A Geodesign Inspired Multiple Criteria Decision Tool for Prioritizing Levee Setback Project Sites

Jesse Reynolds

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Donald H Miller

Timothy Nyerges

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Abstract

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Jesse Reynolds

Chair of the Supervisory Committee:
Prof. Donald H Miller
Urban Design and Planning

This initial planning level tool addresses the complexity of land use decisions within the Lower Green River, WA floodplain by enabling the consideration of multiple views of a wide range of stakeholders. The tool is a four step model process created using ESRI ArcInfo and ArcGIS Model Builder to summarize the existing conditions in the lands adjacent to levees, standardize the values of eleven chosen criteria, and create an interface where stakeholders can weigh the criteria according to importance. The eleven criteria cover the subjects of cost, hazard mitigation, ecological considerations, and built capital. The individual models are referred to as the Representation Model and Process Model, Spatial Screening Model, Alternatives Criteria Model, and Decision Support Model. The models are run at a parcel level in order to create results that transfer to real world decisions in regards to land purchase and land use change. The resulting output is a prioritization list and associated mapping products ranking parcels on a range from favorable to non-favorable.

The Decision Model was run to show results when weighting all criteria evenly, each criterion by itself in a sensitivity analysis, and with values derived from a hypothetical stakeholder outreach exercise where subject professionals were asked to role-play six hypothetical characters. The results from the different model runs were fairly similar, with the exception of a few criteria outputs in the sensitivity analysis. The parcels downstream of river mile seven (7) were almost exclusively considered least suitable, the parcels in the middle section between river miles seven (7) and fourteen (14) were varied, and the parcels above river mile fourteen (14) were considered most suitable.

Emphasis is made on the tool process and methods more than the individual criteria and results. The goal of this thesis is not to tell a municipality where projects should occur, but to implement a process where stakeholder views can be transferred to weighting multiple criteria, with resulting location prioritization. This is the advantage of using GIS as a decision support tool, versus just a medium for a suitability analysis.

The process and methods of this tool can be applied to many planning and environmental management disciplines beyond floodplain management. Examples are transportation corridor planning, low income housing development, brownfield redevelopment prioritization, and transmission line right-of-way planning. Any planning problem with the questions of what and where could benefit from this tool, as long as there is spatial data available.

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1.0 - Introduction

"Civilization has been a permanent dialogue between human beings and water"[1] -Paolo Lugari

Many associate water issues with a lack thereof. In the case of floodplain management, and the scope of this thesis, the case of too much water is considered.

Throughout the past few centuries an interventionist approach has been taken to flooding, led by engineers who apply scientific modeling and skilled construction. One of the first examples of this approach is the drainage of the English Fens by Dutch engineers in the 17th Century.[2] Engineering feats of this scale initially proved to be successful. But after the realization that no engineered solution is fail-safe, and often requires ongoing maintenance, engineers have recently changed focus. This is now coupled with the belief that climate change exposes the limitations of what has traditionally been a technocratic approach to flood infrastructure. The need to work with nature instead of supposedly conquering it is becoming mainstream in the world of floodplain management. We are recognizing the necessity to live

[1] Weisman, Alan, *Gaviotas:* A Village to Reinvent the World (White River Junction, Vermont: Chelsea Green, 2009), 64.
[2] White, Iain, *Water and the City:* Risk, Resilience and Planning for a Sustainable Future (New York: Routledge, 2010), 42-45.

with rivers and the risks they inherently have. The 'Room for the River' guidance released in the Netherlands in 2006 does just this.[3]

The importance of spatial planning within floodplain management has been realized. The function and management of land links directly to risk and resilience agendas.[4] This understanding deepens with each 'natural' disaster that exposes the vulnerabilities of the built environment to the natural world. Land use regulation can be seen as the most effective tool to ward off flood risk and its increasing uncertainty. Secondary benefits to this are increased ecological health, and a better connection to natural systems for all society.

Conflict management in water resources has several unique problem features.[5] Problems of this type often have multidisciplinary complexities involving social, and economic impacts; as well as hydrologic and hydraulic analysis. These disciplines are interdependent, change over time and space, and carry with them levels of uncertainty. Often a challenge is to deal with simultaneously using qualitative and mathematical data; requiring engineers, environmental scientists and economists to work together. A multiple criteria approach is needed for a problem with multiple facets.

Bringing focus to the Puget Sound area of Washington State, floodplain management is often involved with issues of conflicting land uses and maintaining or restoring salmon habitat.[6] Historically projects have either been driven by one or the other. But in recent years the nature

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[3] "Spatial Planning Key Decision 'Room for the River': Investing in the safety and vitality of the Dutch river basin region," Ministry of Transport, Public Works and Water Management (V&W), Netherlands Government, September 2006, http://www.hollandexploringtours.nl/pdf/spacefortheriver.pdf.
[4] See note 1.
[5] Ximing Cai, Leon Lasdon, and Ari M. Michelsen. 2004. "Group Decision Making in Water Resources Planning Using Multiple Objective Analysis". Journal of Water Resources Planning & Management. 130 (1).
[6] See Figure 1.1.

of river restoration and flood mitigation projects has changed from single driver projects, to projects addressing multiple goals. This approach which benefits multiple stakeholders instead of just one has gained in popularity and is evident in changing funding mechanisms. A recent example of this is The Nature Conservancy Coordinated Investment, where $50 million was dedicated to nine multiple benefit projects in the Greater Puget Sound area.[7] These projects are seen as the future of river restoration as it is played out in our region, addressing increased complexity, intensified land use, and increased climate uncertainty.

One important fact to address is that not all proposed multi-benefit projects are equal in regards to potential successes, stakeholder sentiments, and cost. For this reason it is important to properly triage what river segments see attention when, and to what degree. If not, projects come to fruition through political means solely, not through an impartial benefit weighting process.[8] This thesis sets out to define a spatially enabled multi-criteria analysis method for the purpose of defining a repeatable process involving stakeholder participation that defines and ranks locations for multi-benefit river restoration projects, specifically levee setbacks.

The goal of this thesis is to provide a GIS-based multi-criteria decision analysis tool inspired by Carl Steinitz's geodesign framework.[9] The tool will be applied to triaging restoration areas specifically in the Lower Green River in the Puget Sound Basin of Washington State,[10] but the processes used can be applied to any watershed or sub-watershed in the Puget Sound.

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[7] Kris Knight, Julie Morse, The Nature Conservancy, interview at The Nature Conservancy Mt. Vernon Office, November 21, 2013.
[8] Ibid.
[9] Steinitz, Carl, "A Framework for Geodesign," ESRI Press, Redlands CA, 2012, Pg. 26.
[10] See Figure 1.2

Figure 1.1 - Conceptual Model

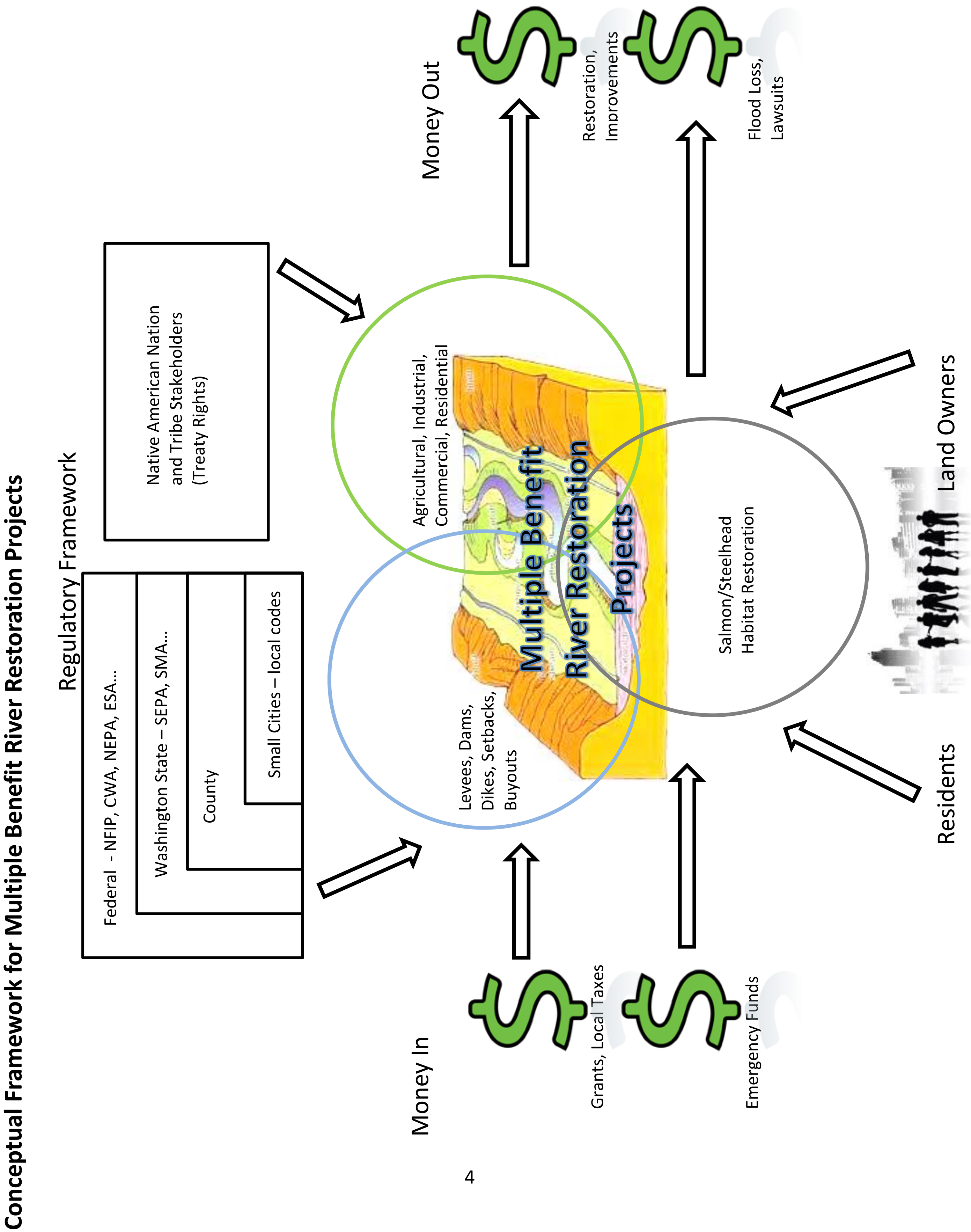
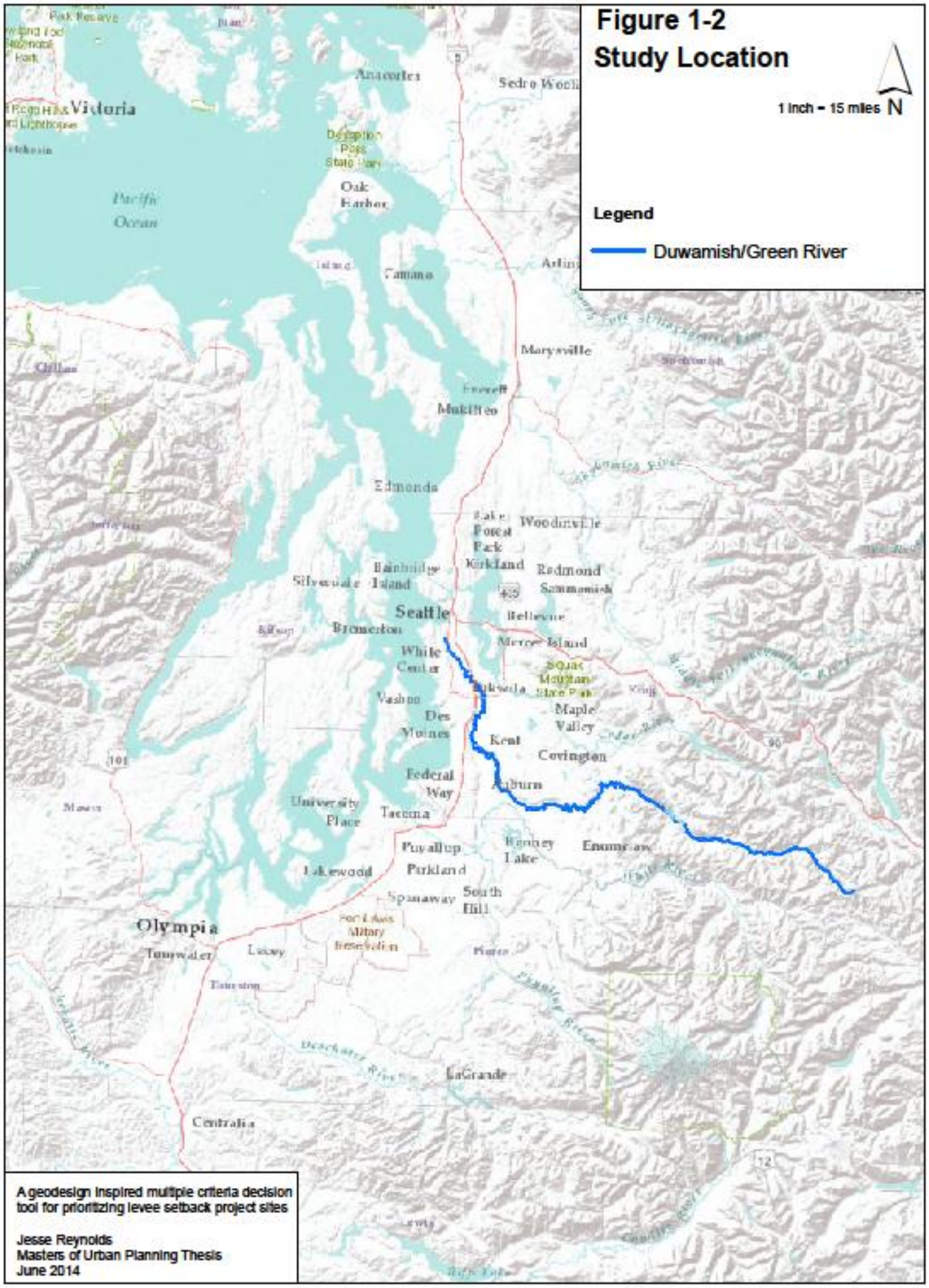


Figure 1.2 - Study Location



2.0 - Methodological and Substantive Foundations

This purpose of this chapter is to help frame the foundations used in this thesis. The title Methodological and Substantive Foundations was chosen to encompass the major components of this chapter. The components are Multi-criteria decision analysis (MCDA), Geographic Information Systems (GIS)-Based MCDA, the geodesign framework, and levee setbacks. The first three components are seen as the methodological foundations. The final, levee setbacks, is the substantive foundation. The substantive foundation is the subject to which the methodological foundations are applied.

In the combined world of river restoration and floodplain management there are multiple goals with multiple stakeholders. Most agree flood hazards and loss of land are bad, and water quality and river ecosystem health are good. But how can steps be made to address all the concerns found within a watershed? MCDA is seen as an excellent tool to address multi-faceted problems such as this. More specifically, GIS-Based MCDA will be examined because it is spatially enabled, and so is useful in solving spatial issues dealing with land use such as the problems of floodplain management. Different evaluation methods of MCDA will be covered, focusing on how it applies specifically to floodplain management and river restoration. We then use the geodesign framework as an inspiration to the methodology used. Applications of GIS-based MCDA in floodplain management are introduced. Finally, the concept of levee setbacks are introduced as the multi-benefit river restoration projects being examined. Reasons why they are significant and how they can benefit rivers and hazards are introduced

The goal of this section is to help frame how making choices of restoration areas via levee setbacks can be answered by using GIS-Based MCDA within the geodesign framework, and why specific techniques are used.

2.1 - Introduction and background to MCDA

MCDA can be defined as “a collection of formal approaches which seek to take explicit account of key factors in helping individuals or groups explore decisions that matter.”[11] It is an excellent tool for assessing courses of action for projects and plans that have multiple goals and objectives.[12] It has the ability to assess inputs and outputs of alternatives that are valued in ways other than by money or market value, unlike cost-benefit analysis.

MCDA is seen as more than just rating alternatives to a problem quantitatively. The value in MCDA is it allows the decision making process to be transparent, something seen as priceless in the world of multiple stakeholders and public interest. It provides a basis for deliberation among stakeholders, helping them understand and accept the evaluation, and support the decision.[13] The transparency that this provides to the decision making process is crucial because it involves applying subjective weights of importance to objective measurements for the purpose of understanding their implications.[14] It is better to refer to MCDA as decision analysis or aiding, rather than decision making. The latter is the role of the managers, stakeholders, and public.

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[11] Belton, V. and Stewart, T. (2002). Multiple criteria decision analysis: an integrated approach. Boston, MA: Kluwer Academic Publishers.
[12] Miller, Donald, “An Introduction to Multicriteria Methods of Evaluation,” Working Paper (Seattle: U.W., 2004)
[13] Ibid.
[14] See note 1.

2.1.1 - MCDA basic steps

There are many ways to conduct an MCDA, but there are basic steps that remain constant regardless of the method chosen, or the nature of the problem question. It starts with asking what the goals and objectives are for that the decision is intended to meet.[15] A list of decision options are made, as well as the decision criteria that will be used to rank the options. The performance of each of the criteria data is given a numerical value of expected performance. These numerical values need to be comparable, often requiring a recalculation step. For example acres, minutes, days and dollars need to become comparable and thus standardized. In the case of impacts these criteria can be assigned a negative value. Differences in importance of criteria need to be accounted for by weighting the criteria accordingly, unless all criteria have equal importance. This is often the most crucial step for stakeholder involvement. The influence of weights on alternative rankings can be tested in a sensitivity analysis. These scores are summarized for each alternative by multiplying the effectiveness score for every criterion by its assigned weight, then they are added together to find a total. Alternatives can then be ranked in order of performance to each other, and scaled to show their relative performance to the other options. Results are then displayed to stakeholders, identifying why some alternatives are stronger than others. The results can be final, or they can be used to design new alternatives. If one alternative is better in regards to one criterion, and another alternative is better with another criterion, the strong points of each can be combined for an even better alternative.

[15] See note 2.

2.1.2 - Schools of thought in brief

The use of MCDA started during World War II as an alternative to linear programming, but flourished in the 1960s and 1970s in both Europe and the United States through different philosophies.[16] The American school focused on precise knowledge and judgment, where the European school accepted imprecision and considered optimal decision making not favorable, considering MCDA more fuzzy than precise. The reason the Europeans did not favor optimal decision making is because they believed they did not have a precise idea of the relative importance of each criterion.

2.1.3 - Strengths, weaknesses, and considerations for MCDA

The greatest strength of MCDA is its ability to compare qualitative and quantitative data simultaneously, as long as the qualitative data can be measured in an ordinal or continuous scale. Another strength is when applied to complex economic issues such as ecosystem goods and services this method can overcome biases towards things such as jobs and exports by using non-monetary units, or completely avoiding converting criteria from original values.[17]

The types of problems common to all MCDA scenarios involve the act of making a choice, or making a preference order of alternatives.[18] These involve deciding how to rank (preference order of alternatives), sort (separating alternatives into classes or groups),

[16] Roy, B. (1996). Multicriteria methodology for decision aiding. Dordrecht: Kluwer Academic Publishers.
[17] Herath, G. and Prato, T. (eds) (2006). Role of multi-criteria decision making in natural resource management. In: Using multi-criteria decision analysis in natural resource management. Aldershot, UK: Ashgate, pp. 1–10.
[18] Greene, R., Devillers, R., Luther, J. E. and Eddy, B. G. (2011), GIS-Based Multiple-Criteria Decision Analysis. Geography Compass, 5: 412–432.

description (learning about the problem), design (developing new alternatives for possibly addressing the problem) and portfolio (selecting a subset of alternatives).

Other considerations affecting choice and implementation of MCDA include: the number of decision makers, decision phasing, number of objectives, number of alternatives, existence of constraints, and risk tolerance. The number of decision makers affects how to implement MCDA. Techniques can be designed for group decisions encouraging consensus through collaborative decision making.[19] Otherwise approaches must be extended through aggregated weighting or voting. Group dynamics plays a large role in the success or failure of using MCDA in reaching a final decision. The decision phase can be completed in many ways in order to organize group decision making. Optimal times to implement a decision making process can be between the problem exploration and structuring phase, or the evaluation and recommendation phase of a project.[20]

The number of objectives within a problem can determine what kind of MCDA to use. With single objectives, like increasing Chinook salmon habitat, decision makers can focus on criteria with measurable attributes. The best MCDA methods to use in these problems are multiple-criteria evaluation (MCE), or multiple-attribute decision making (MADM).[21] Multiple-objective decision making (MODM) is necessary to decide if objectives are congruent to each

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[19] Malczewski, J. (2006). GIS-based multicriteria decision analysis: a survey of the literature. International Journal of Geographical Information Science 20 (7), pp. 703–726.
[20] Anderson, D. R., Sweeney, D. J. and Williams, T. A. (2003). An introduction to management science: quantitative approaches to decision making. 10th ed. Mason, OH: South-Western College Publishing
[21] Malczewski, J. (1999). Spatial multicriteria decision analysis. In: Thill, J. C. (ed.) Spatial multicriteria decision making and analysis: a geographic information sciences approach. Aldershot, UK⁄ Brookfield, VT: Ashgate, pp. 11–48.

other, and to group the criteria by objective.[22] These methods will be discussed further in the next section.

The number of alternatives will affect the kind of result one gets from MCDA.[23] Decisions with a limited number of alternatives, like three or less potential flood mitigation sites for example, usually end in a single discrete decision. Large or infinite alternatives signify a continuous problem that could have a screening or rating process. The existence of constraints also limits the potential of alternatives. A minimum contiguous size is a common constraint in spatial problems.

The level of risk tolerance a group has, and the desire to quantify risk will influence the decision making process.[24] Risk tolerant decisions may involve accepting alternatives that only meet some or one of the criteria. It is possible that all the alternatives that meet every criterion involve more risk than what is accepted. Defining an acceptable level of uncertainty is an important element to accounting for risk. It can play a factor in analysis, or be completely left out.[25] This decision can be based on the nature of the criteria modelling preference. Boundaries can be crisp or fuzzy.

The type of available analytical resources can greatly affect the process. In regards to available intellectual capital, the training and experience of analysis and decision makers

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[22] Malczewski, J. (2004). GIS-based land-use suitability analysis: a critical overview. Progress in Planning 62 (1), pp. 3–65.
[23] Chakhar, S. and Mousseau, V. (2008). GIS-based multicriteria spatial modeling generic framework. International Journal of Geographical Information Science 22 (11), pp. 1159–1196.
[24] See note 8.
[25] See note 7.

involved is very important.[26] There can be a large range of methods and associated assumptions which can result in technique bias, potentially skewing results. Available hardware and software is important too because computational capacity can have major implications on abilities to analyze spatial data.

One last consideration is the direction of problem solving used. Problems are typically worked forward when deciding on alternatives for projects.[27] Problems can also be worked backwards for the purpose of providing value judgments to support a decision.

2.2 - MCDA model type review

There are multiple MCDA method options to choose from. It is best to be sure to pick the most appropriate method for the problem at hand. The clearest separation to make is whether or not there are multiple objectives.[28] If multiple objectives are complimentary, or could be prioritized, MADM can be applied. If multiple objectives are in conflict MODM methods are required. The choice is based on the number of alternatives, the process of locating an optimal solution, and what parameters are decided. Unfortunately there is no specific definition as to what these thresholds are.

2.2.1 - Compensatory versus non-compensatory methods

It is important to delineate between compensatory and non-compensatory methods. In compensatory methods the increase in the value of one criterion offsets the value in others.

[26] See note 12.
[27] Siskos, Y. (2005). UTA methods. In: Figueira, J., Greco, S. and Ehrgott, M. (eds) Multiple criteria decision analysis: state of the art surveys. New York: Springer, pp. 297–343.
[28] See note 7.

Non-compensatory methods mean increases in the value of one criterion cannot be offset by decreases in the value of another.[29] This non-compensatory approach is easy to understand and use, but it requires hard cut-offs for including and excluding criteria. Compensatory approaches are more realistic with subtler modeling. Outcomes can be traded at a continuous scale so the loss of one criterion is the gain of another. This is a much more dynamic and realistic approach.

Both MODM and MADM methods are based on the number of alternatives. Each method is not mutually exclusive.[30] For example, a non-compensatory technique can be used in a primary screening of alternatives, followed by a compensatory technique for final decision support. Both can be run together to test results. Or one can be run for multiple iterations with small adjustments of inputs to gauge sensitivity of final outputs to a particular criterion.[31] More on this will be discussed in Section 2.3.3.4 which covers sensitivity analysis.

2.2.2 - Weighting methods

Weighting methods are used to derive relative levels of importance, or influence of criteria before applying compensatory aggregation.[32] Several weighting techniques can be used, including ranking, rating, trade-off analysis, and analytic hierarchy process. Ranking can be done by rank sum, rank reciprocal, and rank exponent. Rank sum is where each rank value is divided by the sum of all rank values. Rank reciprocal is where 1 is divided by each rank value. Rank exponent is where a rank sum is raised to a power between 0 and 1 reducing the results

[29] Ibid.
[30] See note 12.
[31] See note 7.
[32] See note 12.

of weight differences. It is useful to remember that using rank order of preference assumes that the intervals between these preferences are equal, otherwise using this ordinal data in subsequent calculations produces nonsense. Rating is where a common scale is used to rate criteria. Examples of this are using points on a range of 0 to 100, or 0 and 1. Trade-off analysis is where tradeoffs are assessed between pairs of criteria to determine thresholds of where they are evenly important.

2.2.3 - Aggregation methods

Once criteria are weighted they must be combined for a final score for the sake of comparing alternatives. These methods can involve standardizing criteria values for the purpose of comparison on a common scale, or using non-additive methods that keep the original scores. Outranking aggregation method uses pair-wise comparisons for ranking. Heuristic methods are excellent for spatially continuous problems that need simplification.

Standardizing methods include weighted linear combination, fuzzy additive weighting, and order weighted averaging. Weighted linear combination involves simple additive weighting. It multiplies normalized criteria scores by relative criteria weights for each alternative.[33] This method can weight all criteria in a single step, or do so hierarchically if some criteria are better related than others. Fuzzy additive weighting uses weighted linear combination values applied to non-crisp criteria and weights to fuzzy quantifiers like high,

[33] Nyerges, Timothy L., and Piotr Jankowski. 2010. Regional and urban GIS: a decision support approach. New York: Guilford Press, 145.

medium and low.[34] Order weighted averaging takes weighted linear combination and places criteria along a continuous spectrum of risk tolerance.[35]

Non-additive methods, where original criteria scores are used, can be done using ideal point, non-dominated set, and reasonable goals methods. Ideal point identifies the preferred value for each criterion and comes up with an ideal point for an outcome value.[36] This value may be far from a feasible alternative meaning that additional selection methods should be used. Non-dominated set identifies a set of alternatives that score at least as high as every other alternative for one criterion.[37] This can also be called the efficient, or Pareto set. Reasonable goals method uses two-dimensional graphs to help select alternatives to their location in outcome space.[38]

2.2.4 - MCDA methods for intensive stakeholder analysis

Once stakeholders and their sentiments becomes a main contributor to dealing with alternatives and their associated criteria, methods must address these subjective/qualitative data differently. Below are methods catered to address stakeholder values.

Outranking aggregation methods use pair-wise comparisons of discrete sets of alternatives in order to rank them based on concordance (dominating criteria) and discordance

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[34] Gemitzi, A., et al. (2007). Combining geographic information system, multicriteria evaluation techniques and fuzzy logic in siting MSW landfills. Environmental Geology 51 (5), pp. 797–811.
[35] Malczewski, J. (2006). Ordered weighted averaging with fuzzy quantifiers: GIS-based multicriteria evaluation for land-use suitability analysis. International Journal of Applied Earth Observation and Geoinformation 8 (4), pp. 270–277.
[36] Ibid.
[37] Lotov, A. V., Bushenkov, V. A. and Kamenev, G. K. (2004). Interactive decision maps: approximation and visualization of Pareto frontier. Boston, MA: Kluwer Academic Publishers.
[38] Jankowski, P., Lotov, A. V. and Gusev, D. (1999). Application of a multiple criteria trade-off approach to spatial decision making. In: Thill, J. C. (ed.) Spatial multicriteria decision making and analysis: a geographic information sciences approach. Aldershot, UK/ Brookfield, VT: Ashgate, pp. 127–148.

(opposite set).[39] This method takes into account the subjective and changing value judgments of stakeholders during the decision process. ELECTRE is a group of outranking methods developed in Europe. It introduces the use of thresholds to declare where there is indifference between alternatives or if there is preference. This is an excellent method for qualitative criteria that cannot be weighted.

PROMETHEE is another outranking aggregation method that supports various functions. These functions include linear/integer programming, goal/compromise programming, and interactive programming.[40] Linear/integer programming optimizes a problem by converting multi-objective problems into a single objective by using value functions. This is done by maximizing or minimizing a single criterion value by using its constraints. Goal/compromise programming finds the alternative that deviates the least from the stakeholder's ideal points for multiple objectives.[41] Interactive programming is similar to goal/compromise programming, but looks at each objective individually.

Heuristic methods are excellent experience based-techniques for stakeholder decisions involving a large number of alternatives. These methods are good for spatially continuous problems using raster data. [42] [43] These methods can be used to analyze cells with conflicting objectives, striving for a close to optimal solution. Heuristic methods include multiple-objective land allocation, genetic algorithms, and simulated annealing. Multiple-objective land allocation

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[39] See note 13.
[40] Malczewski, J. (1999). GIS and multicriteria decision analysis. New York: J. Wiley & Sons, 226.
[41] See note 13.
[42] Raster data refers to cellular, or tabular data where each square is given a value. A common use of raster data is a digital picture, where each cell is given a red, blue and green value.
[43] See note 13.

brings each cell to an objective with the closest ideal point. Objectives can be weighted unequally so that a cell is allocated to an objective with higher weight despite being closer to another objective. Genetic algorithms are a trial and error process introducing small changes that allocate cells. Simulated annealing is an iterative and random process that allocates cells for overall improvement.

Multiple attribute value theory is a form of MCDA used to quantify stakeholder positions.[44] It can be used as a tool to take the emotionally charged discussions of stakeholders and assign values. The problem is that stakeholders typically attach themselves to a preferred alternative prematurely in the decision process. Multi-objective analysis is a version that was developed for the UN funded "North China Water Resources Management" project in 1994.[45] This analysis was based on several hydrologic, agronomic and economic models to create water resource development plans and evaluate social, economic, and environmental performance.

2.2.5 - Section Conclusion

These methods include some of the options available for MCDA models. There are numerous options available. This section is seen as a general overview of what is available for MCDA. Each decision situation is unique, requiring a unique set of tools and methods to properly assess alternatives.

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[44] Hostmann, Markus, Thomas Bernauer, Hans-Joachim Mosler, Peter Reichert, and Bernhard Truffer. 2005. "Multi-attribute value theory as a framework for conflict resolution in river rehabilitation". *Journal of Multi-Criteria Decision Analysis.* 13 (2-3): 91-102.

[45] Ximing Cai, Leon Lasdon, and Ari M. Michelsen. 2004. "Group Decision Making in Water Resources Planning Using Multiple Objective Analysis". Journal of Water Resources Planning & Management. 130 (1).

2.3 - GIS-Based MCDA

The use of MCDA has been growing steadily since the early 1990s, creating a well sized research community.[46] The disciplines leading in use are environmental/ecology, transportation, urban and regional planning, and other resource based professions. But despite its broad use, GIS application in MCDA is still a niche field. A research group and related journal did not survive, and MCDA publications rarely publish GIS related articles. One has to look in GIS-specific, Environmental, and Planning literature to find GIS-based MCDA. No academic institution is the clear leader in GIS-based MCDA, though there are a few outstanding individuals. Despite its lack of prevalent academia, GIS is seen as the ideal tool for executing the analysis in this thesis.

In any situation involving location, such as floodplain management, or salmon habitat restoration, having exact locations to options and criteria is value adding. The following subsections will help explain why. First GIS will be presented as a decision support tool. Next an explanation will be given as to how GIS can be used in stakeholder participation. Finally, GIS-based multi-criteria evaluation methods will be explained.

2.3.1 - GIS as a decision support tool

GIS, in the context of planning, stakeholder involvement, and MCDA is a decision support tool. It is a system involving the integration of spatially referenced data into a problem

[46] See note 13.

solving environment.[47] By itself it is a rational planning tool. When stakeholder involvement is added it becomes a more democratic process. GIS is merely a tool to extend human capabilities of visualization, analysis, computing capabilities, and memory.[48] With this comes the ability to model scenarios such as several possible future floodplain conditions, Individual situations, and decisions fitting specific scenarios. These can all be modeled in what is called a spatial decision support system.[49] The key is to appropriately apply these support systems to a planning context in order to get meaningful results.

The addition of GIS to MCDA is for the purpose of adding the question of 'where' to 'what'.[50] GIS can be applied to many MCDA problems. In addition to normal MCDA methodology GIS enables the user to analyze criteria of a spatial nature, such as distance, travel time, slope, and general proximity of a criterion to a feature in question. Unfortunately MCDA can be applied to only a limited amount of problems, which limits the problems one is able to analyze. This limitation can be alleviated by creating smaller amounts of discrete data from continuous data, i.e. converting raster data with a small resolution to vector polygons.[51] One technique of doing this is classifying similar values into homogenous zones. For example, slopes ranging from 10-20% become one value, while slopes ranging from 20-30% become another value. In the context of MCDA this can be done for criteria values or categories, though when simplifying data one risks losing precision.

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[47] Cowen, D. 1988. GIS versus CAD versus DBMS: What are the differences?, Photogrammetric Engineering and Remote Sensing, 54(11), 1551-1555.
[48] Nyerges, Jankowski, 23 (see page 7).
[49] Nyerges, Jankowski, 23 (see page 8).
[50] See note 13.
[51] Vector data is discrete GIS data representing points, lines, and polygons. Examples are fire hydrants as points, street centerlines and lines, and ownership boundaries at polygons.

MCDA integrated GIS software falls into different levels ranging from a full integration single software package, to two separate software packages requiring data exchange.[52] Most MADM techniques can be done in a single software package such as ESRI's ArcGIS. Functionality in this software package includes the Weighted Overlay tool and Map Algebra in the Spatial Analyst software extension.[53] These tools have the capability to reclassify, weight, and combine criteria in raster form into a single raster output layer.

GIS is a value adding package to MCDA. There are many options and methods to use when executing this nature of analysis. One can argue what technique is best, but regardless of the methods used one thing is definite in the world of planning: stakeholder participation is crucial. Without proper public outreach GIS-based MCDA is a technocratic tool only a few people can use.

2.3.3 - GIS and stakeholder participation

Public participation has become a mainstay in planning over the past twenty years, with the goal of creating an environment that provides access to all and an equal opportunity to voice one's opinions regarding projects affecting the public. GIS researchers have been encouraging groups to adopt GIS and have been attempting to help assist in community decision support.[54] Most municipalities/communities achieve some level of public participation, but achieving this with information technology support thus far has required more resources than what most communities have. When GIS is introduced higher levels of

[52] See note 7.
[53] "Key Features: ArcGIS Spatial Analyst," ESRI website, http://www.esri.com/software/arcgis/extensions/spatialanalyst/key-features, Accessed on February 25, 2014.
[54] Nyerges, Jankowski, 23 (see page 22).

participation occur.[55] Ample participation is crucial to making successful decisions during times of human and environmental change.

Taking GIS-based MCDA a step beyond merely analysis is Participatory GIS and WebGIS MCDA, which more actively involve stakeholders by allowing them to add criteria weights to the applications directly, either during a meeting or via an online web-mapping interface.[56] This is an effort to supplement the limitations of public meetings where often those who can make the meetings and speak up are a select few. In some cases all the public has to do is log in to a website. GIS has typically been seen as an expensive, technocratic tool requiring expert users to maintain and update operations and data. This creates a gap between those who know the system and those who don't. Participatory GIS and WebGIS are seen as a way to bridge this gap by increasing data availability and understanding, as well as enhancing public participation.[57] This democratization of GIS also offers a response to those who have criticized the tool for being too rigid for complex systems involving human input such as urban planning.

2.3.4 - GIS decision support methods and workflow

In order to effectively use GIS as a planning decision support tool several steps must be completed before even making a map, let alone a final decision. There are currently two general schools of thought in regards to project workflow. The first is the Simplified Workflow which executes four basic steps to create a complete bare-minimum application of GIS for decision support. These steps are: identify project objectives, develop a database, perform

[55] Ibid.
[56] Boroushaki, Soheil, Malczewski, Jacek, "ParticipatoryGIS: A Web-based Collaborative GIS and Multicriteria Decision Analysis," URISA Journal, Vol. 22, No.1, 2010.
[57] Dunn, Christine E. 2007. "Participatory GIS -- a people's GIS?" *Progress in Human Geography.* 31 (5).

analysis, and report the results. A more thorough and robust process is the Nuanced Workflow.[58] This six step process is modeled after a landscape design process developed by Carl Steinitz, a Harvard landscape architecture professor.[59] It is also known as the geodesign framework. A geodesign framework inspired model is the model used in this thesis.

2.3.5 - Geodesign explained

Nuanced Workflow, an all-encompassing six step process was coined for the term geodesign in 2010 by Jack Dangermond, President and Founder of Environmental Systems Research Institute (ESRI), the largest, and most influential GIS software company to date.[60] Though the term is new, its framework was first conceived in 1965 by Mr. Dangermond's landscape architecture professor, Dr. Carl Steinitz.[61] Geodesign is a melding of large scale design with GIS enabled information support. A concise definition of geodesign is "changing geography by design."[62]

The methodology of geodesign used today first appeared in a report written by Dr. Steinitz in 1990 titled "A Framework for the Education of Landscape Architects and Other Design Professionals." The six step process he presented in the paper is basically the same six questions used in geodesign today. The questions forming the basis of the framework are:[63]

1. How should the study area be described?

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[58] Nyerges, Jankowski, 23 (see page 63).
[59] "A Conversation with Carl Steinitz," ArcWatch: GIS News, Views, and Insights, Environmental Systems Research Institute, April 2012, http://www.esri.com/news/arcwatch/0412/a-conversation-with-carl-steinitz.html.
[60] "Jack Dangermond Talks about GeoDesign at TED2010," TED Talks video, February 11, 2010, http://video.esri.com/watch/125/jack-dangermond-talks-about-geodesign-at-ted2010.
[61] See note 49.
[62] Ibid.
[63] Steinitz, Carl, "A Framework for Geodesign," ESRI Press, Redlands CA, 2012, Pg. 3.

2. How does the study area function?
3. Is the current study area working well?
4. How might the study area be altered?
5. What difference might the changes cause?
6. How should the study area be changed?

2.3.6 - The geodesign six step process

These six questions are transformed into processing and analysis steps within a GIS enabled project. GIS is merely a tool to process, house, analyze and display data. By itself it is not equipped with the intelligence to handle the complicated problems facing the world's landscapes today without the knowledge to execute proper processing of the data of complex projects and their goals.[64] With the geodesign framework GIS technology can be properly used to help solve large issues through designing at an urban and regional scale through answering the six questions. When the six questions are converted to modeling steps they become:[65]

1. Representation modeling
2. Process modeling
3. Scenario modeling
4. Change modeling
5. Impact modeling
6. Decision Support Modeling

[64] See note 53.
[65] Nyerges, Jankowski, 23 (see page 60).

Representation modeling, how the study area should be described, covers how an urban or regional area should be described according to the particular issue at hand. This is the decision point as to what data should be used and what database design is best. Identifications of objectives and database development occur here. The database design should be described in content, space, and time.[66]

Process modeling, how the study area functions, is where critical relationships among features are identified, as well as how they interact. Change modeling explores what changes occur when features are added, such as population density, industry, or habitat enhancement. It also asks what is still unknown.

Scenario modeling, or evaluation modeling, asking whether the current study area is working well, selects characteristics relative to different scenarios. This question is usually answered through stakeholder outreach. Cultural knowledge and local decision making both play a large role in forming the geodesign model.[67] Consideration should be given to resources available when considering the amount of scenarios one can compute.

Change modeling, asking what changes occur due to an added feature, looks into different policies and actions that will change the future. Features like additional density or industry, or, in the case of this thesis land dedicated to habitat and flood attenuation, are considered. The data generated in this part of the geodesign will be used as a representation of different possible future conditions. It is important to consider what is still unknown at the end of this process.

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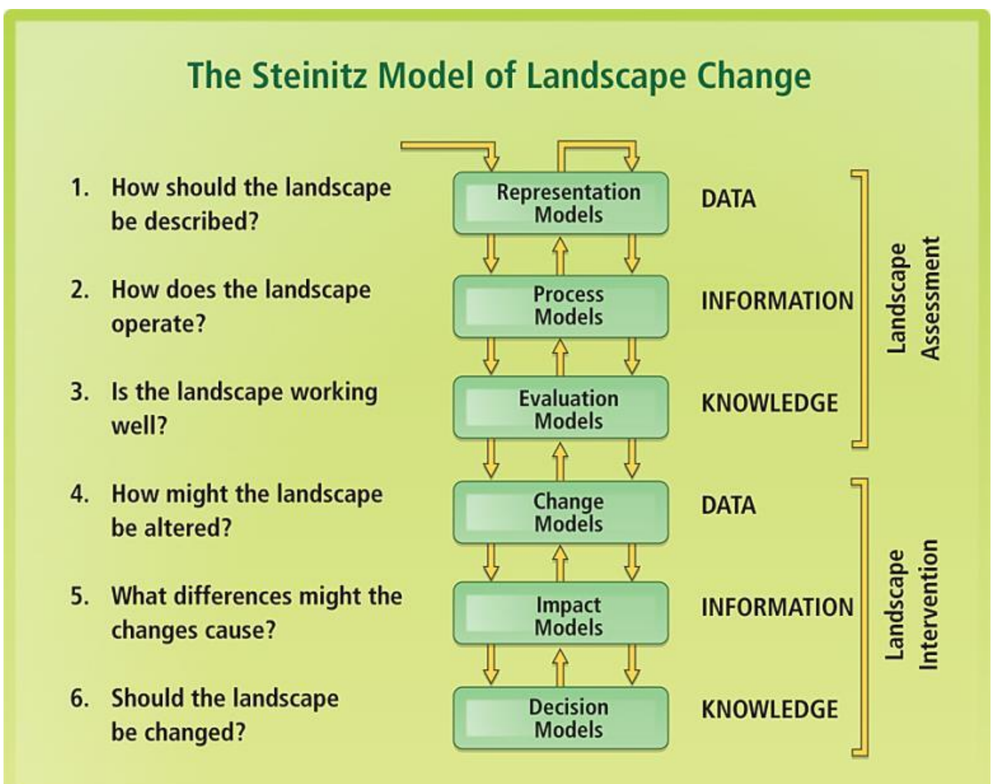
[66] Steinitz, 56 (see page 26).
[67] Ibid.

Impact modeling asks what differences the changes might cause. It explores the externalities of the additional features. It looks at the assessments produced by the process models in Step 2 with the addition of different changes in conditions.

Finally, Decision Support Modeling is a decision support tool that weights multiple objectives, or site criteria. It can be seen as a tradeoff analysis. The majority of this thesis will be within this step. It asks how the study area should be changed. It is similar to the evaluation model in Step 3, but is dependent on local/cultural knowledge of stakeholders and decision makers. This step is seen as the conclusion of the study.

Figure 2.1: The six geodesign steps



Source: http://www.esri.com/news/arcnews/summer09articles/gis-designing-our-future.html

The power of this framework is the ability to design beyond the geographic scale of a single project, but at more of a city to regional scale.[68] Dr. Steinitz believes the serious issues of the world cannot be tackled by the sum of normal sized projects at the local scale, but only with a larger focus which geodesign takes.[69] This is exactly what is need when tackling issues such as an individual watershed area in Puget Sound, now referred to as a Water Resource Inventory Area (WRIA) by the Washington State Department of Ecology for planning and policy purposes.[70]

2.3.7 - Abridged version of geodesign used

This six step process is a time tested method of an all-encompassing geodesign.[71] Unfortunately, due to limited time and resources for this thesis an abbreviated version of the six step process will be implemented. It was decided the best approach was to keep Step 1, the Representation Model and Process Model intact in order to develop content and structure through database development.[72] Step 3 through Step 5, with some elements of Step 2, are combined into two phases appropriately named the Spatial Screening Model and the Alternatives Criteria Model. Step 6 was kept and is used as the context phase, the part of the model where stakeholders decide the importance of criteria, leading to the outputs in the decision tool. The formulas and techniques used for the processing and context phases are

[68] Steinitz, 56 (see page 33).
[69] See note 49.
[70] "Watershed Updates by Water Resource Inventory Areas (WRIA)," My Watershed, Washington State Department of Ecology, accessed on February 18, 2014, http://www.ecy.wa.gov/apps/watersheds/wriapages/.
[71] Nyerges, Tim, Professor of Geography, University of Washington, Interview on February 18, 2014.
[72] Ibid.

discussed in the next section. Greater detail of this abridged version of the model will be provided in the next section as well.

2.3.8 - GIS-based multi-criteria evaluation methods used

The previous sections give a general overview of the overall format used for this thesis. Now we will dive into the specific GIS-based MCDA techniques used for the data processing and decision aiding. It should be noted this is just an overview of concepts. Actual equations used in the analysis parts of this thesis are explained in detail in the Methods section.

GIS-based MCDA techniques are not generally available in GIS software with the exception of the Weighted Overlay and Map Algebra tools in ESRI's ArcGIS Spatial Analyst extension mentioned earlier. GIS-based MCDA involves transformations of data characterizing impacts of an alternative into a single summary score, or appraisal score, in order to rank the alternatives from best to worst.[73] In order to get to a final appraisal score several steps must take place. These include data standardization, and transformation of decision-maker preferences for various criteria into weights and decision rules. Once a final appraisal score is calculated the influence of the chosen weights can be tested in a sensitivity analysis. All of these steps are briefly explained below.

2.3.8.1 - Data standardization

[73] Nyerges, Jankowski, 23 (see page 136).

Data standardization in GIS-based MCDA is the transformation of criteria into a single scale characterization called criterion standardization.[74] This step is important because often time criteria do not come in the same units. Things like acre/feet of water need to be related to land value, agricultural soils, etc. These transformation methods reclassify values into a relative scale format that can fit all criteria. Transformation techniques include linear and non-linear approaches. Formulas are called linear because they produce proportional or linear transformations of raw input data.

The Maximum Score Procedure, the procedure used in this thesis, is the simplest linear formula. It is where each raw criterion is divided by the maximum criterion value.[75] These values range from 0 to 1 and are related to their performance relative to other features within a criterion. This method only works for beneficial criteria, meaning the higher the value the better the criterion performance [*Xraw/Xmax*]. In the case of cost criteria where the smaller score is more favorable place a 1 in front of the original formula and subtract it [*1 - (Xraw/Xmax)*]. An alternative method for the cost criteria is to place the minimum score in the numerator and the raw score in the denominator [*Xmin/Xraw*]. A plus to this method is scores are in order of preference. A limitation to this method is the minimum score does not always equal 0. This can make it difficult for interpretation.

If raw values cover positive and negative values non-linear transformations should be used.[76] For non-linear transformations the difference in a raw score to the minimum score can be divided by the range of scores [*(Xraw-Xmin)/(Xmax-Xmin)*]. The advantage to these

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[74] Ibid (see page 137).
[75] Ibid.
[76] Nyerges, Jankowski, 23 (see page 136).

methods is every value will be between the range of 0 and 1, which is also true for negative values. A disadvantage is these values are not linearly related to raw scores.

2.3.8.2 - Transformation of decision-maker preferences into weights

Once criteria are transformed into a scale where everything can be related, the importance of each criterion needs to be decided. This step in the GIS-based MCDA process is usually the most stakeholder intensive because weights should relate to the values of those involved with the results. Criteria are often given uneven weights of importance for various causes: policies, established hierarchies, relative influence on end results and stakeholder preference often play a part in some criteria being weighted more heavily than others.[77] A weight is a numeric value given to each criterion showing its level of importance relative to other criteria in a normative scale. Common ways to transfer decision maker preferences to a normative scale are through ranking, rating, and pairwise comparison.

In straight ranking, the most important criterion gets the smallest value. In inverse ranking the least important criterion gets the smallest number.[78] This method is simple, but the larger the number of criteria, the harder it is to assign reliable ranking, plus this method lacks foundations in theory. This is because ordinal ranking data, if used mathematically, assumes that the intervals between the rankings are equal, which is seldom the case. One exception to this is using a distance to a criterion from a feature in question, as can be the case in GIS-based MCDA.

[77] Ibid, (see page 138).
[78] Ibid, (see page 139).

Rating is where decision makers are asked to assign weights to criteria.[79] In the case of using a scale of 0 - 100 where a total 100 points are given to decision makers to distribute to all criteria, assigning 0 symbolizes ignoring the criteria completely, whereas assigning 100 symbolizes ignoring all else. This method provides trade-off information, since any assignment of points to one criterion reduces the balance available to all other criteria. It is easy to understand when thinking of weighting as allocating amounts of money to things with corresponding importance. This method, like ranking, lacks foundations in theory, but is an excellent way for stakeholders to simulate scarcity.

This weighting method used in this thesis takes from the rating process. This is where limited number of points can be given to decision makers so that they distribute them among criteria as a form of weighting. The points are then multiplied by the criteria rating to get a score, then all criteria scores are added together in what is referred to as a final appraisal score.[80] This complete process is referred to as the rank sum method.[81]

Pairwise comparison is a relative comparison of individual criteria pairs to each other in order to rate importance.[82] The advantage to this method is its theoretical support. Plus it uses a standard regression output. One major disadvantage is the large number of individual judgments needed with a large number of criteria.[83] However this is a means of differentiating between a large set of criteria, since the judgments are pairwise. It is on the other hand often

[79] Ibid, (see page 140).
[80] Ibid, (see page 136).
[81] Herath, G. and Prato, T. (eds) (2006). Role of multi-criteria decision making in natural resource management. In: Using multi-criteria decision analysis in natural resource management. Aldershot, UK: Ashgate, pp. 1–10
[82] Nyerges, Jankowski 23, (see page 141).
[83] Ibid, (see page 145).

more difficult for participants to understand and to be comfortable with, unlike the assignment of a budget of points over criteria on the basis of relative importance. Because of the amount of criteria used in this thesis, and a lack of direct contact with stakeholders, it was decided this method would be too cumbersome given the amount of time and resources available. Rating is seen as the best method for this thesis where a limited number of points are given to decision makers to distribute among the criteria.

2.3.8.3 - Decision rules

Decision rules are methods for ordering alternatives from least to most desired. The purpose of this is to select the best alternative and group alternatives in order of desirability. This is all determined, or informed by the overall appraisal score.[84]

Two popular functions are weighted linear combination and ideal point. Weighted linear combination is a popular method for its simplicity. The standard score for each criterion is multiplied by its weight then combined with the comparable products for other alternatives for a final appraisal score.[85] The assumption in this method is that each criterion is independent. This method has been implemented in GIS packages with their overlay capabilities. As mentioned before, the Weighted Overlay tool in ArcGIS processes raster data for weighted linear combination.

[84] Voogd, H. 1983. "Multicriteria Evaluation for Urban and Regional Planning. London, Pion.
[85] See note 24.

Ideal point calculates a final appraisal score by calculating an alternative's relation to the combined alternative outcome's distance from an ideal point.[86] The ideal point represents a hypothetical outcome that best suits the analysis, and is essentially the full accomplishment of all the objectives. The alternative that scores closest to the ideal point is best.

2.3.8.4 - Sensitivity analysis

Sensitivity analysis is the investigation of changes and errors in criteria and their potential impacts on the calculated solutions.[87] It is necessary to conduct a sensitivity analysis in order to truly understand the stability of an outcome and the potential changes that may happen as errors occur. This may be done either by examining one criterion at a time, or by testing globally the interdependencies of multiple criteria.[88] In this thesis each criterion will be tested individually.

The sensitivity of criteria is important because priorities may shift for various reasons affecting the final score of alternatives. Small changes in priority may or may not affect final rankings. When examining individual criteria each criterion can be tested for sensitivity by giving one a full weight of 100 and others 0 to test the overall appraisal score.[89] Criteria can be deleted or added to test outcome differences. This can be done systematically in order to identify criteria with the least influence on the outcome. Another more involved method is the

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[86] Nyerges, Jankowski, 23 (see page 146).
[87] Ibid, (See page 149).
[88] Ligmann-Zielinska, A., and P. Jankowski. 2008. "A Framework for Sensitivity Analysis in Spatial Multiple Criteria Evaluation". *Lecture Notes in Computer Science.* (5266): 217-233.
[89] Nyerges, Jankowski, 23 (see page 150).

Fourier amplitude sensitivity test which uses first-order sensitivity to a criterion's contribution to the variance of a final appraisal score.[90]

2.3.9 - Section conclusion

We have just covered the general steps in GIS-based multi-criteria evaluation methods: coming to a common scoring unit, weighting criteria, final scores, and sensitivity. These are seen as the building blocks of the analysis methods that will be used. It is now time to cite examples of how GIS-based MCDA and geodesign have been implemented in the realm of floodplain management.

2.4 - GIS-based MCDA applied to floodplain management

GIS over the years has matured to handle several complicated urban and rural issues such as floodplain management, and its associated water and land use implications. Floodplain management is seen as an ideal subject for the application of GIS-based MCDA. There are overlapping land uses inside a dynamic natural system producing complicated land management practices. Large decisions will most likely involve several stakeholders. How this stakeholder involvement plays in to the MCDA process is unique to each watershed, its issues, and the regulatory and policy frameworks that exist. In some instances a GIS-based MCDA tool can be technocratic from start to finish, where the criteria and weights are decided by the modelers and stakeholders make a decision in the end. The opposite would be for the

[90] Crosetto, M., and Trantola, S. 2001. Uncertainty and sensitivity analysis: Tools for GIS-based model implementation. International Journal of Geographic Information Science, 15(5), 414-437.

stakeholders to decide everything including criteria, preferences, weights and finally decisions. Most GIS-based MCDA tools within floodplains fall somewhere in between.

2.4.1 - Technocratic approach

A technocratic approach to GIS-based MCDA in the Rhone-Thur watershed in Switzerland showcases an example of how GIS can enable a holistic approach to floodplain management, versus addressing single issues with single drivers, which is a common approach from the past.[91] In this 2004 study the Swiss attempt to use spatially explicit information within Environmental Systems Research Institute's (ESRI) ArcGIS Model Builder tool with a goal of balancing accuracy and cost of ranking areas for the purpose of developing a floodplain restoration strategy.

Two key questions in the study are: Where are the river-stretches which are less likely to be undermined by poor environmental conditions? And where shall we spend our money and space to fulfill the various social demands and ecological requirements concerning rivers and their floodplains?[92] To answer these questions river ecologists were used to answer each of the following restoration drivers: hydrology, bed load, connectivity, biodiversity, and water quality. Planners were used to assess the following socioeconomic factors: flood protection, and public attitude.

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[91] Rohde, S., M. Hostmann, A. Peter, and K.C. Ewald. 2006. "Room for rivers: An integrative search strategy for floodplain restoration". Landscape and Urban Planning. 78 (1-2): 50-70.
[92] See note 82.

A filtering process was made to focus on local eco-morphological floodplain restoration by means of river widening, man-made secondary channels, and flood levee relocation.[93] A pre-selection was based on limiting constraints such as slopes above 6%, and location within built-up areas. The evaluation of ecological suitability was based on a combination of abiotic and biotic factors such as hydro-peaking, poor connectivity, and ecological suitability. Hydrology values were based on water abstraction (changed annual water regime flow and depths) from hydropower production, hydropeaking, and dams. Bed load was quantified by analyzing sediment regimes and river bed erosion. The presence of riprap can greatly affect this. Water quality was quantified by analyzing chemical water quality, percentage of arable land in a watershed, and the presence of riparian woodlands. Connectivity was quantified by analyzing artificial migration barriers (dams, weirs, etc.), distance from current floodplains, and distance from gravel pits for species habitats. Biodiversity was quantified by the presence of riparian species.

Calculating the physical features of the floodplain was a straight-forward process. Combining the physical factors with socioeconomic factors was the crux of the exercise.[94] Flood protection needed to be analyzed to find where current deficits exist. Built capital and its distance to the river needed to be considered. Recreational opportunities were graded by the distance between the river and populated areas. Finally, public attitudes specific to environmental projects was surveyed. The final output was three land classifications: highly suitable, fairly suitable, and moderately suitable, with sub-indices reported.

[93] Ibid.
[94] See note 82.

This example is seen as an almost purely technocratic approach, where the assignment of criteria, revaluing, weighting, and ranking of alternatives was done completely within the model. Stakeholder involvement was most likely brought into the process after the analysis was complete. This is one way of executing GIS-based MCDA. Another would be to involve stakeholders in multiple steps of the process.

2.4.2 - Stakeholder intensive approach

Unlike a highly technocratic approach to GIS-based MCDA for floodplain management as just presented, we will now explore a more stakeholder involved exercise. Despite the absence of empirical data, modeling of stakeholder opinions and interests is seen as an efficient way to summarize and weight priorities in management decisions.[95] Keys to effective modeling for decision making include: multiple objective analysis, open and shared vision modeling, combined qualitative and quantitative modeling, and an adaptive and learning environment.

A multiple objective analysis is necessary for multidisciplinary complexity of water resources planning. It involves the integration of common sense with empirical, quantitative, normative, descriptive and value-judgment based analysis.[96] There is a need to represent competing objectives clearly so they are understandable and acceptable by all parties.

An open and shared vision of modeling is best developed jointly by stakeholders, water managers, and water planners.[97] It should incorporate planning objectives and performance measures into a single framework in order to develop alternatives. Typically this framework

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[95] See note 35.
[96] Flyvberg, Bent, Landman, Todd, Schram, Sanford, "Real Social Science, Applied Phronesis," Cambridge University Press, Cambridge UK, 2012, Pg. 27.
[97] See note 35.

contains social, economic and environmental impacts, as well as hydrologic and hydraulic. It is absolutely necessary to transform models from adversarial tools to facilitation tools in public process.[98] The barrier between technocrat and public must be broken down to optimize the use of modeling in conflict resolution. Consensus is easier to obtain when the public understands the process, and those conducting the modeling understand the needs of the public.

Combined qualitative and quantitative modeling is necessary to address complexity and to address tangible and intangible factors.[99] Hydrologic and economic analysis can be structured quantitatively. Goals, sub-goals and participant preferences cover the qualitative, intangible factors. Though it should be noted most intangible factors such as feelings and attitudes are difficult to add to a model.

Creating adaptive and learning environments in conflict management are a learning process. They are a requirement in the negotiating process.[100] Participants need to understand relationships between hydrologic, environmental and economic outcomes. They need to learn trade-offs between private benefits and social value. Institutional constraints must be understood as well to help frame parameters of goals.

[98] Palmer, R. (1999). ''Modeling water resources opportunities, challenges, and trade-offs: The use of shared vision modeling for negotiation and conflict resolution.'' Preparing for the 21st Century, Proc., 26th Annual Water Resource Planning and Management Conf., ASCE, Reston, Va.
[99] See note 35.
[100] Ibid.

An example of a stakeholder involvement intensive GIS-based MCDA process for floodplain management took plane in the White River watershed in Vermont.[101] In this particular instance group selection of participating parties was already formed before the study. They were a decision making body as well as an interest group, and public outreach facilitators. Monthly group meetings were conducted to develop values and criteria for restoration prioritization. Originally eighteen criteria were reduced to five measurable criteria: maximum amount of agricultural or developable land taken over a thirty year period, maximum acceptable cost borne by local taxpayers to manage one river mile, desired number of high quality pools for recreation and fishing, desired percent of river sections minimizing flood damage through meandering river access to floodplains, and desired percent of river sections with more than thirty five feet of vegetative buffer.

The three variables in this study were economic, social/cultural, and environment. The economic variable was measured by acreage lost, and cost of river management per mile per year. Social/cultural variable was measured by the percentage of high quality pools. The environmental variable was measured by the percentage of available meandering section of streams, as well as width of vegetative buffer.

This is an excellent example of stakeholder involvement in a GIS-based MCDA exercise for floodplain management because of the closeness between the stakeholders/advocates and those who implemented the model. The methods used allowed for science to become part of

[101] Hermans, C., J. Erickson, T. Noordewier, A. Sheldon, and M. Kline. 2007. "Collaborative environmental planning in river management: An application of multicriteria decision analysis in the White River Watershed in Vermont". Journal of Environmental Management. 84 (4): 534-546.

the stakeholder conversation.[102] As a result the criteria and variables used were locally decided and customized to fit the specific needs and desires of the people in that watershed.

2.4.3 - Use in King County, WA

King County Department of Land and Natural Resources uses GIS-based MCDA for floodplain and general watershed management planning.[103] They use a web-based GIS interface for landscape scale conservation priority setting. The model, which pulls from a county-wide geodatabase, stores and accesses thousands of attribute fields to help prioritize which lands they would like to purchase for the sake of conservation and restoration. The criteria goals they consider are: agricultural soil, forestry, flood risk reduction, ecological reasons (terrestrial wildlife, salmon, general ecosystem value), historic and cultural resources, scenic open space, regional and local trails, potential park additions and inholdings, natural corridors, and passive recreation. All of these criteria are attached to a parcel dataset which provides assessed values. From this the county ranks parcels in importance for purchase and potential for transfer of development rights.

2.5 - Levee Setbacks and Associated Criteria

In an effort to narrow the scope of this thesis and the models created, focus is made on levee setbacks as multiple benefit river restoration projects. Levee setbacks are where an existing levee blocking a river from its historical floodplain is removed and replaced by a levee farther away from a river channel, restoring connection between the river and the surrounding

[102] Ibid.
[103] Murphy, Michael, Program Manager, Open Space Acquisitions, King County, WA, phone interview on February 28, 2014.

lands. These newly connected lands in most cases were historically part of the floodplain. Levee setbacks are seen as a way to improve habitat, while potentially increasing floodwater retention by allowing the river channel and floodway more room to migrate. Also, this topographically complex surface newly added to the floodplain often increases roughness of the floodway, which in effect slows water movement and flood spiking as a result.[104] Levee setbacks may not be as economically feasible as other habitat enhancing or flood attenuating methods because of the need to outright purchase the land if it is not already owned by the jurisdiction in charge of flood control. This is seen as justification to create a decision support tool in this thesis covering such a land use change.

Levee setbacks are seen as beneficial to improving ecological health of riverine systems for several reasons. One important aspect to ecosystem health is that an armored river lacks bank erosion. Bank erosion is a critical part of riverine ecosystems by providing areas for vegetation succession and diverse habitat for a wide range of plants and animals.[105]

Unfortunately the dynamic natural processes of rivers have been historically seen as a hindrance for river managers and policy makers in regards to the economic vitality of the lands on and adjacent to the river system. They have sought a more static, predictable system, minimizing geomorphic uncertainties. For this reason rivers all over the world and locally have been armored by levees.

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[104] Reinhardt, C., J. Bolscher, A. Schulte, and R. Wenzel. 2011. "Decentralised water retention along the river channels in a mesoscale catchment in south-eastern Germany".Physics and Chemistry of the Earth. 36 (7-8): 309-318.
[105] Florsheim, Joan L., Jeffrey F. Mount, and Anne Chin. 2008. "Bank Erosion as a Desirable Attribute of Rivers". BioScience. 58 (6): 519-529.

Starting in the late 1980s and early 1990s traditional river management policies have been reconsidered due to the recognition of the necessary presence of bank erosion, and its role in geomorphic function and ecosystem services.[106] Part of this process is setting back levees to allow more room for channel migration, erosion, and sediment transport. Because ecological health, its associated ecosystem services, and economic health are necessary, compromises need to be made. Strategically placing levee setbacks in areas of most ecological value, least economic loss, and highest potential water retention is seen as a way to find a balance between the health of both the natural and built capital, ultimately aiding social capital as well.

2.6 - Methodological and Substantive Foundations Conclusion

The purpose of this section is to cover a broad range of topics in order to build a foundation and reason for the methodologies and subject matter chosen for this thesis. MCDA is introduced as a discipline with its roots in planning and resource management. MCDA model types and their associated methodologies are then explained. The sub-topic of GIS-based MCDA, the chosen methodology of this thesis, is then introduced, along with its roots, applications and processes. The all-encompassing geodesign framework is then explained, as well as the abridged version that will be used in this thesis. Different GIS-based MCDA's applications in floodplain management are presented. Finally levee setbacks, the specific river restoration project type being analyzed are explained. Next is the Methodology section overviewing the study area and the chosen GIS-based MCDA methods.

[106] Piégay, H., S. E. Darby, E. Mosselman, and N. Surian. 2005. "A review of techniques available for delimiting the erodible river corridor: a sustainable approach to managing bank erosion". River Research and Applications. 21 (7): 773-789.

3.0 - Methodology

The GIS models that comprise the tool are introduced and explained in this section. First we introduce the study area, the Duwamish/Green River watershed. An abbreviated version of the geodesign framework is then introduced as the analysis method. Finally, the three components of the method are explained in a step by step process.

3.1 - Duwamish/Green River case study (WRIA 9)

The Puget Sound Basin, home to over 4 million people and comprising 16,000 square miles is the second largest estuary in the United States.[107] The area contains more than twenty major river systems and their tributaries flowing from the Cascade and Olympic mountains, starting at elevations above 7,000 feet and dropping to sea level within 50 to 70 miles. The stretches of river within the Puget Sound Basin cross forest, farmland, resource lands, industrial areas, and urban areas, which comprise more than two-thirds of Washington State's population.[108]

The watershed within the Puget Sound this study will focus on is the Duwamish/Green River watershed in King County, also known as Washington State Department of Ecology (Ecology) Water Resource Inventory Area (WRIA) 9.[109] It can be seen as one of the most diverse

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[107] "Puget Sound Salmon Recovery Region," State of Salmon in Watersheds Report , Washington State Recreation and Conservation Office, 2010, http://www.rco.wa.gov/documents/gsro/2010_SOS_rpt/PugetSoundRegion.pdf.

[108] "Salmon Habitat Plan," Salmon Conservation and Restoration: Green/Duwamish and Central Puget Sound Watershed, August 2005, http://www.govlink.org/watersheds/9/plan-implementation/HabitatPlan.aspx#download

[109] WRIA stands for Water Resource Inventory Area, and is the watershed unit used by the Washington State Department of Ecology. For more information please visit the following website: http://www.ecy.wa.gov/services/gis/maps/wria/wria.htm

watersheds in the United States in regards to land use and land cover. Its headwaters, located at the crest of the Central Cascade Mountains, are largely pristine alpine and sub-alpine terrain.[110] The Green River meanders through mountainous forests through Howard Hanson Dam, and into the Kent and Auburn Valleys where the human footprint on the landscape becomes drastically intensified. Light farming and exurbs turns into suburbs and industrial/manufacturing/warehousing areas. The Green River changes its name to the Duwamish River. At this point the river is almost completely surrounded by impervious surface. The river finally terminates at one of the busiest ports in the Western United States, the Port of Seattle.

Goals for the Green/Duwamish watershed, like most watersheds of the Puget Sound, are maximizing salmon habitat restoration while minimizing flood damage to existing built capital. The flood protection system in King County is an aging system in need of millions of dollars of repair.[111] King County has more than 500 control facilities, with over 100 miles of levees. A large portion of these levees were built by farmers in the first half of the 20th Century, and were updated by United States Army Corps of Engineers in the 1960s. This system is aging and eroding, partially caused by levees being originally built too steep. In 2006 alone $33 million of damage was caused by floods. It is estimated that flood protection infrastructure in King County protects $7 billion of built capital.[112] Fortunately steps have been made to fix and update this system. King County has an in depth flood management plan, and is one of the

[110] "Green - Duwamish River Watershed," Watersheds, rivers and streams, King County website, last updated February 18, 2014, http://www.kingcounty.gov/environment/watersheds/green-river.aspx
[111] "Preventing flood disasters," King County Connects, Video, King County website, last updated February 18, 2014, http://www.kingcounty.gov/environment/watersheds/green-river.aspx
[112] Ibid.

highest rated flood mitigation programs in the nation according to FEMA's Community Rating System. This is in part due to the county's flood warning center, flood plan, education and outreach. The plan is tied together with improving salmon habitat which is seen as a major factor for levee replacements and levee setbacks.

Salmon need several ecological characteristics to ensure health. Fortunately their needs fit in well with overall watershed health. These characteristics are cool unpolluted water, spawning gravels, freshwater habitats such as side channels and off-channel marshes and sloughs, nearshore marine habitats, and the opportunity to return to their original streams to spawn.[113] In order to guarantee these watershed characteristics for a long-term salmon recovery several actions must take place. Existing high quality habitat must be protected, as well as protecting and improving water quality and streamflows.[114] Restoration of degraded rivers, streams, and estuaries must take place. Hatcheries need to be reformed to support viable salmonid populations and harvests must be managed to ensure adequate escapement of wild-spawning fish.

The Green/Duwamish watershed has many challenges in regards to balancing salmon habitat restoration, flood hazard mitigation, and preserving existing land uses. Accomplishing all goals is a daunting task, but with proper planning, budget, and tools much improvement can be made. GIS-based MCDA for flood attenuation/river restoration projects is seen as an excellent tool to help guide and implement proper programming.

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[113] See note 96.
[114] Ibid.

The sub-watershed in specific focus for this study is the Lower Green River. A larger focus was desired, but due to limited levee data focus is made on lands adjacent to levees.

Figure 3.1 - WRIA 9 Location

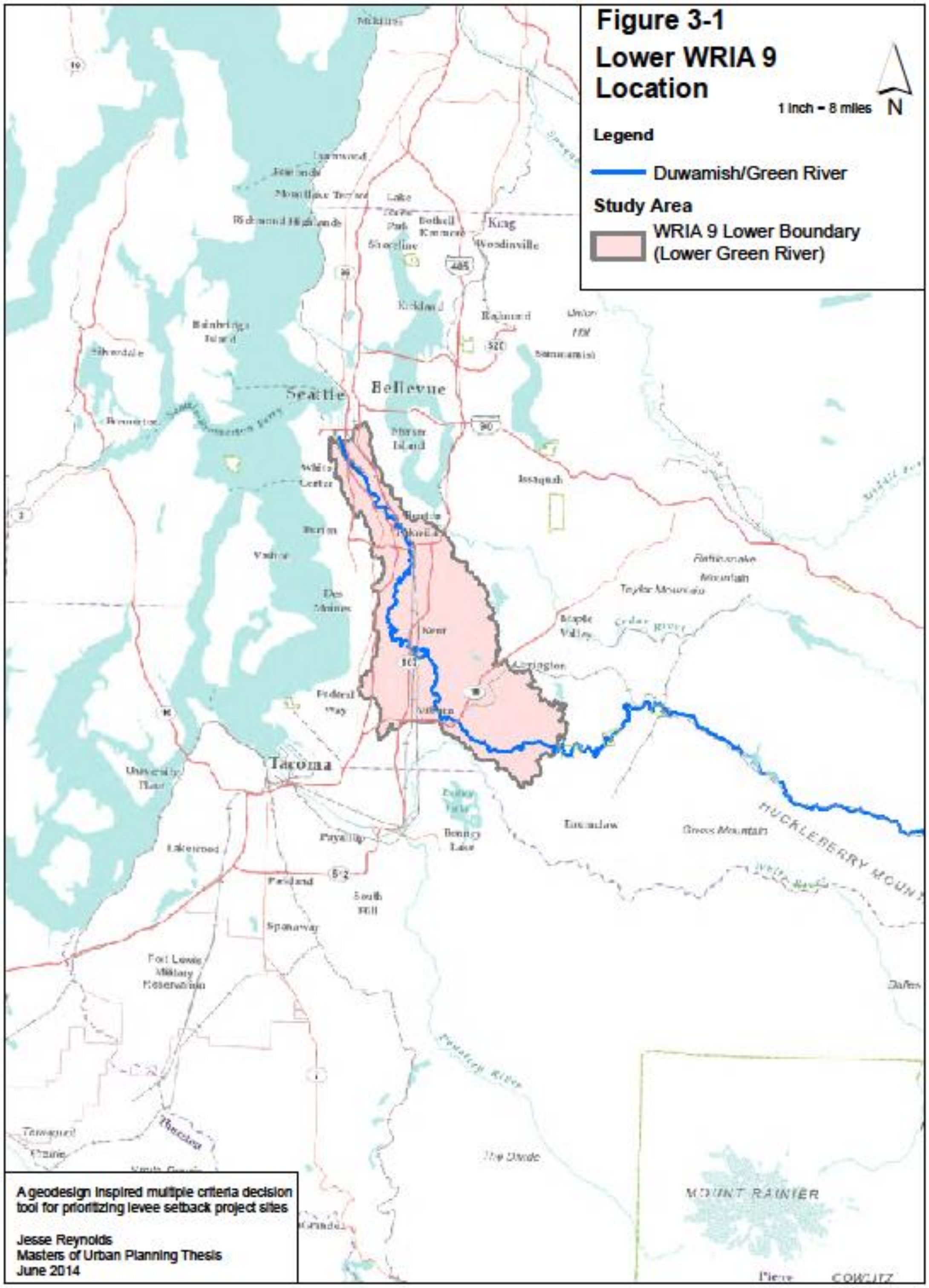
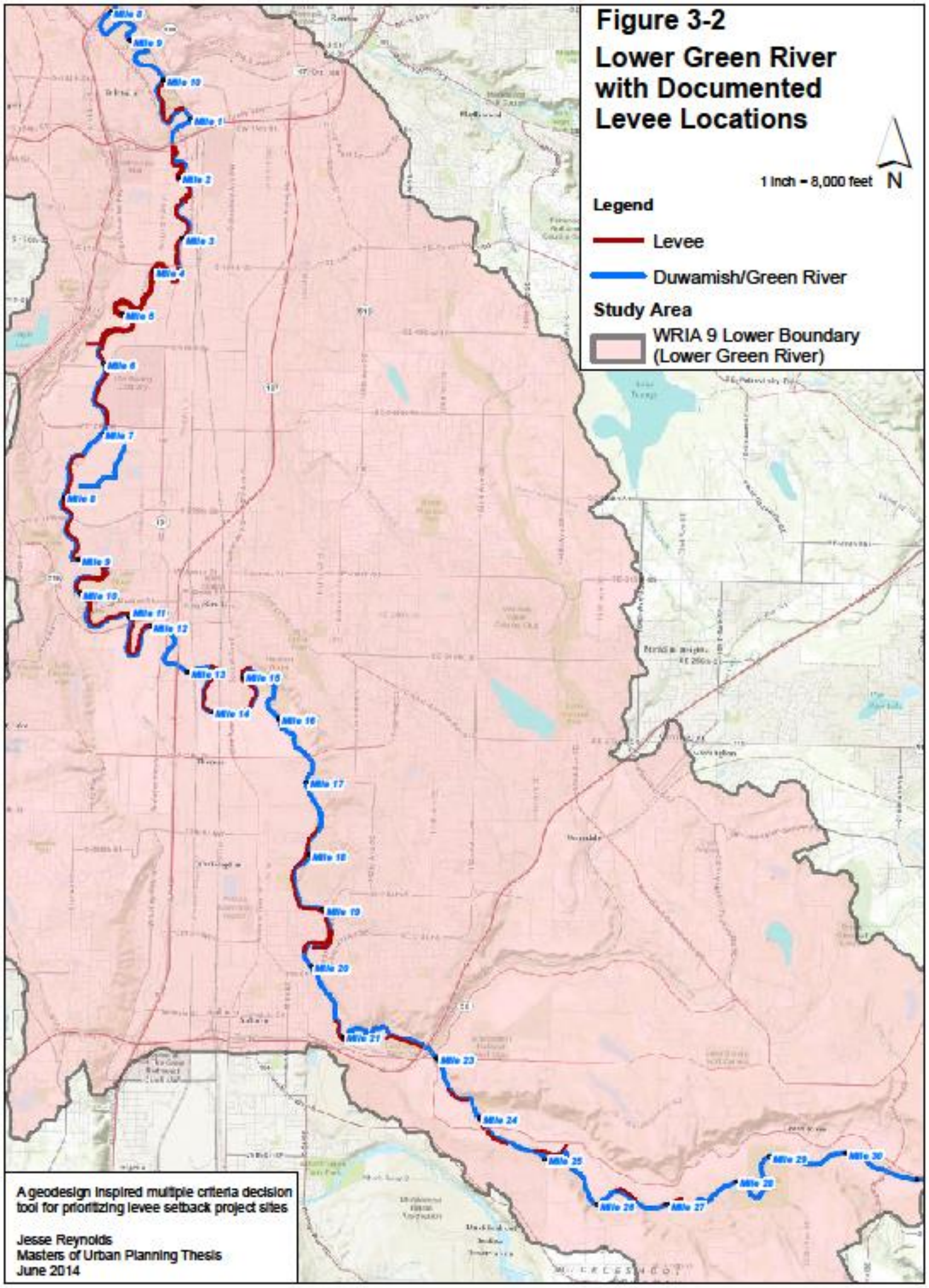


Figure 3.2 - Lower Green River with documented levee locations



3.2- Geodesign inspired methodology

Efforts are made to keep the modeling process simple as a response to data availability, processing time and limited resources. The goal of this thesis is not to provide King County with information they don't possess, but more to leverage their resources to create a tool other counties and jurisdictions with less resources could use. This will be accomplished by maintaining an equal resolution for all criteria; the resolution being planning level estimations. Also, focus is made on the processes in the tool itself, versus what goes in it. Criteria can be changed or added relative to the specific study site, and problem statement.

As mentioned in the Geodesign section (Section 2.3.5) of the Methodological and Substantive Foundations section, this framework is referred to as an inspiration for the models developed for this thesis. Unfortunately, due to limited resources, a complete framework requires more resources than what are available for this thesis, so an abbreviated version is used instead. For this reason we will refer to the chosen format as geodesign inspired. Below are elements of Carl Steinitz's framework derived from his book "A Framework for Geodesign", with explanations as to how these elements will be used. [115]

The complete geodesign framework consists of a six step process that is repeated three times in separate iterations. The first iteration works from step one to six, the second works backwards from steps six to one. The final iteration solidifies the six steps by working from one to six once again. This thesis turns the six step process in to four by combining the middle steps into a **Spatial Screening and Alternatives Criteria Model**. The first model, the **Representation**

[115] Steinitz, Carl, "A Framework for Geodesign," ESRI Press, Redlands CA, 2012.

Model and Preprocess Model remains intact. The same is the case for the final model, the **Decision Support Model**. This is because a proper geodesign process involves intimate knowledge of the study area and stakeholder involvement at several points. This thesis is seen as a preliminary overview of the criteria effecting the prioritization of levee setbacks in the Green/Duwamish watershed of King County, with hypothetical stakeholder involvement for ranking criteria during the Decision Support Model.

The original six questions,[116] shown in Section 2.3.5, can be combined into the following three: 1. How should the study area be described? 2. How can the study area be modeled in a way to adequately show desired and undesired levee setback locations including stakeholder opinion? and 3. Where changes should take place in the study area?

1. **How should the study area be described?**

The first step in this process is to describe the study area.[117] Areas outside of documented levees are seen as the areas of importance. The decisions will be specifically focused on the lands surrounding levees, but the entire floodplain needs to be understood to get a full perspective of the system being changed. Sources and specific content of data will be defined here.[118] Data from King County and Ecology are used.

2. **How can the study area be modeled in a way to adequately show desired and undesired impacts of levee setbacks according to stakeholder opinion?**

[116] Steinitz, 1 (see page 4).
[117] Steinitz, 1 (see page 37).
[118] Steinitz, 1 (see page 74).

The spatial screening and alternatives criteria model section of this question will be examining the interrelatedness of the criteria being analyzed.[119] The spatial screening and alternatives criteria models can be accomplished by creating a framework that allows decision makers to view each parcel in regards to which lands have built capital of importance and which areas have most potential for habitat restoration.[120]

3. How should the study area be changed?

This is the part of the model where stakeholders (hypothetical or not) are asked to weight the criteria presented within the GIS-based MCDA process. It is the part of the process that will aid stakeholders in rating and ranking parcels adjacent to sections of levees most suitable for setbacks.

3.3 - Model 1: Representation Model and Process Model

The Representation Model and Process Model consist of data acquisition, preprocessing, organizing and aggregating into a single geodatabase. The majority of the data comes from the King County GIS website, with a couple of layers from Ecology. Already created data was used for the purpose of simplicity due to resource constraints. Also, it was desired to keep everything at the same level of detail. A data dictionary was created to document layers used. The data dictionary documents the information needed, the source of the data, the name of the data from its source, its purpose, the feature and feature group used in this thesis, and the original format of the data. This can be seen on Figure 3.3 - Data Dictionary.

[119] Ibid.
[120] Steinitz, 1 (see page 38).

Each of the features used in the models, as well as ancillary data used for further assessment were categorized into groups according to their general theme. These groups of are referred to as feature groups. The groups define how the data is represented to stakeholders in the surveys. These feature groups are defined as Base, Ecological, Hazard, and Land Use/Cultural. The Base Feature Group serves two purposes: as a placeholder for data used only for cartographic purposes, and as a location for the central data layers used in the analysis. Layers for cartographic purposes only include River Mile, Rivers and Streams, and the WRIA 9 Boundary. Tribal Lands also are in this category as a reference only, because their land is not directly adjacent to levees. The central features of the analysis include Levees and Parcels, levees being the features that are potentially changed, and parcels being the decision units. Within the study area there are 21.42 Miles of levees whose adjacent lands will be assessed.

The Ecological Feature Group was made to summarize the areas of ecological importance in the study area. The features include Chinook Salmon Distribution,[121] Erosion Prone Areas[122], Wetland Areas[123], and Restoration and Preservation Prioritization Areas defined by Ecology. This last feature was not used in any of the models, but is examined during the results section. From these features it is realized that the study area is a flood hazard area with intense development, yet it still has ecological value. Parcels with a presence of these features are considered positive influences for levee setbacks.

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[121] Matella, Mary. 2013. Floodplain restoration planning for a changing climate: Coupling flow dynamics with ecosystem benefits. http://digitalassets.lib.berkeley.edu/etd/ucb/text/Matella_berkeley_0028E_13355.pdf

[122] Malczewski, Jacek, Terry Chapman, Cindy Flegel, Dan Walters, et al. 2003. "GIS - multicriteria evaluation with ordered weighted averaging (OWA): case study of developing watershed management strategies". Environment & Planning A. 35 (10).

[123] Ibid.

The Hazards Feature Group includes features that are considered positive influences for levee setbacks because of their threat to lives and built capital, as well as their contribution to natural processes. These features include the River Channel Migration area, 100 year Floodplain, Landslide hazard area, and Vulnerable Built Capital area.[124] The Vulnerable Built Capital area is not included in the model, but is used as a reference to the results.

The Land Use/Cultural Feature Group includes features that are considered negative influences on potential levee setback areas. This is because the taking of these lands for levee setbacks would create a negative impact on human use. These features include Urban Growth Areas, Roads, and Farmland Preserve. If an area is designated as urban this is considered negative. Lands already in the King County Farmland Preservation Program are considered negative.[125] Roads, considered critical infrastructure are negative as well.

All data was projected in to NAD 1983 HARN State Plane Washington North, the projection commonly used by King County. The data was then clipped to WRIA 9 for the purpose of only analyzing data within the study area. With the data clipped, reprojected and organized in a single geodatabase everything is ready for the first of the three analysis models, the Spatial Screening Model.

Figure 3.4 below shows these features adjacent to the levees. As you can see there are a lot of overlapping features and conflicting land uses, with a large portion of them covered by the 100 year floodplain.

[124] King County Critical Areas Ordinance, Title 21A Zoning, Ordinance 15051, last updated February 5, 2014, http://www.kingcounty.gov/council/legislation/kc_code/24_30_Title_21A.aspx.

[125] "Farmland Preservation Program," Water and Land Resources Division, King County, WA, updated on November 6, 2013, http://www.kingcounty.gov/environment/wlr/sections-programs/rural-regional-services-section/agriculture-program/farmland-preservation-program.aspx

Figure 3.3 Data Dictionary

Figure 3-3
Data Dictionary

Information Needed	Source	Source Name	Purpose/Use	Feature	Feature Group	Original Format
Floodway	King County	hydro/floodway	Cartography, demonstration of existing area	Floodway	Base	.shp
River Mile	King County	hydro/river_mile	Cartography, point of reference	RiverMile	Base	.shp
Rivers and Streams	King County	hydro/wtrcrs	Cartography, stream ID	HydroLine	Base	.shp
Levee	Washington State Dept of	Levee database	Levees to analyze	Levee	Base	.shp
Lower WRIA 9 Bountary	Washington State Dept of	WRIA	Analysis area delineation	WRIA9_Lower	Base	.shp
Parcels	King County	property/parcel_address	The unit to aid in decision making (ownership, land	Parcels	Base	.shp
Tribal Lands	King County	politicl/tribal_lands	Cartography	TribalLands	Base	.shp
Chinook Salmon Distribution	King County	enviro/chinbuff	Salmon habitat delineation	ChinookDist	Ecological	.shp
Erosion prone areas	King County	enviro/erode	Locate areas prone to erosion	Erosion	Ecological	.shp
Wetland areas	King County	enviro/wetlands	connectivity of river to wetlans	Wetland	Ecological	.shp
Restoration and Preservation Prioritization	Washington State Dept of	PSWCP	Restoration and preservation prioritization per	PSWCP_WaterFlow	Ecological	.shp
Channel Migration	King County	hydro/chnlmigr	3	ChannelMigration	Hazard	.shp
Vulnerable built capital area	FEMA	reploss_GIS.xlsx	compare levee setbacks to vulnerable areas	RepetitiveLoss	Hazard	.xls
Floodplain	King County	hydro/fldplain	Cartography, demonstration of existing area	Floodplain	Hazard	.shp
Landslide hazard area	King County	enviro/slide	Locate areas prone to landslides	Landslide	Hazard	.shp
Designated Urban Growth Area	King County	planning/urban_growth	Areas to avoid	UGA	LandUseCultural	.shp
Roads	King County	transportation/trans_network	Mostly for cartography	Roads	LandUseCultural	.shp
Designated farmland preservation	King County	natres/farmland	to ID already preserved farmlands	FarmlandPreserve	LandUseCultural	.shp
Land Use	Washington State Dept of	Land Use: Washington State 2010	May join to parcels	LandUse	LandUseCultural	.shp

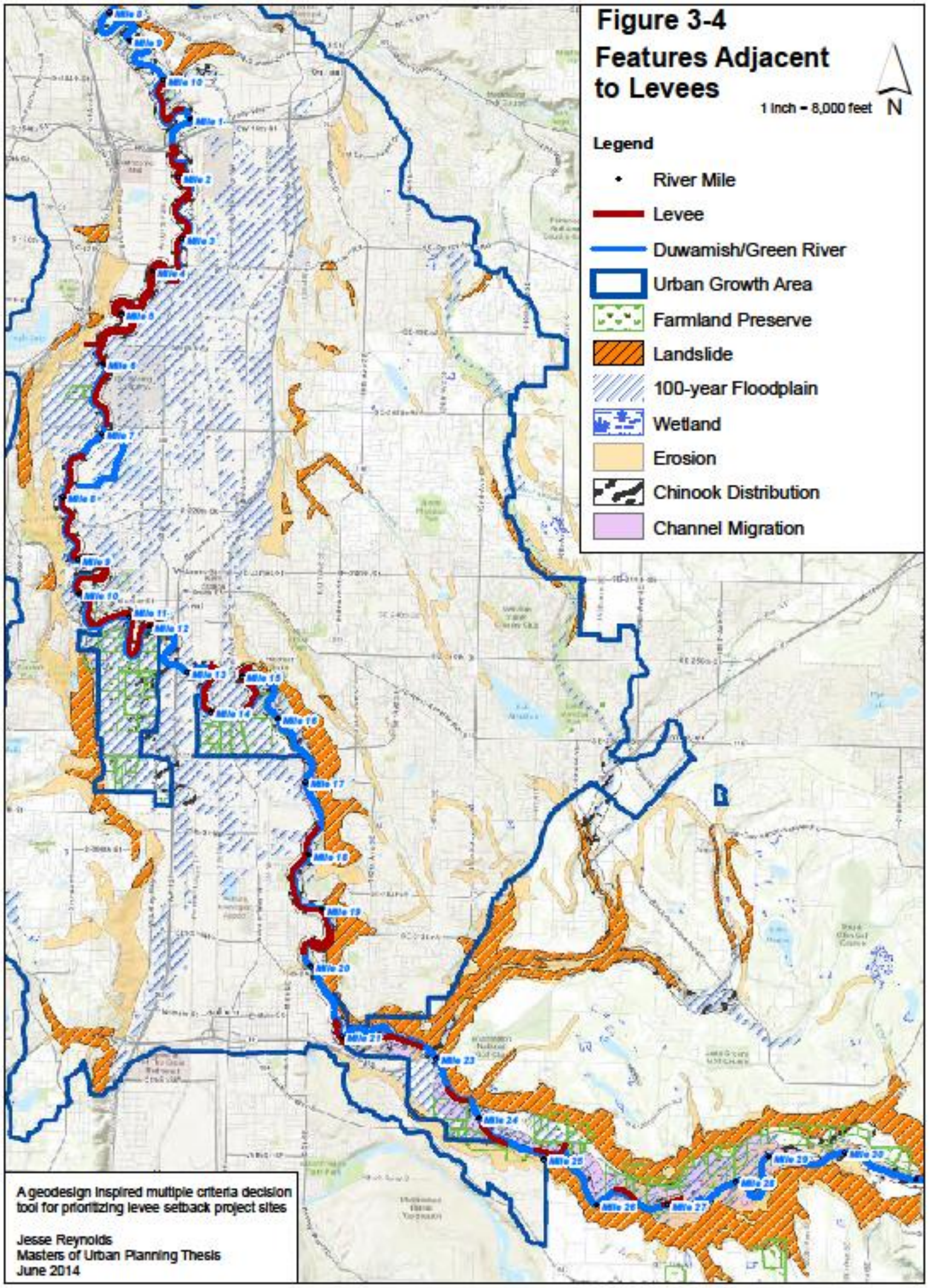
Signifies model criteria

Signifies centerpiece of model

A geodesign inspired multiple criteria decision tool for prioritizing levee setback project sites

Jesse Reynolds
Masters of Urban Planning Thesis
June 2014

Figure 3.4 - Features Adjacent to Levees



3.4 - Model 2: Spatial Screening Model

The following three models are constructed in ESRI's ArcGIS 10.1 ArcToolbox Model Builder, a graphical interface alternative to scripting used to link geoprocessing steps together.[126] The purpose of the Spatial Screening Model is to isolate the parcels of interest in order to focus our analysis where stakeholders should influence levee setback decisions. The first step in a tool of this sort should always be a pre-selection based on limiting constraints.[127] This can be done manually by hand picking parcels of interest. In the case of this model we automated the process by choosing parcels adjacent to levees.

This automated process can be seen in Figure 3.5 which is the graphical output of the Spatial Screening Model. The first step in the model was to bring in the parcels layer as well as the levee layer, both previously clipped to the WRIA 9 Boundary. The 'Near' Tool found in ArcToolbox was used to identify parcels within 100 feet of levees. Once these were defined parcels with hydrographic features, i.e. parcels that lie within the Green River, were queried out of the dataset. This query will be unique for each study depending on the format of the data and the area covered. That is why this query was made a model parameter, as seen in the user interface at the end of this chapter. In this case parcels with identifiers considering their present use to be River/Creek/Stream, Tidelands, Fresh Water Bodies, or hydrography in general were queried out. The result was 330 parcels totaling an area of 2090.66 Acres, which can be seen in Figure 3.6.

[126] For more on Model Builder please visit - http://resources.arcgis.com/en/help/main/10.1/index.html#//002w00000001000000

[127] Rohde, S., M. Hostmann, A. Peter, and K.C. Ewald. 2006. "Room for rivers: An integrative search strategy for floodplain restoration". Landscape and Urban Planning. 78 (1-2): 50-70.

Figure 3.5 - Spatial Screening Model

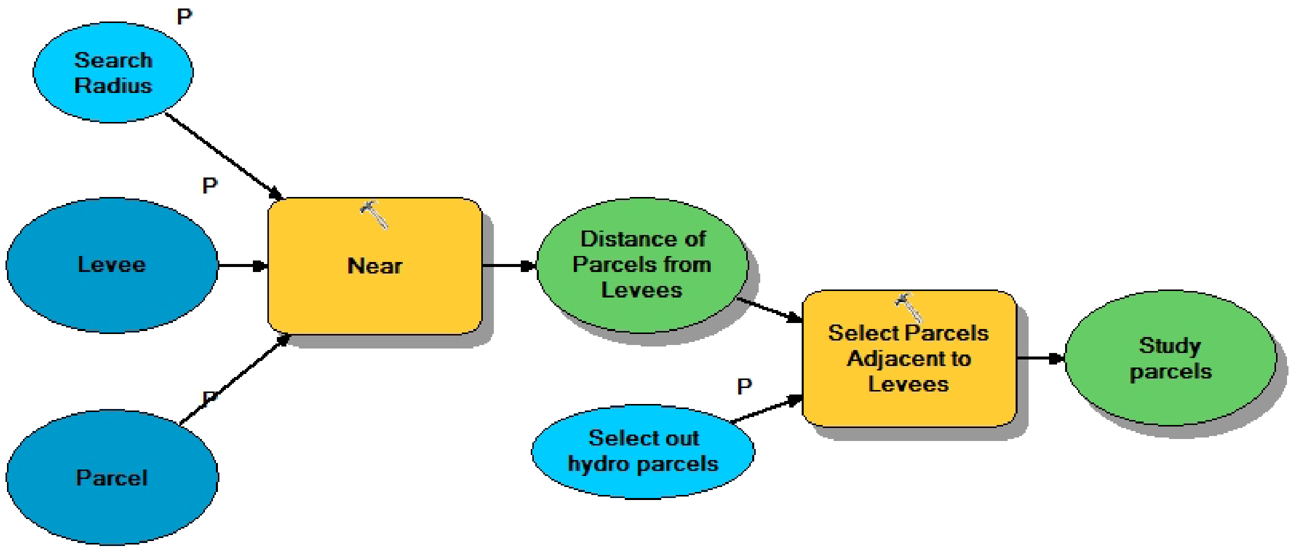
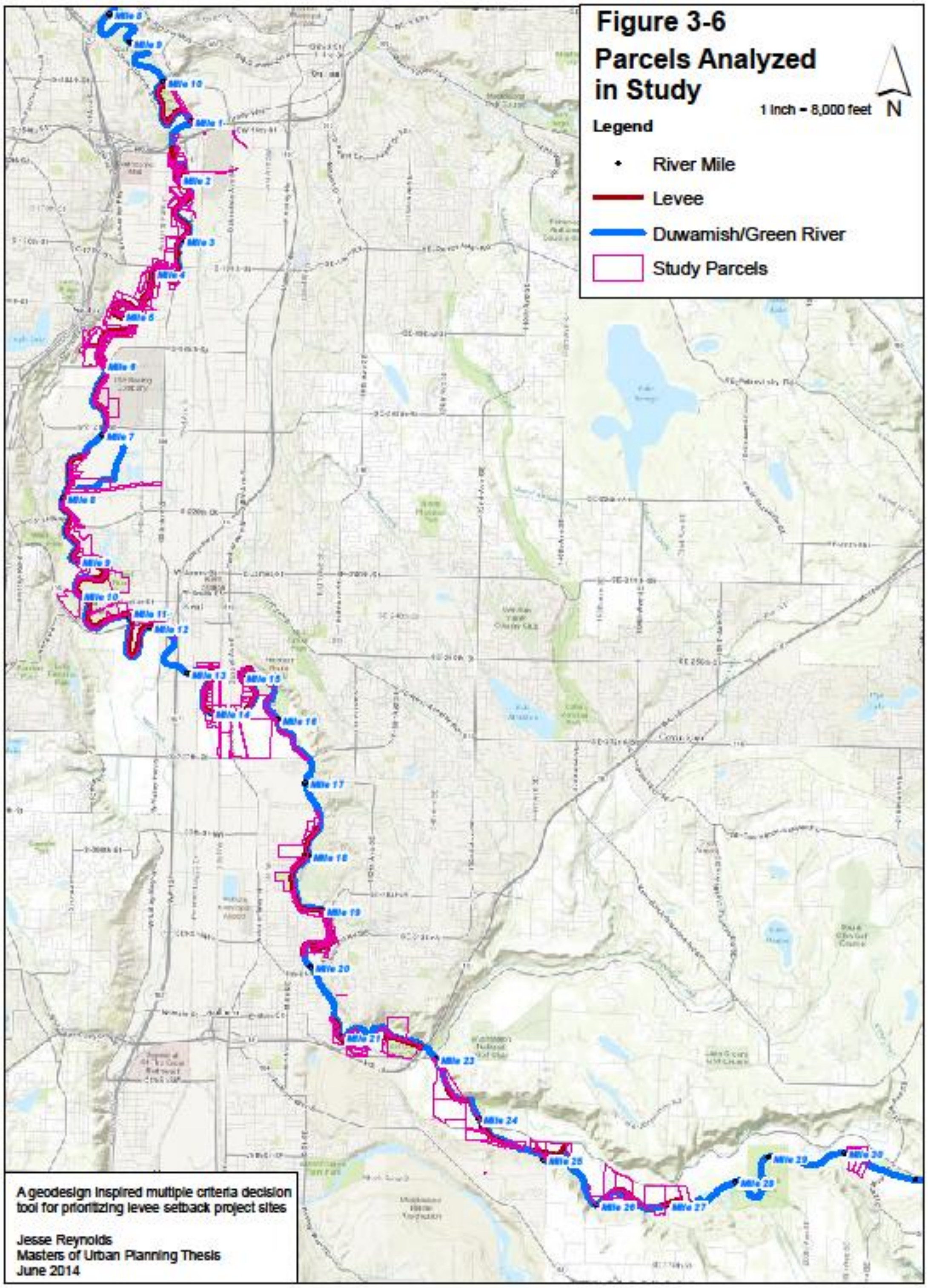


Figure 3.6 - Parcels Analyzed in Study



3.5 - Model 3: Alternatives Criteria Model

Now that the study area has been defined in the Spatial Screening Model, each individual criterion, found in separate features or within the parcels data, becomes its own feature class and is standardized so that it can be comparable to all the others. This is done by creating copies of the parcel layer to represent each criterion. Then a series of calculations occurs in an effort to standardize the data. With the exception of built capital value and total appraised value of parcel, the parcel layers are rated according to their distance to each criterion, whether it be a positive, or negative (inverse value) distance.

Criteria associated with existing land uses were first examined for negative influence. The first criterion involves the Roads layer. The model asks how near roads is to a given parcel, and then assigns a value on a scale from 0 to 100 to each parcel on their relative proximity. Parcels far away from roads are ranked more favorable than those closer to roads, which are ranked more favorably than those containing roads. The 'Near' tool found in ArcToolbox is used to define these distances. Once this is calculated the minimum and maximum values can be defined, which is key to complete the two-step rank sum procedure used. With these values the rank magnitude is calculated first using the following equation: (Maximum Distance - Minimum Distance) / 100. Once rank magnitude is known for the roads criterion the Rank is calculated with the following equation: 100 - ((Maximum - [Distance of individual feature] /

[Rank Magnitude][128129]. Now each parcel has a road proximity rank associated with it and is ready to be weighted by stakeholders.

The next criterion considers built capital present. Appraised value of built capital, also referred to as improvements, can be found in the parcels layer. Because we are not ranking each individual parcel by proximity to another feature, but using values already in its attribute table, the steps used are slightly different. The amount of built capital in dollar value in each parcel is compared relative to all other parcels in the study. Aside from dollar value being different than proximity to a feature, this process is the same as roads, calculating the rank magnitude using maximum and minimum appraised land improvement values, than calculating the rank. The equations are almost the same as those in the Roads except that smaller values are seen as favorable.[130]

Urban Growth Areas are ranked the same as roads in regards to a parcel's proximity to urban areas. There is just one initial step that is in addition. Urban lands are isolated from the other lands in the Urban Growth Areas feature so their proximity to parcels are the only land classifications considered. The equations used are the same as those in the Roads feature because this too is a negative influence attribute.

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[128] Nyerges, Timothy L., and Piotr Jankowski. 2010. Regional and urban GIS: a decision support approach. New York: Guilford Press, 139.

[129] Note the 100 in front of the equation. If roads were a positive influence the 100 would be absent and the equation would be as follows: ((Maximum - [Distance of feature] / [Rank Magnitude].

[130] See note 25.

The importance of maintaining local farmlands is considered, so the King County Farmland Preservation Program feature is used.[131] The process and equations used are the same as those used in the Roads feature, because this too is a negative influence. Originally Tribal Lands were going to be included as well, but on initial inspection it was found that though the Muckleshoot tribal land is close to the parcels in the study, its lands do not actually comprise them.

For the subject of hazard resilience the proximity of three features to the parcels in question are explored: Channel Migration areas, 100-year Floodplain, and Landslide prone areas. These particular hazards are considered because they are all within the King County Critical Areas Ordinance.[132] The process and equations used for these three features almost completely mirrors that described in Roads, but because the proximity of these features are all considered positive influences for levee setback areas the rank equation used is slightly different.[133] These features are seen as positive influence because by allowing parcels to become an active part of the river once again we are reducing human exposure to the associated hazards with rivers, hence a more favorable ranking is given the closer parcels are to these features.

Ecological health is considered next. The three features examined are Chinook Distribution[134], Erosion[135], and Wetlands[136]. Like the Hazards Group, parcels with a closer

[131] "Farmland Preservation Program," Water and Land Resources Division, King County, WA, updated on November 6, 2013, http://www.kingcounty.gov/environment/wlr/sections-programs/rural-regional-services-section/agriculture-program/farmland-preservation-program.aspx
[132] See note 20.
[133] See note 25.
[134] Matella, Mary. 2013. Floodplain restoration planning for a changing climate: Coupling flow dynamics with ecosystem benefits. http://digitalassets.lib.berkeley.edu/etd/ucb/text/Matella_berkeley_0028E_13355.pdf

proximity to these features are weighted more favorably. The process and equations used are exactly the same as those in the Hazards Group.

The last feature examined is Purchase Cost. As a surface view in to the financial realities of levee setbacks the purchase cost per square foot of each parcel is used to determine rank.[137] The appraised land value and appraised improvements are added together then divided by the square footage of the parcel. The rank magnitude is calculated by taking the range of the values and dividing by 100. Rank is then calculated using the same equations used for the Hazards Group. This is because like proximity, the less the number for cost, the more favorable.

For a graphical interpretation of this model please refer to Figure 3.7 below. It is recommended to zoom in to see each of the individual steps labelled. Blue is an input or model parameter, yellow is a process, and green is a result.

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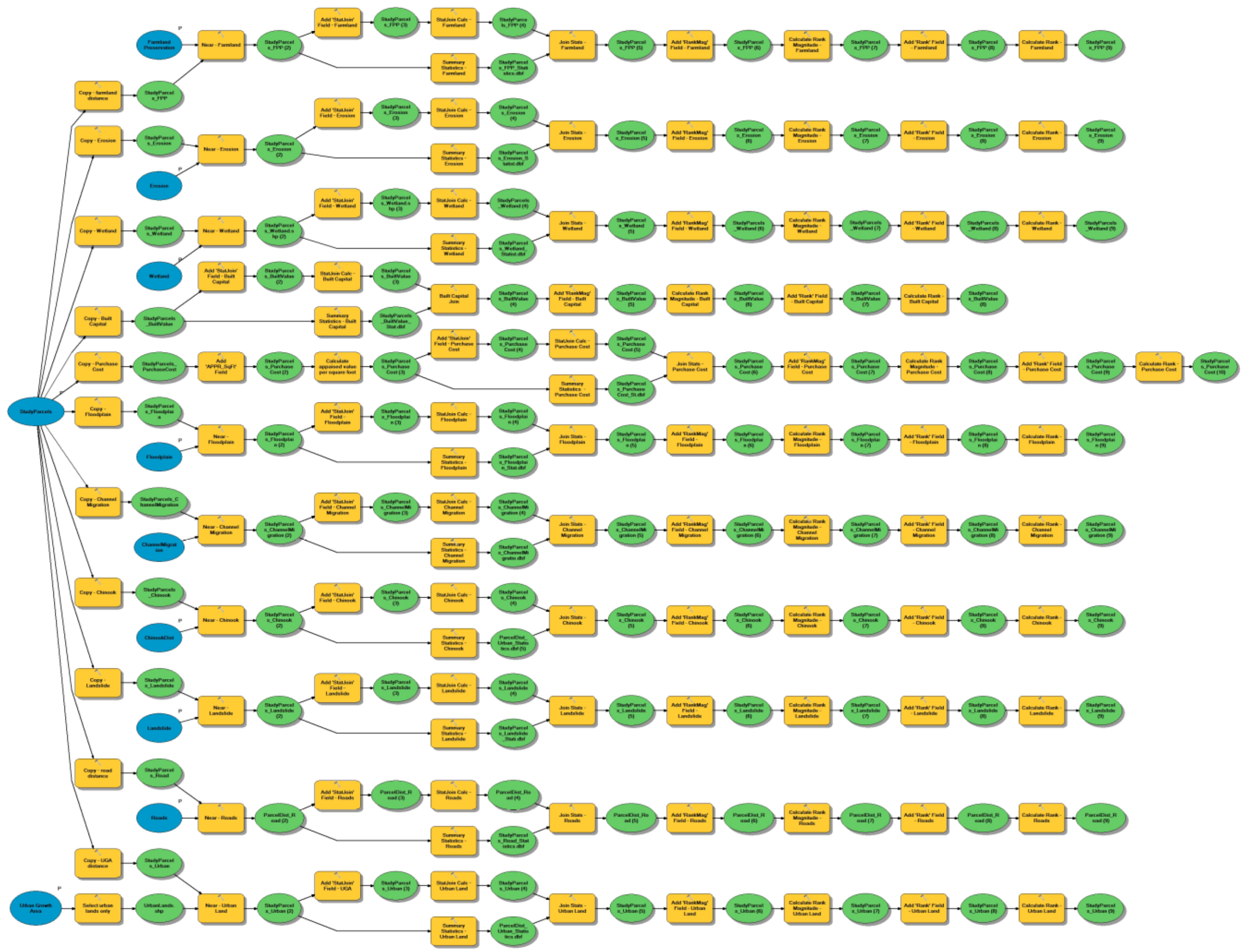
[135] See note 18.
[136] Ibid.
[137] Simonetta Angioni, Salvatore Cinus, Francesco Mazzeo Rinaldi, Roberto Wolfler Calvo, 2000. " A Decision Support System for Interventions Planning Aimed at Flood Damages". European Conference on Advances in Flood Research 553-561.

Figure 3.7 - Alternatives Criteria Model



3.6 - Model 4: Decision Support Model

The Decision Support Model is where the principal stakeholder participation occurs. To this point we have designated the parcels of interest, standardized and rated each of the eleven chosen criteria. Now it is the stakeholder's job to assign weights to each of the criteria according to their preferences and what they feel is most important. Combining this information with the objective performance information just discussed will result in all 330 parcels ranked as to level of suitability for levee setbacks. In this section the Decision Support Model is explained, as well as the methods used for stakeholder participation.

This first step of this model copies all eleven layers from the Alternatives Criteria Model to this model thus avoiding overwriting issues. A final results layer is copied over as well. A weight field is added to each of the Features and made a model parameter so stakeholders could input their desired criteria values in to the tool directly, without opening the model. The rank sum method is used by having 100 points total to distribute between the eleven criteria.[138] A score criteria field is added in order to multiply the rank of each criteria parcel by its assigned weight. Once this is calculated for each feature the scores are then added together in the final results layer to get a final appraisal score.[139] The final step is to rename the resulting layer in order to keep the results and avoid overwriting issues.

[138] Herath, G. and Prato, T. (eds) (2006). Role of multi-criteria decision making in natural resource management. In: Using multi-criteria decision analysis in natural resource management. Aldershot, UK: Ashgate, pp. 1–10
[139] Nyerges, Jankowski, 23 (see page 136).

For a graphical interpretation of this model please refer to Figure 3.8 below. It is recommended to zoom in to see each of the individual steps labelled. Blue is an input or model parameter, yellow is a process, and green is a result.

The next part of this section is deciding on the values to input for the weights. The original thought was to develop a character profile and reasons explaining the weights assigned for each of the six hypothetical stakeholders: single family home owner, floodplain manager, tribal member, farmer, land developer, and environmental non-profit. But instead of doing a role-play exercise where the author assigns these values, it was decided to take it a step closer to real world results and solicit professionals who are in floodplain management or in a field directly related to the subject. Responses were received from five professionals who were asked to play the roles of these various affected parties. The values these professionals chose were averaged. These values and the associated model results can be seen in the following Results section. Results from a sensitivity analysis can be seen as well.

Figure 3.9 at the end of this section is an example of the spreadsheets sent to the floodplain management professionals when soliciting their assistance.

Figure 3.8 - Decision Support Model

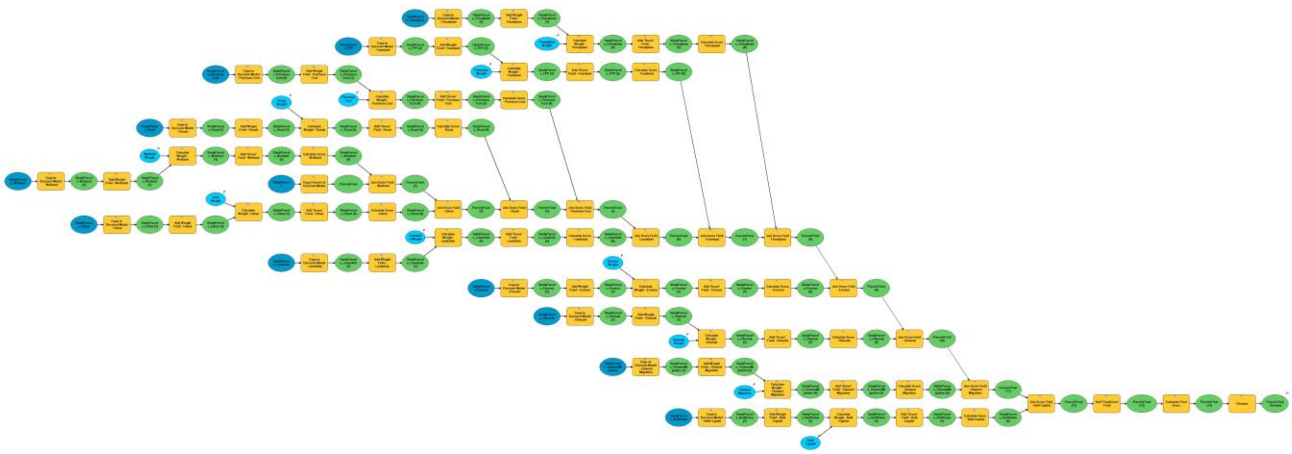


Figure 3.9 - Sample Stakeholder Participation Sheet

Figure 3-9
Sample Stakeholder Participation Sheet

Single Family Home Owner				
General Consideration	**Criteria**	**Brief Explanation**	**Influence**	**Assign Weight Here**
Cost	Land Purchase Cost	The total cost of land and improvements on a parcel. Criteria is standardized by calculating cost per square foot	negative	
Ecological	Chinook Habitat	Proximity of parcels to Chinook salmon habitat	positive	
Ecological	Erosion	Proximity of parcels to erosion areas	positive	
Ecological	Wetlands	Proximity of parcels to wetlands	positive	
Existing Land Use/Cultural	Built Capital	The total cost of improvements on a parcel	negative	
Existing Land Use/Cultural	Farmland Preservation	Proximity to King County Farmland Preservation Program lands	negative	
Existing Land Use/Cultural	Roads	Proximity to roads	negative	
Existing Land Use/Cultural	Urban Growth Area	Proximity to Urban designated areas under the Washington State Growth Management Act	negative	
Hazards	100yr Floodplain	Proximity of parcels to the 100 year flood plain	positive	
Hazards	Channel Migration	Proximity of parcels to river channel migration zones	positive	
Hazards	Landslide	Proximity of parcels to landslide prone areas	positive	
			Total weight (should be 100)	**0**

A geodesign inspired multiple criteria decision tool for prioritizing levee setback project sites

Jesse Reynolds
Masters of Urban Planning Thesis
June 2014

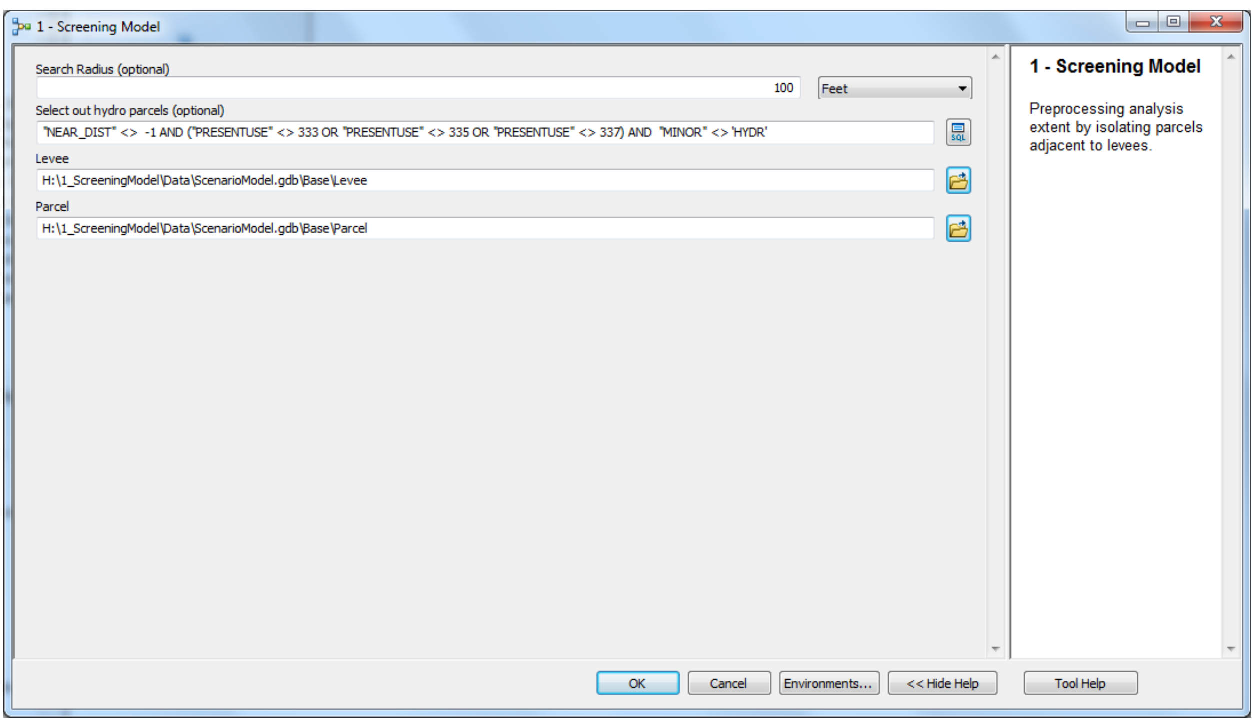
3.7 - Chapter Summary

We now conclude the Methodology Section. The study area, the Lower Green River, WA was first introduced, and its significance was explained. The model format was then explained in the context of being geodesign framework inspired. Each of the four models and their processing was laid out. With this background we are now able to explain the results the model produced employing weights from the hypothetical stakeholder exercise as well as a sensitivity analysis in the next section.

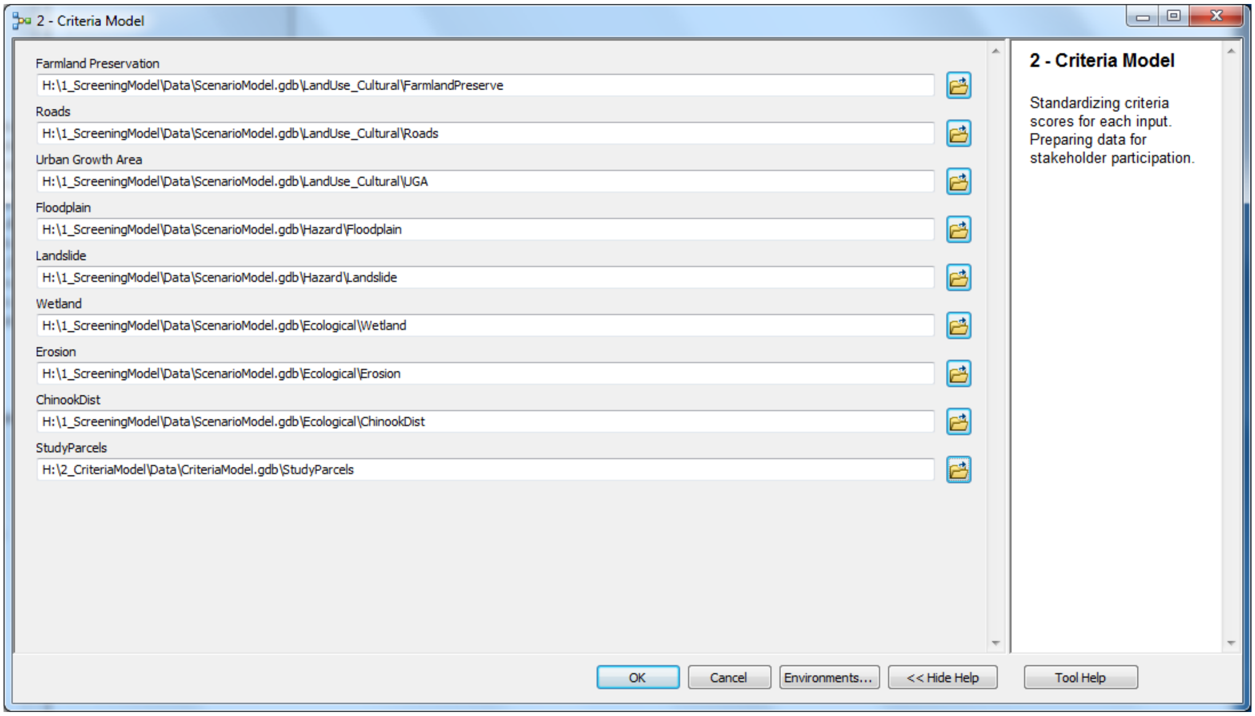
Figure 3.10 below shows the resulting user interface for the model.

Figure 3.10 - Model Interface

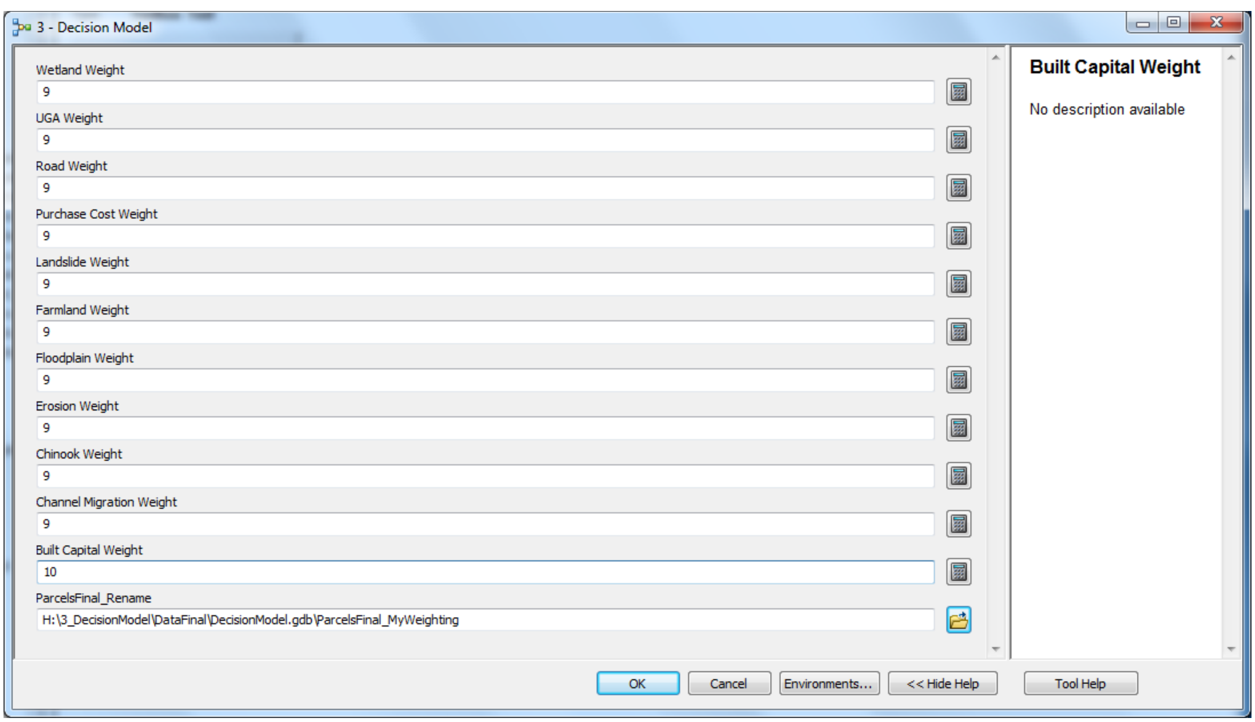
1 – Spatial Screening Model



2 – Alternatives Criteria Model



3 – Decision Support Model



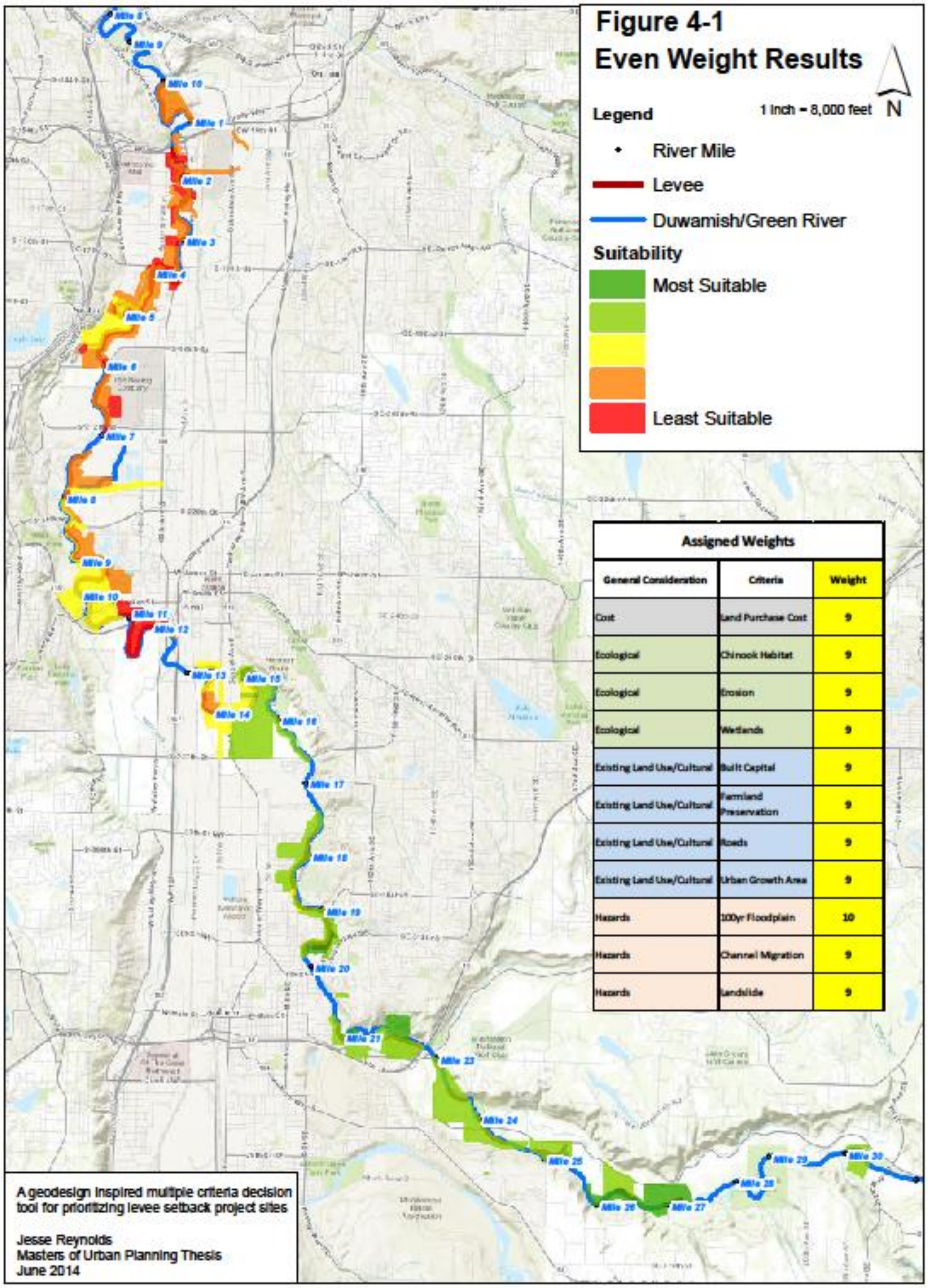
4.0 - Results

The following are explanations and resulting maps from running the Decision Support Model with different weights. An (almost) even weight distributed to all criteria is first explored. Next is a sensitivity analysis. Finally, the results we received from the hypothetical stakeholder outreach exercise are shown.

4.1- Even weighted results

In an effort to apply an even weight to all the criteria we gave every criterion nine points, with the exception of the 100-year floodplain criterion, which we arbitrarily gave ten. This is because there are 100 points for eleven criteria, which means there is no single integer to evenly distribute. The 100-year floodplain was chosen as the criterion with one extra weighting point because this is a thesis focusing on floodplain management. The results can be seen in the map in Figure 4.1 below. In Figure 4.1 the suitability color scale is calculated by taking the range of the final score, dividing it by five, then using that result as the equal interval between the five relative grades ranging from most suitable to least suitable. This method is the same for all of the maps in this section that follow. From running the model with an almost even weight distribution obvious patterns emerge. Parcels become more favorable the farther up the river one goes. Above Mile 15 parcels are rated on the most suitable side of the range. Below they are for the most part rated least suitable.

Figure 4.1 - Even Weight Results



Assigned Weights

General Consideration	Criteria	Weight
Cost	Land Purchase Cost	9
Ecological	Chinook Habitat	9
Ecological	Erosion	9
Ecological	Wetlands	9
Existing Land Use/Cultural	Built Capital	9
Existing Land Use/Cultural	Farmland Preservation	9
Existing Land Use/Cultural	Roads	9
Existing Land Use/Cultural	Urban Growth Area	9
Hazards	100yr Floodplain	10
Hazards	Channel Migration	9
Hazards	Landslide	9

4.2 - Sensitivity analysis

In an effort to test the sensitivity of each criterion to the resulting prioritization list of parcels the Decision Support Model was run eleven individual times giving each criterion all 100 points. This method is referred to as one-at-a-time criterion examination.[140] Separate maps were made showing the results when all points were allocated to a specific criterion. Figures 4.2a through 4.2k show how the individual criteria influence the results. The color scale was made using the same methodology as the even weighted results in Figure 4.1.

Running the sensitivity analysis for each criterion shows its individual pattern of parcels favored. When added all together we get the results seen in Figure 4.1. When separated we get the following. Figure 4.2a shows parcels suitable and least suitable for levee setbacks due to cost. This was done by calculating the cost of a square foot of a parcel, so size of a parcel is not an influence. The results of this study show a few highly expensive parcels in the lower reaches of the study area, with almost all others categorized as most suitable.[141] This is because the few parcels that are considerably more expensive per square foot than all others cause a positively skewed distribution. Figure 4.2b, showing favorable parcels for Chinook habitat has most parcels as most suitable. This is because the Chinook Habitat layer taken from the King County website covers almost all of the lands in and adjacent to the river. This is discussed further in the Discussion section.

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[140] Ligmann-Zielinska, A. and Jankowski, P. (2008). A Framework for Sensitivity Analysis in Spatial Multiple Criteria Evaluation. Lecture notes in computer science. no. 5266, 217-233.

[141] The suitability grades in the sensitivity maps are the same methods used in the even score maps, where the suitability color scale is calculated by taking the range of the final score, dividing it by five, then dividing it by five to create equal intervals between the five relative grades ranging from most suitable to least suitable.

Areas prone to erosion, seen as favorable sites for levee setbacks, were shown in Figure 4-2c. Virtually all of the areas in the upper section of the study, and most of the areas in the middle section of the study are suitable. Only areas towards the bottom of the study area are considered marginally, or least suitable. Figure 4-2d, showing parcels favorable for wetlands connecting back to the river provides a common pattern for natural resources results in this analysis, upper areas of the study area are most suitable, while areas in the lower reaches are not.

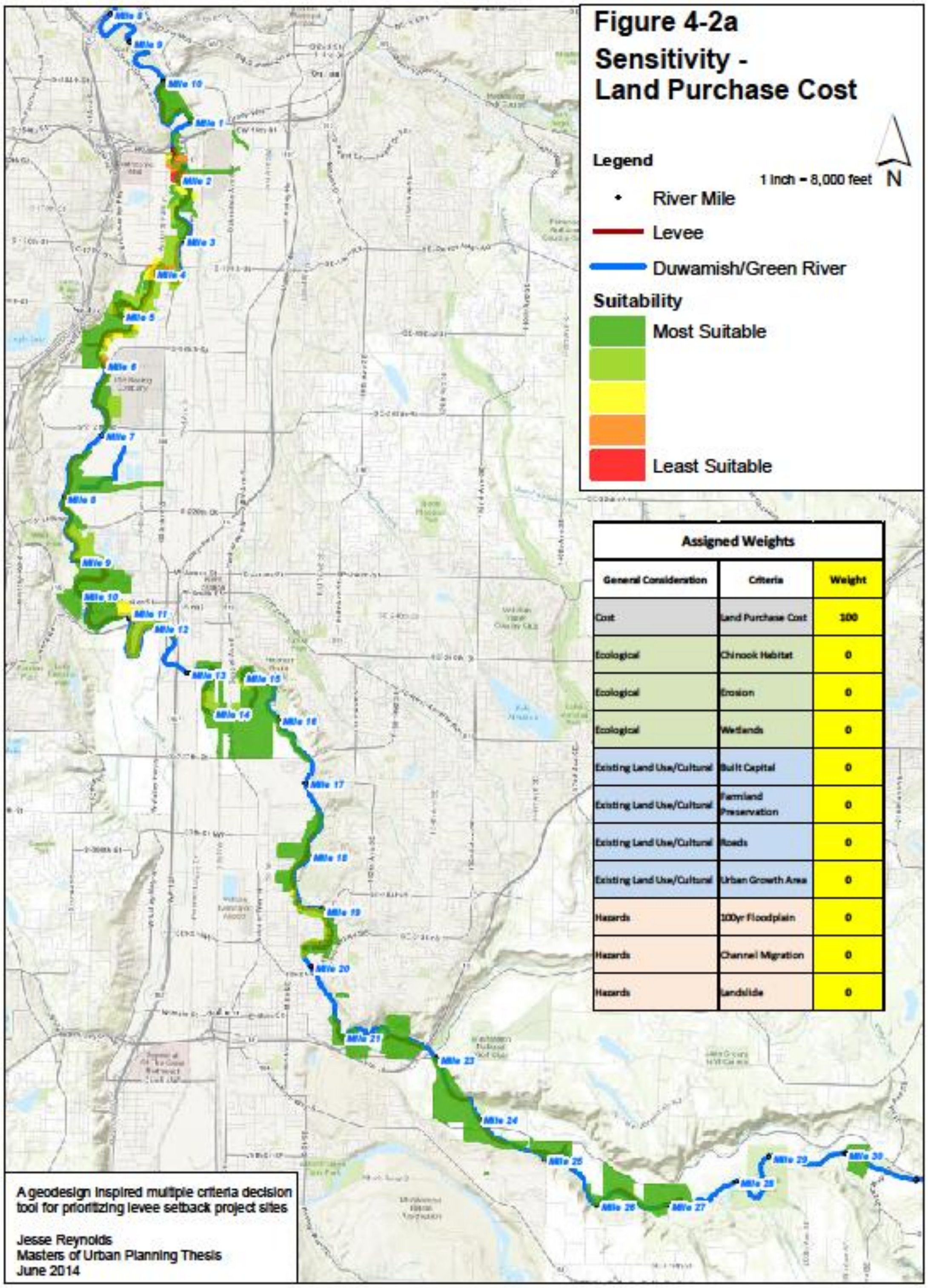
The built capital sensitivity results seen in figure 4-2e are abnormal. Most of the parcels are considered most suitable where one is considered least suitable because the value of its improvements is considerably higher than the others at $50million. Because the colors in the maps are designated at equal interval there is only one at the least suitable end of the spectrum, with all others at the most suitable end. The farmland sensitivity results in Figure 4-2f shows a pattern differing from most of the other criteria. With King County Farmland Preservation Program lands scattered throughout the middle and upper reaches of the study area most parcels range from marginally to least suitable. The lower reaches, being the most heavily influenced by development, show as most favorable because these lands are farthest away from farms.

With the exception of a few parcels in the upper reaches of the study area almost all of the parcels are considered least suitable for the roads sensitivity analysis in Figure 4-2g. This is because roads cross almost all of the parcels giving them a least suitable score. The urban growth area results in Figure 4-2h show similar results to roads. All of the parcels in the lower and middle reaches of the study area are shown as least favorable, with nothing favorable until the very top of the study area at Mile 27. This is because the urban growth area covers almost all of these lands adjacent to the lower river.

To contrast what we saw in Figure 4-2h, Figure 4-2i showing lands favorable according to the floodplain criterion have most parcels as most favorable. This is because almost all of the lands adjacent to the river are found within the 100-year floodplain according to the latest King County data. There are only a few exceptions in small parcels in the lower reaches. Channel migration in Figure 4-2j is a similar result to the ecological criteria with most favorable parcels in the upper reaches, and least favorable parcels in the lower reaches. The last criterion examined in this section, landslides in Figure 4-2k shows mixed results in the lower and middle reaches of the study, with almost all of the parcels deemed as favorable in the upper reaches.

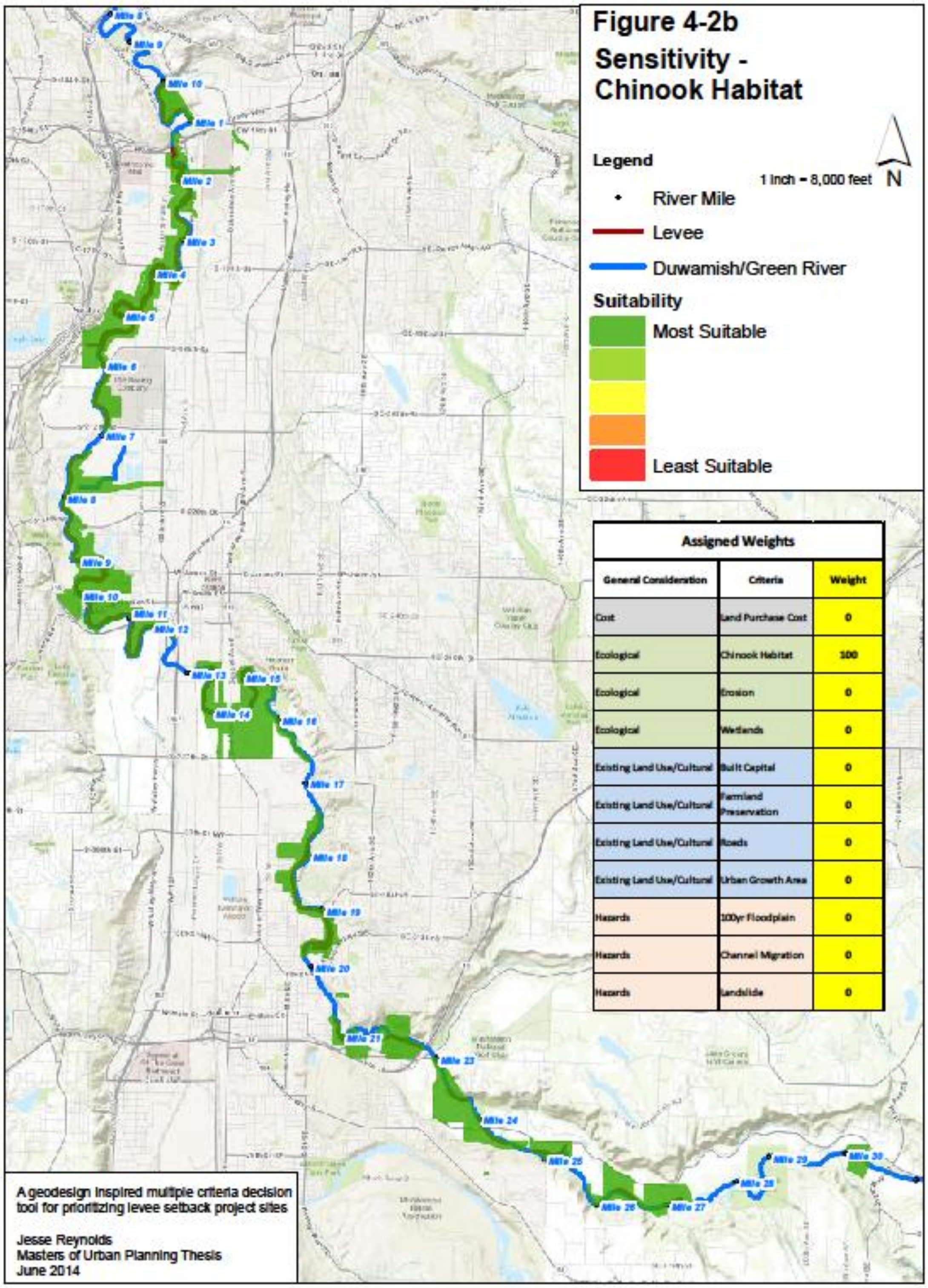
This was a simple exercise to show how each of the eleven criteria influence the results. Each criterion was given complete influence, as if it were the only criterion studied. The goal of this section was to give the reader insight as to how each of the criteria interacts with each other to form final results. Next we will examine how the criteria are combined in model results through the hypothetical stakeholder exercise.

Figure 4.2a - Sensitivity - Land Purchase Cost



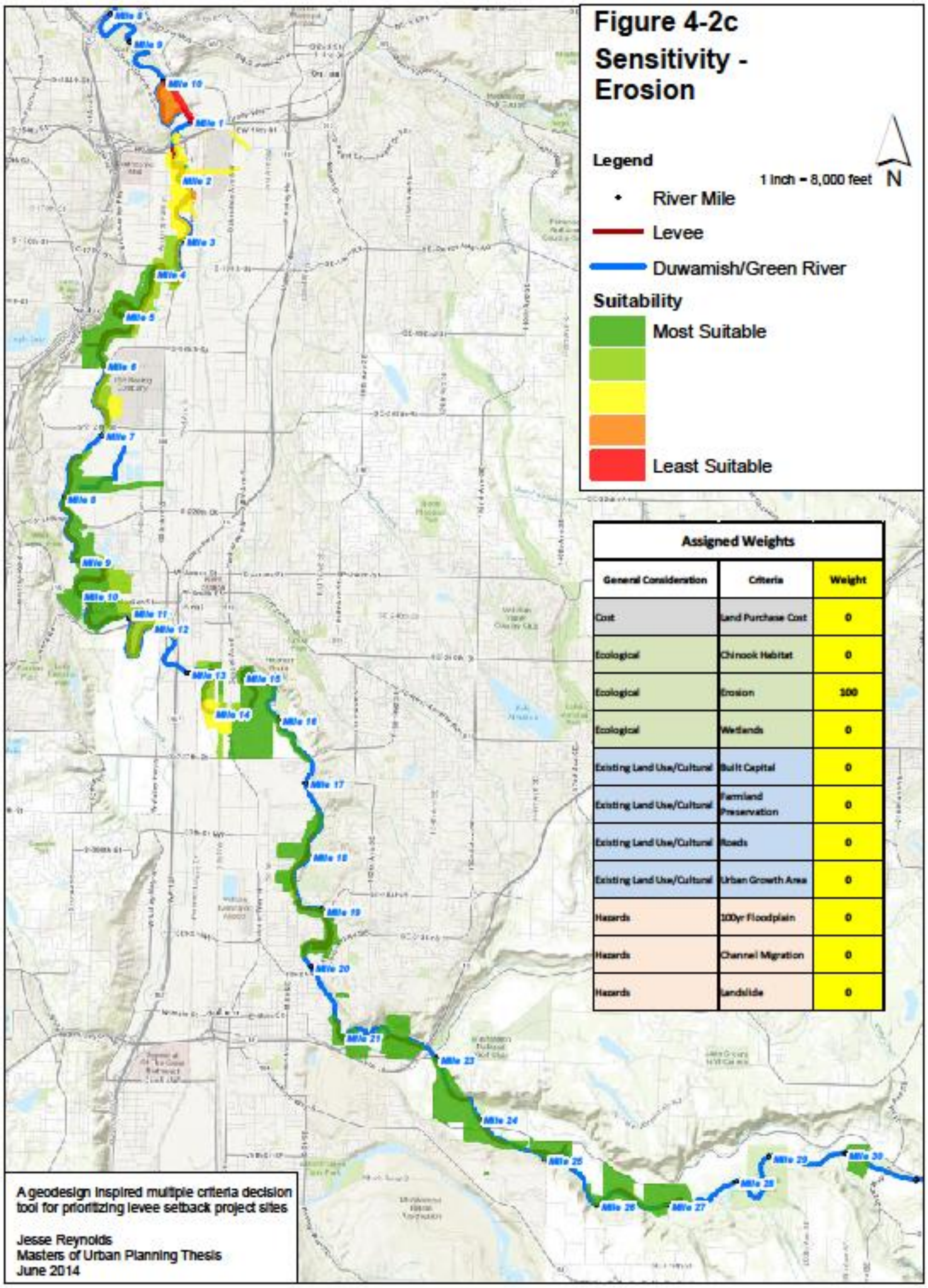
General Consideration	Criteria	Weight
Cost	Land Purchase Cost	100
Ecological	Chinook Habitat	0
Ecological	Erosion	0
Ecological	Wetlands	0
Existing Land Use/Cultural	Built Capital	0
Existing Land Use/Cultural	Farmland Preservation	0
Existing Land Use/Cultural	Roads	0
Existing Land Use/Cultural	Urban Growth Area	0
Hazards	100yr Floodplain	0
Hazards	Channel Migration	0
Hazards	Landslide	0

Figure 4.2b - Sensitivity - Chinook Habitat



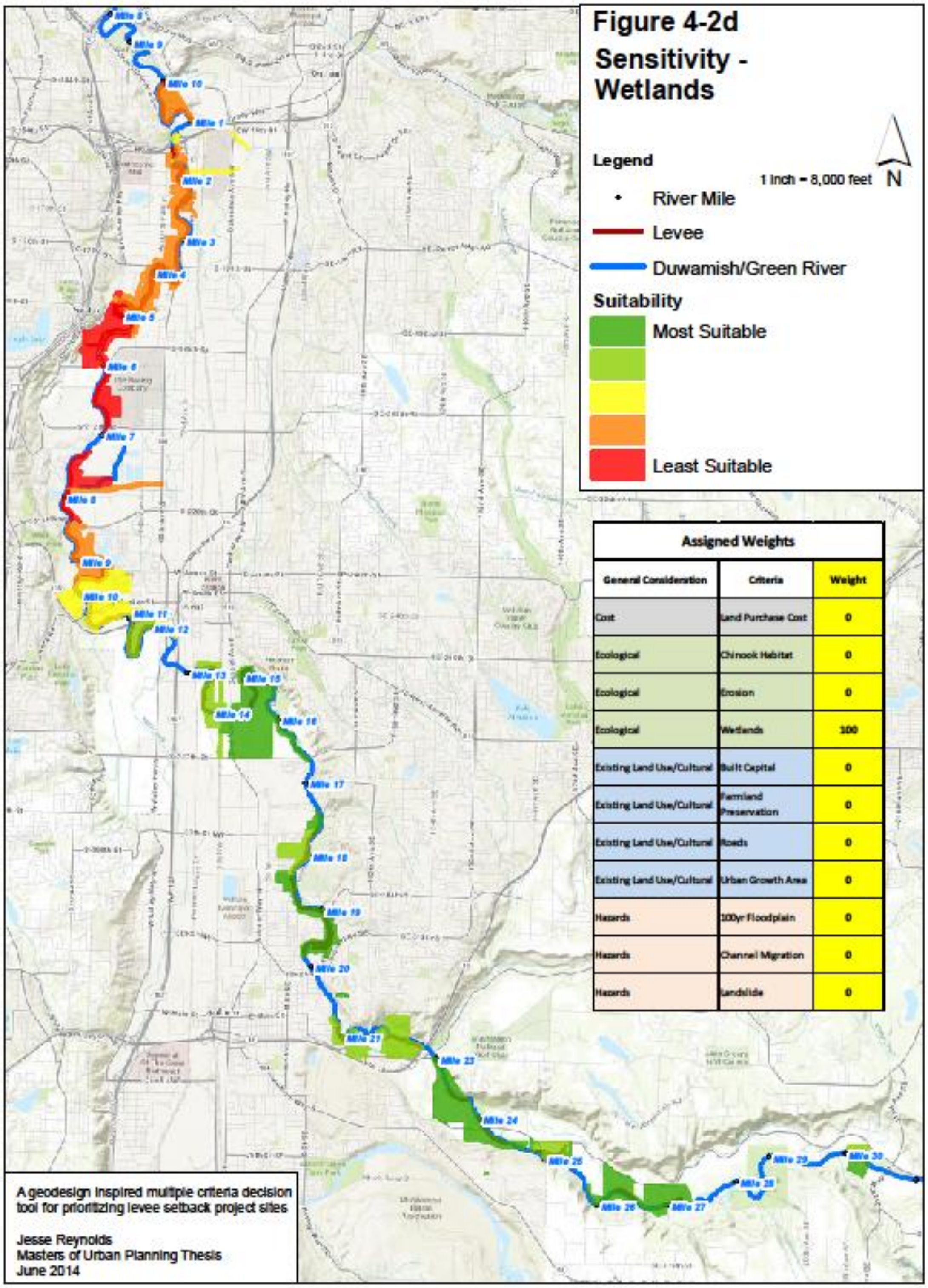
Assigned Weights		
General Consideration	Criteria	Weight
Cost	Land Purchase Cost	0
Ecological	Chinook Habitat	100
Ecological	Erosion	0
Ecological	Wetlands	0
Existing Land Use/Cultural	Built Capital	0
Existing Land Use/Cultural	Farmland Preservation	0
Existing Land Use/Cultural	Roads	0
Existing Land Use/Cultural	Urban Growth Area	0
Hazards	100yr Floodplain	0
Hazards	Channel Migration	0
Hazards	Landslide	0

Figure 4.2c - Sensitivity - Erosion



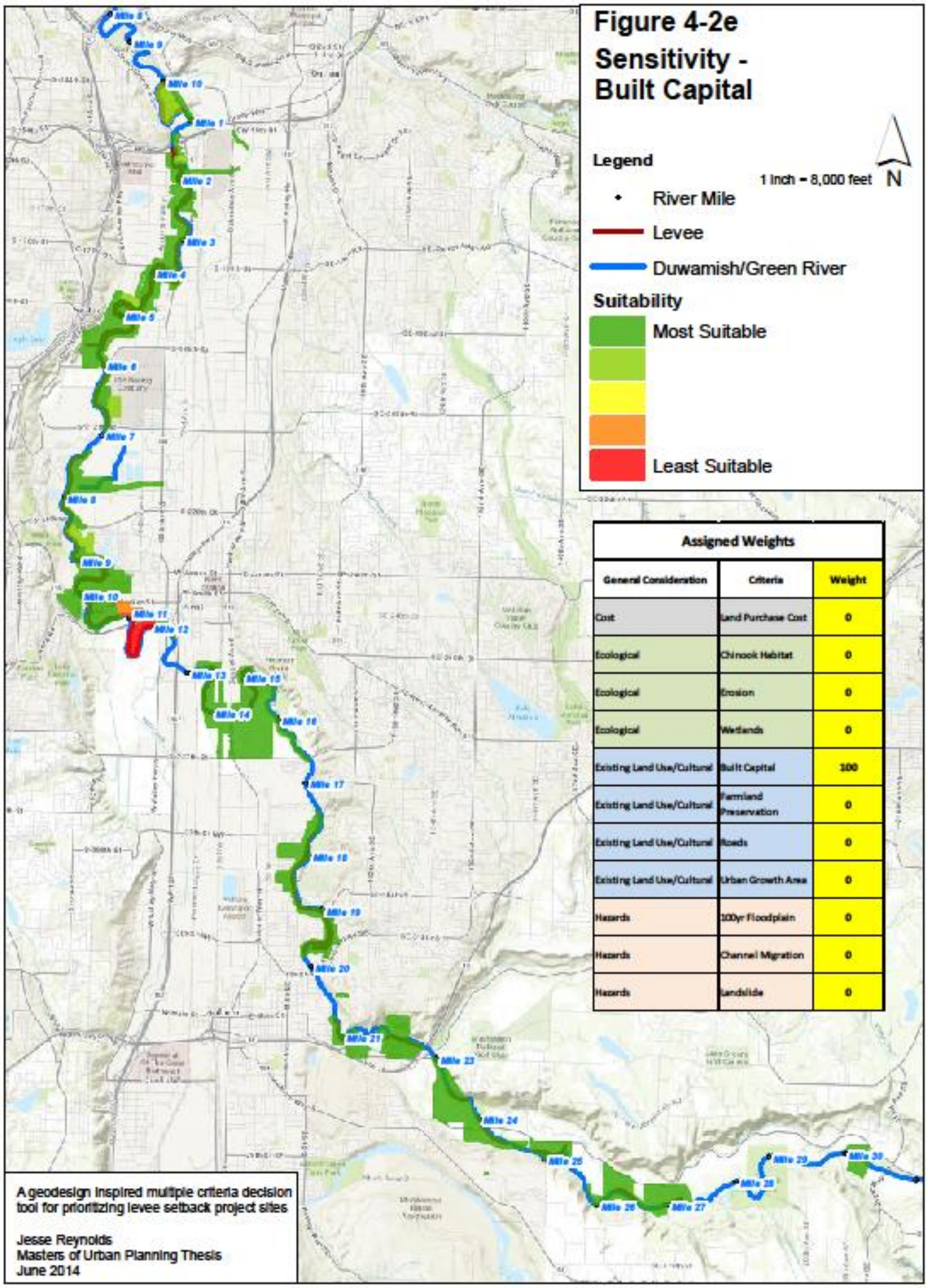
General Consideration	Criteria	Weight
Cost	Land Purchase Cost	0
Ecological	Chinook Habitat	0
Ecological	Erosion	100
Ecological	Wetlands	0
Existing Land Use/Cultural	Built Capital	0
Existing Land Use/Cultural	Farmland Preservation	0
Existing Land Use/Cultural	Roads	0
Existing Land Use/Cultural	Urban Growth Area	0
Hazards	100yr Floodplain	0
Hazards	Channel Migration	0
Hazards	Landslide	0

Figure 4.2d - Sensitivity - Wetlands



Assigned Weights		
General Consideration	Criteria	Weight
Cost	Land Purchase Cost	0
Ecological	Chinook Habitat	0
Ecological	Erosion	0
Ecological	Wetlands	100
Existing Land Use/Cultural	Built Capital	0
Existing Land Use/Cultural	Farmland Preservation	0
Existing Land Use/Cultural	Roads	0
Existing Land Use/Cultural	Urban Growth Area	0
Hazards	100yr Floodplain	0
Hazards	Channel Migration	0
Hazards	Landslide	0

Figure 4.2e - Sensitivity - Built Capital



Assigned Weights		
General Consideration	Criteria	Weight
Cost	Land Purchase Cost	0
Ecological	Chinook Habitat	0
Ecological	Erosion	0
Ecological	Wetlands	0
Existing Land Use/Cultural	Built Capital	100
Existing Land Use/Cultural	Farmland Preservation	0
Existing Land Use/Cultural	Roads	0
Existing Land Use/Cultural	Urban Growth Area	0
Hazards	100yr Floodplain	0
Hazards	Channel Migration	0
Hazards	Landslide	0

Figure 4.2f - Sensitivity - Farmland Preservation

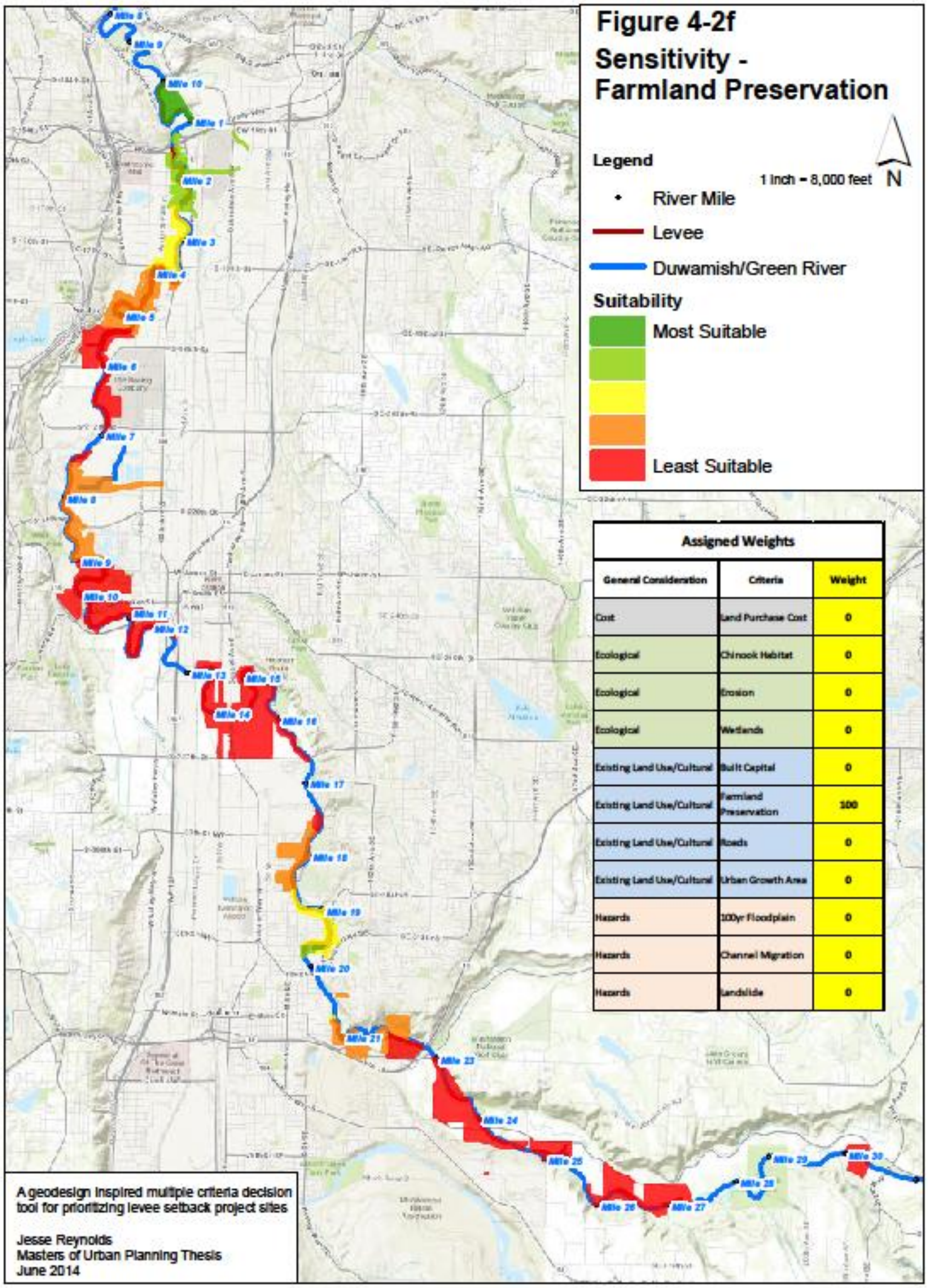


Figure 4.2g - Sensitivity - Roads

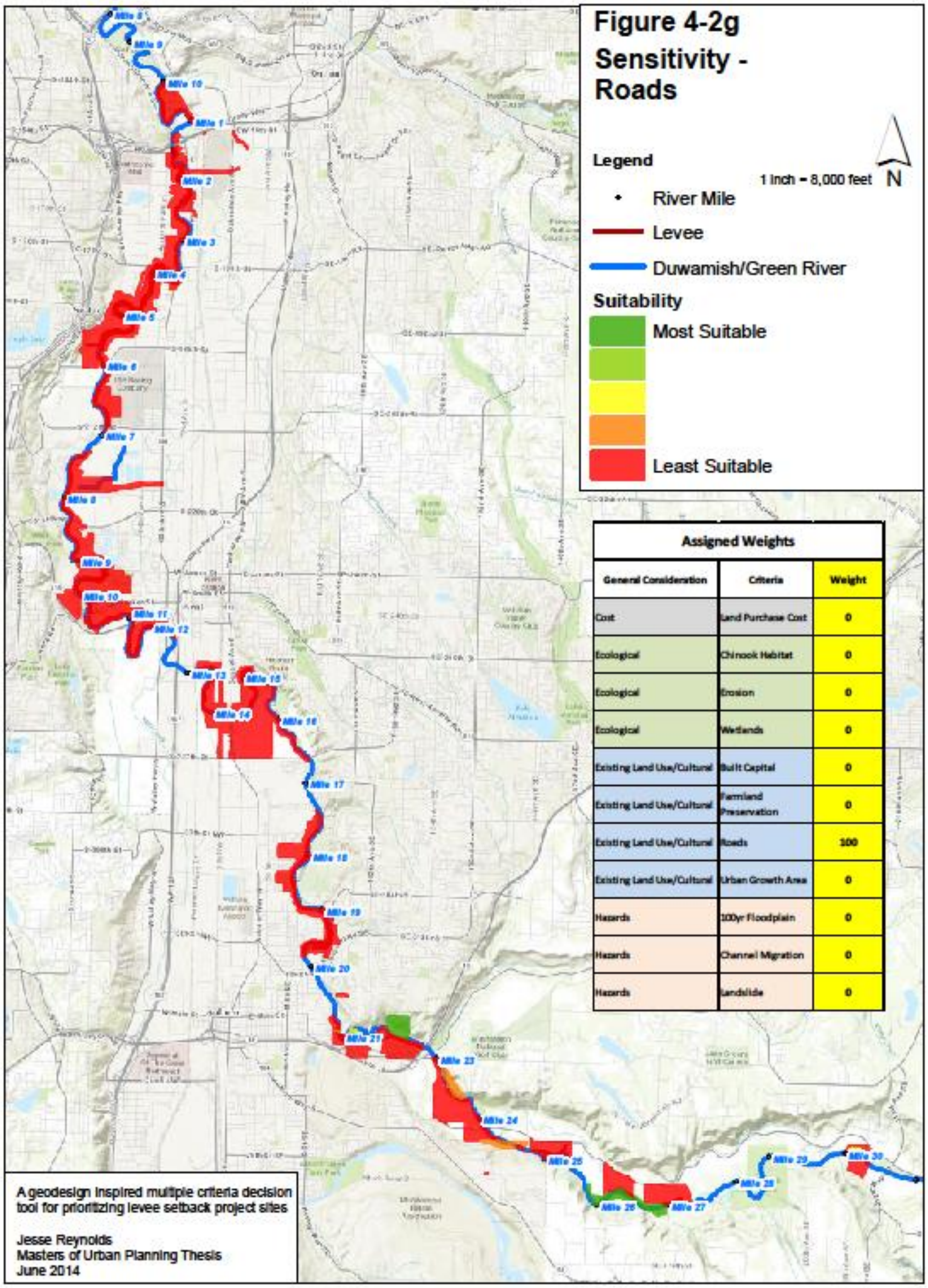
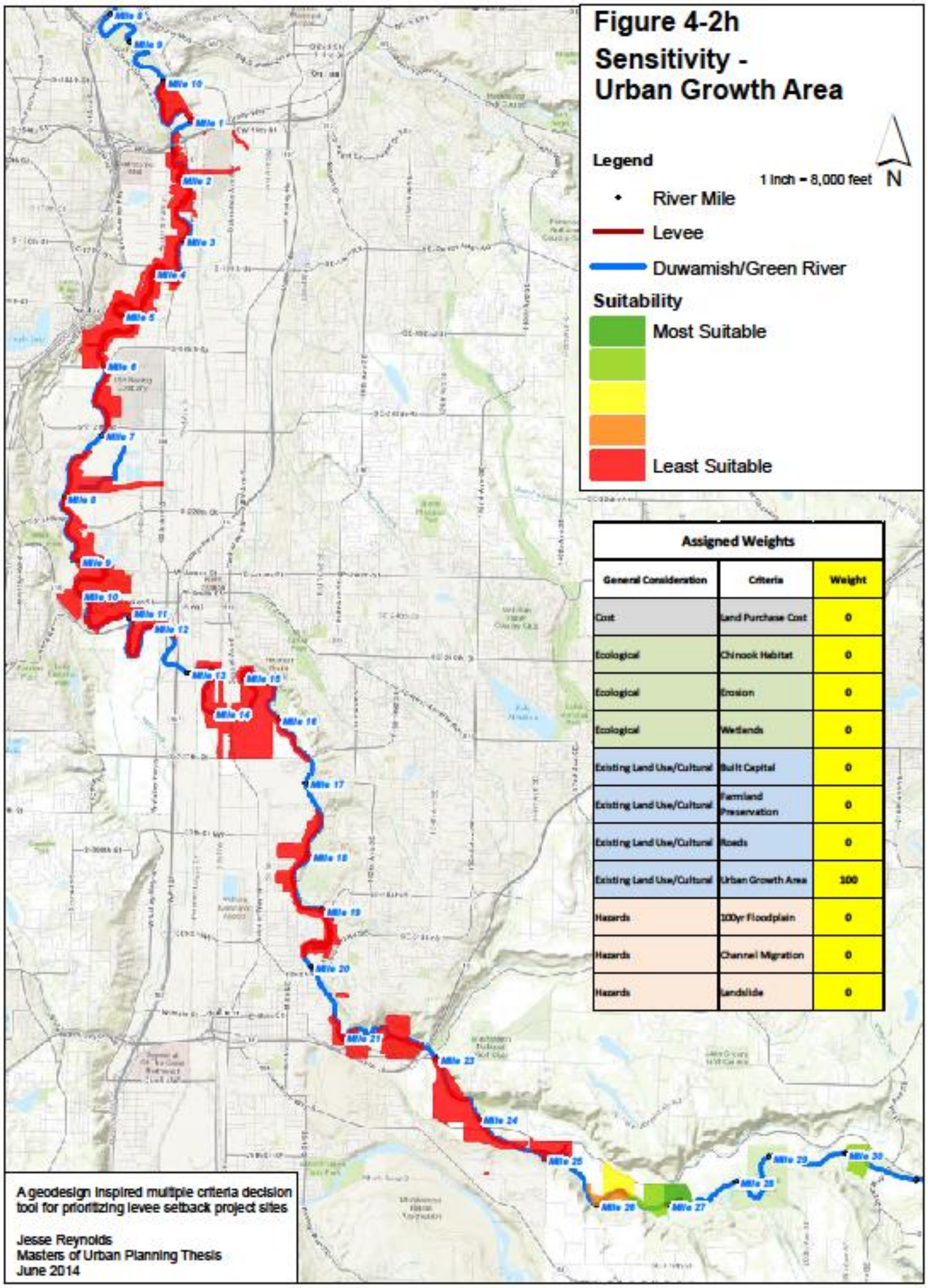
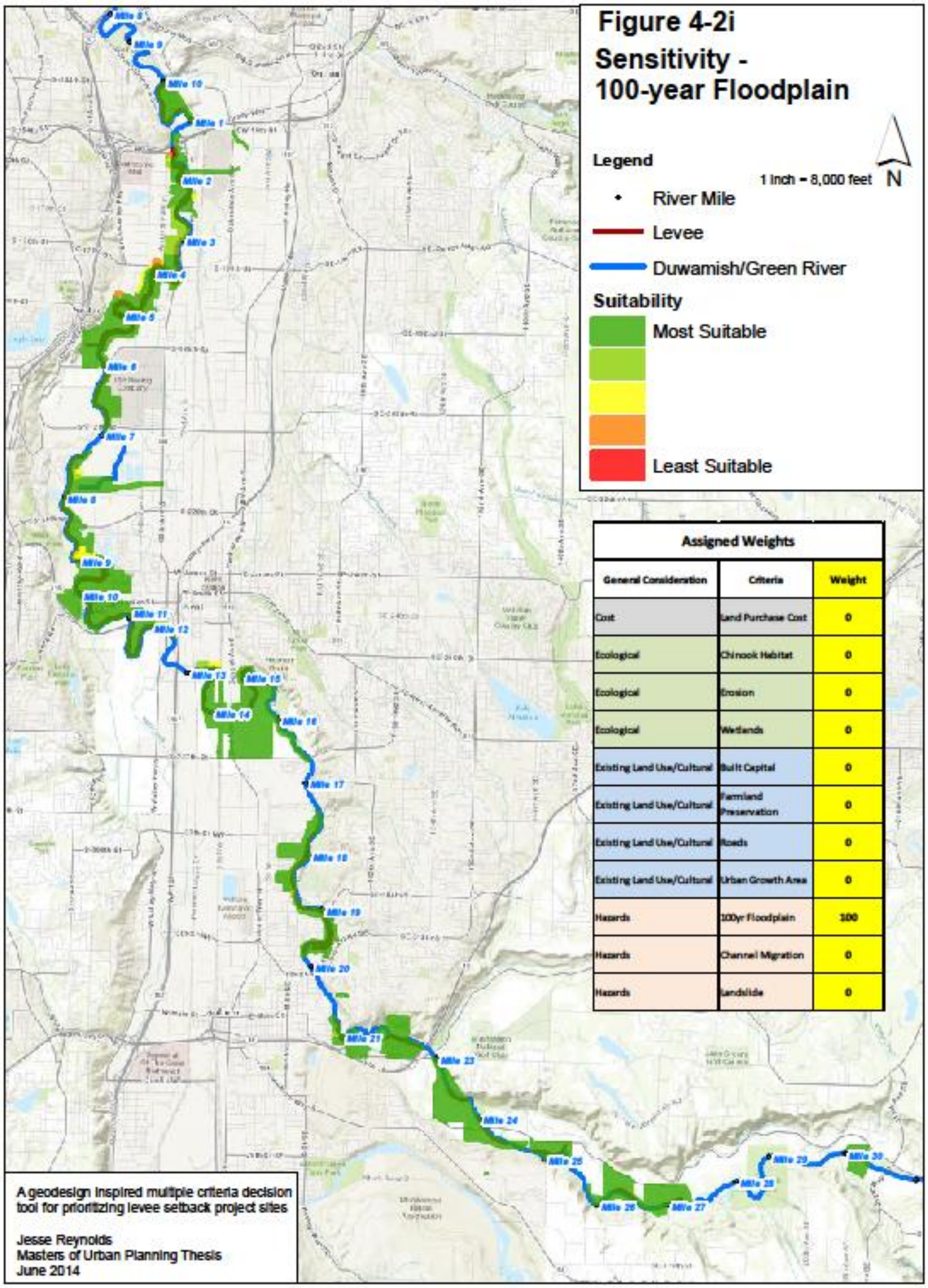


Figure 4.2h - Sensitivity - Urban Growth Area



Assigned Weights		
General Consideration	Criteria	Weight
Cost	Land Purchase Cost	0
Ecological	Chinook Habitat	0
Ecological	Erosion	0
Ecological	Wetlands	0
Existing Land Use/Cultural	Built Capital	0
Existing Land Use/Cultural	Farmland Preservation	0
Existing Land Use/Cultural	Roads	0
Existing Land Use/Cultural	Urban Growth Area	100
Hazards	100yr Floodplain	0
Hazards	Channel Migration	0
Hazards	Landslide	0

Figure 4.2i - Sensitivity - 100-year Floodplain



Assigned Weights		
General Consideration	Criteria	Weight
Cost	Land Purchase Cost	0
Ecological	Chinook Habitat	0
Ecological	Erosion	0
Ecological	Wetlands	0
Existing Land Use/Cultural	Built Capital	0
Existing Land Use/Cultural	Farmland Preservation	0
Existing Land Use/Cultural	Roads	0
Existing Land Use/Cultural	Urban Growth Area	0
Hazards	100yr Floodplain	100
Hazards	Channel Migration	0
Hazards	Landslide	0

Figure 4.2j - Sensitivity - River Channel Migration

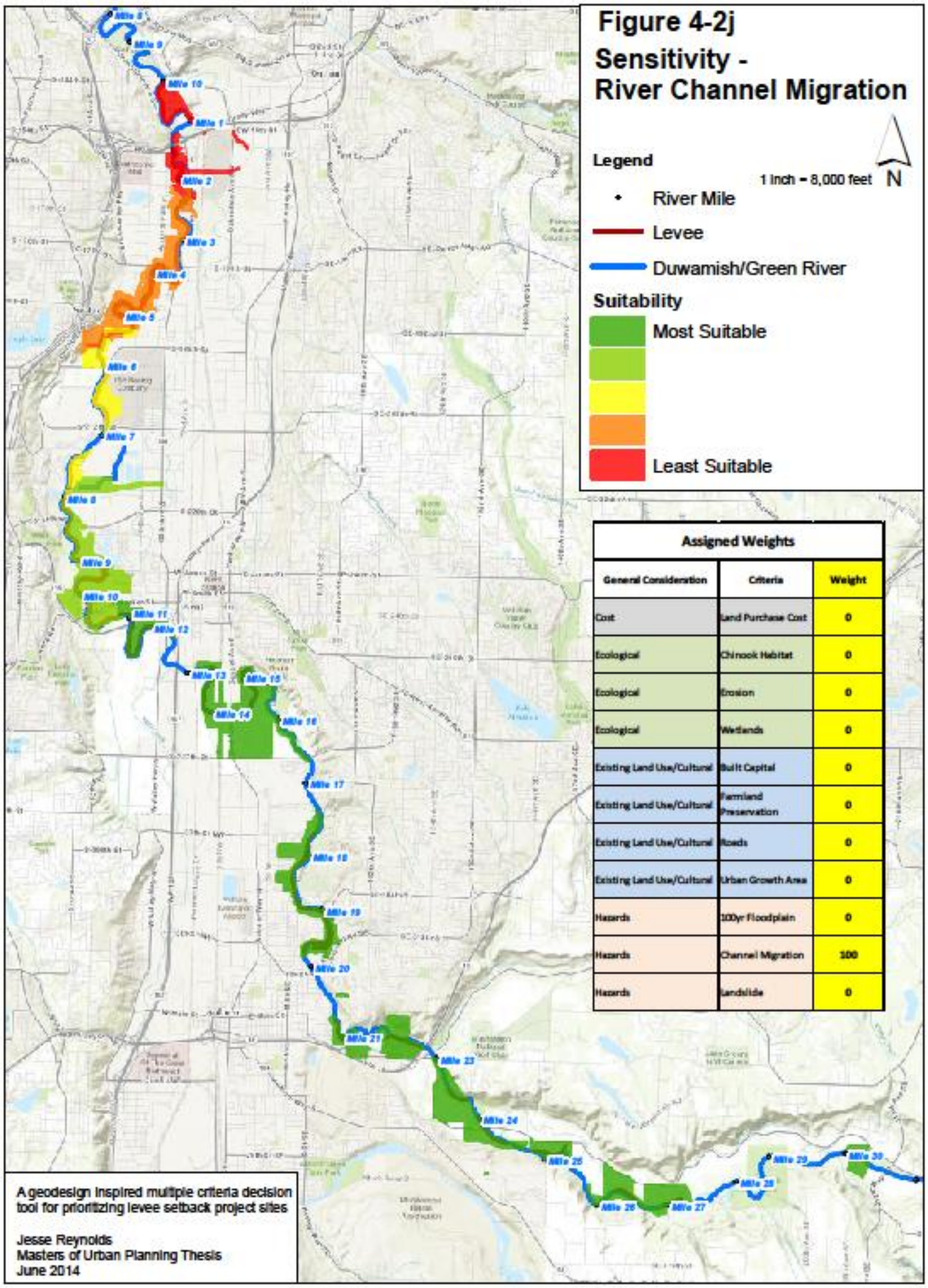
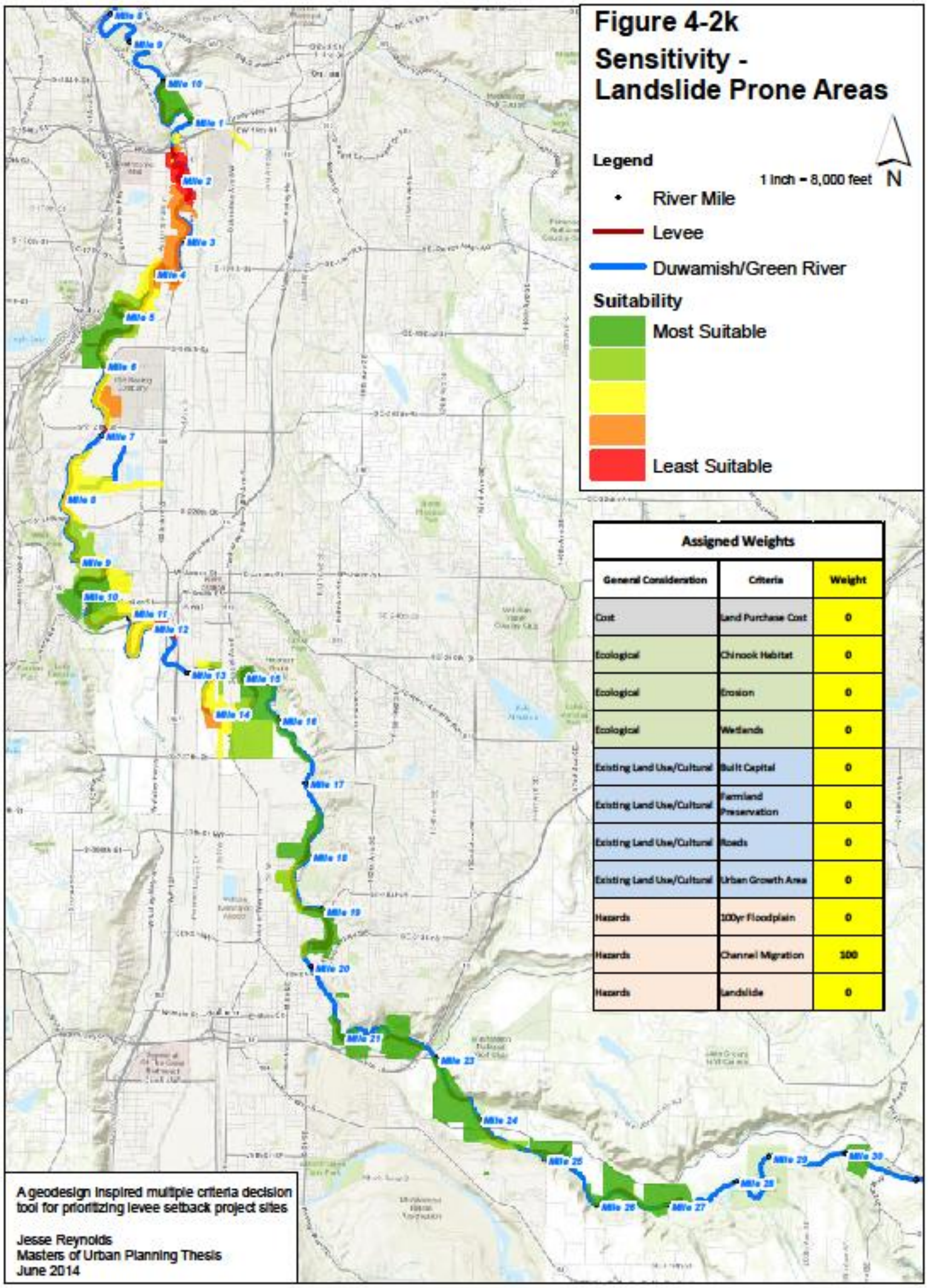


Figure 4.2k - Sensitivity - Landslide Prone Areas



4.3 - Hypothetical Stakeholder involvement

Five professionals, whose specializations and experiences are closely related to floodplain management, returned the survey sheets quick enough to incorporate their results in this section. One of the professionals is a local county employee involved in open space acquisitions; some of the acquisitions are specifically for river restoration and flood attenuation projects. Another local county employee who is a floodplain manager and PhD in river ecology also participated. Another participant is from an environmental non-profit pursuing multiple benefit river restoration projects. One is a project engineer from a local consulting firm involved in river restoration projects. The final person who returned the survey is a GIS Manager for the natural resources department of a tribe in Western Washington. Each participant was asked to use their professional knowledge of the opinions and feelings of stakeholders in regards to river resources and floodplain management and role-play the six hypothetical characters depicted in the exercise. The participants gave scores for each hypothetical character and their results were averaged and applied to the Decision Support Model. The resulting values and model outputs can be seen in the following maps: Figure 4.3 - Single Family Home Owner, Figure 4.4 - Floodplain Manager, Figure 4.5 - Tribal Member, Figure 4.6 - Farmer, 4.7 - Land Developer, and 4.8 - Environmental Non-Profit.

Figure 4.3 shows the results of the survey for the hypothetical single family home owner. The two most influential criteria for this stakeholder are first land purchase cost, followed by built capital. The least influential were the urban growth area then farmland preservation. The resulting suitability layer shows more or less progressive suitability the farther up the river one goes. Almost all of the parcels above Mile 14 were near most suitable, and almost all of the parcels below Mile 5 are near or at least suitable.

Figure 4.4, the results for the hypothetical floodplain manager, shows similar results to Figure 4.3. The largest emphasis on criteria for this stakeholder was farmland preservation, followed by a three way tie for Chinook habitat, 100-year floodplain, and channel migration. All of the most suitable or near most suitable category parcels are found above Mile 14. Almost all of the least suitable parcels are found below Mile 8.

The hypothetical tribal member was shown in Figure 4.5. The largest criterion weight for this stakeholder was Chinook habitat, followed by land purchase cost. The least weighted criteria are farmland preservation followed by a tie between urban growth area and landslides. The results are similar to the previous two with all of the most suitable parcels above Mile 14, and almost all of the least suitable parcels below Mile 7.

The hypothetical farmer stakeholder results can be seen in Figure 4.6. Cost was the most favored weight with almost twice as many points as received by the second place criterion, which is the roads criterion. The least weighted criteria are the urban growth area, followed by wetlands. Almost all of the near to and most suitable parcels are above Mile 14. Almost all of the least suitable parcels are below Mile 8.

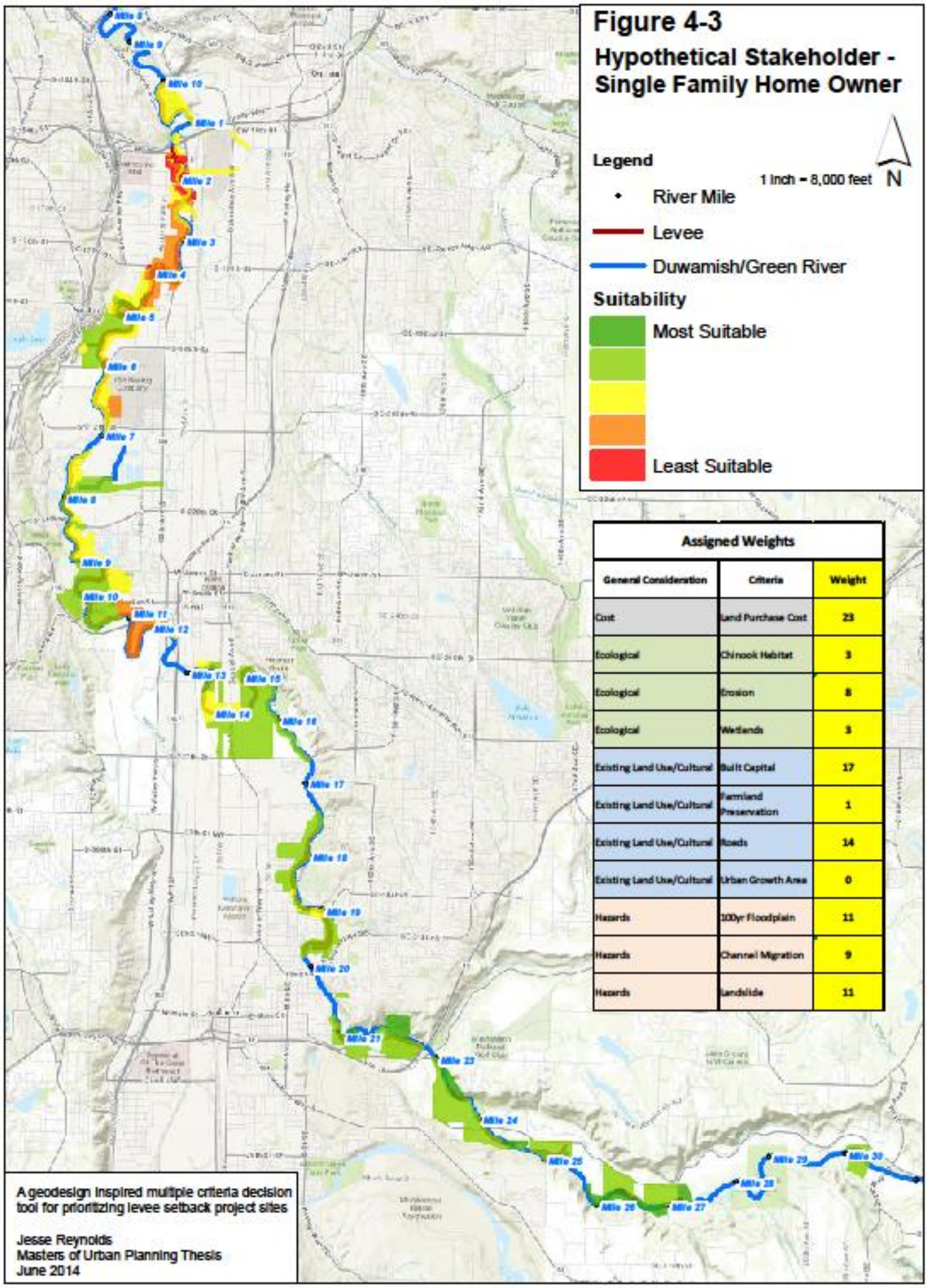
Figure 4.7 shows the results for the hypothetical land developer. The most weighted criteria for this stakeholder is land purchase cost that received almost twice as many points as the second most influential, built capital. The least weighted criteria are a tie between Chinook habitat and Wetlands. Once again, the majority of most suitable parcels are upstream of Mile 14. Most of the least suitable parcels are below Mile 7.

The final hypothetical stakeholder, the environmental non-profit worker, can be seen in Figure 4.8. The most heavily weighted criterion is Chinook habitat followed by wetlands. The least weighted is a tie between roads and urban growth area. Almost all of the most suitable lands can be seen above Mile 13, with almost all of the least suitable elands below Mile 7.

If the results of this model are followed then levee setbacks would only occur on the upper reaches of this study area. It is hard to tell the implications of this in regards to flood intensity without running a hydrologic model. One could infer levee setbacks upstream could reduce peak flows everywhere. It is also possible that levee setbacks upstream could only affect flooding intensity on adjacent lands. Regardless a detailed hydrologic analysis should take place in order to calculate changes in flood heights before a levee setback projects is started.

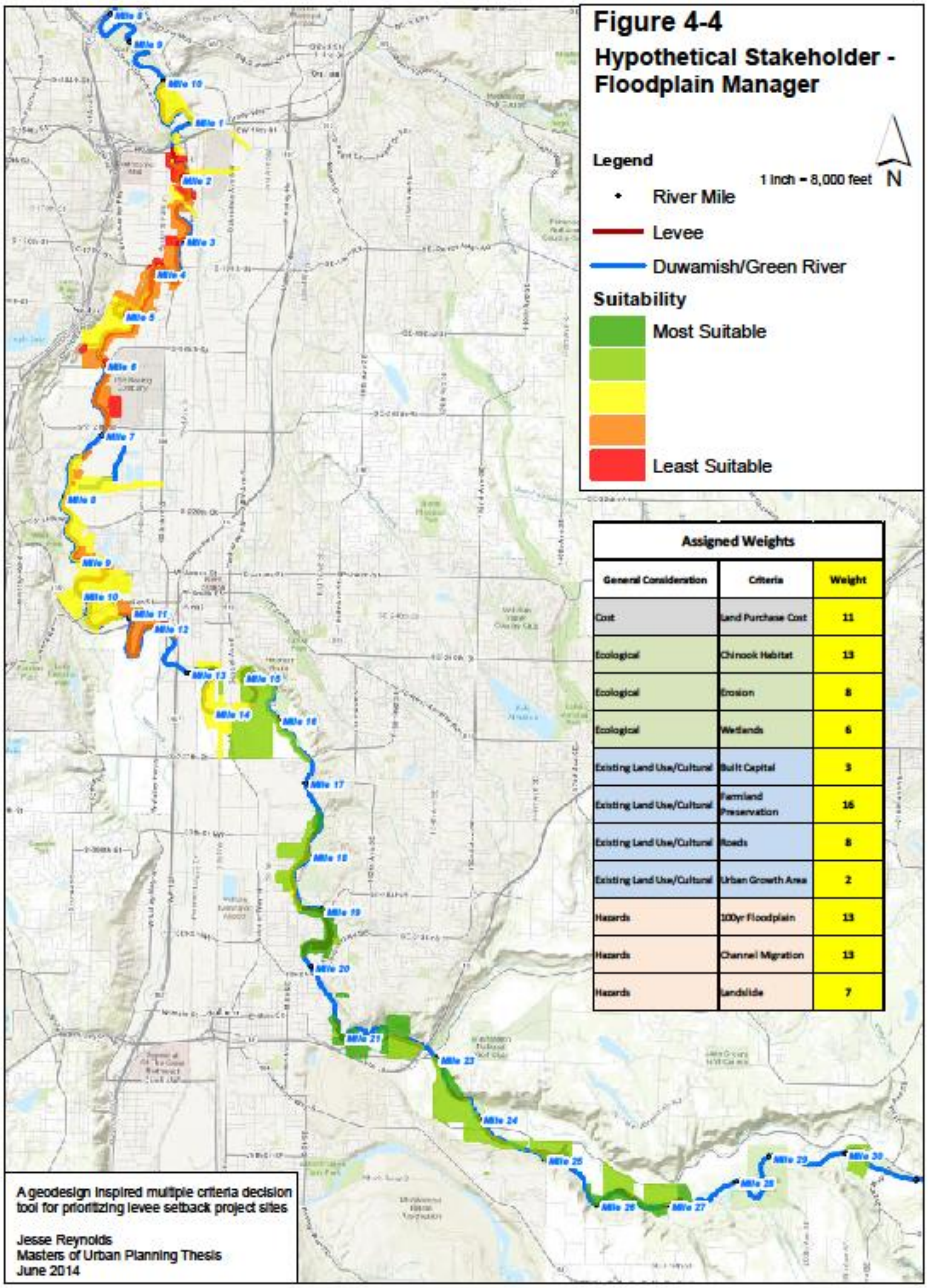
After viewing the results of all six hypothetical stakeholders it is obvious there is not much variation between which parcels are deemed most to least suitable for levee setbacks. In all of the results the majority of close to most and most suitable parcels are located upstream of Mile 14. The reach between Mile 14 and Mile 7 and 8 can be seen as a transition zone, with a wide range of results. Downstream of Mile 7 almost all of the least suitable parcels can be found, with the majority of least suitable located in the lowest reaches.

Figure 4.3 - Single Family Home Owner



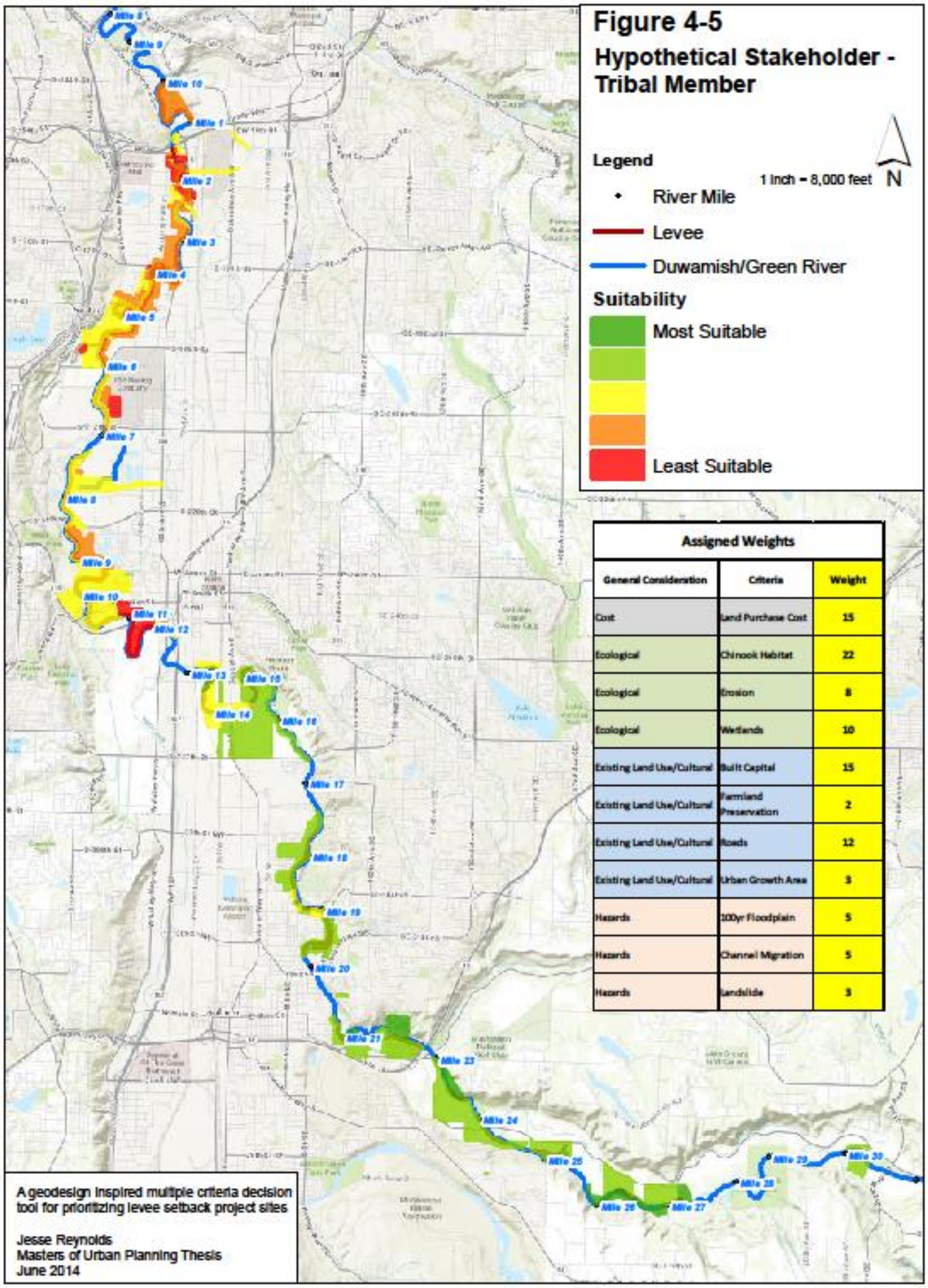
Assigned Weights		
General Consideration	Criteria	Weight
Cost	Land Purchase Cost	23
Ecological	Chinook Habitat	3
Ecological	Erosion	8
Ecological	Wetlands	3
Existing Land Use/Cultural	Built Capital	17
Existing Land Use/Cultural	Farmland Preservation	1
Existing Land Use/Cultural	Roads	14
Existing Land Use/Cultural	Urban Growth Area	0
Hazards	100yr Floodplain	11
Hazards	Channel Migration	9
Hazards	Landslide	11

Figure 4.4 - Floodplain Manager



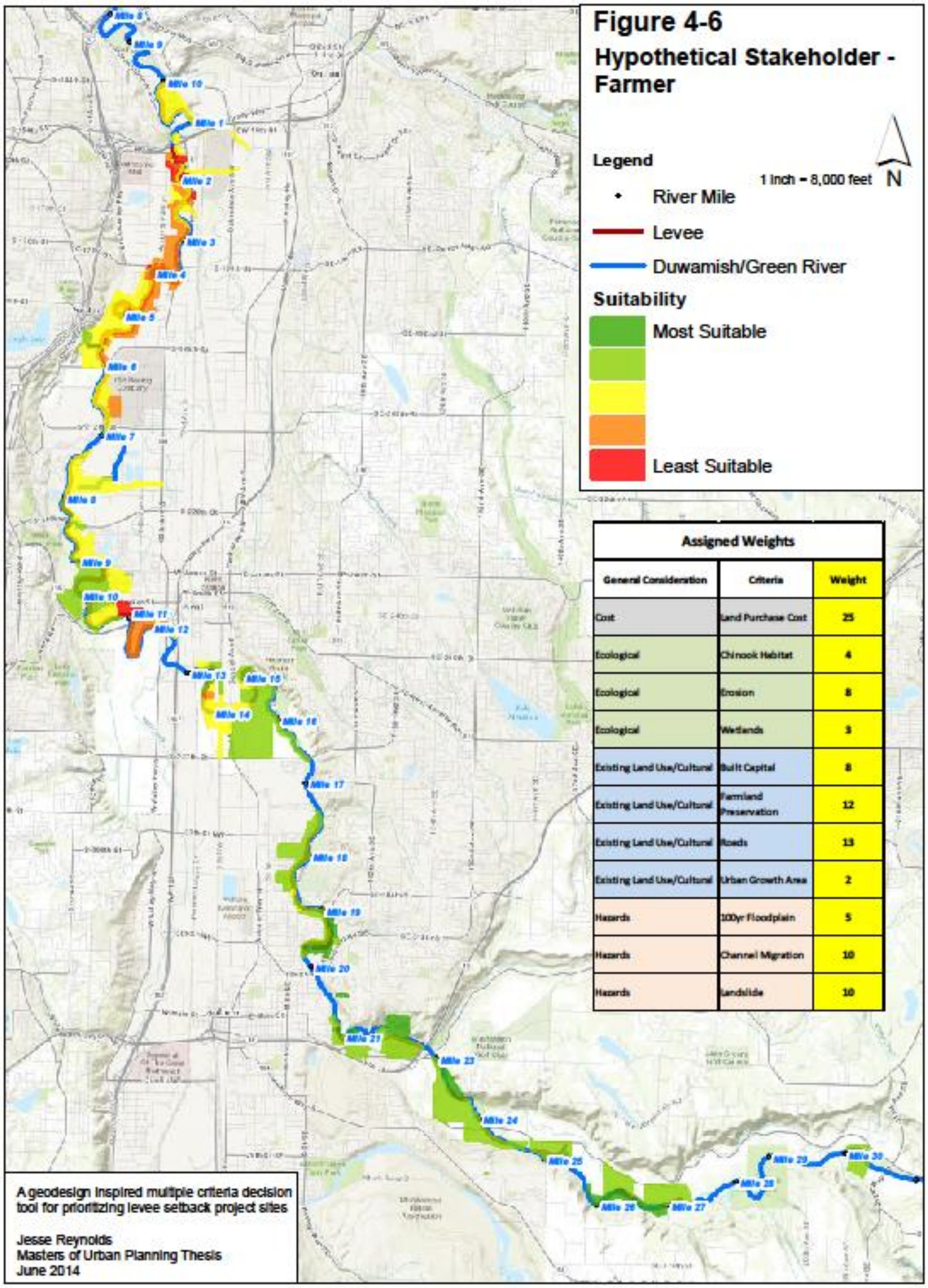
Assigned Weights		
General Consideration	Criteria	Weight
Cost	Land Purchase Cost	11
Ecological	Chinook Habitat	13
Ecological	Erosion	8
Ecological	Wetlands	6
Existing Land Use/Cultural	Built Capital	3
Existing Land Use/Cultural	Farmland Preservation	16
Existing Land Use/Cultural	Roads	8
Existing Land Use/Cultural	Urban Growth Area	2
Hazards	100yr Floodplain	13
Hazards	Channel Migration	13
Hazards	Landslide	7

Figure 4.5 - Tribal Member



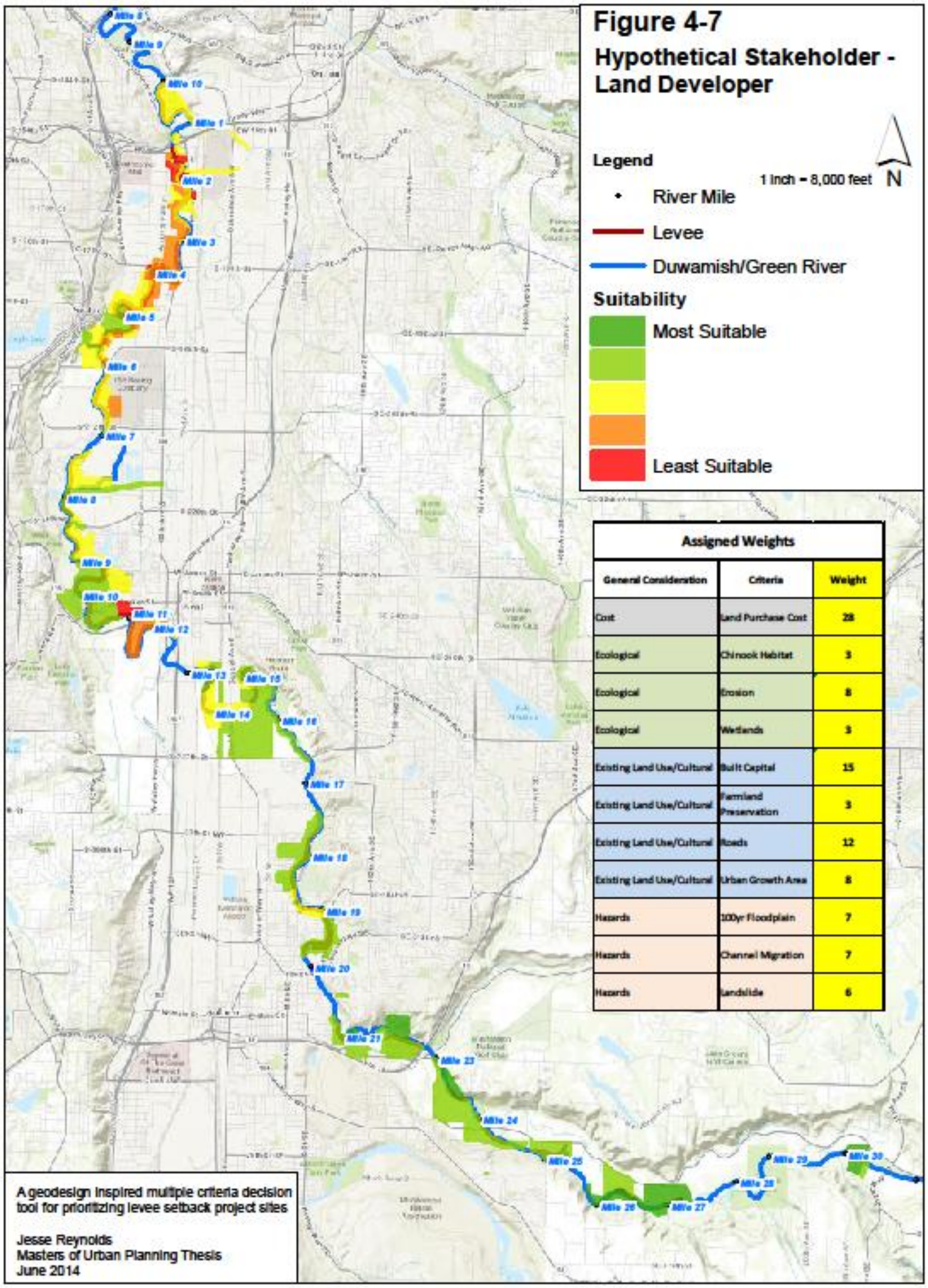
Assigned Weights		
General Consideration	Criteria	Weight
Cost	Land Purchase Cost	15
Ecological	Chinook Habitat	22
Ecological	Erosion	8
Ecological	Wetlands	10
Existing Land Use/Cultural	Built Capital	15
Existing Land Use/Cultural	Farmland Preservation	2
Existing Land Use/Cultural	Roads	12
Existing Land Use/Cultural	Urban Growth Area	3
Hazards	100yr Floodplain	5
Hazards	Channel Migration	5
Hazards	Landslide	3

Figure 4.6 - Farmer



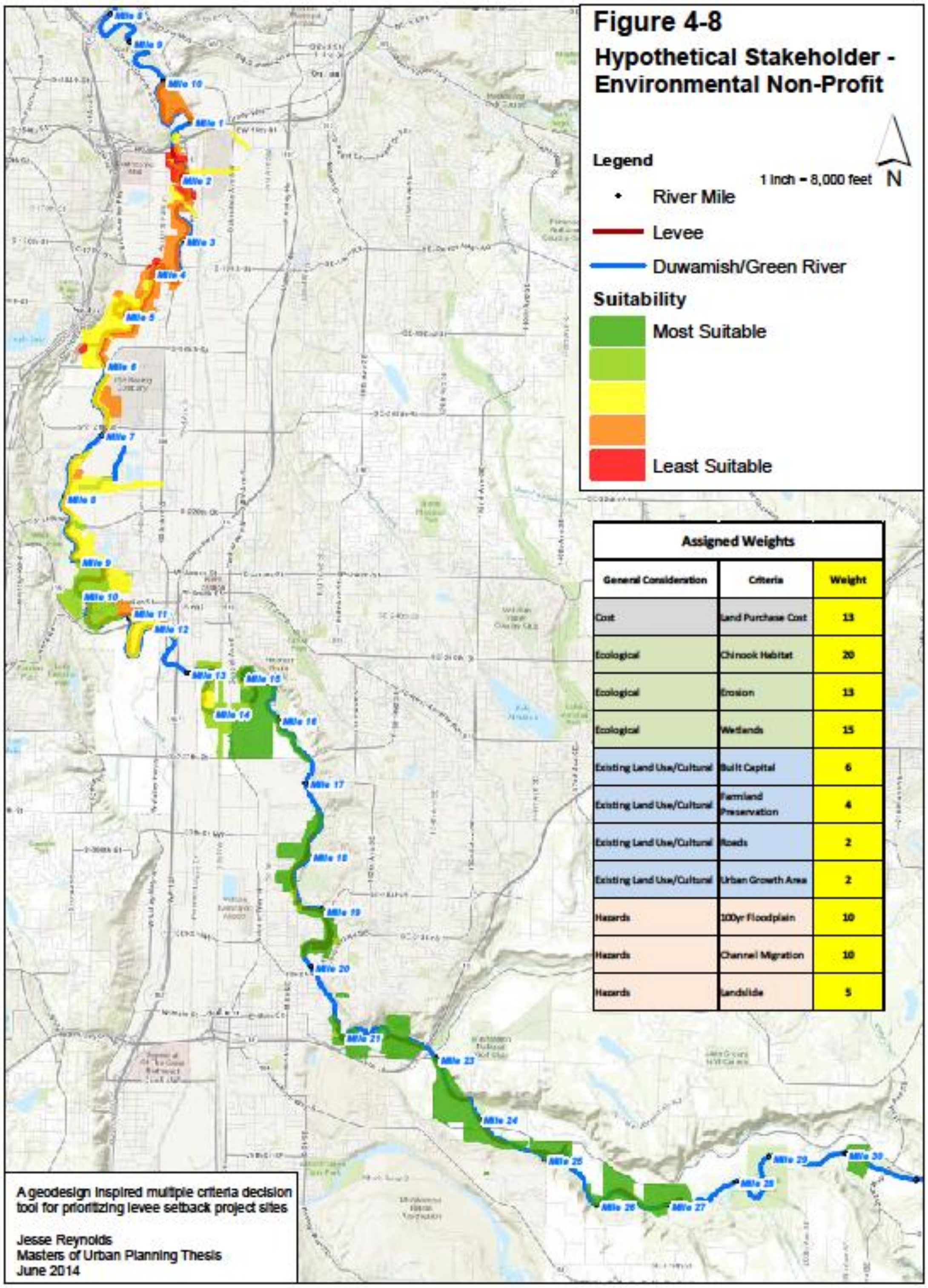
Assigned Weights		
General Consideration	Criteria	Weight
Cost	Land Purchase Cost	25
Ecological	Chinook Habitat	4
Ecological	Erosion	8
Ecological	Wetlands	3
Existing Land Use/Cultural	Built Capital	8
Existing Land Use/Cultural	Farmland Preservation	12
Existing Land Use/Cultural	Roads	13
Existing Land Use/Cultural	Urban Growth Area	2
Hazards	100yr Floodplain	5
Hazards	Channel Migration	10
Hazards	Landslide	10

Figure 4.7 - Land Developer



General Consideration	Criteria	Weight
Cost	Land Purchase Cost	28
Ecological	Chinook Habitat	3
Ecological	Erosion	8
Ecological	Wetlands	3
Existing Land Use/Cultural	Built Capital	15
Existing Land Use/Cultural	Farmland Preservation	3
Existing Land Use/Cultural	Roads	12
Existing Land Use/Cultural	Urban Growth Area	8
Hazards	100yr Floodplain	7
Hazards	Channel Migration	7
Hazards	Landslide	6

Figure 4.8 - Environmental Non-Profit



General Consideration	Criteria	Weight
Cost	Land Purchase Cost	13
Ecological	Chinook Habitat	20
Ecological	Erosion	13
Ecological	Wetlands	15
Existing Land Use/Cultural	Built Capital	6
Existing Land Use/Cultural	Farmland Preservation	4
Existing Land Use/Cultural	Roads	2
Existing Land Use/Cultural	Urban Growth Area	2
Hazards	100yr Floodplain	10
Hazards	Channel Migration	10
Hazards	Landslide	5

4.4 - Chapter Summary

The Decision Support Model has been executed in several different ways. We have seen results from even weighting, from a sensitivity analysis that looks at each criterion individually, and from six hypothetical stakeholder groups whose weighting was derived from averaging the results of professionals playing the roles of each. Aside from some fine grained variations and a few outlying results from criteria in the sensitivity analysis, results remain relatively consistent. Almost all of the suitable parcels are located in the upper sections of the study area, with almost all of the least suitable parcels in the lower sections. Next is the Discussion Section where we will explore the significance and context of the tool and its results, the limitations of the tool, and finally its future directions.

5.0 - Discussion

The tool, comprised of the individual models, has been constructed and run with hypothetical weights to produce expected outcomes. This section is dedicated to critiquing the model as it stands, its usability, and suggestions for improvements are provided. First, the significance of the model will be explained in the context of its chosen applicability, levee setbacks. Local examples of programs that use different analysis methods for similar floodplain management studies will be explored. Next, limitations of the model will be discussed. The main purpose of the model will be framed once again, and the associated shortcomings of the methods will be exposed. Finally, the potential future directions of the model will be discussed, ending with suggested next steps.

5.1- Significance and Context

It is important to properly frame the goals and intentions of this thesis to help the reader understand what the tool is capable of doing, and what it is not. This way the results of a model run are used for their intended purpose, and nothing more. It is important to explain how local agencies are coming to the same decisions this thesis aids by using different methods. Also, ways in which other studies could have helped this tool will be explored.

5.1.1- Finding meaning from the results

It is important to emphasize this thesis is not a suitability analysis, per se, in terms of its major emphasis; it is more about a GIS-based decision support tool applied to levee setbacks. Though patterns emerge in the maps shown in the results section, the results are only a demonstration of how a stakeholder's values transform into the prioritization of individual parcels. With that in mind, the results in the last section show enough similarities to reveal where levee setback projects should occur. The obvious answer is the farther upstream the better. This is evident in King County's creation of the "Middle Green River Levee Setback Feasibility Study" (KC FS).[142] The ten recommended sites that study examines are on the stretch of the river between Miles 32 and 45, a section just upstream of the section of river examined in this thesis. Ideally this thesis would have covered this area as well, but no publicly available GIS data for levee locations in this area could be obtained.

An attempt was made at comparing Ecology's "Puget Sound Watershed Characterization Project" (PSWCP) to the thesis results.[143] When comparing to results from the PSWCP Water Flow assessment it was discovered that all of the subwatershed units covering the area studied in the thesis were categorized as 'Restoration'. This could be because the subwatershed units (98 in total in WRIA 9) are too coarse to be used against individual parcels. It could also be because this entire stretch of the Green River is seen as being a valuable natural asset in need of repair.

An attempt was also made at comparing point data showing multiple National Flood Insurance Program (NFIP) claims sites, but it was discovered that only one multiple claims site is within the study area. Using a single point to find any correlation between multiple claims and

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[142] *"Middle Green River Levee Setback Feasibility Study," King County Department of Natural Resources and Parks, Water and Land Resources Division, January 2013.*

[143] *Stanley, S., S. Grigsby, D. B. Booth, D. Hartley, R. Horner, T. Hruby, J. Thomas, P. Bissonnette, R. Fuerstenberg, J. Lee, P. Olson, George Wilhere. 2011. Puget Sound Characterization. Volume 1: The Water Resources Assessments (Water Flow and Water Quality). Washington State Department of Ecology. Publication #11-06-016. Olympia, WA.*

thesis results would be insignificant. Plus the connection between the two datasets is a distant one at best.

5.1.2 - Other methods with similar applications

GIS-based MCDA is not the only way to rank and prioritize river restoration sites. In fact, there are a few current examples showing other methods within the Puget Sound. Two of them were mentioned in the previous subsection. The PSWCP study is a regional attempt at categorizing subwatersheds in the context of their level of importance and level of degradation.[144] That report presents a decision support dataset that is a result of detailed watershed studies in the Puget Sound. It considers such things as wildlife habitat, salmon spawning habitat, flow attenuation, flood storage, and groundwater recharge. Subwatersheds with a high level of importance and a low level of degradation are put in a category of protection. Subwatersheds with a high level of importance and a high level of degradation, like most of the Lower Green River, are put in a category of restoration.   Subwatersheds with a low level of importance and a high level of degradation are put in a category of development. Subwatersheds with a low level of importance and a low level of degradation are put in a category of conservation. That study uses a two dimensional graph/matrix to depict how subwatersheds fit into the categories it covers. This method could be seen as a more robust way of categorizing lands in comparison to the one-dimensional scale ranging from least suitable to most suitable in this thesis. Decision makers and land managers can use these results as an aid to set prioritization for areas in need of certain interventions.

[144] Ibid.

The KC FS mentioned above uses similar methods to this thesis in comparison to the PSWCP study, using the term “multiple objective” versus multi-criteria.[145] It is an excellent example of the type of study that would take place after an initial planning level tool like this thesis has been executed, or after PSWCP results have been examined. In the case of King County, with its deep level of knowledge, talent, and resources, an initial planning level study is not necessary because sites of interest are already known. A site screening exercise can be skipped and focus can be made on actual project costs as well as expected successes and risks. Ten sites of interest were already known at the beginning of the KC FS study. This allowed the feasibility of each site relative to each other to be explored through analyzing habitat, cost and land availability. Together those three objectives were scored allowing overall rank of the sites to be established.[146] Some consideration was given to flood, agriculture, and other floodplain uses, but it is noted in the report that further development and discussion needs to take place with stakeholders in order to assure other land uses are taken into account.

Like this thesis, these two studies show results for the purpose of assisting in land use decisions. The main difference between this thesis and the studies is that they come at different phases of the investigation process. The PSWCP is a larger scope, and coarser grained approach to regional land use recommendations at a subwatershed scale. This would be a study used before this thesis takes place, showing what subwatershed should take prioritization for levee setbacks. The KC FS is a study showing what could take place after the results of this thesis are received and specific parcels are considered for levee setbacks.

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[145] See note 1.
[146] Ibid (see page 8).

Another application similar to this thesis in regards to multiple benefit river restoration projects is the effort by The Nature Conservancy in their "Floodplains by Design" program.[147] The main goal of this program is to "ensure floodplains are used and managed in ways that enable them to provide these valuable services, while maintaining or even improving flood protection." They are pursuing this multiple benefit goal by attempting to restore natural processes at project sites. The metrics used for prioritizing future projects are in the process of being defined, but when the author spoke with The Nature Conservancy Mt. Vernon, WA office in November 2013 the preliminary score matrix covered criteria that would rank sites on the basis of habitat restoration, flood risk reduction, natural resource industry viability, water quality, socio-economic, public access and open space, alignment of other funding, and climate adaptation.[148]

Above are three examples of how agencies are ranking potential future river restoration, flood attenuation, habitat enhancement projects in the Puget Sound region. The ideal litmus test of this thesis would have been to compare even weighted and hypothetical stakeholder results to the locations of the ten sites chosen for the KC FS. Unfortunately the GIS data representing levees downloaded from the Ecology GIS website does not include this reach, but only the levees registered in the Lower Green River, limiting the study area of this thesis.[149] This lack of available data is one of the many limitations of this thesis discussed in the next section.

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[147] "Floodplains by Design - Nuts and Bolts," The Nature Conservancy, accessed on May 4, 2014, http://www.nature.org/ourinitiatives/habitats/riverslakes/floodplains-by-design-feature.xml

[148] Kris Knight, Julie Morse, The Nature Conservancy, interview at The Nature Conservancy Mt. Vernon Office, November 21, 2013.

[149] "GIS Data," Geographic Information Systems (GIS), Washington State Department of Ecology, updated on April 22, 2014, http://www.ecy.wa.gov/services/gis/data/data.htm.

5.2 - Tool Limitations

Deciding on the level of detail and topics covered for this thesis was an act of prioritization in itself. Due to limited time for completion, limited access to data, scheduling conflicts, and no budget, this thesis is a simplified version of what a study using the methodology that is presented could be. Below are a few considerations and limitations the author feels are significant enough to mention.

5.2.1 - Initial planning level scope - for implementation in other areas

The best stage for applying the methodology presented in this thesis is at the initial planning level, a result of the detail of the criteria inputs. It was important to keep all criteria a similar level of detail, versus exploring a few criteria greatly and the rest at a basic level. Exploring some criteria at greater depths was considered. An example of this would be to conduct a hydrological analysis to calculate potential acre feet of water retention per parcel during a modeled flood event, while keeping all other criteria in the form of basic shapefiles downloaded from the King County website. Keeping everything at the same level of detail was at the recommendation of several King County River and Flood Division (River and Flood) employees. Because of the level of detail, emphasis should be made on the model processes and stakeholder interaction, versus the level of detail and accuracy of the criteria. The framework of the model is developed. More precise criteria could be added to the model later when more time and resources are available.

From the beginning of discussions with River and Flood it became clear that the results of this thesis would not tell them anything they would not already know; unless they decided to significantly change their criteria and methods, which did not seem apparent. Instead it was decided to use the available data within King County to create a model that can be implemented in jurisdictions with fewer resources as a simple and inexpensive way to initially prioritize levee setback areas on other waterways.

5.2.2 - Data inputs - far from ideal

The detail and accuracy of the criteria available for the model is less than ideal, as is shown above with the flood inundation example. Maintaining an even level of detail among criteria and emphasizing the model processes took precedent over using only some criteria with a high level of detail. There are several ways to enhance the level of detail in the criteria, analyzing more than just the distance a parcel is from a feature, and the cost of land and improvements. The following are a few suggested data enhancements that could produce more valuable results.

One criterion in the model was Roads. Or in other words, whether or not a parcel contained a road, or was in close proximity to one. Not all roads are equal in necessity and importance. Some are side streets that see dozens of cars a day. Others are main thoroughfares that see thousands of cars a day. Roads could be categorized according to importance by using the average total vehicles per day. This number could then be multiplied by the road's proximity to each parcel, creating a more robust way to standardize the data. Unfortunately the search for this data came up short. Each jurisdiction has its own traffic data requiring time spent aggregating it all to cover the complete study area, which overlaps multiple municipalities. When just looking at data for King County it was noted this data has major gaps, only covering major roads.[150] Because of this it was decided to leave all roads as equals, and only rate them according to the distance between each parcel and road.

When examining the Chinook habitat results in the Sensitivity Analysis (Figure 4.2b) one can see nearly all of the parcels are considered most suitable. It appears as though this is because the Chinook layer was created by making a buffer of a Green River hydrography line. As a result Chinook habitat crosses residential and other terrestrial areas. A better dataset resulting from actual Chinook surveys would be ideal, but none were found in time for this thesis.

The 100-year floodplain layer was the most updated layer available, where parcels could only be examined in regards to whether or not they are close to the floodplain. This binary approach as to whether or not a parcel is within the floodplain does not reveal much in regards to potential acre feet of water retention a parcel would take if given back to the river via levee setback. Ideally acre feet would be calculated by creating height-above-water-surface maps with recent LiDAR elevation models. King County willingly provided cross-section flood heights for a 100-year event, unfortunately there was not enough time to process the data and accurately interpolate acre feet per parcel.

There were several other criteria that could have been considered, but even eleven criteria seemed like much, and were adequate to demonstrate and assess the model. Other

[150] See King County traffic count website - http://gismaps.kingcounty.gov/TrafficCounts/

criteria considered that would have had similar detail to the criteria used included a greater look into social equity. Existing transit lines could have been considered much in the same way the Roads criterion was analyzed. Data delineating areas of low-income housing, and/or potential areas of low-income housing could have been used as a criterion. Park space and public open space could have been considered as well.

The above mentioned are some ways criteria could have been improved or added to the model. Adjusting criteria is one of the ways the entire process of this thesis could have been improved. Some other ways are worth mentioning as well. For example, the hypothetical stakeholder outreach exercise whose results are shown in Section 4.3 has much room for improvement.

5.2.3 - Stakeholder outreach - a hasty attempt

The stakeholder outreach section exercise was a last minute attempt to use some realistic proxy input. It was originally planned for the author to estimate how each of the six hypothetical stakeholders would distribute the one hundred points among the eleven criteria. It was suggested by a thesis committee member partway through the process for the author to solicit help from floodplain management professionals. The author had already been in contact with some professionals, so it was easy to call upon their deep familiarity with the study area and stakeholder groups. Being a much preferred alternative to the original plan, a last-minute attempt was made to create and send a survey to these professionals.

As is the case with many surveys, a limited response was received. Of the sixteen professionals asked, about half responded stating they would fill the survey out, but only five people actually returned the surveys. This limited the perspectives received, but was still a much preferred alternative to the original plan. Perhaps there could have been more surveys returned if better instructions were provided more time given.

Among the professionals asked to participate, those in actual floodplain management positions found the exercise to be relatively self-explanatory, and an overall fun exercise. Those in professions not directly involved in floodplain management tended to have a harder time conceptualizing the exercise. The process of distributing a set amount of points to both positive and negative influences on the levee setback locations seemed to confuse a few people. One person, even after several emails and a phone call attempting to explain the exercise instructions, still found the survey too confusing to complete and gave up. It was apparent a better explanation was needed. Ideally a face to face exchange explaining the model steps and showing hypothetical results could have taken place.

Per request in the instructions, some of the professionals returned the surveys with comments. One professional was unclear whether the hypothetical environmental non-profit was buying out the land or being bought out. The same question was asked about the developer. The same person wanted elaboration of the hypothetical farmer's perspective on hazards, and if they cared about being bought out. This person also would have liked elaboration on the tribal member's perspective on land purchase cost. They wanted to know if the tribe was purchasing property, or if they were looking at this as a way to spend taxes. For the single-family home owner they were confused on how to weight their preferences, especially with land purchase cost. This person made it clear I should have done a better job in explaining this as an exercise where a hypothetical stakeholder is solely inserting weights as a representation of their values, and it is not for a literal land transaction, or project location.

One person, when filling in the weights of the hypothetical stakeholder representing their own profession put significant weight on both Chinook habitat and wetlands, but with the explanation that the parcel will reconnect the area to river habitat and reconnect wetlands to the floodplain. Unfortunately the tool in this thesis is not sophisticated enough to guarantee this. It merely ranks these criteria based on linear proximity, not hydrology.

One professional stated assumptions for every hypothetical stakeholder. This is exactly what the author was hoping for, when being intentionally vague with the hypothetical stakeholders in order to avoid any influencing statements. For the single family home owner they assumed the resident was relatively uninformed with floodplain management, and whose main preoccupation as a taxpayer was maintenance of existing roads. For the floodplain manager they assumed their primary goal was to implement a good project with the greatest overall benefit and the least overall cost. They assumed the tribal member's main concern was fish habitat, followed by responsible land use, i.e. limiting new development in floodplain areas. They assumed the farmer's main interest was ensuring a project won't detract from farmable land, access to lands, and that the project would reduce flood impacts. They assumed the land developer's main preoccupation was with effects of a project on the future development of land in close proximity. For the environmental non-profit it was assumed they had an interest in the broader public good and long-term public benefit of the project.

One final note about the stakeholder outreach exercise is that the scores used in the results section, because they were an average of the scores from all those who participated, appear more normal and less extreme than if it were the score of one individual. All the scores appeared fairly similar. If the scores were from six individual people representing each of the stakeholder groups it is believed they would most likely not appear so close.

There are many ways the stakeholder outreach exercise could be improved. Time was limited to create the survey, limited responses were returned, and there was a considerable level of confusion expressed by those who did return the surveys. Despite these shortcomings, the results obtained and used in the tool are much better than would have been the case with the author subjectively estimating the values of the six stakeholders groups and deciding on the weights. This exercise is a more objective way to execute the hypothetical stakeholder part of the results section.

5.2.4 - Tool simplicity - a strength and a weakness

The simplicity of the tool and the models comprising it can be seen as both a strength and a weakness. The Representation Model and Process Model is merely a geodatabase resulting from chosen publicly available data clipped to the study area. The Spatial Screening Model merely identifies parcels next to levees. The Alternatives Criteria Model almost exclusively considers criteria on the basis of their proximity to a parcel. The latter two models and the Decision Support Model were made completely in ArcGIS ArcToolbox Model Builder. There was no programming or scripting involved. This means that the models have a graphical output to represent the processing steps. It also means that the model could be used by a wider audience of GIS users. Adding criteria, changing criteria or taking away criteria can be a simple process.

Having all three of the models in Model Builder also has its shortcomings. Model Builder is a very basic geoprocessing tool with limited functionality. This makes for a model that is less elegant than it could be. Every small step, such as creating a field, a process repeated several times, has to have its own process workflow. An elegant alternative would be writing a basic script to populate all of the criteria features with their proper fields in a single step. This makes for a model that appears much more complicated than it actually is. It also makes for slow processing time. The Alternatives Criteria Model on average took around twenty minutes to run. The Decision Support Model took on average three minutes to run.

Limited functionality in the Decision Support Model could lead to unrealized user error. Ideally there would be an error message if weights assigned are any different than one hundred points total distributed among the eleven criteria. Unfortunately there is no easy way to do this in Model Builder. Luckily, at this stage the only person who implements the model is the author.

The tool used is basic in the tasks that it accomplishes, though it took quite a long time to make. This should not be the case for a tool with simple functionality, but which has much value in regards to participatory GIS. It is suggested that ESRI create an automated GIS-based MCDA tool like this one, but with many of its steps built in to minimize processing time. This would surely help the subdiscipline gain traction in the GIS, planning, environmental resources and associated decision support fields by enabling GIS-based MCDA for the masses. It would also provide a more sophisticated and customizable vector data processing alternative to what currently exists, allowing jurisdictional units such as parcels and watersheds to be examined. Currently the only GIS-based MCDA tool existing in ArcGIS is the raster data processing Weighted Overlay tool mentioned in Section 2.3.1 that executes a very simple GIS form of weighted linear combination. Because the data inputs can only be raster (cell based) data, connecting results to jurisdictional or natural boundaries is cumbersome. A vector based tool would not only alleviate boundary issues, but also allow multiple attributes in a single layer to be used.

5.3 - Future Directions

This thesis accomplished palpable results, but there are many ways to build upon and implement the tool created for broader uses than it currently accomplishes. This section explores practical uses of this tool and the models that comprise it, within floodplain management and beyond. Like many exercises in research, more resources could be used to build upon this decision support tool increasing its robustness, use, and functionality.

5.3.1 - A simple demonstration of its application

This thesis is seen as a basic demonstration of applying GIS-based MCDA to defining potential locations of multiple benefit river restoration projects in the Puget Sound region. Through standardizing data and creating an opportunity to insert stakeholder weights it creates a window into spatial analysis and suitability analysis for non-GIS users to participate in GIS aided decision support. It is the author’s hope that the tool can be used and improved upon by jurisdictions that have the desire to execute river restoration/flood attenuation projects, but do not have the resources to conduct expensive studies determining what project sites should take priority. This tool can be built upon or parts removed in order to fit the local concerns and unique attributes of any river with levees. The model is as precise as the data put into it.

The author feels this tool could have a place in decision making in areas of the Pacific Northwest that have minimal resources including GIS staff, but have large issues in regards to river and floodplain management. Many places rural in nature may not have the technical and financial resources of King County, but still deal with the same issues. Salmon habitat, protection of lives and built capital, social equity, and overall environmental health are important to most people. This tool can help these communities decide which areas adjacent to waterways they should treat first so they can get the most from their money.

5.3.3 - Transferability to other realms of planning

This model was made specifically for levee setbacks on rivers, but the tool's application could span many disciplines in urban and regional planning, as well as environmental management. In its simplicity it is a tool to rank parcels by what is contained within and adjacent to them. Any discipline that asks the questions of what and where, and has multiple things to consider could use this method.

One application would be transportation corridor improvements. A new rail line or widening a right-of-way for increased capacity and functionality has many considerations. Elements such as land value, land ownership, social equity, and environmental sensitivity all are concerns of major transportation projects. Parcels adjacent to these right-of-ways, or future right-of-ways, like was done here for parcels adjacent to levees, can be ranked according to what is within and near them.

The same can be done with water supply and water infrastructure improvements in regards to what project improvements and what additions should go where. Often many improvements are needed, but where are they needed the most? A way to supplement projects coming to fruition through political means solely, this tool could help transfer stakeholder considerations into actual locations on a map. Water project site locations could be ranked by adjacent environmental sensitivities, known contaminants within close proximity, water stresses, and new development.

Siting low income housing could be another use. The Spatial Screening Model can be used or bypassed if a list of sites to consider is already made. Criteria such as grocery stores, jobs, schools and transportation can be ranked according to their proximity. Stakeholders can weigh in on which criteria are most to least important by assigning weights. From there sites can be ranked.

This model could be used when comparing the suitability of future electricity transmission line alternatives. Multiple factors can be considered, as long as they have a location. Criteria such as schools, environmental sensitivities, future development plans, and electricity load forecasting could all be weighted in multiple iterations to see which prospective areas are the most favorable. One could consider the sensitivities of parcels within, or adjacent to a proposed transmission line, ultimately helping aid decision makers with educated choices.

These are a few brief examples of applications in planning that the methodology developed here could be used to assist with. Many more exist, as long as a location and multiple interests are involved. It is believed this thesis provides an excellent decision aiding tool spanning many fields. The key is to enable people's access to it.

5.3.4 - Next steps - online access

A successful stakeholder outreach tool must have public access. Currently this tool sits on a desktop application, meaning one has to be a GIS user with a GIS software license to use it. This makes for major constraints in regards to access. A next step beyond this thesis that would alleviate these constraints would be to publish the tool and associated maps online. Because ArcGIS is used, the recommended web-GIS application is ArcGIS Online.[151] Once online, anyone with internet access could add their criteria weights and view the results. This would be a key move to take participation beyond meetings that a limited number of people can attend.

5.4 - Chapter Summary

This section addresses a broad scope of topics. First the significance of the model results and the context in which they can be applied were addressed. Other local studies with parallel goals were introduced. The limitations of this thesis were then addressed. Great diligence was taken to create a complete thesis with a valuable tool capable of benefiting local planning issues while requiring minimal resources. This involved several decisions along the way limiting the scope and depth of the tool created and the criteria used. The most significant

[151] "ArcGIS Online," Environmental Systems Research Institute (ESRI) website, accessed on May 5, 2014, http://www.esri.com/software/arcgis/arcgisonline

of these choices were covered. Future directions of the thesis were discussed, mentioning other planning issues that could use the model, and next steps. We now conclude.

6.0 - Summary, Conclusions, and Recommendations

6.1- Summary

The balance of human and natural systems is getting more complicated. Our aging infrastructure coupled with climate change and increased population adds levels of stress to our river systems and natural environment that we have not seen in recent past. Choices will need to be made as to where we will focus limited resources for the purpose of increasing community resilience, improving social equity, and maintaining a healthy and sustainable environment. The tool created in this thesis is seen as one way to help arrive at decisions that can help promote a sustainable and resilient future.

In this thesis the relationship between humans and too much water is introduced. The Methodological and Substantive Foundations section provides the framework for GIS-based MCDA, its use with multiple benefit river restoration projects, the geodesign framework, and levee setbacks as an approach. The methods for this tool are explained and the study area is presented. Results are shown employing different weighting schemes, representing the concerns of a range of stakeholder groups within the model. Discussion is made on the significance of the thesis, its limitations, and potential future directions.

6.2 - Conclusions

In the combined world of river restoration and floodplain management there are multiple issues with multiple concerns that should be taken into account when deciding how to solve them. Sometimes the processes it takes to gather and synthesize these views alone can take a significant amount of time and resources. Creating a tool that can help facilitate multiple stakeholders with multiple views to work toward a consensus on where land use changes and their associated projects should occur can be extremely valuable. GIS-based MCDA as a tool within the geodesign framework is seen as an excellent way to help account for these multiple opinions and values into a cohesive format that can help educate stakeholders on how their opinions and values translate to prioritizing project sites.

GIS-based MCDA is a tool to assist in informing decisions, not make decisions, per se. Geodesign is an all-encompassing framework that GIS-based MCDA can work within to help design and implement these informed decisions at a landscape scale. This thesis has created a tool to be used within a collapsed version of the geodesign framework for prioritizing levee setback locations, which ultimately increases the performance of coupled human-natural systems. Ideally the complete geodesign framework would be implemented for the research and design of a better floodplain on the Lower Green River. This thesis takes the narrow focus of relating stakeholder views and values to where the levee setbacks should take place. For this reason the collapsed version of the geodesign framework is used. If one were to complete a geodesign framework exercise for the area the tool created in this thesis could be one part of it.

The results were very similar in almost all of the model runs with the exception of a few the criteria in the sensitivity analysis. These similarities were especially apparent in the stakeholder outreach exercise. This is a hypothetical example showing that despite differences in values, these stakeholders agree that the upper river sections of the study area are more suitable for levee setbacks than lower sections. Or at least that is what is implied when transferring their values to this thesis tool.

6.3 - Recommendations

A basic GIS-based multi-criteria decision tool is complete, tested, and ready for implementation. Because one can only test so much in a hypothetical setting, it is recommended to apply the methods used in each of the models to an actual problem that needs a tool such as this to aid in decisions. Most likely the criteria inputs and subsequent formatting of the tool need to be customized to fit the unique characteristics of a specific problem in a specific area, whether it is a levee setback or a different spatial planning problem as mentioned in Section 5.3.3. Ideally the model would be presented to stakeholders in a web-GIS interface, where they can apply their desired weights to the criteria at their convenience during a set timeframe. Stakeholder weights should be tested and the results should be presented back to them so they can see how their values translate to prioritization of parcels of land. The successes and failures of the tool as a decision aid should be documented. From these observations appropriate improvements can be made, resulting in increased usability and ultimately bringing stakeholders and the general public closer to informed decision making.

7.0 - Contact Information

For any inquiries please contact Jesse Reynolds at jessereynoldz@gmail.com