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Regional risk assessment of the Puyallup River Watershed and the evaluation of low impact development in meeting management goals

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By
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Accepted in Partial Completion
Of the Requirements for the Degree
Master of Science

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MASTER'S THESIS

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A Thesis
Presented to
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ABSTRACT

The Relative Risk Model (RRM) is a tool used to calculate and assess the likelihood of effects to endpoints when multiple stressors occur in complex ecological systems. In this study a Bayesian network was used to calculate relative risk and uncertainty (BN-RRM) in the Puyallup River Watershed. First, I calculated the risk of prespawn mortality of coho salmon. Second, I evaluated the effect of low impact development (LID) as a means to reduce risk. Prespawner mortality in coho salmon within the Puyallup watershed was the endpoint selected for this study. A conceptual model showing causal pathways between stressors and endpoints was created to show where linkages exist. The greatest risk of prespawner mortality was found in the urbanized risk regions with large amounts of impervious surface. The greatest risk reduction due to LID was observed in more developed regions, and implementing types of LID that are most effective in retaining and filtering stormwater during large storm events would be the most effective type. However, a great deal of surface area would have to be converted to LID to reduce the risk of stormwater impact to the coho fisheries. The structure of the BN-RRM also provides a framework for water quality-related and water quantity-related endpoints within this and other watersheds. The adaptability of using BNs for a relative risk assessment provides opportunity for the model to be adapted for other watersheds in the Puget Sound region.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF TABLES

SUPPLEMENTAL MATERIALS

Netica Bayesian network files: available on CD included.

INTRODUCTION

The Puget Sound Partnership is the Washington State agency responsible for the restoration of Puget Sound including the numerous watersheds that compose the Salish Sea. The Puyallup River is one of those rivers within that management area. While the Partnership has identified numerous endpoints of concern (Puget Sound Partnership 2011), the task of creating a Puget Sound basin-wide restoration plan has yet to come to fruition. An impediment to managing the Salish Sea and other large systems is the lack of a quantitative causal framework in which to examine likely impacts and management alternatives. Landscape scale management involves multiple stressors interacting both spatially and temporally to induce a variety of effects. A tool that has found use in contaminated sites and other scenarios has been ecological risk assessment.

Ecological risk assessment (ERA) has been a field of study since the mid-1980s (Suter 2008). Since then, ERAs have evolved to model situations involving numerous stressors acting on several endpoints over landscape and temporal scales (Hart Hayes and Landis 2004, Colnar and Landis 2007, Landis and Wiegers 2007). The relative risk model (RRM; Landis and Wiegers 1997, 2005) currently uses Bayesian networks (BN) within the RRM framework (BN-RRM; Ayre and Landis 2012).

Bayesian networks are now used in risk assessment and specifically in the RRM for a number of reasons (Uusitalo et al. 2007, Hart and Pollino 2008, Ayre and Landis 2012). Bayesian statistics evaluate the opposite of frequentist, or classical, statistics which evaluate the probability of the evidence given a hypothesis. Bayesian modeling creates an output of *posterior probability* distributions based on inputs of *prior probability* distributions determined by site-specific data or expert knowledge (Hart and Pollino 2008). Bayesian networks differ from other ecological approaches by combining quantitative data and qualitative knowledge to generate probabilistic risk. The causal pathways between multiple stressors on a given endpoint are described by BNs, which makes BN models able to assess synergistic and antagonistic effects between stressors (Hart and Pollino 2008). As Bayesian belief and decision networks work well as modeling tools for adaptive management (Nyberg et al. 2006), the BN-RRM lends itself well to adaptive management applications. Multiple management scenarios may be examined to inform management decisions and key stressors may be identified with a sensitivity analysis. New information may be incorporated into the model as it becomes available. Once the model framework is created, the model may be used for other watersheds with similar characteristics and endpoints.

Low Impact Development (LID) has been considered an effective management tool for several decades (Taylor and Fletcher 2007). Rain gardens, pervious pavement, and bioswales are a few examples of LID. The main objective of LID is to implement structures that aim to restore hydrological processes to predevelopment state by filtering and retaining stormwater. There has been little progress, however, to collect data on the actual effectiveness of LID, despite such data having been called for by researchers and managers since the 1980s (see Finnermore and Lynard 1982). Therefore, I elvaluated LID as a management tool, posing the question: *How effectively can watershed scale management plans that implement low impact development (LID) strategies reduce nonpoint runoff inputs to meet Puget Sound restoration?*

My study area included portions of the Puyallup River Watershed (PRW) and the City of Tacoma within Pierce County and a small portion of King County. This area was selected to allow relative comparisons throughout a watershed and to compare areas with different land uses. Managers in this region are interested in the use of LID. After considering several endpoints, the PRW coho salmon (*Oncorhynchus kisutch*) population was chosen, with prespawn mortality (PSM) as the endpoint to be considered. Prespawn mortality is currently only recognized as a syndrome occurring in adult coho salmon shortly after returning to the fresh water to spawn (Wild Fish Conservancy 2008, Feist et al. 2011, Scholz et al. 2011, Spromberg and Scholz 2011). While PSM has not been officially reported in my study area, very high PSM, sometimes exceeding 90%, has been observed for returning adult coho in southern Puget Sound lowland urban streams (McCarthy et al. 2008). The cause for PSM is currently unknown, although the cause is suspected to be related to stormwater runoff associated with specific land uses. Land use within the lower PRW and City of Tacoma is consistent with the types of land use found in areas where PSM has been reported (see Feist et al. 2011).

In summary, a BN-RRM incorporating LID was created to predict risk and evaluate the usefulness of LID to reduce risk. Regions characterized largely by areas of impervious surface and urban influence were found to have the highest risk. Although LID can reduce risk in the high risk areas, large proportions of these areas would need to implement LID to reduce these regions to low risk. The process used here is transferable to other endpoints within the watershed. The combination of risk assessment and management evaluations may be transferable to other watershed within the Salish Sea region.

MATERIALS AND METHODS

Study Area

The study area encompassed by my study includes two major watersheds, Water Resource Inventory Areas (WRIAs) 10 and 12 in Washington State (Figure 1). WRIA 12 drains an area of 467 km^2, which consists of independent drainages to southern Puget Sound and includes the City of Tacoma. WRIA 10 drains an area of 2679 km^2, and consists of the PRW, which splits into two main forks, the White River to the north and the Carbon/Puyallup rivers to the south. Originating in the highlands of the Mt. Rainer and The Cascade Range in forested parkland, the watershed flows through agricultural, residential, and commercial land before terminating in an urbanized, industrial harbor area feeding into Puget Sound (Department of Ecology 1995). The temperate climate of Pierce County averages 101 cm of rainfall a year but has suffered from extensive flooding events, including recent floods in 2005, 2006, 2008 and especially during the severe New Year's flooding of 2009. Puyallup River Watershed coho salmon adult returns from 1983 to 2011 have varied annually between 391 and 5,153, and were rated as "healthy" in 2002 due to considerably higher escapement values since 1992 (Washington Department of Fish and Wildlife 2011). Spawning coho return to this watershed in fall through winter months when rivers and streams tend to be high enough for adult fish passage, coinciding with the rain season (Puyallup Tribe 2011).

Determination of Risk Regions

Geographic data on watersheds (Pierce County 2003), salmon (Washington Department of Fish and Wildlife 2013a, 2013b), land use (Department of Ecology Washington State 2013), roads (Pierce County 2001-2013; Puget Sound Regional Council 2010), and impervious surfaces (Department of Ecology Washington State 2010) for WRIA 10 and 12 were compiled. Major watershed basin layers for WRIA 10 and 12 were broken down as shown in Table 1 for a total of 6 risk regions. Risk regions were defined based on the criteria of land use, separating watersheds dominated by heavily forested, agricultural, residential, commercial, and industrial use (Figure 1). The use of GIS to gather input information for nodes is described below in the *Model Parameterization* section. The majority of the study area lay within Pierce County; however, a small portion of risk region 4 lies within King County, so that GIS data from both counties had to be pooled for my assessment.

Structure of the BN-RRM Process

A step-by-step description of the formulation of a RRM is presented by Landis and Wiegers (2005). First, management goals and associated endpoints, potential stressors, sources, and habitats linked to endpoints were identified and a map delineating risk regions was created. The next step was to create a conceptual model demonstrating the causal pathways to link sources to spatial and temporal overlaps with habitat and management endpoints (Figure 2). This was then formatted into a BN structure (Figure 3), and the model was parameterized. Rankings were defined for each node in the model based on management goals (Table 2). Risk was calculated, once the structure of the model was created, using conditional probability tables (CPTs) to describe causal relationships based on existing knowledge. The model was then evaluated for uncertainty and a sensitivity analysis for the endpoint examined using an entropy reduction analysis. As one of the final steps, risk was calculated for management scenarios using other relative amounts of LID to evaluate how an increased abundance of LID may affect the overall calculated risk. Details of this specific application are presented in the *Model Parameterization* section.

Conceptual model- The conceptual model (Figure 2) shows the causal pathways for the risk posed to WRIA 10 and 12 coho populations due to the threat of PSM. Prespawn mortality in this model is represented by the effect due to stormwater and contaminants in stormwater runoff from specific land use. Specifically, commercial property, roads, and other impervious surfaces were used as the three land use types assumed to contribute the contaminants responsible for PSM and are used here as predictors (Wild Fish Conservancy 2008, Feist et al. 2011, Scholz et al. 2011, Spromberg and Scholz 2011). The link to roads and other impervious surfaces implies that motor vehicles and a mixture of heavy metals and polycyclic aromatic hydrocarbons (PAHs) are likely linked to thus syndrome (Scholz et al. 2011). Both the amount of rainfall and amount of contaminants present in stormwater are assumed to affect the likelihood of PSM (Scholz et al. 2011), with LID possibly lowering the likelihood of PSM. Coho migratory habitat and observed escapements are also incorporated into the model to demonstrate the likelihood coho will encounter an overlap and exposure with the stressors that cause PSM.

Bayesian network structure- A BN model structure was derived directly from the conceptual model where each source, stressor, habitat, and effect, as well as the endpoint were converted into either nature nodes when probability distributions were available or decision nodes when only a one-time discrete value could be used (Figure 3). The BN-RRM is generally transparent about uncertainty. However, decision nodes are not presented as probability distributions, masking the uncertainty regarding those decisions. The BN structure consists of tiers of nodes; here sources of stressors make up the first tiers, habitats in the middle tier, and ecological endpoints in the last tiers. Nodes are linked based on causal relationships defined by CPTs, which are developed after relative ranking schemes have been determined. Relative ranks were defined for each node. Table 1 summarizes each model node, including sources, rationale, and definitions of rankings. Three or four potential discrete states were determined for each node. When there was greater uncertainty, three discrete states were used, while four discrete ranks were used when there was less uncertainty. Throughout the model, “zero” or “low” was used to describe an unlikely contribution to the overall risk score to the endpoint, while “high” was used to describe a high likelihood that there exists a greater risk to the endpoint due to that node. For example, because a low relative abundance of LID is considered to increase watershed risk, the risk rank for the abundance of LID is set to “high.”

Interactions between nodes and tiers are determined by CPTs that define posterior probability distributions for output nodes given the prior probability distributions from input nodes. Next, the model was parameterized. The BN software Netica (Norsys Software Corp., Vancouver, B.C., Canada) was used to calculate and evaluate the BN-RRM. This software may be downloaded for free.

Model Parameterization

This section describes my decisions and assumptions for each node and causal relationships based on existing knowledge available at the time of the creation of the model (Table 2). Model parameters were defined using a combination of spatial analysis data, empirical data from published and state government data, and expert judgment gathered from published reports. Using this knowledge, casual relationships were used to parameterize the model and develop CPTs reasonably to our current knowledge.

Land use- Land use nodes include the input nodes for Commercial Property, Roads, and Other Impervious Surfaces (Figure 3). These three land use types were used as indicators for the presence of contaminants that are suspected to cause the acute and fatal toxicological effect of PSM (Feist et al. 2011). Impervious surfaces, roads, and commercial land use types were defined by the percent cover and categorized as low (0-10%), moderate (11-40%), or high (41-100%) for each risk region (Tables 1 and 3). These three input nodes were set as decision nodes because the input values can only be discrete values, not distributions describing likely or observed occurrences for each rank.

Geographical analysis data from Pierce County (Pierce County 2001-2013) and the Puget Sound Regional Council model transportation network dataset (Puget Sound Regional Council 2010) were combined to find total road length data for each region. Combining these two sources allowed for a more complete quantification of possible surfaces regardless of road classification and also allowed for the inclusion of road length count in areas within WRIA 10 that extend into King County but were not included in the Pierce County database.

Commercial property type areas were found with Washington Department of Ecology Land Use 2010 data based on tax parcel shapefiles (Table 4). Metadata (Department of Ecology Washington State 2013) helped determine how commercial property was defined. For the final model inputs, the commercial area for each region was then converted into a total percentage per risk region.

Impervious surface percent cover per risk region was found using remote sensing information from 2006 Washington Department of Ecology (Department of Ecology Washington State 2010).

Large stormwater event- Contaminants in stormwater are often found at the highest concentrations when a large storm event occurs after a sustained period of little to no rain. The accumulation of contaminants on impervious surfaces in the absence of stormwater runoff contributes to these high concentrations (Booth et al. 2002). To calculate risk, this model needs to predict when coho adults return to fresh water and the chance of these returns coinciding with a storm event. Coho salmon typically return to the PRW during November and December, but coho spawners have been known to enter fresh water as early as August or as late as March in the PRW (Puyallup Tribe 2011). To coincide with migratory coho returns, daily precipitation data from 1 August through 15 March were used dating from 1 August 2007 through 15 March 2012. Rankings were determined using the Western Regional Climate Center “Precipitation Probability by Quantity” predictive modeling for station Tacoma 1 for a period of one-day rainfall (Applied Climate Information Systems 2013). The distribution in the input node for *Large Stormwater Event* reflects the frequency at which storm events occur at the levels described for each of the rankings, given any spawner year.

LID abundance- In my examination of the literature, LID projects were not documented in a readily available format. The most extensive documentation of LID was found to have over 100 LID sites within the southern Puget Sound region (approximately 85 of which are located within the study area) and are documented in an online interactive map by the Stewardship Partners and the Washington State University Extension as part of a *12,000 Rain Gardens in Puget Sound* campaign (Stewardship Partners 2011). Because LID projects typically are less than a hectare (0.01 km^2) in size while the areas for the risk regions totaled 149-1035 km^2, abundance of LID by percent cover per region was considered negligible. Rankings for all nodes were defined as "high" because of an increased probability of high overall risk, and a small relative abundance of LID was assumed to increase the probability of overall risk. These nodes, like the land use nodes, were discrete because the abundance per risk region is a discrete number and therefore does not have a distribution.

LID filtration- An extensive literature review was conducted to determine the effectiveness of LID to filter polycyclic aromatic hydrocarbons (PAHs) and heavy metals. The input node in the model was defined by three categories: low, moderate, and high. This input node is the same for each risk region. For my model, the distribution for LID effectiveness was defined as 65% of the time being able to reasonably filter/retain stormwater; 25% of the time as being moderately able to filter/retain stormwater; and 10% of the time LID effectively fails to filter/retain stormwater. Although some studies suggest that LID is likely to be more successful than the input prior distribution used (Dietz 2007), other studies showed that LID often failed to be optimally effective during increased water volumes for large storm events (Diblasi et al. 2009). Due to the fact that my study was interested in LID performance during large storm events, the distribution was skewed towards ineffectiveness. It should also be noted that there is not enough information on the effectiveness of specific types of LID, and therefore this input node represents the frequencies of effectiveness of LID found in the literature regardless of LID type. The various types of LID studied are reasonably representative of LID that may be found within my study area.

Coho migratory habitat- This input node brings into the model the overlap of a stressor and habitat, which affects the probability that PSM will occur within a region. Even if a large storm event occurs in a region with high risk from land use, if there is no overlap with habitat, then PSM will not occur without a receptor to receive the stressor. Coho habitat for each risk region was assessed by combining two factors: Washington Department of Fish and Wildlife (WDFW) habitat status and overall length of river migratory habitat. First, the relative amount of coho habitat was assessed, then the condition of habitat was accounted for in the model. Salmon habitat categories included critical, depressed, healthy, and unknown as defined by WDFW's Salmonid Stock Inventory (SaSI) Status (Washington Department of Fish and Wildlife 2013a). The amount of coho habitat for each category of habitat status in each risk region was found by querying the total number of river miles of coho migratory habitat according to WDFW's salmon scape within each region (Washington Department of

Fish and Wildlife 2013b; Table 5). Next, the rankings for amount of habitat and status were weighted between zero and six and averages between the two calculated. This was put into the node as a discrete number since no distributions exist.

Coho population status- Numbers of returning adult spawner coho salmon were found in WDFW and Puyallup Tribe salmon spawner surveys per reach (Washington Department of Fish and Wildlife 2012a, 2012b). Each survey reach was matched with the risk region with which it corresponded, and then total numbers of returning fish were calculated for each region by return year, as available from surveys. The annual numbers of returning fish were categorized as zero, low, medium, and high as defined in Table 6. These input nodes represent a distribution of the frequency at which coho were recorded returning annually in the defined categories as far back as WDFW data were available.

Prespawner mortality- The PSM node represents the probable percentage of returning coho population die-off due to land use factors that are suspected to be correlated to PSM (Feist et al. 2011) after LID has both filtered and retained stormwater. Here, roads, commercial property types, and other impervious surfaces are the main sources of contaminants that run off in stormwater and cause PSM. LID also has a limited effectiveness to reduce stormwater quantity and quality. Stormwater is not as strong of an indicator of PSM occurring in comparison to the presence of contaminants. The CPT for this node reflected that PSM was more likely to occur if there was a high probability that toxicants were present while less likely to occur in the event of a large storm event without toxicants.

Coho population- The coho population node represents the fishability of the WRIA 10 and 12 coho stocks. Rankings were defined partially by WDFW escapement goals to maintain a sustainable fishery for the PRW coho stock as well as where natural breaks occurred based on past return numbers (Washington Department of Fish and Wildlife 2011).

Sensitivity and Uncertainty Analysis

The sensitivity analysis was calculated in Netica. The degree of entropy reductions for each BN node was recorded. The degree of entropy reduction describes to what degree an input variable influences the response variable, where a greater entropy value indicates a greater degree of influence (Marcot et al. 2006). These entropy reduction scores were then used to inform which parameters had the greatest influence on risk estimates for each region.

RESULTS

Risk in the PRW

The mean risk score for each relative region generally increased with the downstream gradient of the watershed (Figure 4). The lower risk regions, 3, 5, and 6, had the highest mean risk scores of 4.57±1.2, 4.57±1.2, and 4.55±1.2 respectively (Table 7). Regions 5 and 6 are the mouths of WRIAs 10 and 12 respectively. Region 3 is upstream and adjacent to region 5, composed of the southern fork of the Puyllup River system. The distributions for these indicate the probability of high risk (Figure 5). The likelihood of a high-risk outcome was predicted to occur 84.7%, 84.7%, and 83.0% of the time for risk regions 3, 5, and 6, respectively (Table 8).

Risk region 4, in the middle of the watershed, had a mean risk score 14% lower than the highest risk regions (3.93±1.7). The distribution outcome for region 4 was similarly skewed towards high risk, but to a lesser degree with a 64.5% chance of high risk (Figure 5). At the start of the watershed, risk regions 1 and 2 had the lowest mean scores of 3.03±2.1 and 2.78±2.0, respectively; however, the posterior probability distribution demonstrated a higher uncertainty in the outcome. Table 8 shows that regions 1 and 2 had a more even distribution than the other regions. This means that each rank had closer to a 1 in 4 chance; although, these regions were still skewed towards high risk with a 43.9% and 37.8% probability of a high-risk outcome for regions 1 and 2, respectively.

Sensitivity Analysis

The risk of prespawn mortality was the greatest contributor to total risk for each region according to the sensitivity analysis. The next two top contributors varied among regions (Table 9 and 10). The land use nodes were not included in the sensitivity analysis (*Road, Commercial Property,* and *Other Impervious Surfaces*) because these were decision nodes. Regions 3, 5, and 6 all had in common at least one or more high ranks for one of the three land use types while the regions at lower risk did not (Table 3), indicating that land use may influence the endpoint considerably.

Alternative Management Scenario Results

One purpose of my model was to investigate alternative management scenarios. Because it is unlikely that the land used for development will decrease, altering the amounts of LID was evaluated in the model to determine how much LID could minimize the risk PSM poses to coho populations (Table 11). The results confirmed that increasing the relative abundance of LID decreased the overall risk score for each region. The largest change in risk reduction was observed in the most developed risk regions, 3, 5, and 6. Risk was reduced more than a full integer in the overall risk score between evaluating a low amount of LID (high risk rank) to a large amount of LID (low risk rank). Optimally, LID would be implemented to a scale that would reduce imperviousness effectively to below 10 percent land cover per region (Booth and Jackson 1997). Intermediate abundances of LID will also reduce risk, although to a lesser degree.

DISCUSSION

Patterns of Risk

The predicted relative risk for coho populations due to PSM fell within the range of medium to high, with the highest score of 4.57 out of 6.0. With a range of mean risk scores of 2.78 to 4.57, a gradient was observed (Figure 4). Lower risk was found in the upper stream reaches and increased downstream to where WRIA 10 and 12 drain into Puget Sound. This gradient matches a land use gradient where the upper watershed has less development and the lower watershed is the most heavily developed.

Because the highest risk was found in regions 3, 5, and 6 at the bottom of the watershed, management efforts to reduce the risk of PSM should be focused here. Managing the bottom of the watershed for returning adult salmon makes sense because coho are anadromous fish that migrate upstream, the returning adult salmon must pass through at least one or more of the downstream high risk regions in order to spawn.

Data Gaps

During the creation of my model, data gaps were identified for LID and PSM. While comprehensive empirical data for LID have been requested by managers for several decades, there is still considerable uncertainty in the relationship between LID and reducing impacts to non-point sources of contaminants (Taylor and Fletcher 2007). As more data become available on the overall watershed impacts in relation to LID, this data can be incorporated into the model to reduce the uncertainty of what kind of LID or how much LID is needed.

In spite of the uncertainties, a pattern was apparent. Past studies indicated that 10% or less impervious surface in a watershed can impact salmon populations (Booth and Jackson 1997). Risk regions 3, 5, and 6 have as much as 49%, 70%, and 67% impervious surface, respectively, indicating that LID may be needed on a very large scale to reduce risk. Region 2 had the lowest risk to PSM and had 6% impervious surface. A better understanding of how LID can reduce the impacts of impervious surface will allow a calculation of how much needs to be constructed to reach an acceptable likelihood of meeting the management goal for coho in the PRW.

The cause of PSM and where PSM is occurring in the PRW is currently unknown. My model identified where PSM is likely to occur, so the next step is for the Puyallup Tribe Fisheries and WDFD to document observations of PSM. NOAA Fisheries is continuing research to determine the direct stressors of PSM. Once this syndrome is better understood, specific stressors instead of land use associated with the occurrence of PSM can be incorporated into the model. Closing these information gaps could result in a more informative BN-RRM with the ability to reduce uncertainty and display the interactions in the model more accurately.

Risk Assessment as a Management Tool

The BN-RRM works well within a management framework. Management scenarios can be evaluated, such as examining different relative abundances of LID and the change in overall risk scores. In my model, an increase of LID was found to decrease risk; however, a large increase of LID will be needed to decrease the most risk. This same framework can be applied to other management scenarios for other endpoints and watersheds within the Salish Sea region to aid in management decisions.

An overall benefit of producing a risk assessment with LID incorporated is identifying where and how much LID needs to be implemented. My model quantitatively demonstrates that a large amount of LID will be needed in the most developed regions to reduce the risk of PSM. Long term management will need to take into consideration tradeoffs between the cost of installing LID and the overall potential to reduce risk. Additionally, my model characterized a high risk in the developed regions before PSM was officially documented in WRIAs 10 or 12, thus identifying a management goal before the problem was observed.

Adaptive Management

As models are created for restoration endpoints, the adaptive management framework outlined by Nyberg et al. (2006) could be followed. My model showed that LID could lower the potential risk of PSM. For this BN-RRM and management to effectively work together in the future in an adaptive management framework, first, the current coho population affected by PSM should be assessed. Next, after a measured amount of LID is installed within risk regions 3, 5, and 6, the response in occurrences of PSM should be monitored and evaluated. This could provide insight into the accuracy of the model predictions and provide information about how much LID may be needed to reduce the risk of PSM. Similar experiments that include monitoring and evaluating management decisions should be implemented when possible. Such an adaptive management scheme may also provide useful information as to what scale LID is actually necessary to reduce risk. The Puget Sound Partnership uses the *Open Standards for the Practice of Conservation* that builds on this adaptive management framework by adding the component of capturing and sharing lessons learned (Puget Sound Partnership 2010). This is an important step; Taylor and Fletcher (2007) identified that educated communities were a key driver for implementing LID practices.

Next steps

The next steps will be to create models for other Puget Sound restoration management objectives in WRIA 10 and 12. An overall conceptual model has already been created for all identified endpoints for the watershed. If anthropogenic sources are linked as sources for other endpoints, the same gradient of increasing risk moving down the watershed may be expected. The model structure already created here for water quality and water quantity may be transferable to other endpoints within the area that demonstrate the same causal pathways. Once a risk assessment has been calculated and completed for each of the endpoints, the cumulative risk due to all the endpoints for each risk region can be calculated. This would provide a broader presentation of risk by region within WRIA 10 and 12, with the information of which regions are most in need of watershed management to protect restoration endpoints. Once proven valuable on the scale of one major watershed of Puget Sound, similar models may be used for other major watersheds of Puget Sound.

FIGURES

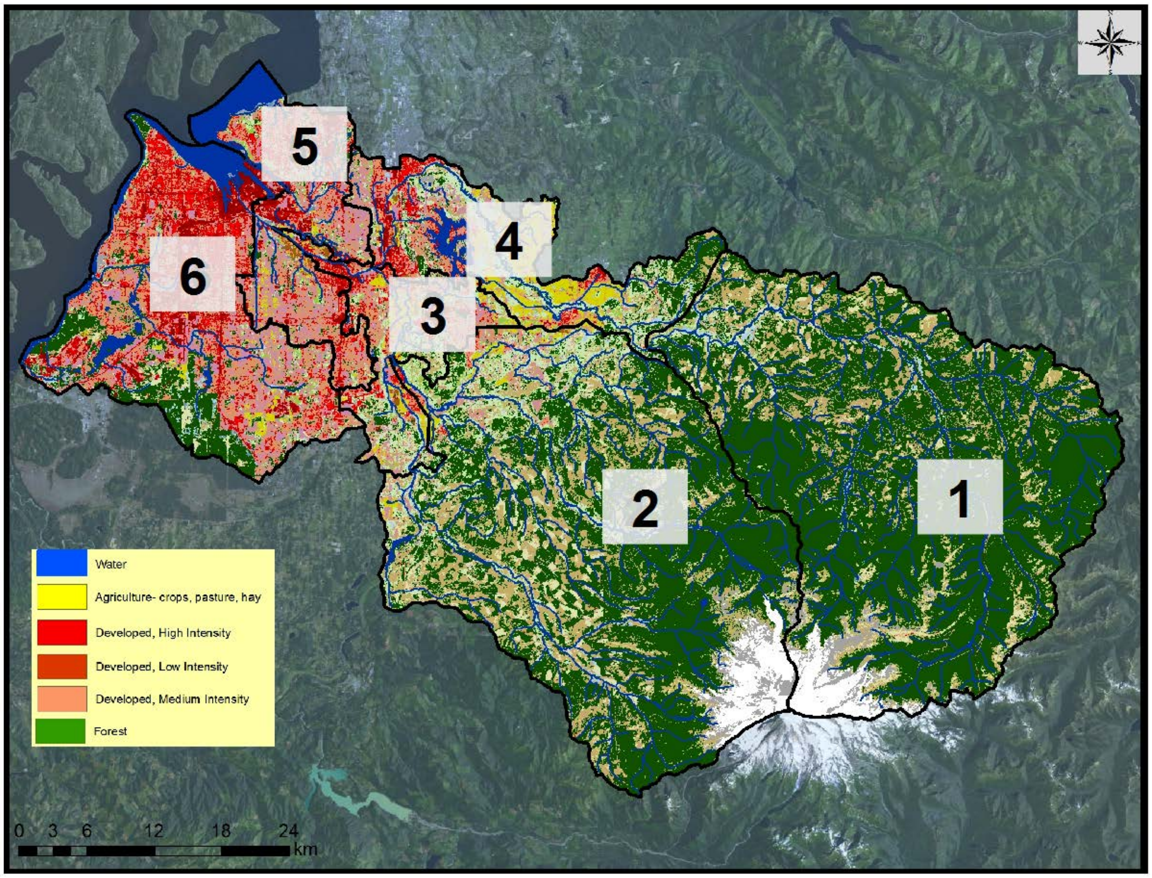

Figure 1. Map of Water Resource Inventory Areas (WRIAs) 10 and 12 summarizing land use and risk regions. Risk regions 1-5 compose WRIA 10 and risk region 6 encompasses WRIA 12. The start of the Puyallup River Watershed starts at Mount Rainer in forested parkland, in the southeast corner of the map and drains to the northwest into southern Puget Sound, which is much more densely populated with higher industrial, commercial, and industrial land use. WRIA 12 consists of mostly independent drainages.

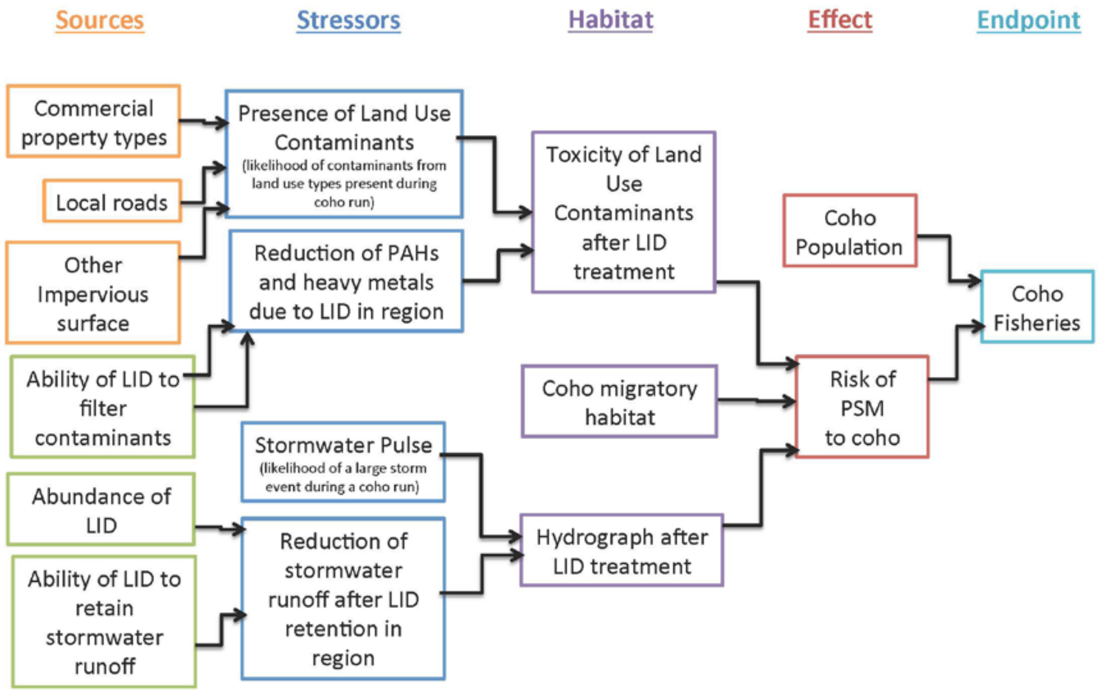

Figure 2. Conceptual model for the relative risk present to WRIA 10 and 12 coho salmon stocks. Causal pathways between sources, stressors and overlap with habitat to induce an effect to the endpoint are demonstrated here.

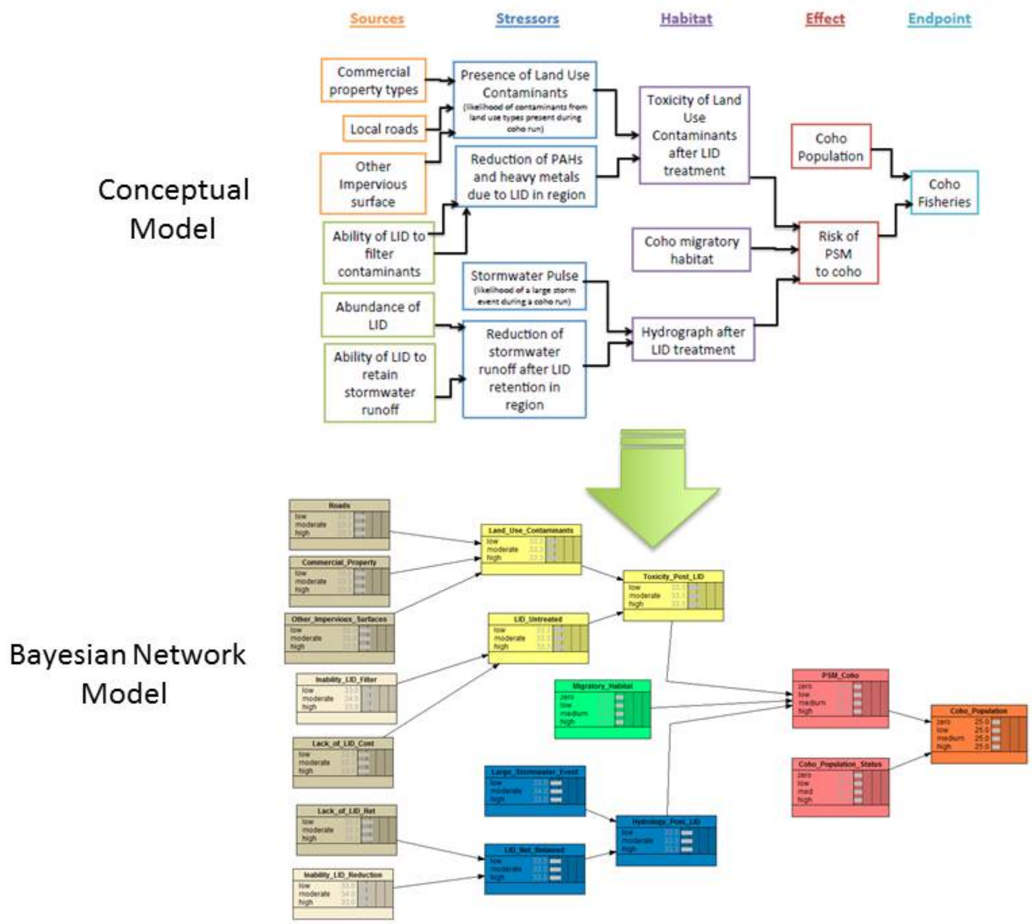

Figure 3. The structure of a conceptual model demonstrating causal relationships between stressors, habitat, and endpoints translates easily to the structure for a Bayesian network (BN) model. Coho populations with prespawn mortality as the effect contributing to a decline in coho are shown above. The BN does not have inputs yet; therefore distributions show equal probabilities for nature nodes. Decision nodes show only one possible state. Here decision nodes are set to where they most likely occurred for all regions.

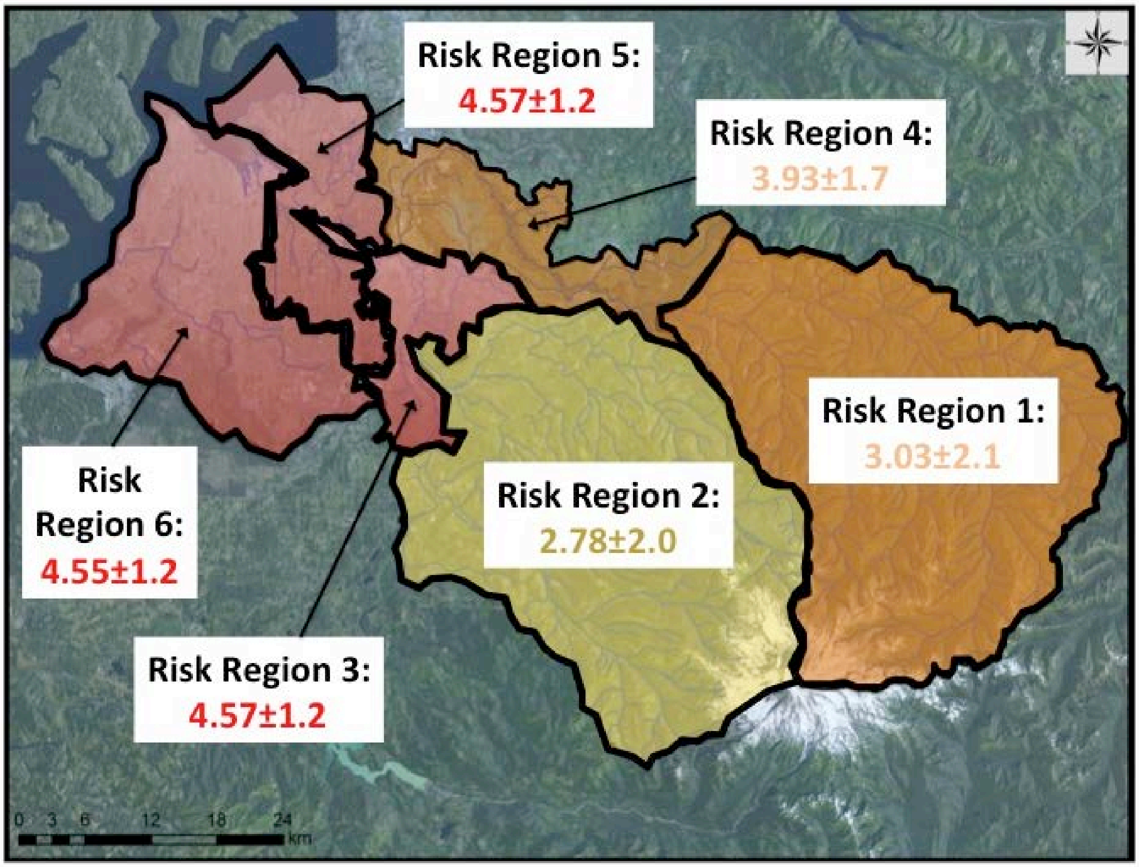

Figure 4. Map of study area relative risk regions with overall risk scores for coho populations. Top of watershed is split between risk regions 1 and 2, beginning at Mount Rainer. Overall risk of prespawn mortality generally increases down the watershed where land use is more developed in risk regions 3, 5, and 6.

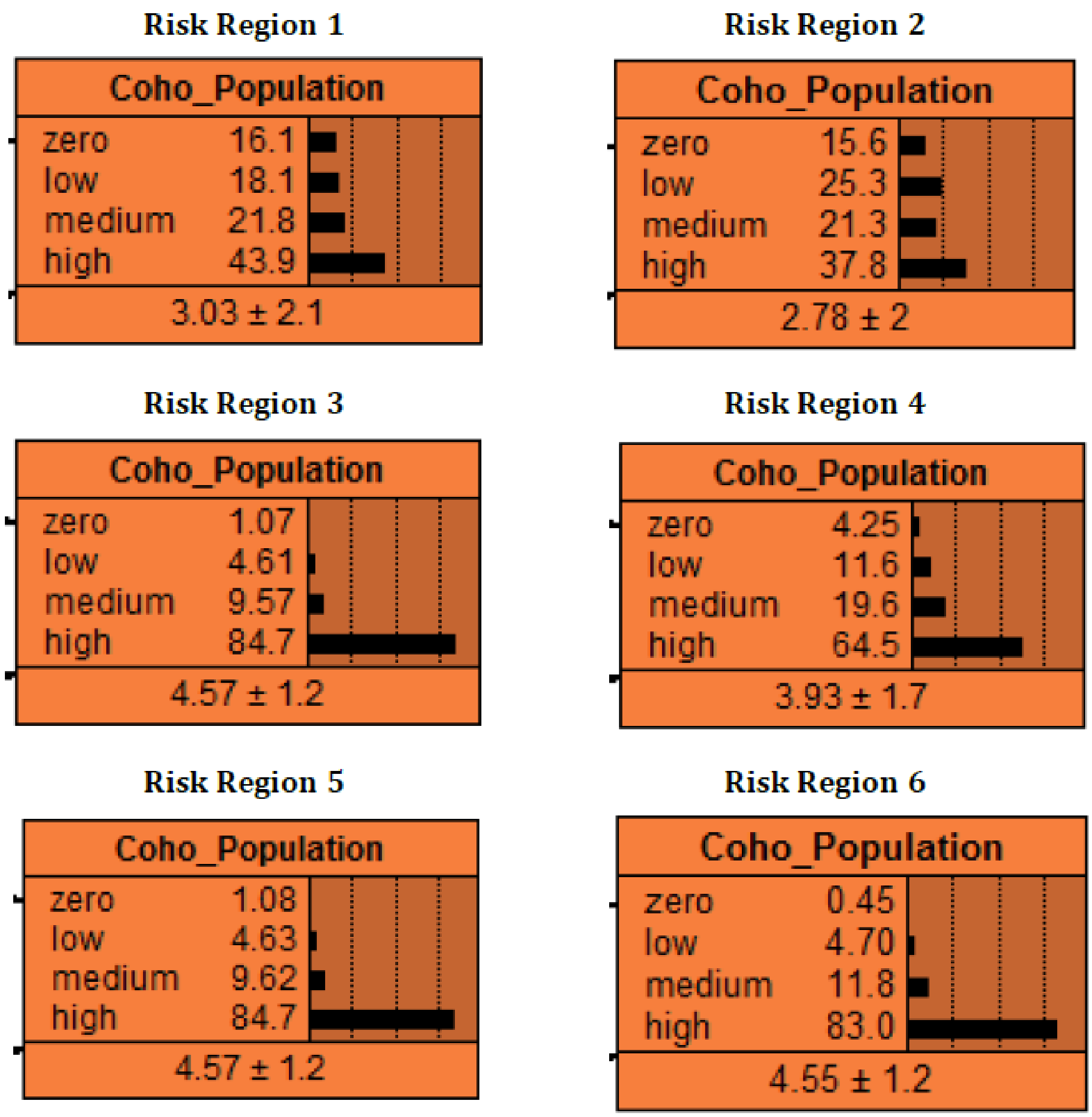

Figure 5. Graphical representations from Netica show the posterior distributions for overall risk by region. Only the last node for each region's BN-RRM is shown here, including the overall mean risk scores and standard deviations. These distributions give a better representation of the probability of risk rather than a risk score alone. In each case the distribution is skewed.

TABLES

Table 1. Each relative risk region was broken down by watersheds within Water Resource Inventory Areas (WRIAs) 10 and 12. Watersheds in Pierce County are identified below for each risk region. Risk regions 1, 4 and 5 had small areas of watersheds overlapping into King County.

Risk Region	**RR1**	**RR2**	**RR3**	**RR4**	**RR5**	**RR6**
Watersheds included	• Upper White River • Partial overlap of water-sheds in Pierce and King Counties	• South Prairie • Lower Carbon River • Upper Puyallup River • Upper Carbon River	• Mid-Puyallup River	• Mud mountain • Lower White River • Partial overlap of water-sheds in Pierce and King Counties	• Clear Clark's Creek • Hylebos • Partial overlap of water-sheds in Pierce and King Counties	• All of WRIA 12
Water Resource Inventory Area (WRIA)	WRIA 10	WRIA 10	WRIA 10	WRIA 10	WRIA 10	WRIA 12

Table 2. Summary explanation of model variables, definitions, rankings, and sources for the BN-RRM for the Puyallup River Watershed, examining LID as a management tool to reduce the risk of prespawner mortality in coho salmon.

Model Variable	Model Variable Definition	Variable States	Data Sources
Roads	Intensity of road lengths	Low: <1868 km Moderate: 1869-2267 km High: >2268 km (length of roads)	• Feist et al. 2011 (casual pathway) • Pierce County 2001-2013(ranks) • Puget Sound Regional Council 2010 (ranks)
Commercial Property	Intensity of commercial property land use	Low: 0-10% Moderate: 11-40% High: 41-100% (percent land cover)	• Feist et al. 2011 (casual pathway) • Booth et al. 2002 (ranks) • Department of Ecology Washington State 2013 (ranks)
Other Impervious Surfaces	Intensity of other impervious surface land use	Low: 0-10% Moderate: 11-40% High: 41-100% (percent land cover)	• Feist et al. 2011 (casual pathway) • Booth et al. 2002 (ranks) • Department of Ecology Washington State 2010 (ranks)
Inability LID Filter	The probability of LID failing to filter toxicants	Low: 80-100% Moderate: 50-79% High: 0-49% (percent toxicants reduced)	• The Use of BMPs in Urban Watersheds (Field et al. 2006)
Lack of LID Cont	The absence of LID capable of filtering contaminants	Low: 41-100% Moderate: 11-40% High: 0-10% (percent land cover)	• Booth et al. 2002 (ranks)
Lack of LID Ret	The absence of LID capable of retaining stormwater	Low: 41-100% Moderate: 11-40% High: 0-10% (percent land cover)	• Booth et al. 2002 (ranks)
Inability LID Reduction	The probability of LID failing to retain stormwater volume	Low: 80-100% Moderate: 50-79% High: 0-49% (percent stormwater volume reduced)	• The Use of BMPs in Urban Watersheds (Field et al. 2006)
Land Use Contaminants	The probability of the presence of contaminants due to land use that are likely to cause PSM	Low: 80-100% Moderate: 50-79% High: 0-49% (percent toxicants reduced)	• Feist et al. 2011 • Spromberg and Scholz 2011

LID Untreated	The probability of LID failing to filter toxicants due to the predicted effectiveness of LID to filter contaminants given the overall abundance within the region	Low: 80-100% Moderate: 50-79% High: 0-49% (percent toxicants reduced)	• The Use of BMPs in Urban Watersheds (Field et al. 2006)
Large Stormwater Event	The probability of a large storm event occurring that is large enough to cause PSM	Low: <0.10 in. Moderate: 0.10-0.99 in. High: >1.00 in. (inches of rainfall in a day)	• Spromberg and Scholz 2011 (causal pathway) • Western Regional Climate Center (rankings)
LID Not Retained	The probability of LID failing to retain stormwater due to the predicted effectiveness of LID to retain runoff given the overall abundance within the region	Low: 80-100% Moderate: 50-79% High: 0-49% (percent stormwater volume reduced)	• The Use of BMPs in Urban Watersheds (Field et al. 2006)
Toxicity Post LID	The probability of toxicants present due to land use after the filtration of LID, which are suspected to cause PSM	Low: 80-100% Moderate: 50-79% High: 0-49% (percent toxicants reduced)	• Spromberg and Scholz 2011 • Feist et al. 2011
Migratory Habitat	The intensity of migratory coho habitat and WDFW habitat category	Habitat in River Mile Lengths: Zero: <285018 (weight= 0) Low: 285019 – 369741 (weight= 2) Medium: 369742 – 479708 (weight= 4) High: 479709 – 642600 (weight= 6) Habitat by status: Low: Healthy/unknown (weight= 1) Moderate: Depressed (weight= 3) High: Critical (weight= 6)	• WDFW and Puyallup Tribe Fisheries • Washington Department of Fish and Wildlife 2013a • Washington Department of Fish and Wildlife 2013b
Hydrology Post LID	The probability of stormwater runoff present due to stormwater runoff after retention of LID, which is suspected to contribute to PSM	Low: 80-100% Moderate: 50-79% High: 0-49% (percent stormwater volume reduced)	• The Use of BMPs in Urban Watersheds (Field et al. 2006) • Spromberg and Scholz 2011

PSM Coho	The likelihood of PSM occurring due to the presence of contaminants, stormwater runoff, and the amount and quality of coho migratory habitat	Zero: 0-25% Low: 26-40% Medium: 41-50% High: 50-100% (percent population die-offs)	• Scholz et al. 2011 • Spromberg and Scholz 2011 • Feist et al. 2011
Coho Population Status	The frequency of returning coho spawning salmon	Zero: >3000 Low: 3000 - 1001 Medium: 1000 - 401 High: <400 (number of returning coho adults)	• WDFW and Puyallup Tribe Fisheries (up to 2011 returning year)
Coho Population	Predicted coho population after exposure to PSM	Zero: >3000 Low: 3000 - 1001 Medium: 1000 - 401 High: <400 (number of returning coho adults)	• WDFW and Puyallup Tribe Fisheries

Table 3. Summary of land use model input ranks and percent land cover for each risk region, including total risk region areas. Road length ranks were determined by natural breaks while commercial property types and other impervious surface ranks were determined by Booth et al. (2002) and Department of Ecology Washington State (2010).

Risk Region	Area (km^2)	Commercial Property (% of region)	Roads (length in km)	Other Impervious (% of region)
1	1035	Low (0%)	Low (650)	Low (4%)
2	1026	Low (0%)	Low (960)	Low (6%)
3	149	Low (5%)	Moderate (1557)	High (49%)
4	248	Low (6%)	Moderate (1488)	Moderate (32%)
5	221	Moderate (11%)	High (2503)	High (70%)
6	467	High (71%)	High (4052)	High (68%)

Table 4. List of categories from Department of Ecology Washington State (2013) used in GIS data as *commercial property*.

Land Use CD	Description
16	Hotels/motels
51	Wholesale trade
52	Retail trade - building materials, hardware, and farm equipment
53	Retail trade - general merchandise
54	Retail trade - food
55	Retail trade - automotive, marine craft, aircraft, and accessories
56	Retail trade - apparel and accessories
57	Retail trade - furniture, home furnishings, and equipment
58	Retail trade - eating and drinking
59	Other retail trade
61	Finance, insurance, and real estate services
62	Personal services
63	Business services
64	Repair services
65	Professional services
66	Contract construction services
67	Government services
68	Educational services
69	Miscellaneous services
72	Public assembly
73	Amusement

Table 5. Weights and rankings for Migratory Habitat input node. Each region's habitat was assessed based on the total river miles of habitat and the salmon habitat status based on Washington Department of Fish and Wildlife definitions.

	Salmon Habitat Length			Salmon Habitat Status			
Risk Region	Total River Miles (ft)	Rank	Weight	Ecology Category	Weight	Overall Weight	Habitat Rank Input
1	505099	High	6	all healthy	1	3.5	Medium
2	642600	High	6	all healthy	1	3.5	Medium
3	237218	Zero	0	all healthy	1	0.5	Low
4	335946	Low	2	all healthy	1	1.5	Low
5	268042	Zero	0	all healthy	1	1	Low
6	403536	Medium	4	153965 depressed (38%); 227969 healthy (56%); 19238 unknown (5%)	1.33 depressed; 1.12 healthy; 0.15 unknown*	2.6	Medium

**Risk region 6 contained three categories of habitat. These weights represent the additive weights for each category

Table 6. Summary table for coho salmon spawner returns from Washington Department of Fish and Wildlife (WDFW) data.

Risk Ranks	Definitions	Risk Region 1		Risk Region 2		Risk Region 3		Risk Region 4		Risk Region 5		Risk Region 6	
		Occurr-ences	Relative Frequency (%)	Occurr-ences	Relative Frequency (%)	Occurr-ences	Relative Frequency (%)	Occurr-ences	Relative Frequency (%)	Occurr-ences	Relative Frequency (%)	Occurr-ences	Relative Frequency (%)
zero	>9000	6	22.2	4	6.7	0	0	1	3.2	0	0	1	5.9
low	9000 - 1001	3	11.1	8	13.3	0	0	4	12.9	0	0	6	35.3
medium	1000 - 401	3	11.1	8	13.3	1	1.9	7	22.6	1	2.9	6	35.3
high	<400	15	55.6	40	66.7	53	98.1	19	61.3	34	97.1	4	23.5

Table 7. Summary of risk region node scores. Scores are given for each node, with standard deviations given. The overall risk score for each region given in the bottom row for *Coho_Population*.

Node	Risk Region Node Scores					
	1	2	3	4	5	6
Roads*	0±0	0±0	3±0	3±0	6±0	6±0
Commercial_Property*	0±0	0±0	0±0	0±0	3±0	6±0
Other_Impervious_Surface*	0±0	0±0	6±0	3±0	6±0	6±0
Inability_LID_Filter	1.35±2.0	1.35±2.0	1.35±2.0	1.35±2.0	1.35±2.0	1.35±2.0
Lack_of_LID_Cont*	6±0	6±0	6±0	6±0	6±0	6±0
Lack_of_LID_Retention*	6±0	6±0	6±0	6±0	6±0	6±0
Inability_LID_Retention	1.35±2.0	1.35±2.0	1.35±2.0	1.35±2.0	1.35±2.0	1.35±2.0
Land_Use_Contamination*	0±0	0±0	6±0	3±0	6±0	6±0
LID_Untreated	5.73±0.86	5.73±0.86	5.73±0.86	5.73±0.86	5.73±0.86	5.73±0.86
Large_Stormwater_Event	5.25±1.6	5.25±1.6	5.25±1.6	5.25±1.6	5.25±1.6	5.25±1.6
LID_Not_Retained	5.73±0.86	5.73±0.86	5.73±0.86	5.73±0.86	5.73±0.86	5.73±0.86
Toxicity_Post_LID	0.846±1.6	0.846±1.6	5.8±0.75	3.55±1.2	5.8±0.75	5.8±0.75
Migratory_Habitat*	4.0±0	4.0±0	2.0±0	2.0±0	2.0±0	4.0±0
Hydrology_Post_LID	5.21±1.6	5.21±1.6	5.21±1.6	5.21±1.6	5.21±1.6	5.21±1.6
PSM_Coho	3.23±1.5	3.23±1.5	4.81±1.3	3.81±1.2	4.81±1.3	5.45±0.92
Coho_Population_Status	4.0±2.5	3.25±1.4	5.96±0.27	4.84±1.7	5.94±0.34	3.53±1.8
Coho_Population**	3.03±2.1	2.78±2.0	4.57±1.2	3.93±1.7	4.57±1.2	4.55±1.2

* Decision nodes (all unmarked are nature nodes).
** Overall risk scores.

Table 8. Summary table of distributions for each node by risk region.

Node	Rank	Risk Region 1	2	3	4	5	6
Roads*	low	100	100	0	0	0	0
	moderate	0	0	100	100	0	0
	high	0	0	0	0	100	100
Commercial_Property*	low	100	100	100	100	0	0
	moderate	0	0	0	0	100	0
	high	0	0	0	0	0	100
Other_Impervious_Surface*	low	100	100	0	0	0	0
	moderate	0	0	0	100	0	0
	high	0	0	100	0	100	100
Inability_LID_Filter	low	65.0	65.0	65.0	65.0	65.0	65.0
	moderate	25.0	25.0	25.0	25.0	25.0	25.0
	high	10.0	10.0	10.0	10.0	10.0	10.0
Lack_of_LID_Cont*	low	0	0	0	0	0	0
	moderate	0	0	0	0	0	0
	high	100	100	100	100	100	100
Lack_of_LID_Retention*	low	0	0	0	0	0	0
	moderate	0	0	0	0	0	0
	high	100	100	100	100	100	100
Inability_LID_Retention	low	65.0	65.0	65.0	65.0	65.0	65.0
	moderate	25.0	25.0	25.0	25.0	25.0	25.0
	high	10.0	10.0	10.0	10.0	10.0	10.0
Land_Use_Contamination*	low	100.0	100.0	0	0.0	0	0
	moderate	0.0	0.0	0	100.0	0	0
	high	0.0	0.0	100	0.0	100	100
LID_Untreated	low	0.0	0.0	0.0	0.0	0.0	0.0
	moderate	9.0	9.0	9.0	9.0	9.0	9.0
	high	91.0	91.0	91.0	91.0	91.0	91.0
Large_Stormwater_Event	low	5.0	5.0	5.0	5.0	5.0	5.0
	moderate	15.0	15.0	15.0	15.0	15.0	15.0
	high	80.0	80.0	80.0	80.0	80.0	80.0
LID_Not_Retained	low	0.0	0.0	0.0	0.0	0.0	0.0
	moderate	9.0	9.0	9.0	9.0	9.0	9.0
	high	91.0	91.0	91.0	91.0	91.0	91.0
Toxicity_Post_LID	low	76.3	76.3	0	0	0	0
	moderate	19.1	19.1	6.7	81.8	6.7	6.7
	high	4.6	4.6	93.3	18.2	93.3	93.3

Migratory_Habitat*	zero	0.0	0.0	0.0	0.0	0.0	0.0
	low	0.0	0.0	100.0	100.0	100.0	0.0
	medium	100.0	100.0	0.0	0.0	0.0	100.0
	high	0.0	0.0	0.0	0.0	0.0	0.0
Hydrology_Post_LID	low	4.95	4.95	4.95	4.95	4.95	4.95
	moderate	16.50	16.50	16.50	16.50	16.50	16.50
	high	78.60	78.60	78.60	78.60	78.60	78.60
PSM_Coho	zero	0	0	0	0	0	0
	low	54.1	54.2	10.5	22.6	10.5	0.56
	medium	30.4	30.3	38.7	64.3	38.7	26.3
	high	15.5	15.5	50.8	13.1	50.8	73.2
Coho_Population_Status	zero	22.2	0	0	3.2	0	5.9
	low	11.1	50	0	12.9	0	35.3
	medium	11.1	37.5	1.9	22.6	2.9	35.3
	high	55.6	12.5	98.1	61.3	97.1	23.5
Coho_Population	zero	16.1	15.6	1.07	4.25	1.08	0.45
	low	18.1	25.3	4.61	11.6	4.63	4.7
	medium	21.8	21.3	9.57	19.6	9.62	11.8
	high	43.9	37.8	84.7	64.5	84.7	83

*Decision nodes do not have a distribution and are set to only one rank per node.

Table 9. Summary table of input parameters with largest contribution to overall risk scores from sensitivity analysis. Note that decision nodes (such as inputs for land use and abundance of low impact development (LID)) were not included in this analysis as Netica software only includes Bayes nets currently in the sensitivity analysis.

	Parameter	Percent contribution
Risk Region 1	1.) PSM_Coho	37.70%
	2.) Coho_Population_Status	15.80%
	3.) Toxicity_Post_LID	13.70%
Risk Region 2	1.) PSM_Coho	51.20%
	2.) Toxicity_Post_LID	18.40%
	3.) Coho_Population_Status	6.38%
Risk Region 3	1.) PSM_Coho	35.80%
	2.) Toxicity_Post_LID	1.47%
	3.) LID_Untreated	1.07%
Risk Region 4	1.) PSM_Coho	32.50%
	2.) Coho_Population_Status	5.58%
	3.) Toxicity_Post_LID	2.18%
Risk Region 5	1.) PSM_Coho	35.80%
	2.) Toxicity_Post_LID	1.47%
	3.) LID_Untreated	1.08%
Risk Region 6	1.) PSM_Coho	10.60%
	2.) Coho_Population_Status	6.83%
	3.) Hydrology_Post_LID	0.66%

Table 10. Summary of entropy scores and percent entropy reduction for each risk region and Bayes nets. No entropy data available for decision nodes.

	Risk Region 1		Risk Region 2		Risk Region 3		Risk Region 4		Risk Region 5		Risk Region 6	
Input Parameter	Entropy	Percent Entropy Reduction	Entropy	Percent Entropy Reduction	Entropy	Percent Entropy Reduction	Entropy	Percent Entropy Reduction	Entropy	Percent Entropy Reduction	Entropy	Percent Entropy Reduction
PSM_Coho	5.29E-02	10.4	6.27E-02	11.8	0.02567	17.1	0.02902	8.6	0.02571	17	0.0088	5.4
Coho_Population_Status	1.60E-02	3.16	6.00E-03	1.13	0.0001109	0.0737	0.005796	1.72	0.0001676	0.111	0.007985	4.9
Toxicity_Post_LID	2.21E-02	4.37	2.79E-02	5.26	0.0016	1.06	0.004569	1.35	0.001604	1.06	0.0005857	0.359
Hydrology_Post_LID	3.12E-04	6.15E-02	3.01E-04	5.67E-02	2.59E-04	1.72E-01	1.53E-04	4.53E-02	2.60E-04	1.72E-01	5.29E-04	3.24E-01
Large_Stormwater_Event	2.99E-04	-6.00E-02	2.90E-04	5.47E-02	2.33E-04	1.55E-01	1.37E-04	4.06E-02	2.34E-04	1.54E-01	4.99E-04	3.06E-01
LID_Untreated	1.57E-04	-3.00E-02	1.82E-04	3.42E-02	1.22E-03	8.14E-01	8.46E-06	2.50E-02	1.23E-03	8.12E-01	4.39E-04	2.69E-01
Inability_LID_Filter	1.91E-06	3.77E-04	2.26E-06	4.26E-04	1.50E-05	9.80E-03	9.69E-07	2.87E-04	1.51E-05	9.77E-03	5.13E-06	3.14E-03
LID_Not_Retained	1.67E-06	3.71E-04	1.23E-06	2.32E-04	3.99E-06	2.65E-03	2.48E-06	7.35E-04	4.01E-06	2.65E-03	4.10E-06	2.51E-03
Inability_LID_Reduction	1.85E-08	3.65E-06	1.36E-08	2.57E-06	4.39E-08	2.92E-05	2.75E-08	8.13E-06	4.41E-08	2.92E-05	4.53E-08	2.78E-05

Table 11. Summary of overall risk scores per region given varying relative amounts of overall LID during large storm events to reduce the risk of PSM.

	Risk Management Scenarios for alternative amounts of LID		
Risk Region	**Current conditions (high)**	**Moderate**	**Low**
1	3.03±2.1	2.75±2.1	2.56±2.0
2	2.78±2.0	2.46±2.0	2.24±1.9
3	4.57±1.2	4.1±1.6	3.57±1.8
4	3.93±1.7	3.66±1.8	3.08±1.9
5	4.57±1.2	4.09±1.6	3.56±1.8
6	4.55±1.2	4.03±1.7	3.1±2.0

REFERENCES

Applied Climate Information Systems. 2013. NOWData – NOAA Online Weather Data. [2013 March 8]. http://nowdata.rcc-acis.org/SEW/pubACIS_results.

Ayre KK, Landis WG. 2012. A Bayesian approach to landscape ecological risk assessment applied to the Upper Grande Ronde watershed, Oregon. Hum Ecol Risk Assess 18(5):946-970.

Booth DB, Jackson R. 1997. Urbanization of aquatic systems: degradation thresholds, stormwater detection, and the limits of mitigation. J Am Water Resour Assoc 33:1077–1090.

Colnar AM, Landis WG. 2007. Conceptual model development for invasive species and regional risk assessment case study: the European green crab, *Carcinus maenas*, at Cherry Point, Washington, USA. Hum Ecol Risk Assess 13(1):120-155.

Diblasi CJ, LI H, Davis AP, Ghosh U. 2009. Removal and fate of polycyclic aromatic hydrocarbon pollutants in an urban stormwater bioretention facility. Envriron Sci Technol 43:494-502.

Dietz ME. 2007. Low impact development practices: a review of current research and recommendation for future directions. Water Air Soil Poll 186:351-363.

Department of Ecology Washington State. 1995. Puyallup-White watershed initial assessment. Science Applications International Corporation, Shapiro and Associates, Taylor Associates/ Environmental Sys terns Research Institute WR-95-1 56.

Department of Ecology Washington State. 2010. Western Washington Impervious Surfaces Metadata. [2013 March 8].

http://www.ecy.wa.gov/services/gis/data/landcover/metadata.asp?name=impervious2006.

Department of Ecology Washington State. 2013. GIS Land Use: Washington State 2010. [2013 March 8]. http://www.ecy.wa.gov/services/gis/data/data.htm.

Feist BE, Buhle ER, Arnold P, Davis JW, and Scholz NL. 2011. Landscape ecotoxicology of coho salmon spawner mortality in urban streams. PLoS ONE. V. 6(8) e23424.

Finnemore EJ, Lynard WG. 1982. Management and control technology for urban stormwater pollution. Res J Water Pollut C 54(7):1099-1111.

Hart BT, Pollino CA. 2008. Increased use of Bayesian network models will improve ecological risk assessments. Hum Ecol Risk Assess 14:851-853.

Hart Hayes E, Landis WG. 2004. Regional risk assessment of a near shore marine environment: Cherry Point, WA. Hum Ecol Risk Assess 10(2):299-325.

Landis WG, Wiegers JK. 1997. Design considerations and a suggested approach for regional and comparative ecological risk assessment. Hum Ecol Risk Assess 3:287-297.

Landis WG, Wiegers JK. 2005. Introduction to the regional risk assessment model using the relative risk model. *In* Landis W (editor), Regional Scale Ecological Risk Assessment Using the Relative Risk Model. CRC press, Boca Raton, FL, USA. Pp. 11-36.

Landis WG, Wiegers JK. 2007. Ten years of the relative risk model and regional scale ecological risk assessment. Hum Ecol Risk Assess 13(1):25-38.

Marcot BG, Steventon JD, Sutherland GD, McCann RK. 2006. Guidelines for developing and updating Bayesian belief networks applied to ecological modeling and conservation. Can J For Res 36:3075-3086.

McCarthy SG, Incardona JP, Scholz NL. 2008. Coastal storms, toxic runoff, and sustainable conservation of fish and fisheries. American Fisheries Society Symposium. 64:000-000: 1-21.

Netica. Norsys Software Corp., Vancouver, B.C., Canada.

NOAA's National Marine Fisheries Service. 2010. Puget Sound/Georgia Strait coho ESU species of concern. [2012 February 15]. http://www.nwr.noaa.gov/ESA-Salmon-Listings/Salmon-Populations/Coho/COPUG.cfm.

Nyberg JB, Marcot BG, Sulyma R. 2006. Using Bayesian belief networks in adaptive management. Can J For Res 36:3104-3116.

Pierce County. 2003. Chinook salmon distribution. Pierce County, Washington. Department Planning and Land Services. [2013 April 15]. http://yakima.co.pierce.wa.us/MapGallery/documents/chindoc.pdf.

Pierce County 2011. Pierce County Map Gallery. [2012 January 24]. http://yakima.co.pierce.wa.us/MapGallery/index.cfm.

Pierce County Washington 2001-2013. GIS Data Express. Roads Data [2013 March 8]. http://yakima.co.pierce.wa.us/geodataexpress/main.html.

Pollino CA, Woodberry OW, Nicholson A, Korb K, Hart BT. 2006. Parameterisation and evaluation of a Bayesian network for use in an ecological risk assessment. Environ Modell Softw 1-13.

Puget Sound Partnership. 2011. Puget Sound Ecosystem Recovery Targets. . [2012 April 5]. http://www.psp.wa.gov/downloads/AA2011/2011_Targets_11_03_11.pdf.

Puget Sound Partnership. 2010. Open standards for the practice of conservation in Puget Sound. [2013 April 15]. http://www.psp.wa.gov/pm_openstandards.php.

Puget Sound Regional Council. 2010. GIS Shapefiles. Census Tract – King County and Census Tract – Pierce County. [2013 March 8] http://www.psrc.org/data/gis/shapefiles.

Scholz NL, Myers MS, McCarthy SG, Labenia JS, McIntyre JK, Ylitalo GM, Laetz CA, Stehr CM, French BL, McMillan B, Wilson D, Lynch KD, Davis JW, Collier TK. 2011. Recurrent die-offs of adult coho salmon returning to spawn in Puget Sound lowland urban streams. PloS ONe. 6(12) e28013

Slonecker ET, Tilley JS. 2004. An evaluation of the individual components and accuracies associated with the determination of impervious area. GIScience and Remote Sensing 2:165-184.

Spromberg JA, Schlolz NL. 2011. Estimating the future decline of wild coho salmon populations resulting from early spawner die-offs in urbanizing watersheds of the Pacific Northwest, USA. Integrated Environ Assess Manag 7(4):648-656.

Stewardship Partnership. 2011. Rain gardens in Puget Sound. [2013 March 8]. https://maps.google.com/maps/ms?hl=en&ie=UTF8&msa=0&msid=111929249298421516685.00047cd62337040441a8b&z=9.

Suter GW. 2008. Ecological risk assessment in the United States Environmental Protection Agency: a historical overview. Integrated Environ Assess Manag 4(3):285-289.

Taylor AC, Fletcher TD. 2007. Nonstructural urban stormwater quality measures: building a knowledge base to improve their use. Environ Mange 39:633-677.

Uusitalo L. 2007 Advantages and challenges of Bayesian networks in environmental modelling. Ecol Model 203:313-318.

Wild Fish Conservancy. 2008. Coho Prespawning mortality assessment in Washington and Oregon. EPA Assistance ID:X5-96007101-0.

Washington Department of Fish and Wildlife. 2011. Puyallup Coho Details. [2013 March 8]. https://fortress.wa.gov/dfw/score/score/species/population_details.jsp?stockId=3160.

Washington Department of Fish and Wildlife. 2012a. Spawning ground surveys WRIA 10 1938 to 2012 Coho. Spawning Ground Survey Database. [2013 February 15]. http://wdfw.wa.gov/conservation/fisheries/sgs/.

Washington Department of Fish and Wildlife. 2012b. Spawning ground surveys WRIA 12 1962 to 2012 Coho. Spawning Ground Survey Database. [2013 February 15]. http://wdfw.wa.gov/conservation/fisheries/sgs/.

Washington Department of Fish and Wildlife. 2013a. Fisheries management – salmonid stock inventory (SaSI). [8 March 2013] http://wdfw.wa.gov/conservation/fisheries/sasi/.

Washington Department of Fish and Wildlife. 2013b. Salmon Scape. [2013 March 8]. http://wdfw.wa.gov/mapping/salmonscape/.