrier Partial Barrier
Rearing Temperature	Determines if the culvert is located within OR DEQ designated cold core water habitat.	Yes No
Rearing Capacity	The intrinsic potential of a stream reach to rear juvenile steelhead; which is based on the gradient, mean annual flow and calibrated valley width index.	High Medium Low
Habitat Suitability	The potential habitat suitability for steelhead defined by rearing temperature and rearing capacity.	High Medium Low
Culverts Below	A surrogate for the ability of a fish to utilize habitat that may be made accessible.	Yes No
Benefit	The potential biological benefit gained by replacing a culvert.	High Medium Low

Table 2.2. Qualitative relationships for the nodes: *Culvert Status* (a), *Habitat Suitability* (b) and *Benefit* (c), within the Expert Opinion (EO) and Counting Algorithm (CA) models.

(a)

Culvert Status **node**

Parent nodes and states		*Child node and states*
Adult Barrier	Juvenile Barrier	Culvert Status
No	No	Not Barrier
No	Yes	Partial Barrier
Yes	No	Barrier
Yes	Yes	Barrier

(b)

Habitat Suitability **node**

Parent nodes and states		*Child node and states*
Rearing Temperature	Rearing Capacity	Habitat Suitability
No	Low	Low
No	Medium	Low
No	High	Medium
Yes	Low	Medium
Yes	Medium	High
Yes	High	High

Table 2.2 Continued

(c)

***Benefit* node**

Parent nodes and states			*Child node and states*
Culvert Status	Habitat Suitability	Culverts Below	Benefit
Barrier	High	No	High
Barrier	High	Yes	Medium
Barrier	Medium	No	High
Barrier	Medium	Yes	Low
Barrier	Low	No	Medium
Barrier	Low	Yes	Low
Partial Barrier	High	No	High
Partial Barrier	High	Yes	Medium
Partial Barrier	Medium	No	Medium
Partial Barrier	Medium	Yes	Low
Partial Barrier	Low	No	Medium
Partial Barrier	Low	Yes	Low
Not Barrier	High	No	Low
Not Barrier	High	Yes	Low
Not Barrier	Medium	No	Low
Not Barrier	Medium	Yes	Low
Not Barrier	Low	No	Low
Not Barrier	Low	Yes	Low

Table 2.3. Expert Opinion (EO) model Conditional Probability Table (CPT) relationships for the *Culvert Status* (a), *Habitat Suitability* (b) and *Benefit* (c) node.

(a)

***Culvert Status* node**

Probability of a state given the combinations of parent node states

Parent nodes and states		*Child node and states*		
Adult Barrier	Juvenile Barrier	Barrier	Partial Barrier	Not Barrier
No	No	0	0	100
No	Yes	0	90	10
Yes	No	85	5	10
Yes	Yes	85	5	10

(b)

***Habitat Suitability* node**

Probability of a state given the combinations of parent node states

Parent nodes and states		*Child node and states*		
Rearing Temperature	Rearing Capacity	High	Medium	Low
No	Low	0	0	100
No	Medium	0	40	60
No	High	10	65	25
Yes	Low	0	60	40
Yes	Medium	35	65	0
Yes	High	100	0	0

Table 2.3 Continued

(c)

Benefit **node**

Parent nodes and states			*Child node and states* Probability of a state given the combinations of parent node states		
Culvert Status	Habitat Capacity	Culverts Below	High	Medium	Low
Barrier	High	No	95	5	0
Barrier	High	Yes	20	60	20
Barrier	Medium	No	70	30	0
Barrier	Medium	Yes	10	30	60
Barrier	Low	No	30	70	0
Barrier	Low	Yes	0	20	80
Partial Barrier	High	No	90	10	0
Partial Barrier	High	Yes	10	60	30
Partial Barrier	Medium	No	30	70	0
Partial Barrier	Medium	Yes	0	20	80
Partial Barrier	Low	No	20	60	20
Partial Barrier	Low	Yes	0	5	95
Not Barrier	High	No	0	5	95
Not Barrier	High	Yes	0	5	95
Not Barrier	Medium	No	0	5	95
Not Barrier	Medium	Yes	0	5	95
Not Barrier	Low	No	0	5	95
Not Barrier	Low	Yes	0	5	95

Table 2.4. Counting Algorithm (CA) model Conditional Probability Table (CPT) relationships for *Culvert Status* (a), *Habitat Suitability* (b) and *Benefit* (c) node.

(a)

***Culvert Status* node**

Parent nodes and states		*Child node and states* Probability of a state given the combinations of parent node states		
Adult Barrier	Juvenile Barrier	Barrier	Partial Barrier	Not Barrier
No	No	5.9	5.9	88.2
No	Yes	7.7	84.6	7.7
Yes	No	96.7	1.6	1.6
Yes	Yes	96.7	1.6	1.6

(b)

***Habitat Suitability* node**

Parent nodes and states		*Child node and states* Probability of a state given the combinations of parent node states		
Rearing Temperature	Rearing Capacity	High	Medium	Low
No	Low	4	4	92
No	Medium	16.7	16.7	66.7
No	High	25	50	25
Yes	Low	1.8	96.4	1.8
Yes	Medium	60	20	20
Yes	High	50	25	25

Table 2.4 Continued.

(c)

Benefit **node**

Probability of a state given the combinations of parent node states

Parent nodes and states			*Child node and states*		
Culvert Status	Habitat Capacity	Culverts Below	High	Medium	Low
Barrier	High	No	50	25	25
Barrier	High	Yes	20	60	20
Barrier	Medium	No	94.1	2.9	2.9
Barrier	Medium	Yes	7.7	7.7	84.6
Barrier	Low	No	9.1	81.8	9.1
Barrier	Low	Yes	11.1	11.1	77.8
Partial Barrier	High	No	50	25	25
Partial Barrier	High	Yes	20	60	20
Partial Barrier	Medium	No	16.7	66.7	16.7
Partial Barrier	Medium	Yes	12.5	12.5	75
Partial Barrier	Low	No	25	50	25
Partial Barrier	Low	Yes	25	25	50
Not Barrier	High	No	16.7	16.7	66.7
Not Barrier	High	Yes	16.7	16.7	66.7
Not Barrier	Medium	No	16.7	16.7	66.7
Not Barrier	Medium	Yes	20	20	60
Not Barrier	Low	No	12.5	12.5	75
Not Barrier	Low	Yes	14.3	14.3	71.4

Table 2.5. The entropy reduction values for the expert opinion (EO) and counting algorithm (CA) based models and the corresponding number of links between nodes. High entropy reduction values indicate nodes (e.g. variables) that are the most influential on the *Benefit* node. Node links indicate the distance of a node from the Benefit node. Nodes with one link are expected to be highly influential, while nodes with more than one link are expected to have a decreased influence on the *Benefit* node.

Expert Opinion		
Node	**Mutual Information**	**Node Links**
Culverts Status	0.30361	1
Culvert Below	0.21744	1
Juvenile Barrier	0.15390	2
Adult Barrier	0.10860	2
Habitat Suitability	0.04593	1
Rearing Temperature	0.01355	2
Rearing Capacity	0.00891	2

Counting Algorithm		
Node	**Mutual Information**	**Node Links**
Culverts Below	0.22409	1
Habitat Suitability	0.13470	1
Rearing Temperature	0.09261	2
Culvert Status	0.07680	1
Adult Barrier	0.04168	2
Juvenile Barrier	0.03485	2
Rearing Capacity	0.00344	2

Table 2.6. Confusion matrix and error rates for the CA model. The error rate indicates the number of incorrect predictions of case data by the model. In this test, false positives (type II errors) were the cause of the errors.

		Predicted		
		High	Medium	Low
Actual	High	20	0	0
	Medium	2	4	0
	Low	1	0	13

Error Rate = 7.5%

CHAPTER 3 - GENERAL CONCLUSIONS

We present a novel BN to organize information surrounding the critical and complex decision to replace a culvert using winter run steelhead in the lower North and South Santiam River basins as a case study. The model predicts the overall benefit to be obtained when replacing or removing a culvert. This model can be used as decision support tool for land managers when prioritizing restoration of aquatic connectivity. The model is derived from the main drivers of barrier removal: passage impairment, habitat suitability upstream of the surveyed culvert and the probability of habitat use. The three main drivers were quantified and arranged in an influence diagram depicting conditional dependencies between variables. Two models of identical structure, but differing CPTs, were compared by evaluating a range of common data scenarios.

BNs offer several advantages over existing scoring and ranking methods or an ad hoc approach to restoration. BNs clearly illustrate the relationship between all model variables; thus allowing a diverse audience the ability to decipher the system being modeled. The model output is probabilistic; illustrating a predicted range of benefit to be gained. In addition, BNs readily account for uncertainty and can incorporate expert opinion.

The models allow culverts to be quickly evaluated and a coarse catalogue of potential project sites produced. This model provides a clear and transparent framework for justifying the need to fund restoration opportunities. While the final decision is up to the land manger, BNs can help facilitate the process of project assessment and potential data needs.

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APPENDICES

Appendix A - Node Definitions and Justification

The following section provides justification for using each variable (e.g. node) in model construction and variable interactions. The data sources for each model component are listed in addition to a qualitative uncertainty assessment for each model variable.

Node: Adult Barrier

Considering passage impairment of adult fish at a culvert is consistent with efforts by numerous organizations within Oregon (Mirati 1999; Oregon Plan 1997). It is important to consider adult fish as this is the life stage that lays eggs (Pauley et al. 1986). Culverts that block access to habitat restrict the locations this critical life history stage may occur (Hoffman and Dunham 2001) and thus may impede population growth. A higher percentage of adults laying eggs in suitable habitat may result in a larger amount of young fish produced (Bjornn and Reiser 1991). This increase in the production of juveniles may lead to an increase in returning adults, thus increasing the local population over time.

The *Adult Barrier* node depicts whether the culvert is an unconditional barrier to upstream migrating adult winter run steelhead during the return period of December to May (Primozich and Bastasch 2004). A culvert is defined as an unconditional barrier to adult steelhead if, as determined by FishXing analysis, there are no flow conditions at the culvert during the return period December to June that enables a 60cm fish to pass through the culvert (FishXing 2006). The range of flow conditions are defined as being between the 5% and 95% exceedance flows predicted to occur at the surveyed culvert (NOAA 2005; Risley et al. 2008). If a road stream crossing had multiple culverts, each was assessed for passage (FishXing 2006).

Adult Barrier States	Definition
Yes	Culvert is impassable during all flows
No	Culvert is not impassable during all flows

Data Sources:

Oregon Department of Fish and Wildlife Natural Resources Information Management Program (http://nrimp.dfw.state.or.us/nrimp/default.aspx)

Fish Xing software (http://www.stream.fs.fed.us/fishxing)

Potential Sources of Uncertainty:

Surveyor bias during collection of field data, protocol effectiveness (e.g. FishXing tends to overestimate culverts as barriers (Burford et al. 2009)), accurate stream flow modeling (regression equations, methods used to calculate parameter data for regression equations), inadequate representation of culverts (e.g. not enough sites to represent “reality”).

Types of Uncertainty:

Inexactness, Lack of Observations or Measurements (van Asselt and Rotmans 2002)

Node: Juvenile Barrier

Juveniles are a critical component in the life history of steelhead, as juveniles (e.g. smolts) outmigrate to the ocean and mature. A higher number of outmigrating young fish may translate into a higher number of returning adults. The movement of juvenile fish should be considered when assessing a culvert (Mirati 1999). Juvenile steelhead can spend one to four years in freshwater prior to migrating to the ocean (Pauley et al. 1986). During this time young fish commonly move upstream and downstream in response to environmental conditions, food resources or competition from conspecifics (Kahler et al. 2001; Pauley et al. 1986). Because juveniles spend extended time in freshwater they are especially vulnerable to fragmented stream networks.

A culvert is defined as an unconditional barrier to upstream migrating juvenile steelhead if, as determined by FishXing analysis, there are no flow conditions at the culvert during the entire year that enables a 15cm fish to pass through the culvert. If a road stream crossing had multiple culverts, each was assessed for passage. The range of flow conditions are defined as being between the 5% and 95% exceedance flows (NOAA 2005; Risley et al. 2008). All streams were ungaged and had the exceedance flow values determined using regression equations for the Willamette Valley (Risley et al. 2008). It was assumed that any barrier to adult fish was a barrier to juvenile fish.

Juvenile Barrier States	Definition
Yes	Culvert is impassable during all flows
No	Culvert is not impassable during all flows

Data Sources:

Oregon Department of Fish and Wildlife Natural Resources Information Management Program (http://nrimp.dfw.state.or.us/nrimp/default.aspx)

Fish Xing software. (http://www.stream.fs.fed.us/fishxing)

Potential Sources of Uncertainty:

Surveyor bias during collection of field data, protocol effectiveness (e.g. Fish Xing tends to overestimate culverts as barriers, (Burford et al. 2009)), accurate stream flow modeling (regression equations, methods used to calculate parameter data), inadequate representation of culverts (e.g. not enough sites to represent “reality”).

Type of Uncertainty:

Inexactness, Lack of Observations or Measurements (van Asselt and Rotmans 2002)

Node: Culvert Status

Habitat loss is a primary factor in salmonid declines worldwide (Nehlsen et al. 1991). Culverts commonly fragment stream networks and reduce the amount of habitat available for stream fishes (Meixler et al. 2009; Park et al. 2008; US GAO 2001). A stream network truncated by barrier culverts effectively provides returning fish less area to spawn. Assessing culverts for passage impairment to fish and remedying problem sites is a common and successful management action (Paul et al. 2002; Roni et al. 2002). While a culvert that blocks upstream migration may not always eliminate downstream migration; it still acts as a threat to the local fish population. Fish populations above culverts are at an increased risk of local extirpation from perturbations in environmental conditions or demographic effects (Morita and Yamamoto 2002; Neville et al. 2009; Shaffer 1981).

The Culvert Status Node depicts whether the culvert has been established as a barrier to an adult, a juvenile, both or neither. It is assumed that if the culvert is a barrier to adult fish it is a barrier to juveniles. If the culvert is not a barrier to adults, it still may be a barrier to juveniles. It was assumed that no culvert would be a barrier to adults but not juveniles. Combining the analysis for both life stages allows for an overall measure of impairment at the culvert. FishXing tends to overestimate culverts as barriers (Burford et al. 2009), thus introducing uncertainty into the decision making process. In order to account for the uncertainty, the CPT values were altered to reflect the possibility that a culvert assessed as a barrier may not be a barrier in reality.

Accounting for uncertainty in this node allows for an unaltered depiction of the FishXing assessment in the parent nodes.

It is assumed that the most benefit would be obtained by replacing culverts that are barriers to adults and juveniles; therefore the model predicts a higher benefit in these situations. Less benefit is assumed to be gained by replacing a culvert that is a barrier to only juveniles. The least important culverts to replace are non-barriers. It is assumed that if fish passage is the goal, then replacing culverts that already pass fish is an unnecessary diversion of resources from sites that do block one or more life stages.

Culvert Status States	Definition
Barrier	Culvert is impassable to adults and juveniles at all modeled stream flows
Partial Barrier	Culvert is passable to adults but not juveniles at all modeled stream flows
Not Barrier	Culvert is passable to adults and juveniles at all modeled stream flows

Source:

Adult Unconditional node, Juvenile Unconditional node.

Potential Sources of Uncertainty:

Conditional probability table values, proper weighting of nodes, field data, also see uncertainty in source nodes.

Type of Uncertainty:

Inexactness, Lack of Observations or Measurements (van Asselt and Rotmans 2002)

Node: Rearing Temperature

Water temperature is a major regulating factor on aquatic ecosystems and affects salmonids in numerous ways (Allan and Castillo 2007; Bjornn and Reiser 1991; Hynes 1970). Steelhead have preferred water temperatures and will migrate out of areas that are unsuitable (Bjornn and Reiser 1991). The rate of egg development, juvenile growth, population density and overall metabolism is regulated by temperature (Pauley et al. 1986; Quinn 2005; Sullivan 2000). Extremes of temperature can be lethal to juvenile steelhead (Pauley et al. 1986).

Because adult winter run steelhead return at a time of naturally cool water temperatures, it was assumed that stream temperature would not be a critical factor to adults. This assumption was verified by examining historical water temperature data for the North and South Santiam rivers during the period December through June. Recorded data was obtained from the USGS Surface water monthly statistics for Oregon database (http://waterdata.usgs.gov/or/nwis). River temperatures were below 16 degrees Celsius for this period, confirming our assumption.

There are logistical problems in acquiring thorough stream temperature data across large spatial scales. Collecting extensive stream temperature data is expensive and not always practical. Modeling stream temperature can be data intensive (Dent et al. 2008; Risley et al. 2003). Therefore a proxy variable was used for actual stream temperature. Rearing temperature is defined as whether the surveyed culvert is located within an Oregon State Department of Environmental Quality listed ‘Cold Core Water Habitat’ (OR DEQ 2009). Streams within cold core water habitat must not have a seven day average temperature exceeding 16 C (60.8 F) (OR DEQ 2009). It is assumed that streams within the cold core water habitat should have cooler water temperatures than streams not within the designated habitat. There are limitations to using this proxy variable. All streams in cold core water habitat may not meet stated temperature requirements. Several large rivers within the Santiam basin exceed temperature requirements stated in OR DEQ regulations. Furthermore, determining the number of small tributaries actually meeting temperature requirements within the cold core water habitat is difficult due to a lack of stream temperature monitoring throughout the study area in smaller tributaries.

Rearing Temperature States	Definition
Yes	Culvert is within an OR DEQ cold core water habitat
No	Culvert is not within an OR DEQ cold core water habitat

Source:

OR DEQ Standards OAR 340-041-0028(4)

http://arcweb.sos.state.or.us/rules/OARs_300/OAR_340/340_041.html

Potential Sources of Uncertainty:

Streams can exceed desired temperatures in the ‘cold core water habitat,’ location of temperature gages can influence temperature recordings.

Potential Sources of Uncertainty:

Inexactness, Lack of Observations or Measurements, Practically Immeasurable

Node: Rearing Capacity

The physical characteristics of a stream influence the distribution of fish within that stream (Montgomery 1999; Quinn 2005; Vannote et al. 1980). Juvenile steelhead do not distribute evenly within a stream network, but prefer certain physical conditions (Bisson et al. 1988; Raleigh 1984). Water velocity, water depth, quantity of pools and instream cover are all characteristics driving the allocation of young salmonids within a stream (Bjornn and Reiser 1991). While channel gradients between 1-5% are considered prime for steelhead spawning and could be considered high priority (Steel et al. 2004); juvenile steelhead are known to use gradients of up to 6% for rearing habitat (Burnett et al. 2007). Instream habitat is a limiting factor for all life stages of winter run steelhead in the Upper Willamette River (ODFW 2010), thus identifying areas with the best potential to support juvenile steelhead is useful in planning restoration.

The rearing capacity node depicts the ‘intrinsic potential’ of a stream segment to support juvenile steelhead under pristine conditions (Burnett et al. 2007). Intrinsic potential is a metric (zero to one) based on the geometric mean of habitat suitability curves for stream gradient, mean annual flow and calibrated valley width. High intrinsic potential values indicate optimal rearing conditions for juvenile steelhead under pristine conditions. Existing fish populations are not modeled with this approach. Only stream lengths with intrinsic potential values of 0.75 to 1.00 (e.g. high intrinsic potential) were used in analysis. High intrinsic potential stream reaches were summed upstream of a surveyed culvert to the next upstream culvert. The summed stream reaches were then binned using a logarithmic scale to provide high, medium and low categories. A logarithmic scale was chosen to provide an objective means of binning the summed high intrinsic scores.

Rearing Capacity States	Definition
High	<10,000 m and >1,000 m stream reach with IP value > .75
Medium	<1,000 m and > 100 m stream reach with IP value > .75
Low	<100 m stream reach with IP value > .75

Source:

Burnett et al 2007, intrinsic potential GIS layer:

http://www.blm.gov/or/plans/wopr/data/final/data-details.php?data=ds000147

Potential Sources of Uncertainty:

Habitat suitability curves that establish intrinsic potential values, stream networks are modeled and could be inaccurate, assumption of pristine conditions.

Type of Uncertainty:

Inexactness, Lack of Observations or Measurements, Practically Immeasurable, and Reducible Ignorance (van Asselt and Rotmans 2002)

Node: Habitat Suitability

The decision to replace a culvert is partly driven by the instream habitat that is to be made accessible (Pess et al. 2003; Roni et al. 2002). Providing access to higher quality habitat would translate to a larger biological benefit than low quality habitat (Keeley 1996). Habitat suitability can be measured in numerous ways, but is generally a combination of quantity and quality of habitat (O’Hanley and Tomberlin 2005).

The habitat suitability of a culvert is a function of its parent nodes: rearing temperature and rearing capacity. While we define habitat suitability as consisting of two variables, there are other habitat factors influencing fish habitat. We opted for these two variables because we assume they are the most influential elements of habitat suitability. The nodes are not equally weighted. Rearing temperature is assumed more influential than rearing capacity given the overall affect of temperature on aquatic ecosystems.

Habitat Suitability States	Definition
High	Within cold core water habitat and high rearing capacity
Medium	May or may not be in cold core water habitat, with rearing capacity of high, medium or low.
Low	Not in cold core habitat and with low or medium rearing capacity.

Source:

Rearing Potential, Rearing Temperature nodes

Potential Sources of Uncertainty:

Conditional probability table values, proper weighting of nodes, also see uncertainty in source nodes

Type of Uncertainty:

Inexactness, Lack of Observations or Measurements, Practically Immeasurable, and Reducible Ignorance (van Asselt and Rotmans 2002)

Node: Culverts Below

Fish must be able to use habitat that is made available when a culvert is replaced for the highest biological benefit to be achieved. Many possible routes of determining fish use were examined prior to choosing the proxy variable culverts below.

There is no accurate data describing the current distribution of steelhead in the Santiam, and therefore other measures of deriving fish presence were explored. The presence of redds can be used as a surrogate to predict adult numbers. However, limited redd surveys are conducted in the Santiam basin, and the areas where the surveys are conducted are not similar to the areas I surveyed culverts. Models have been developed to predict the abundance of steelhead redds in some Santiam subbasins (Steel et al. 2004). However, the models are not applicable to the majority of the sites surveyed for this study. Oregon Department of Forestry (ODF) fish presence maps do not identify the species in a particular stream. The ODF stream maps indicate fish use as present, absent or suspected. Due to these limitations, the use of a proxy variable was necessary.

The ‘culverts below’ node acts as the proxy variable for potential habitat use. The node assumed that a culvert within the Santiam basin is most likely a barrier. The assumption is supported based on the data I collected that indicates most culverts are barriers to adult and juvenile steelhead in the lower Santiam basin. Therefore, if a culvert is located lower on the stream network, the probability that it is a barrier is greater than the probability it is not a barrier. The benefit to be gained by completing a passage restoration project would be severely diminished if passage was still comprised lower on the stream network. Therefore this node exerts a strong influence within the model.

Culverts Below States	Definition
Yes	At least one culvert is located below the surveyed culvert
No	No culverts are located below the surveyed culvert

Source:

Determined from GIS layers (Linn county road layer) and aerial photos

Potential Sources of Uncertainty:

There is a potential that the culverts that are located on a stream below a particular culvert of interest are not barriers.

Type of Uncertainty:

Inexactness, Lack of Observations or Measurements, Practically Immeasurable, and Reducible Ignorance (van Asselt and Rotmans 2002)

Node: Benefit

The potential biological benefit gained by replacing a culvert is a function of its passage impairment to adults and juveniles, the habitat suitability of the upstream stream reaches and the probability of habitat use as determined by the presence of additional culverts lower on the stream network. The predicted benefit to be gained is grouped in three categories: high, medium or low. Benefit may be in one or all of the categories. The state with the highest probability would indicate the benefit gained.

The lowest benefit would result from replacing culverts that are not barriers; while the highest benefit arises from replacing culverts that are barriers to adults and juveniles with high habitat suitability and a high probability of habitat use. Habitat suitability is highest in areas of cold core water habitat with a high rearing capacity. A site with no downstream culverts would indicate a high probability of use and therefore an increase in the overall benefit of the project.

Benefit States	Definition
High	The probability a culvert replacement would result in a high biological benefit
Medium	The probability a culvert replacement would result in a medium biological benefit
Low	The probability a culvert replacement would result in a low biological benefit

Source: Barrier Status, Probability of Habitat Suitability, Probability of Habitat Use.

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

Type of Uncertainty:

Inexactness, Lack of Observations or Measurements (van Asselt and Rotmans 2002)

Appendix B – Expert Opinion and Counting Algorithm Model Output for All Data Scenarios

Model output for the predicted probability of benefit when considering the complete data scenarios. The Expert Opinion model and Counting Algorithm model results are displayed for each individual complete data scenario that was considered in this modeling exercise.

Complete Data Scenario

					Predicted Probability of Benefit					
Input Nodes and Node States					Expert Opinion Model			Counting Algorithm Model		
Adult Barrier	Juvenile Barrier	Rearing Temperature	Rearing Capacity	Culverts Below	High	Medium	Low	High	Medium	Low
No	No	No	High	No	0	0.05	0.95	0.190	0.185	0.625
No	No	No	Medium	No	0	0.05	0.95	0.157	0.186	0.657
No	No	No	Low	No	0	0.05	0.95	0.137	0.187	0.676
No	No	Yes	High	No	0	0.05	0.95	0.189	0.182	0.629
No	No	Yes	Medium	No	0	0.05	0.95	0.192	0.181	0.627
No	No	Yes	Low	No	0	0.05	0.95	0.211	0.188	0.602
No	No	No	High	Yes	0	0.05	0.95	0.174	0.185	0.641
No	No	No	Medium	Yes	0	0.05	0.95	0.158	0.166	0.676
No	No	No	Low	Yes	0	0.05	0.95	0.150	0.152	0.698
No	No	Yes	High	Yes	0	0.05	0.95	0.169	0.193	0.638
No	No	Yes	Medium	Yes	0	0.05	0.95	0.170	0.198	0.633
No	No	Yes	Low	Yes	0	0.05	0.95	0.187	0.188	0.625

Complete Data Scenario

					Predicted Probability of Benefit					
Input Nodes and Node States					Expert Opinion Model			Counting Algorithm Model		
Adult Barrier	Juvenile Barrier	Rearing Temperature	Rearing Capacity	Culverts Below	High	Medium	Low	High	Medium	Low
No	Yes	No	High	No	0.302	0.559	0.140	0.289	0.474	0.237
No	Yes	No	Medium	No	0.216	0.581	0.203	0.269	0.468	0.264
No	Yes	No	Low	No	0.180	0.545	0.275	0.238	0.489	0.273
No	Yes	Yes	High	No	0.810	0.095	0.095	0.351	0.391	0.259
No	Yes	Yes	Medium	No	0.459	0.446	0.095	0.376	0.361	0.263
No	Yes	Yes	Low	No	0.234	0.599	0.167	0.231	0.572	0.198
No	Yes	No	High	Yes	0.009	0.187	0.804	0.171	0.263	0.566
No	Yes	No	Medium	Yes	0	0.104	0.896	0.208	0.270	0.522
No	Yes	No	Low	Yes	0	0.050	0.950	0.226	0.240	0.534
No	Yes	Yes	High	Yes	0.090	0.545	0.365	0.188	0.373	0.439
No	Yes	Yes	Medium	Yes	0.032	0.311	0.658	0.190	0.412	0.398
No	Yes	Yes	Low	Yes	0	0.131	0.869	0.130	0.137	0.733

Complete Data Scenario

Input Nodes and Node States					Predicted Probability of Benefit					
					Expert Opinion Model			Counting Algorithm Model		
Adult Barrier	Juvenile Barrier	Rearing Temperature	Rearing Capacity	Culverts Below	High	Medium	Low	High	Medium	Low
Yes	No	No	High	No	0.548	0.355	0.098	0.605	0.284	0.111
Yes	No	No	Medium	No	0.403	0.496	0.101	0.298	0.583	0.119
Yes	No	No	Low	No	0.265	0.630	0.105	0.143	0.749	0.108
Yes	No	Yes	High	No	0.853	0.053	0.095	0.500	0.335	0.165
Yes	No	Yes	Medium	No	0.695	0.210	0.095	0.499	0.318	0.183
Yes	No	Yes	Low	No	0.472	0.429	0.099	0.894	0.059	0.047
Yes	No	No	High	Yes	0.073	0.274	0.653	0.118	0.217	0.665
Yes	No	No	Medium	Yes	0.034	0.215	0.752	0.123	0.188	0.690
Yes	No	No	Low	Yes	0	0.178	0.823	0.116	0.132	0.752
Yes	No	Yes	High	Yes	0.175	0.545	0.280	0.148	0.345	0.507
Yes	No	Yes	Medium	Yes	0.117	0.366	0.517	0.158	0.395	0.447
Yes	No	Yes	Low	Yes	0.051	0.233	0.716	0.082	0.090	0.828

Complete Data Scenario

					Predicted Probability of Benefit					
Input Nodes and Node States					Expert Opinion Model			Counting Algorithm Model		
Adult Barrier	Juvenile Barrier	Rearing Temperature	Rearing Capacity	Culverts Below	High	Medium	Low	High	Medium	Low
Yes	Yes	No	High	No	0.548	0.355	0.098	0.605	0.284	0.111
Yes	Yes	No	Medium	No	0.403	0.496	0.101	0.298	0.583	0.119
Yes	Yes	No	Low	No	0.265	0.630	0.105	0.143	0.749	0.108
Yes	Yes	Yes	High	No	0.853	0.053	0.095	0.500	0.335	0.165
Yes	Yes	Yes	Medium	No	0.695	0.210	0.095	0.499	0.318	0.183
Yes	Yes	Yes	Low	No	0.472	0.429	0.099	0.894	0.059	0.047
Yes	Yes	No	High	Yes	0.073	0.274	0.653	0.118	0.217	0.665
Yes	Yes	No	Medium	Yes	0.034	0.215	0.752	0.123	0.188	0.690
Yes	Yes	No	Low	Yes	0	0.178	0.823	0.116	0.132	0.752
Yes	Yes	Yes	High	Yes	0.175	0.545	0.280	0.148	0.345	0.507
Yes	Yes	Yes	Medium	Yes	0.117	0.366	0.517	0.158	0.395	0.447
Yes	Yes	Yes	Low	Yes	0.051	0.233	0.716	0.082	0.090	0.828

Appendix B continued. Model output for the predicted probability of benefit when considering the partial data scenarios. The Expert Opinion model and Counting Algorithm model results are displayed for each individual complete data scenario that was considered in this modeling exercise.

Partial Data Scenario

Input Nodes and Node States					Predicted Probability of Benefit					
					Expert Opinion Model			Counting Algorithm Model		
Adult Barrier	Juvenile Barrier	Rearing Temperature	Rearing Capacity	Culverts Below	High	Medium	Low	High	Medium	Low
No	No	No	High		0	0.05	0.95	0.184	0.185	0.631
No	No	No	Medium		0	0.05	0.95	0.157	0.179	0.664
No	No	No	Low		0	0.05	0.95	0.142	0.174	0.684
No	No	Yes	High		0	0.05	0.95	0.181	0.186	0.633
No	No	Yes	Medium		0	0.05	0.95	0.184	0.187	0.629
No	No	Yes	Low		0	0.05	0.95	0.202	0.188	0.610
No	No			No	0	0.05	0.95	0.187	0.187	0.626
No	No			Yes	0	0.05	0.95	0.174	0.178	0.648

Partial Data Scenario

Input Nodes and Node States					Predicted Probability of Benefit					
					Expert Opinion Model			Counting Algorithm Model		
Adult Barrier	Juvenile Barrier	Rearing Temperature	Rearing Capacity	Culverts Below	High	Medium	Low	High	Medium	Low
No	Yes	No	High		0.194	0.422	0.385	0.245	0.396	0.359
No	Yes	No	Medium		0.136	0.405	0.459	0.247	0.395	0.359
No	Yes	No	Low		0.114	0.362	0.524	0.233	0.397	0.370
No	Yes	Yes	High		0.544	0.261	0.195	0.291	0.384	0.325
No	Yes	Yes	Medium		0.301	0.396	0.303	0.307	0.380	0.313
No	Yes	Yes	Low		0.148	0.426	0.426	0.194	0.411	0.395
No	Yes			No	0.243	0.563	0.193	0.244	0.530	0.226
No	Yes			Yes	0.004	0.126	0.870	0.164	0.190	0.646

Partial Data Scenario

Input Nodes and Node States					Predicted Probability of Benefit					
					Expert Opinion Model			Counting Algorithm Model		
Adult Barrier	Juvenile Barrier	Rearing Temperature	Rearing Capacity	Culverts Below	High	Medium	Low	High	Medium	Low
Yes	No	No	High		0.373	0.325	0.303	0.425	0.259	0.316
Yes	No	No	Medium		0.267	0.392	0.341	0.233	0.437	0.330
Yes	No	No	Low		0.167	0.463	0.370	0.133	0.521	0.346
Yes	No	Yes	High		0.603	0.234	0.163	0.370	0.339	0.291
Yes	No	Yes	Medium		0.481	0.268	0.251	0.373	0.346	0.281
Yes	No	Yes	Low		0.317	0.357	0.327	0.594	0.070	0.335
Yes	No			No	0.432	0.468	0.101	0.633	0.291	0.076
Yes	No			Yes	0.042	0.231	0.727	0.099	0.126	0.775

Partial Data Scenario										
					Predicted Probability of Benefit					
Input Nodes and Node States					Expert Opinion Model			Counting Algorithm Model		
Adult Barrier	Juvenile Barrier	Rearing Temperature	Rearing Capacity	Culverts Below	High	Medium	Low	High	Medium	Low
Yes	Yes	No	High		0.373	0.325	0.303	0.425	0.259	0.316
Yes	Yes	No	Medium		0.267	0.392	0.341	0.233	0.437	0.330
Yes	Yes	No	Low		0.167	0.463	0.370	0.133	0.521	0.346
Yes	Yes	Yes	High		0.603	0.234	0.163	0.370	0.339	0.291
Yes	Yes	Yes	Medium		0.481	0.268	0.251	0.373	0.346	0.281
Yes	Yes	Yes	Low		0.317	0.357	0.327	0.594	0.070	0.335
Yes	Yes			No	0.432	0.468	0.101	0.633	0.291	0.076
Yes	Yes			Yes	0.042	0.231	0.727	0.099	0.126	0.775

Partial Data Scenario

Input Nodes and Node States					Predicted Probability of Benefit					
					Expert Opinion Model			Counting Algorithm Model		
Adult Barrier	Juvenile Barrier	Rearing Temperature	Rearing Capacity	Culverts Below	High	Medium	Low	High	Medium	Low
		No	High	No	0.423	0.328	0.249	0.494	0.291	0.215
		No	Medium	No	0.310	0.430	0.260	0.270	0.500	0.230
		No	Low	No	0.209	0.520	0.272	0.154	0.620	0.226
		Yes	High	No	0.701	0.057	0.242	0.428	0.316	0.257
		Yes	Medium	No	0.546	0.212	0.242	0.431	0.300	0.270
		Yes	Low	No	0.361	0.385	0.254	0.693	0.146	0.161
		No	High	Yes	0.052	0.225	0.723	0.134	0.217	0.649
		No	Medium	Yes	0.024	0.172	0.804	0.139	0.195	0.666
		No	Low	Yes	0	0.140	0.860	0.136	0.149	0.716
		Yes	High	Yes	0.134	0.460	0.406	0.157	0.322	0.521
		Yes	Medium	Yes	0.086	0.305	0.609	0.164	0.363	0.473
		Yes	Low	Yes	0.036	0.189	0.775	0.107	0.112	0.781

Appendix B continued: Model output for the predicted probability of benefit when considering the limited data scenarios. The Expert Opinion model and Counting Algorithm model results are displayed for each individual complete data scenario that was considered in this modeling exercise.

Limited Data Scenario

Input Nodes and Node States					Predicted Probability of Benefit: Expert Opinion Model			Predicted Probability of Benefit: Counting Algorithm Model		
Adult Barrier	Juvenile Barrier	Rearing Temperature	Rearing Capacity	Culverts Below	High	Medium	Low	High	Medium	Low
No	No				0	0.05	0.95	0.182	0.184	0.634
No	Yes				0.155	0.402	0.443	0.215	0.405	0.381
No		No			0.050	0.184	0.766	0.182	0.269	0.549
No		Yes			0.073	0.206	0.721	0.202	0.281	0.517
No			High		0.183	0.161	0.656	0.222	0.271	0.507
No			Medium		0.105	0.198	0.697	0.223	0.269	0.508
No			Low		0.058	0.201	0.742	0.193	0.278	0.529
No				No	0.103	0.267	0.630	0.211	0.332	0.457
No				Yes	0.002	0.082	0.916	0.170	0.183	0.647

Limited Data Scenario

Input Nodes and Node States					Predicted Probability of Benefit					
					Expert Opinion Model			Counting Algorithm Model		
Adult Barrier	Juvenile Barrier	Rearing Temperature	Rearing Capacity	Culverts Below	High	Medium	Low	High	Medium	Low
Yes	No				0.288	0.381	0.332	0.436	0.230	0.334
Yes	Yes				0.288	0.381	0.332	0.436	0.230	0.334
Yes		No			0.182	0.453	0.365	0.150	0.506	0.344
Yes		Yes			0.338	0.346	0.316	0.571	0.099	0.330
Yes			High		0.529	0.263	0.208	0.388	0.313	0.299
Yes			Medium		0.412	0.308	0.280	0.328	0.375	0.297
Yes			Low		0.269	0.391	0.341	0.446	0.215	0.339
Yes				No	0.432	0.468	0.101	0.633	0.291	0.076
Yes				Yes	0.042	0.231	0.727	0.099	0.126	0.775

Limited Data Scenario

Input Nodes and Node States					Predicted Probability of Benefit Expert Opinion Model			Counting Algorithm Model		
Adult Barrier	Juvenile Barrier	Rearing Temperature	Rearing Capacity	Culverts Below	High	Medium	Low	High	Medium	Low
	No	No			0.012	0.076	0.913	0.145	0.196	0.659
	No	Yes			0.022	0.069	0.910	0.224	0.182	0.594
	No		High		0.034	0.064	0.903	0.195	0.194	0.611
	No		Medium		0.026	0.066	0.907	0.185	0.197	0.619
	No		Low		0.017	0.072	0.911	0.199	0.186	0.615
	No			No	0.028	0.077	0.896	0.215	0.194	0.591
	No			Yes	0.003	0.062	0.936	0.170	0.174	0.656
	Yes	No			0.172	0.440	0.388	0.163	0.489	0.347
	Yes	Yes			0.313	0.357	0.330	0.514	0.147	0.339
	Yes		High		0.514	0.271	0.215	0.371	0.325	0.305
	Yes		Medium		0.387	0.322	0.291	0.322	0.377	0.301
	Yes		Low		0.248	0.393	0.359	0.409	0.245	0.346
	Yes			No	0.403	0.483	0.115	0.573	0.328	0.099
	Yes			Yes	0.036	0.215	0.749	0.109	0.136	0.755

Limited Data Scenario

					Predicted Probability of Benefit					
Input Nodes and Node States					Expert Opinion Model			Counting Algorithm Model		
Adult Barrier	Juvenile Barrier	Rearing Temperature	Rearing Capacity	Culverts Below	High	Medium	Low	High	Medium	Low
		No	High		0.286	0.290	0.424	0.361	0.264	0.375
		No	Medium		0.205	0.335	0.460	0.222	0.387	0.391
		No	Low		0.132	0.379	0.489	0.147	0.446	0.407
		Yes	High		0.492	0.206	0.302	0.328	0.318	0.354
		Yes	Medium		0.376	0.247	0.377	0.332	0.323	0.345
		Yes	Low		0.241	0.313	0.446	0.477	0.134	0.390
No					0.066	0.199	0.736	0.196	0.277	0.527
Yes					0.288	0.381	0.332	0.436	0.230	0.334
	No				0.018	0.071	0.911	0.198	0.187	0.615
	Yes				0.267	0.384	0.349	0.402	0.257	0.342
		No			0.142	0.373	0.485	0.160	0.436	0.405
		Yes			0.259	0.304	0.436	0.461	0.153	0.386
			High		0.426	0.233	0.341	0.338	0.301	0.361
			Medium		0.321	0.275	0.404	0.297	0.344	0.360
			Low		0.206	0.334	0.460	0.371	0.234	0.395
				No	0.334	0.408	0.258	0.507	0.303	0.190
				Yes	0.030	0.187	0.783	0.120	0.143	0.737

Table 2. Raw data used to populate both models.

Barrier ID	**Adult Barrier**	**Juvenile Barrier**	**Culvert Status**	**Rearing Temperature**	**Rearing Capacity**	**Habitat Suitability**	**Culverts Below**	**Benefit**
60101	No	No	Not Barrier	Yes	Low	Medium	No	Low
60102	No	No	Not Barrier	Yes	Low	Medium	No	Low
64684	Yes	Yes	Barrier	No	Medium	Low	Yes	Low
64688	Yes	Yes	Barrier	No	Low	Low	Yes	Low
64689	No	No	Not Barrier	No	Low	Low	Yes	Low
64695	No	Yes	Partial Barrier	Yes	Low	Medium	Yes	Low
64696	Yes	Yes	Barrier	Yes	Low	Medium	No	High
64697	Yes	Yes	Barrier	Yes	Low	Medium	Yes	Low
64708	Yes	Yes	Barrier	Yes	Low	Medium	No	High
64709	Yes	Yes	Barrier	No	Low	Low	No	Medium
64710	Yes	Yes	Barrier	No	Low	Low	No	Medium
64711	Yes	Yes	Barrier	No	Low	Low	No	Medium
64713	Yes	Yes	Barrier	No	High	Medium	No	High
64715	Yes	Yes	Barrier	Yes	Medium	High	Yes	Medium
64716	Yes	Yes	Barrier	Yes	Low	Medium	No	High
64728	No	Yes	Partial Barrier	Yes	Low	Medium	No	Medium
64731	Yes	Yes	Barrier	No	Low	Low	No	Medium
64732	No	Yes	Partial Barrier	No	Low	Low	No	Medium
64733	Yes	Yes	Barrier	No	Low	Low	No	Medium
64749	Yes	Yes	Barrier	No	Low	Low	Yes	Low
64750	No	No	Not Barrier	No	Low	Low	Yes	Low
64751	No	No	Not Barrier	No	Low	Low	No	Low
64753	No	Yes	Partial Barrier	Yes	Low	Medium	No	Medium
64754	Yes	Yes	Barrier	Yes	Low	Medium	No	High
64755	Yes	Yes	Barrier	Yes	Low	Medium	No	High
64756	Yes	Yes	Barrier	Yes	Low	Medium	No	High
64757	No	Yes	Partial Barrier	Yes	Low	Medium	Yes	Low

64759	Yes	Yes	Barrier	Yes	High	High	No	High
64760	Yes	Yes	Barrier	Yes	Low	Medium	Yes	Low
64761	No	No	Not Barrier	Yes	Low	Medium	Yes	Low
64763	No	Yes	Partial Barrier	Yes	Low	Medium	Yes	Low
64764	No	Yes	Partial Barrier	Yes	Low	Medium	Yes	Low
64766	No	No	Not Barrier	No	Low	Low	No	Low
64767	Yes	Yes	Barrier	Yes	Low	Medium	No	High
64770	No	No	Not Barrier	No	Low	Low	Yes	Low
64771	Yes	Yes	Barrier	No	Low	Low	Yes	Low
64783	Yes	Yes	Barrier	No	Low	Low	No	Medium
64793	Yes	Yes	Barrier	Yes	Low	Medium	No	High
64799	No	No	Not Barrier	Yes	Low	Medium	No	Low
64800	Yes	Yes	Barrier	Yes	Low	Medium	No	High
64814	Yes	Yes	Barrier	Yes	Low	Medium	Yes	Low
64815	Yes	Yes	Barrier	Yes	Low	Medium	No	High
64816	Yes	Yes	Barrier	No	Low	Low	Yes	Low
64817	No	Yes	Partial Barrier	No	Low	Low	Yes	Low
64818	Yes	Yes	Barrier	Yes	Low	Medium	No	High
64823	Yes	Yes	Barrier	Yes	Low	Medium	Yes	Low
64825	No	No	Not Barrier	No	Medium	Low	No	Low
64826	No	No	Not Barrier	No	Low	Low	No	Low
64827	Yes	Yes	Barrier	No	Low	Low	Yes	Low
64828	Yes	Yes	Barrier	Yes	Low	Medium	Yes	Low
64829	No	Yes	Partial Barrier	Yes	Low	Medium	Yes	Low
64830	Yes	Yes	Barrier	Yes	Low	Medium	Yes	Low
64832	Yes	Yes	Barrier	Yes	Low	Medium	No	High
64833	Yes	Yes	Barrier	Yes	Low	Medium	Yes	Low
64835	Yes	Yes	Barrier	Yes	Low	Medium	No	High
64836	Yes	Yes	Barrier	Yes	Low	Medium	No	High
65063	Yes	Yes	Barrier	Yes	Low	Medium	No	High
65064	Yes	Yes	Barrier	Yes	Low	Medium	No	High
65066	Yes	Yes	Barrier	Yes	Low	Medium	No	High
65068	Yes	Yes	Barrier	Yes	Low	Medium	No	High

65070	Yes	Yes	Barrier	Yes	Low	Medium	No	High
65072	Yes	Yes	Barrier	Yes	Low	Medium	No	High
65073	Yes	Yes	Barrier	Yes	Low	Medium	No	High
65075	Yes	Yes	Barrier	Yes	Low	Medium	No	High
65077	Yes	Yes	Barrier	Yes	Low	Medium	No	High
65078	Yes	Yes	Barrier	Yes	Low	Medium	No	High
65079	Yes	Yes	Barrier	Yes	Low	Medium	No	High
65080	No	Yes	Partial Barrier	Yes	Low	Medium	No	Medium
65081	Yes	Yes	Barrier	Yes	Low	Medium	No	High
65082	Yes	Yes	Barrier	Yes	Low	Medium	No	High
65083	Yes	Yes	Barrier	Yes	Low	Medium	No	High
65216	Yes	Yes	Barrier	Yes	Low	Medium	No	High
65295	No	No	Not Barrier	Yes	Low	Medium	Yes	Low
65299	No	No	Not Barrier	No	Low	Low	Yes	Low
65703	Yes	Yes	Barrier	Yes	Low	Medium	No	High
65940	Yes	Yes	Barrier	Yes	Low	Medium	Yes	Low
66068	Yes	Yes	Barrier	Yes	Medium	High	Yes	Medium
66074	No	No	Not Barrier	No	Low	Low	No	Low
66088	Yes	Yes	Barrier	Yes	Low	Medium	Yes	Low
80101	Yes	Yes	Barrier	Yes	Low	Medium	Yes	Low