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Cost-Efficient Spatial Placement of
Water Retention Sites (WRS) to Reduce Sediment in
Le Sueur River Watershed, MN

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Abstract

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Since the widespread European settlement, the Minnesota River Basin has undergone dramatic changes in hydrology. The resulting increases in streamflows and the erosion of near-channel features contribute a large amount of sediment to the downstream rivers. In spite of some hydrologic alterations caused by climate change, researchers like Schottler et al.(2014)[62] indicated that it was the local land-use effect, such as artificial drainage, that mainly increased the streamflow in most of Minnesota River tributaries. A recent study by Mitchell(2015)[46] showed that the establishment of Water Retention Sites (WRS) had significant effects on reducing peak flows and sediment loading rates in Le Sueur River Watershed, a subbasin of Minnesota River Basin, and therefore could be a feasible and effective strategy for sediment management. However, implementing WRS at all of the identified potential sites is obviously a cost-inefficient proposition. Ninety percent of areas of the watershed locate in the Western Corn Belt Plains Ecoregion with 82% under agricultural cultivation, which indicates significant opportunity costs associated with agricultural revenue. In addition, the negotiation with landowners to convert all sites identified on their land into wetlands can be encumbered and time-consuming. For the purpose of reducing the conflicts between sediment reduction and economic development in the Le Sueur River Watershed, this study focused on the cost-effective implementation of WRS by optimizing

both the spatial distributions of WRS and the timing to switch land-use from agricultural cultivation to WRS, from the perspective of landowners facing uncertainty in agricultural net returns.

The methods applied in this study include real options analysis and optimization. To better illustrate the opportunity costs of land conversion from agricultural cultivation to WRS, we utilized the real options model to examine the critical easement payment that would induce farmers to sign the leasing contract. Then we used the results of real options analysis to modify Hansen et al.'s (2015)[30] wetland costs model to estimate the variable costs of WRS implementation. Two optimization models applied in the study were benefit-to-cost ratio ranking and spatial optimization. Based on the costs estimations and the sediment reduction coefficients, which were the meta-modelling results from Mitchell's(2015)[46] simplified hydrological model, we ranked all WRS according to their benefits (sediment reduction) relative to costs ratio for cost-efficient sites selection. In aware of the significance of the transaction costs, we built a spatial optimization model by developing "landowner clusters" for WRS cost-efficient spatial placement.

Both of the benefit-to-cost ratio ranking model and the spatial optimization model displayed advantages in achieving economic and environmental objectives, compared with WRS strategies not paying careful attention to the implementation costs. But the spatial optimization could save the total costs more significantly than the benefit-to-cost ratio ranking. Our study would assist local stakeholders in designing sediment management policies cost-efficiently and achieving better results both economically and environmentally.

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Chapter 1

INTRODUCTION

The Minnesota River flows more than 335 miles from its source at Big Stone Lake near the Minnesota-South Dakota border to its confluence with the Mississippi River at Fort Snelling [11]. As the state's largest tributary to the Mississippi River, the Minnesota River drains 16,770 square miles total in the Upper Mississippi River Basin, 14,840 square miles in Minnesota State, along with 1,930 square miles in northern Iowa and eastern South Dakota.

The Minnesota River is one of the most polluted rivers in the state and the nation. It was listed as one of the top ten most endangered rivers in the United States by American Rivers in 2008[11]. Suspended sediment, measured by TSS(Total Suspended Solids), turns out to be one of the primary pollutants that adversely affects both the ecological health and aesthetics of the Minnesota River and its tributaries. The elevation of TSS increases the water turbidity and reduces light penetration, which shifts the stream productivity away from beneficial periphyton to undesirable floating algae. The massive reproduction of floating algae (phytoplankton) further reinforces the problem of turbidity. Moreover, a lot of essential habitats for invertebrates and fish could be degraded by fine-grained sediment that settle on stream beds, as another factor of biodiversity loss and ecosystem impairment. High turbidity will also diminish the river's attractiveness as a recreation area for swimming, boating, and fishing[11].

The sediment-related water quality issues of Minnesota River Basin are closely related to the formation of the landscape during history. The Minnesota River Basin is covered by glacial deposits left behind by large ice sheets that occupied the region as recently as 12,000 years ago[70]. The large volume of meltwater from a vast glacial Lake Agassiz at the end of the last glacial period drained catastrophically and carved out the present-day Minnesota

River Valley. This carving or incision process was experienced by tributaries as a rapid base-level fall, producing the valleys with steep river gradients (knickpoints)[7], actively eroding bluffs and ravines and increasing the sediment loads.

However, the problem of sediment has been exacerbated further by the development of agriculture over the past 150 years. Since the first generation of European-Americans settled into the Minnesota River Valley around 1851, the Minnesota River Basin has been transformed into one of the most productive regions in the world with 92 percent of the land-use tied to primarily corn and soybean crop rotation as well as livestock production. The vast amount of agricultural drainage along with the ongoing loss of wetlands, prairie, forests and set-aside land significantly increased the streamflows and exacerbated the erosion of stream banks and bluffs[27], aggravating the sediment overloading problem further. Lenhart et al.(2011)[37] demonstrated that because artificial drainage for agricultural purposes deprived the hydrologic storage, it diminished water residence times and intensified peak flows, accelerating the erosion and sediment loading problems. Research found that the sediment loads delivered to Lake Pepin, a naturally dammed lake on the mainstream Mississippi River, had increased by an order of magnitude since 1830 CE[22], with 90% of the loads originating from the Minnesota River, and the rate of this supply had increased ten-fold over the past 150 years.

Study Area

The Le Sueur River Watershed, located in south central Minnesota, is one of the 12 major watersheds in the Minnesota River Basin. It is the heaviest contributor of sediment for Minnesota River, delivering as much as 30% of the Minnesota River's annual sediment load, although it drains only 6% of the basin area (about 1,112 square miles)[8]. Therefore, the Le Sueur River Watershed is a great example of Minnesota River Basin associated with erosion and sediment overloading issues.

There are over 30 lakes in the Le Sueur River Watershed with 1,200 miles of streams including the Cobb River, Maple River, and Little Le Sueur Rivers[12]. The Le Sueur River Watershed is mostly rural with 82 percent of the land under agricultural cultivation[1]. The

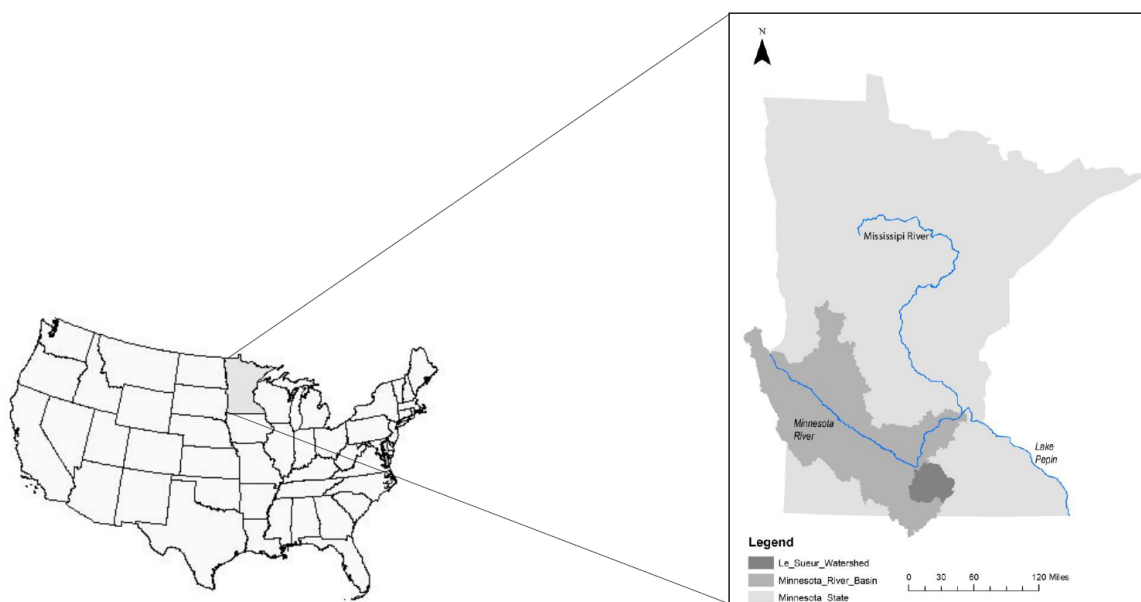


Figure 1.1: Location of the Le Sueur Watershed.

Figure 1.1 shows the location of the Minnesota River Basin, Le Sueur River Watershed, and Lake Pepin relative to the state of Minnesota.

population of approximately 37,000 people in this area is divided into 20 communities and farmsteads in five counties: Blue Earth, Faribault, Freeborn, Steele, and Waseca.

The topographic features of the Le Sueur River Watershed partly explain why the watershed is a primary sediment source to the Minnesota River. The geomorphic history of the watershed leaves the Le Sueur River sharp increases of channel gradient (also called “knickpoints”) at the mouth. The slope-area analyses by Gran et al.(2009)[28] showed that the knickpoints had migrated 30–35 km upstream since 11,500yr B.P., eroding 1.2×10^9 – 2.6×10^9 Mg of sediment from the lower valleys in the process. Meanwhile, the kickpoints divided the watershed into distinct topographic zones with the upper part at the southeast of the watershed, receiving sediment primarily from uplands and streambanks; while the lower zone located in the northwest of the watershed, receiving additional sediment from high bluffs and ravines[28].

Besides the topographic structures, the widespread altered hydrology in the Le Sueur

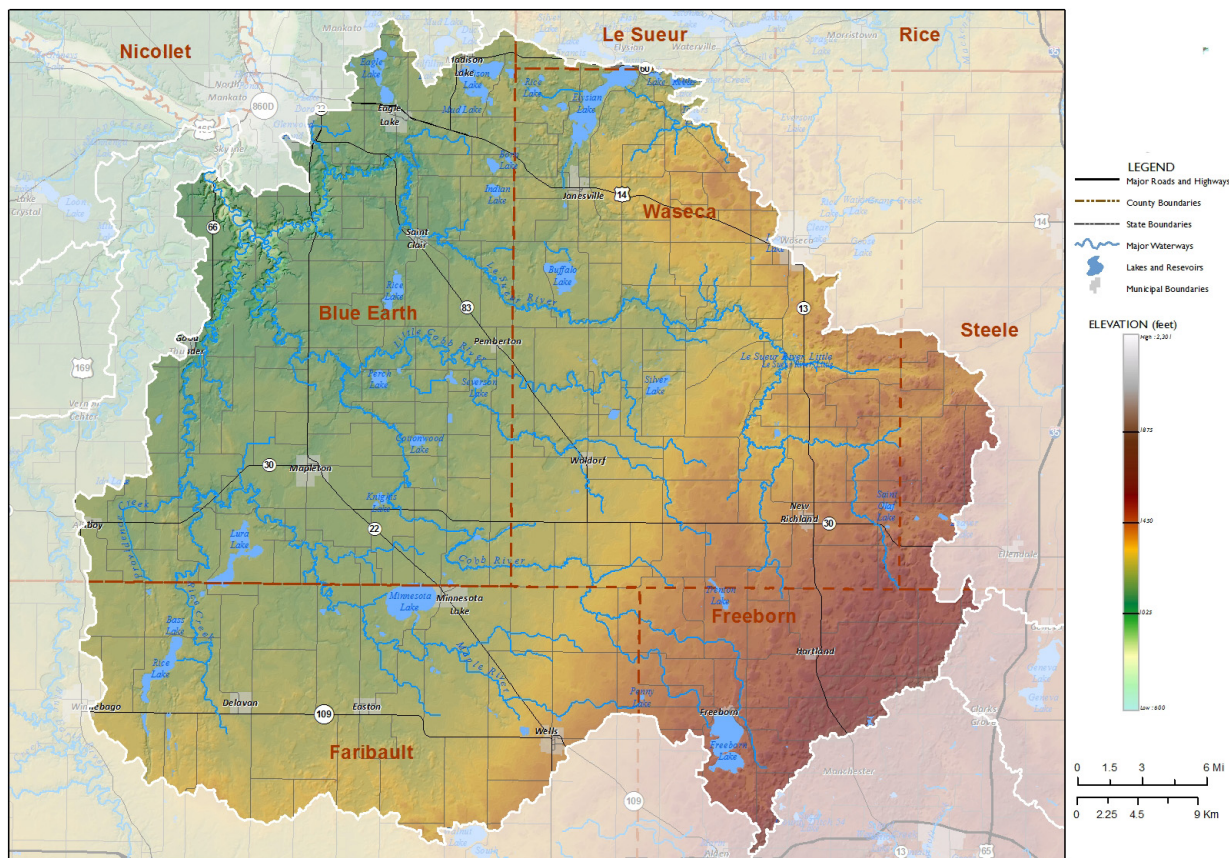


Figure 1.2: The Topography of the Le Sueur River Watershed.

Figure 1.2 shows the topography of the Le Sueur River Watershed.

Source: <http://mrbdc.mnsu.edu/mnnutrients/watersheds/le-sueur-river-watershed>.

River Watershed is believed to be responsible for accelerating the sediment contributions by near-channel sources. These hydrologic alterations, such as the increased river flows and precipitation, the decreased evapotranspiration (ET) and residence time on the landscape, etc. result from both climate change and human activities. Since the 20th century, much of this region has experienced increased annual rainfall. The runoff ratio (the percent of precipitation that enters river flow) of the Le Sueur River has increase from 17% (mid-20th century) to 28% (late-20th century) to 34% (early-21st century)[8]. Meanwhile, since European settlement, almost 90 percent of prairies and wetlands of the Le Sueur River Watershed

have been replaced by agricultural land and nearly all farm fields have artificial drainage systems. In many cases, the drainage-tile outlets empty directly into ravines, increasing peak flows and sediment loading rates dramatically[47]. However, researchers found that changes in precipitation and evapotranspiration explained less than one-half of the increases in river flows, with the remainder highly correlated with the implementation of artificial drainage and the loss of depressional areas for precipitation infiltration and water storage(Schottler et al.,2014)[62]. Wang et al.[69] also found that over 60% of the mid-to-late 20th century's increases in river flows of the Le Sueur River were caused by land-use change.

For the purpose of reducing peak flows and then the sediment loading rates for Minnesota River Basin, Mitchell(2015)[46] proposed a new concept called “Water Retention Sites” in his recent study about increasing water storage in the Le Sueur Watershed. The “Water Retention Sites” (WRS) refers to general depressional storage areas potentially designed to act as either ecologically-functional wetlands or simple detention basins. By applying different combinations of design depth and the hydraulic conductivity with WRS extent in various portions in the Le Sueur River Watershed, Mitchell created a generalized model to assess the effects of a wide range of WRS implementation scenarios on peak flows and sediment loading rates in the lower reaches of the watershed. His study not only showed that WRS could reduce peak flows and sediment loading rates in Le Sueur River Watershed but also found the effectiveness of WRS varied significantly between different scenarios. These various effects potentially indicate an opportunity for cost-effectiveness analysis because within a certain sediment reduction level, selecting some scenarios and locations to implement WRS can cost less than others. Moreover, when we incorporate the WRS strategies into decision-making model, we definitely would like to choose the optimal one that can achieve the sediment reduction goal at minimal costs.

When the economic considerations are included along with the environmental factors for the WRS project, additional important criteria including agricultural profit, land market value, construction costs, property rights, etc. will also affect the decision of whether or not/and where the WRS should be placed. The Le Sueur River Watershed locates in the

Western Corn Belt Plains Ecoregion with 82% of the land under agricultural cultivation. The agricultural revenue remains dominantly critical to the economic vitality for the watershed. Being in the midst of the richest farmland in the country brings a particular challenge of balancing the economic development and water quality improvement for this region. Unless we address drainage as a fundamental cause of poor water quality, it is hard to see an improvement in water quality, whereas the artificial drainage system is essential for agricultural production.

Also, positive externality occurs when the landowner breaks his/her drainage tile for a wetland restoration since this replacement improves the quality of downstream water that leave their property land. Although the positive externality can create a greater marginal social benefit of wetlands, it is a private setting and wetlands are doomed to be undersupplied, and the externality will also cause a net social welfare loss[43]. David Friedman explained the problem of externality as “it is not that one person pays for what someone else gets but that nobody pays and nobody gets, even though the good is worth more than it would cost to produce”[25]. One of the roles of the government is to implement appropriate policies involving subsidies, education or technology supports to encourage farmers’ behaviors of wetland restoration to alleviate the problem of underprovision.

Another important issue that will affect decision-making is property rights. In our case, restoring WRS means depriving the farmer’s rights like draining a wetland on his property to create a field suitable for crops and to gain agricultural profits. Although under the principle of eminent domain, governments are permitted to appropriate private property for public purposes, the Fifth Amendment of the U.S. Constitution requires that the property owner should be fairly compensated. Therefore, an easement leasing payment needs to be given to the farmers as the compensation besides the restoration/construction costs. Even though we purchase the property rights from the farmers according to the land market value, the economic efficiency can still be hampered because of the presence of transaction/negotiation costs. The negotiation with landowners to get their agreement to convert all of the candidate sites identified on their land into wetlands will encounter multiple hurdles and is likely to be

costly and very time-consuming.

To minimize the trade-offs between sediment reduction and economic development in the Le Sueur Watershed, we focus on the cost-effective implementation of WRS by optimizing both spatial distributions of WRS and the timing to switch land-use from agricultural cultivation to WRS from the perspective of landowners. More specifically, the **three hypotheses** of this study are as follows:

- Hypothesis 1: By considering the heterogeneity of sediment reduction ability and implementation costs of candidate WRS, the benefit-to-cost ratio could be an indicator for WRS cost-efficient spatial placement.
- Hypothesis 2: By considering the fact that multiple candidate WRS can belong to a single land-owner, a cost-efficient WRS placement strategy would reduce transaction costs by selecting WRS owned by the same landowner as much as possible.
- Hypothesis 3: By considering the uncertainty of opportunity costs, we would like to apply real options analysis to find the minimal easement payment that farmers will accept to sign a leasing agreement for WRS implementation.

To assess these hypotheses, the study follows the **methodologies**:

- (1) Environmental benefits estimation. We apply Mitchell's (2015)[46] simplified hydrological model to estimate the sediment reduction coefficient for each WRS at different scenarios. The amount of sediment reduced are referred as the "benefits" of each WRS.
- (2) Economic costs estimation. We first adopt Hansen et al.'s (2015)[30] wetland costs model to measure the variable costs of each WRS. And we improve it by applying the real options analysis to identify the minimal easement payment value, at which signing contract for WRS implement will be preferred to agricultural cultivation by the farmers facing uncertainty.

- (3) Benefit-to-Cost Ratio Ranking. According to the benefits and costs information of WRS implementation, we can sort all candidate WRS by their benefit-to-cost ratio, and take it as an indicator for cost-efficient WRS selection within certain sediment reduction constraints.
- (4) Spatial Optimization Model. We create WRS clusters by grouping the WRS parcels that belong to the same landowners, and then build the spatial optimization model.(In the same sediment reduction level, we are able to compare the minimal costs we get from the spatial optimization model with the costs we get from benefit-to-cost optimization.)

Chapter 2

LITERATURE REVIEW

2.1 Wetlands Benefits Simulation

The Federal Geographic Data Committee (FGDC) defines wetlands as “the land transitional between terrestrial and aquatic systems”, which “perform flood protection, pollution control and a variety of other critical functions”.(Wetlands Classification Standard (WCS), 2013). Although it has been widely acknowledged that wetlands conservation/restoration plays a significant role in abating sediment and nutrients (eg., nitrogen and phosphorus), the water management practices usually require a quantitative assessment to show the effects of wetlands on water quality improvement.

During the last decades, numerous hydrologic simulation models have been developed to predict the environmental conditions of a watershed and to evaluate the water management practices. Borah and Bera(2003) [9] reviewed eleven major watershed-scaled hydrologic and nonpoint-source pollution models in their article. They investigated the flow-governing equations and mathematical bases for each model and discussed how to select the most suitable model for an application depending on critical factors such as watershed size, desired spatial and temporal scales, expected accuracy, etc.

Among these models, the Soil and Water Assessment Tool or SWAT [3] is the one that was applied in Minnesota River Basin for its peak flow and sediment reduction rates assessment. It is a promising model for long-term continuous simulations in predominantly agricultural watersheds and is part of U.S. Environmental Protection Agency’s (EPA) Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) modeling system. For the purpose of modeling stream flow alterations, SWAT subdivides a watershed into numbers of subbasins, and each subbasin is simulated as a homogenous area regarding cli-

matic conditions like precipitation, evapotranspiration, snowmelt, etc. Parts of a subbasin that possess unique land use, soil attributes, and topography will be grouped together and defined as one hydrologic response units (HRU)[17]. Each HRU is a basic computational unit assumed to be homogeneous in hydrologic response to land cover change. In application, both the scale (the number of subbasins) and the scenarios (the number of HRU) of a SWAT model need to be determined depending on the data availability and the balance of modeling accuracy and convenience. SWAT model treats wetlands as water bodies located within subbasins[61]. The peak flow reductions from wetlands are determined by how much the water volume exceeds the wetlands normal storage volumes and the maximum storage volumes. Detailed descriptions of the SWAT's simulation for water balance of wetlands and outflow calculation can be found in Neitsch et al.(2009)[51].

For the concern of convenient application in practice, Mitchell (2015)[46] created a generalized hydrological model capable of generating peak flow and sediment loading rates in the lower reaches of the Le Sueur River Watershed based on the original SWAT assessment of Water Retention Sites (WRS) implementation scenarios. This simplified empirical model providing relatively accurate sediment reduction rate projections can be a better choice than the original SWAT model especially when exact optimization programming is applied like this study, which aims at cost-effective sites selection for wetlands placement. The initial 435 WRS implementation scenarios are simplified into 81 generalized scenarios according to different hydraulic conductivity ($K=6 \times 10^{-10}$ m/s, 7×10^{-10} m/s, or 8×10^{-10} m/s), wetlands design depths ($V=0.5$ m, 1m, or 2m), general proximity to the watershed outlet (Zone1, Zone2, or Zone3) and the their locations relative to three sub-watersheds (Le Sueur sub-watershed, Cobb sub-watershed, or Maple sub-watershed). This generalized model allows us to estimate the linear relationship between contributing areas of WRS and the corresponding sediment reduction rates for different scenarios.

2.2 Wetlands Costs Estimation

There are primarily three types of costs that we need to consider for WRS project implementation: opportunity costs, establishment costs, and transaction/negotiation costs. The first two categories are variable costs, and the third one is fixed cost. More specifically, the opportunity costs represent the market value of the farmland if it does not switch to the wetland; the establishment costs indicate the costs of labor, materials, and equipment, etc. either for simple restoration measures like blocking or slowing water movement; or for significant construction like dredging wetland fill. Transaction costs are the ones involved in reaching and implementing the agreement for the land-use conversion, which can include costs of obtaining information (such as surveying the land), time and effort spent in negotiations with the landowners, and costs of enforcing the agreement.

2.2.1 Variable Costs

Initial studies of wetlands economic analysis mainly focused on estimating the establishment costs in terms of geographic regions, wetland types, construction phases, and input categories. Kling and Bohlen(1994)[35] derived costs equations for both agricultural conversion and non-agricultural wetlands projects and found the former were significantly less expensive than the later. However, the costs per size of agricultural conversion project are less sensitive to project area than other projects. Baca and Florey(1994)[6] applied Kling's equations for estimating the costs at three project phases (preconstruction, construction, and postconstruction) for eight categories of wetlands at Southeastern states of Florida, Georgia, and South Carolina. Söderqvist(2002)[63] applied OLS method for wetlands establishment costs estimation and indicated that the dominant determinant of the costs is the extent of necessary excavation, instead of the wetlands areas.

Subsequent studies mostly viewed the wetland costs estimation as a problem of land allocation decision and included both the opportunity costs and establishment costs into their analytical framework. Heimlich(1994)[31] estimated the easement costs that needed

to compensate landowners based on the opportunity costs of capitalized net returns of crop production; he also examined the least-cost ways of creating wetland reserves at different sizes of 1, 2.5, and 5.0-million acre in eight geographic regions of the United States. Prato et al.(1995)[56] evaluated the loss of net agricultural income from the conversion of cropland to wetlands, as well as the construction and maintenance costs, over a finite time horizon and over an infinite time horizon. The results showed that the choice of time horizon influenced the cost-efficiency of wetland conversion and the net benefits of conversion increased with the time horizon but at a decreasing rate. Byström(1998)[10] assumed a 50 years life expectancy and 3% real rate of interest for wetlands, and compared a linear wetland costs function and a quadratic costs function regarding wetlands area, but the statistic test indicated the difference between the linear and the quadratic function is not significant. Besides the current land value for wetland restoration, research found that the easement costs of wetlands will also be driven by the value of land with an easement.(Jones et al.(1997)[33], Earnhart(2001)[21]; Reynolds and Regalado(2002)[59]), and the value of land near the wetland (Doss and Taff (1996)[20], Mahan et al.(2000)[42], Ma and Swinton(2011) [40]). Hansen et al.(2015)[30] took all these factors into consideration and estimated the total variable costs for ten different wetland regions in United States.

2.2.2 Fixed Cost

Besides the variable costs, an additional consideration regarding the overall costs of WRS implementation is the category of transaction costs associated with communication and negotiation with farmers to switch their land from agricultural cultivation to wetland. The report of Le Sueur River Watershed Priority Management Zone Identification(PMZI) Project[14] itemized the categories of fixed costs associated with watershed information compile and review, landowner consultation, data collection and analysis, and project administration. Naidoo et al.(2006)[49] and Newburn et al.(2006)[52] identified this kind of costs as being an important consideration in land-use conversion issues. Söderqvist (2003) [64] did an empirical analysis for investigating farmers' willingness (or reluctance) to participate in a wetland cre-

ation program in an agricultural district. The results supported the idea that good knowledge and communication strategies, related to the fixed costs spent on the program, have significant positive correlation with a high participation rate. Groeneveld(2005)[29] presented an analytical model to demonstrate how transaction costs can affect the socially optimal number of reserve sites under a constraint of the total reserve area. Conrad et al.(2012)[15] indicated that transaction costs were likely to play a more significant role when reserve parcel's granularity was small, as the transaction costs represented a larger proportion of the overall costs of the candidate reservation parcels.

The estimation of transaction costs was quite complicated, as Macher et al.(2008)[41] emphasized, existing empirical research about transaction costs utilized a variety of econometric and historical methods to quantitatively examine how the transaction costs influenced exchange. Conrad et al.(2012)[15] chose \$5000 as an approximation that was in line with reported transaction costs for their conservation lands. Similar to their strategy, based on the time budget & expense of the project implementation described in Le Sueur River Watershed PMZI Project report[14], we set \$5000 as an appropriate estimation of the fixed costs.

2.3 Real Options Analysis

In the case of WRS project, it is farmers' property right of keeping and using the land, indicating an easement payment is needed to purchase the land from farmers for the purpose of WRS implementation. This kind of payment usually has been included in the opportunity costs. In the absence of uncertainty and risk, it can be directly estimated by land prices or assessed land values, which equals the present value of the loss in agricultural net return because of the land conversion. If we consider the risk and uncertainty of land profit, farmers' choice of whether or not sign the contract will be a forward-looking behavior instead of a now or never option. And the calculation of the easement payment to the landowner will become much more complicated and requires extensions from standard discounted cash flow techniques to real options analysis.

Real options is a way of thinking that provides an important perspective on value creation

in an uncertain world when uncertainty is substantial, and the decision of whether to complete an investment program is a contingent decision depending on an uncertain outcome[2]. In other words, the investment opportunity can be viewed as a stream of cash flow plus a set of options. The real options analysis can evaluate these types of opportunities more appropriately than the standard calculation of NPV since it can reflect the value of options.

The real options approach has been widely applied in previous research about land resources re-allocation. Isik et al.(2004)[32] used the real options model to examine the extent to which uncertainty and irreversibility affected the probability of farmers' land retirement decision in the Conservation Reserve Program. Yang and Blyth(2007)[71] concluded that real options analysis was a useful tool to analyze the impacts of the uncertainty of climate change policy and energy price on energy sector investment. In Gazheli et al.(2013)[26], real options theory was applied to identify the critical profit values at which the farmer decided to lease his agricultural land to a company installing a photovoltaic power plant vs.continue farming it. Song et al.(2011)[65] showed that the optimal decision rules about converting traditional cropland into energy crops or not differed significantly from the expected net present value, which ignored uncertainties, and from real options models for irreversible land conversion. Musshoff's real options model (2012) [48] examined the time when farmers should convert set-aside land to short rotation coppice. The results showed that farmers should not convert their land until the present value of the revenues was equivalent to 1.57 times the present value of the expenditures, which indicated a considerable difference between the classical investment theory and the real options approach. Conrad et al.(2013)[16] used real options analysis to study how the decision of converting agricultural land to energy forestry was impacted by the uncertain net returns and government subsidies. They found that the returns of energy forestry were too little to stimulate the decision of land use conversion unless the government subsidies was able to cover at least 75% of the initial investment costs.

2.4 Optimization Model

The simplest set of sites for wetlands restoration in the watershed would be the set of all areas that have been identified as candidates of WRS, which is 7619 with the total area of 60165.836 acres. However, trying to implement all possible WRS would likely to be very costly, and requiring all landowners to convert their land into wetlands, which would be barely practical in most regions for social and economic reasons. For the purpose of balancing environmental protection and economic development, optimization approaches that aim to decrease the potential sites into a smaller but more cost-efficient subsets of sites are performed widely as an alternatives strategy in many research fields of natural resources and environmental management (e.g., Babcock et al.(1996)[5], Feng et al.(2006)[23], Church et al.(2000)[13], McDill et al.(2002)[44], Fischer et al.(2003)[24], Conrad et al.(2012)[15]).

More specifically, for hydrology and watershed management, many optimization models exist for supporting the decision on water policy planning and evaluation. Needham(2002)[50] applied a linear optimization model to estimate the best possible operation of the river-reservoir system and concluded that tandem operating rule would provide appreciable benefits. Li et al.(2012)[38] set a multi-objective optimization model and applied TOPSIS (Technique for Order Preference by Similarity to An Ideal Solution) to identify the location and areas of economic functional zones, ecological functional zones and multi-functional zones for a watershed. Lee et al.(2012)[36] set up two cost minimization models for flow volume and pollutant load reduction. Babbar-Sebens et al.(2013)[4] integrated the optimization algorithm(NSGA II) with SWAT to solve a bi-objective optimization problem for peak flow reduction maximization and total wetlands area minimization.

A long-standing debate in optimal selection problem for a number of candidate sites(eg., watershed, timber production parcels, nature conservation sites, etc.) has centered on the question of establishing a “single large” or “several small” reserves (SLOSS) (Ovaskainen, 2002[54]). Creation of a “single large” reserve requires that each selected site to be connected directly or indirectly (through intermediary selected sites) with every other selected

site. Creation of “several small” reserves, however, is not necessary to satisfy the above conditions. Unless connectivity is encouraged, as numbers of candidate sites increase, there is an increasing chance of solutions that will go well beyond “several small” to “much, highly fragmented” (Fischer et al., 2003)[24]. The discussion of SLOSS didn’t take economic aspects into consideration until Groeneveld (2005)[29] presented an analytical model to show how opportunity costs of nature conservation, land trade, and related transaction costs would affect the optimal number of reserve sites. In our WRS case, continuity or connectivity is not so essential for sites selection because of a quite large number (7619) but small individual area of candidate sites and their high-density distribution. Therefore, we grouped those WRS parcels belonging to the same landowner as a “landowner cluster”, and enforce the spatial optimization model to select parcels in the same cluster as many as possible within the constraint of sediment reduction level.

Chapter 3

METHODOLOGY

This chapter will explain the method of adopting Mitchell’s hydrological model and Hansen et al’s wetland costs model; the way of modifying Hansen et al’s model by applying the real options analysis; the procedures of doing the benefit-to-cost ratio ranking and method of building the spatial optimization model.

3.1 Environmental Benefits Estimation

The simplified hydrological model created by Mitchell (2015)[46] allows us to simulate the linear regression between WRS extent and the sediment loading rates under different scenarios. This is an application of the meta-modeling techniques which aims to simplify the complex relationship between runoff and its impact on sediment loads by estimating the sediment reduction coefficient as a proxy alternative, similar to the point systems in Rabotyagov et al.(2013)[58], and the “delivery coefficients” in Wainger et al.(2013)[68].

For each scenario, by inputting the fraction of the available area for WRS placement, the Mitchell model will generate the corresponding projection of sediment loading rate. Then the WRS areas and sediment loading rates data could be used to estimate the linear coefficients between these two variables. Finally, we take the coefficient times the WRS area as the index for measuring the sediment reduction capability for candidate WRS.

Since the watershed is divided into 30 sub-basins for the model simulation, the sediment reduction coefficients will also be the sub-basin level based on the generalized scenarios which are the combination of hydraulic conductivity, design depth and sites location. The three kinds of hydraulic conductivity scenarios applied in the model are $K=6 \times 10^{-10}$ m/s, $K=6 \times 10^{-10}$ m/s, or $K= 6 \times 10^{-10}$ m/s; the design depths scenarios are $V=0.5$ m,

V=1m, or V=2m. The site placement scenarios are defined by the sub-basins's general proximity to the watershed outlet and their locations associated with the three sub-watersheds in the Le Sueur River watershed. The upper half of the watershed is defined as Zone1, while the lower half is divided into Zone2 and Zone3, with zone 3 being the closest to the outlet.

Zone1, Zone2, and Zone3 have 56.4%, 48.1%, and 44.8% of available WRS placement area in the Le Sueur sub-watershed; 19.2%, 34.9%, and 44.5% in the Cobb River sub-watershed; and 24.4%, 17.0%, and 10.7% in the Maple River sub-watershed. The upper threshold of the WRS area fraction set by Mitchell model for Zone1 Zone2 and Zone3 is: 4.2%, 3.5%, 3.3% in Le Sueur River sub-watershed; 1.4%, 2.6%, 3.3% in the Cobb River sub-watershed; and 1.8%, 1.3%, 0.8% in the Maple River sub-watershed.

Placement Scenario	Le Sueur Rive sub-watershed		Cobb River sub-watershed		Maple River sub-watershed	
	Total WRS candidates	Areas for Placement (acres)	Total WRS candidates	Areas for Placement (acres)	Total WRS candidates	Areas for Placement (acres)
All Zones	3147	287,806.08	2214	193,446.59	2228	219,294.27
Zone1	1905	162,372.87	1031	93,032.54	1145	98,282.70
Zone2	537	55,159.52	872	67,496.06	904	97,481.44
Zone3	705	70,273.70	311	32,917.99	179	23,530.13

Table 3.1: WRS Site Placement Scenarios

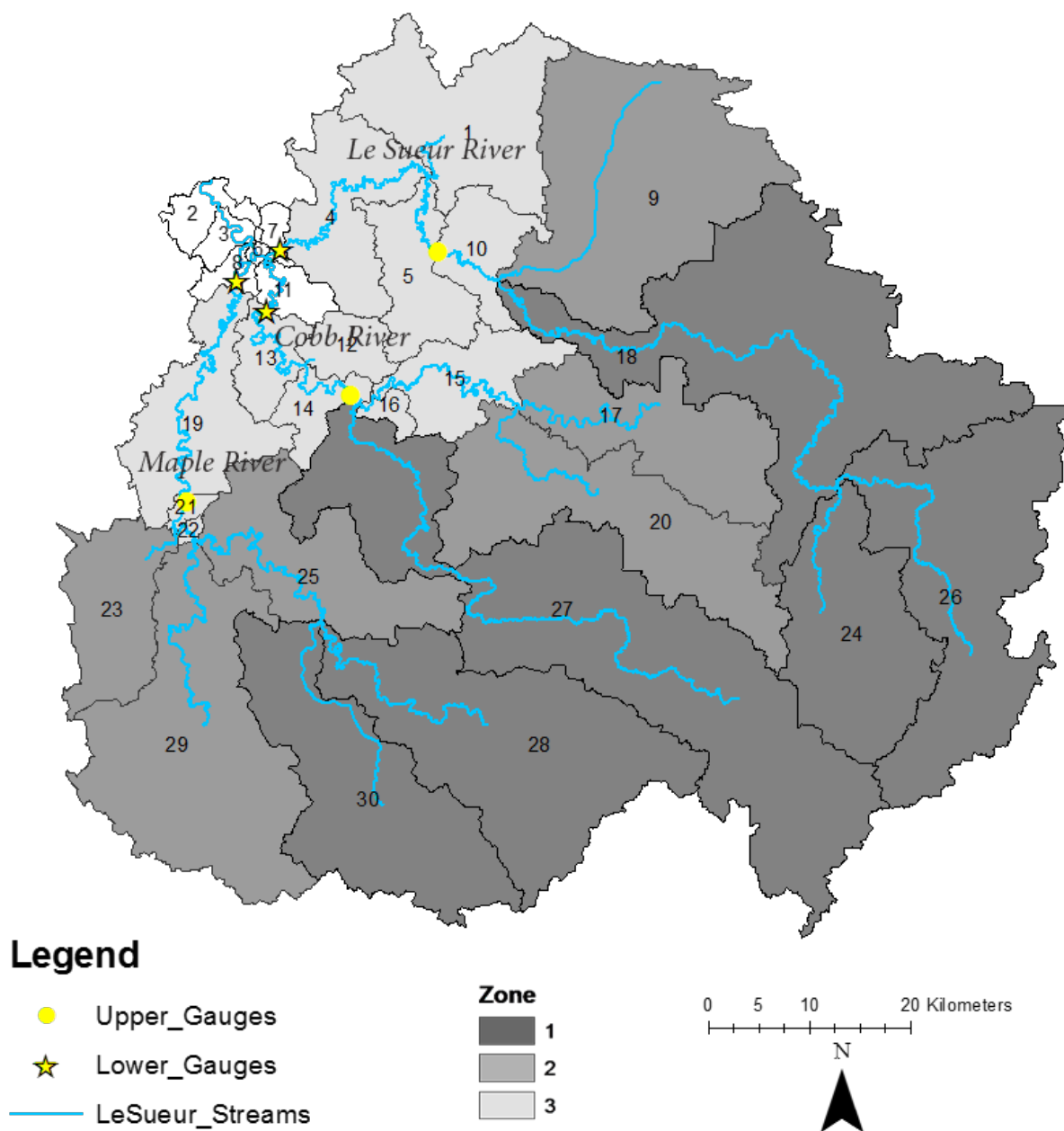


Figure 3.1: WRS Placement Zones in Le Sueur River Watershed.

Figure 3.1 shows the WRS placement scenarios associated with sub-basins and sub-watersheds in the Le Sueur River Watershed.

3.2 Economic Costs Estimation

3.2.1 Hansen et al's model adoption

For the costs part, after comparing those existed wetlands costs model, we choose to apply Hansen et al's model (referred to as "Hansen costs model" thereafter) to estimate the total variable costs (opportunity costs and construction costs) for our WRS project. The reasons that we use their model are 1) their econometric models are based on all contract data (2468 observations) in the Conservation Reserve Program (CRP) supplied by USDAs Farm Service Agency, which is more representative and updated than others. 2) Their estimations include the specific costs model for wetlands in Prairie Pothole Region like Le Sueur River Watershed, which is the more suitable for our project. 3) The statistical test showed that most coefficients are statistically significant, and the estimated Prairie Pothole Region model can explain about 79 percent of the variation in wetland costs, which indicates that their model is fairly reliable for application. The cost model is as follows:

$$Y = -2870.37 + 29.22938X_1X_2 - 0.00016(X_1X_2)^2 - 421.041X_2 + 0.19056X_2^2 \quad (3.1)$$

Where Y is the costs that consist of opportunity costs and restoration costs. X_1 represents the current cash rental rates and X_2 indicates the area in acres of the WRS. X_1X_2 is, therefore, the farmland value, indicating the opportunity costs of WRS implementation. The reason for adding polynomial items for both X_1X_2 and X_2 is to account the nonlinear relationships that caused by the economies of scale or other factors associated with restorations so that the costs may not be proportional to the size of the wetlands.

3.2.2 Real Options Analysis

The theoretical framework for analyzing the land conversion decision under uncertainty follows the application of option theory to economic analysis elucidated by Dixit and Pindyck (1994)[19]. In our WRS example, the risk-neutral farmers' decision whether or not to sign

a land leasing contract is not a *now* or *never* choice but depends on the agricultural net revenues and the level of easement payment. From the perspective of forward-looking farmers, if on the decision date, the agricultural production is more profitable, they will not sign the contracts. However, if the agricultural market turns out poorly at that time, which means the agricultural net profit becomes an exit trigger that is “less than the variable costs minus the interest on the exit costs” (Dixit,1989)[18], they will make the decision to exit from agricultural cultivation and sign the land conversion contract. Since we assume the agricultural net revenues are uncertain and consider the leasing agreement as an irreversible decision for the whole contract duration, we applied the Black–Scholes method¹ to find an agricultural profit criteria and the corresponding payment level, at which leasing the land for WRS restoration will be preferred to agricultural production for the farmers.

The process of doing the real options analysis is as following: First, we test the stationarity of the agricultural net revenue at the county level. If the logarithm of the net revenues shows non-stationarity, it means we can apply the geometric Brownian motion² method to solve the drift and volatility in the Black–Scholes model. Then we write down the equation of net present value (NPV) according to Black–Scholes formula and resolving the critical profit value by using a standard NPV decision rule. Then we put the NPV critical value into the real options model to get a new profit level, at which, accounting to uncertain agricultural profits and a certain leasing payment level, converting land use is preferred to continuing agricultural cultivation. Finally, when we get all the critical values, we can plug them into the NPV equation to resolve the minimal payment that farmer will accept for land conversion.

¹Black–Scholes model was first published by Fischer Black and Myron Scholes in their 1973 paper, “The Pricing of Options and Corporate Liabilities”, which gave a theoretical estimate of the price of options over time.

²Geometric Brownian motion (GBM) is a continuous-time stochastic process that often used in mathematical finance to model stock prices in the Black-Scholes model.

Notations:

T = the leasing contract duration period.

r = the discount rate(%).

L = the sunk costs, which we assumed as the percentage(%) of construction costs that is borne by the farmers.

π_t = net returns(\$) from agricultural land per acre in year t , which are represented by the cash rental rates data.

π^{NPV} = the critical threshold(\$) for land conversion under NPV rule.

p^{NPV} = the annual leasing payment(\$) to the farmer for WRS program by the government according to π^{NPV} .

π^* = the critical threshold(\$) for land conversion by real options analysis.

p^* = the annual leasing payment(\$) to the farmer for WRS program by the government according to π^* .

α = the drift, which is the mean of the time series $\Delta \ln(\pi_t)$, representing the increments or changes to the stochastic process.

σ = the volatility, which is the standard deviation of the time series $\Delta \ln(\pi_t)$, measuring the degree of fluctuation of the agricultural land market price series.

Model Set Up:*Step1:Test Stationarity*

We first construct a time series data by applying the logarithm of the agricultural cash rental rates $\ln(\pi_t)$ of the five counties within the Le Sueur Watershed from 1996-2016. If the time series is non-stationary, it indicates the consistency with the assumption of geometric Brownian motion, which is a continuous time stochastic process:

$$\frac{d\pi_t}{\pi_t} = \alpha dt + \sigma dz_t \quad (3.2)$$

where α and σ are drift and volatility, and dz_t is a standard Brownian motion (also called a Wiener process).

According to geometric Brownian motion, we can estimate the mean and standard deviation of the time series $\Delta \ln(\pi_t)$, and get the drift α and the volatility σ for real options analysis.

$$\begin{aligned}\alpha &= \mu_l + \frac{\sigma_l^2}{2} \\ \sigma &= \sigma_l\end{aligned}\tag{3.3}$$

Step2: Solve the NPV equation for critical value for π^{NPV}

Let p denotes the certain annual leasing payment to a risk-neutral farmer and L is the percentage of construction costs paid by the farmer. We assume during the entire leasing period, the discount rate r is 5% and the land use change is irreversible. Thus, according to Black–Scholes formula, when the farmer signs the contract at the generic time t , the expected net present value of future revenue is equal to:

$$\begin{aligned}NPV(\pi) &= E \left\{ \int_0^T (p - \pi_t) e^{-rt} dt - L \mid \pi_0 = \pi \right\} = \int_0^T (p - \pi_t) e^{\alpha t} e^{-rt} dt - L \\ &= p \frac{1 - e^{-rt}}{r} - \left(\pi \frac{1 - e^{-(r-\alpha)T}}{r - \alpha} + L \right)\end{aligned}\tag{3.4}$$

The first part $p \frac{1 - e^{-rt}}{r}$ is the discounted flow of payments to which the farmer is entitled by contract. The second part includes the opportunity costs of leasing the land during the time period T and the sunk costs L .

According to the standard *NPV* decision rule, the farmer won't sign the contract until $NPV(\pi) \geq 0$, that is:

$$\pi_t \leq \pi^{NPV} = \frac{p \frac{1 - e^{-rt}}{r} - L}{\frac{1 - e^{-(r-\alpha)T}}{r - \alpha}}\tag{3.5}$$

*Step3: Set the Black–Scholes equation and solve for the new critical value π^**

From the real options perspective, there will be an optimal threshold π^* , taking the uncertainty of agricultural profits into consideration, at which the farmer will be triggered to give up their agricultural production and sign the contracts. In other words, when the agricultural revenue is greater than π^* , the farmer will reject the contract, and continue agricultural cultivation, while when agricultural revenue is lower than π^* , a leasing payment p^* will be more attractive than agricultural production for the farmer.

Let $F(\pi)$ be the value of the option to sign the contract, which is given by:

$$F(\pi) = e^{-rt} E \left[F(\pi + d\pi) \right] \quad (3.6)$$

According to the Black–Scholes equation and using Ito’s lemma to expand the right-hand side of (3.6), we obtain:

$$\frac{\sigma^2}{2} \pi^2 F''(\pi) + \alpha \pi F'(\pi) - rF(\pi) = 0 \quad (3.7)$$

And the solution of the equation 3.7 is:

$$F(\pi) = A_2 \pi^{\beta_2} \quad (3.8)$$

where β_2 is the negative root of the characteristic equation:

$$W(\beta) = \frac{1}{2} \sigma^2 \beta(\beta - 1) + \alpha \beta - r \quad (3.9)$$

and A_2 is a constant to be determined.

The value of the option and the critical threshold can be determined by imposing value

matching and the smooth pasting conditions at π^* , that is:

$$\begin{aligned} F(\pi^*) &= NPV(\pi^*) \\ F'(\pi^*) &= NPV'(\pi^*) \end{aligned} \tag{3.10}$$

And then, we can solve the equation group for π^* and A_2 :

$$\pi^* = \frac{\beta_2}{\beta_2 - 1} \pi^{NPV} \tag{3.11}$$

Step4: Solve for the critical payment p^ :*

If we assume the π^{NPV} equals to the current cash rental rate and then solve π^* to plug it into the equation, we can get the critical (minimal) leasing payment that will be accepted by the farmer to sign the contract. That is:

$$p^* = \frac{\pi^* \frac{1-e^{-(r-\alpha)T}}{r-\alpha} + L}{\frac{1-e^{-rT}}{r}} \tag{3.12}$$

Step5: Modify Hansen's costs model by including the results from real options model:

As we described above, the wetland costs model developed by Hansen et al (2015) took both the opportunity costs and restoration costs into consideration. Since the opportunity costs could also be simply viewed as the product of current cash rental rates(X_1) and land area(X_2), by subtracting it from the total costs estimated from Hansen's model, we will get an approximation of the restoration costs (R).

$$R = Y_{Hansen} - X_1 X_2 \tag{3.13}$$

Then we can combine the minimal easement payment value from real options analysis with the restoration costs estimation to get a new total costs estimation for WRS implementation.

$$Y_{RealOptions} = R + p^* X_2 \tag{3.14}$$

3.3 Benefit-to-Cost Ratio Ranking

Considering the heterogeneity both in sediment abatement ability as well as the different costs level, we did the cost-effectiveness analysis seeking to achieve a given sediment reduction objective at the lowest costs.

The benefit-to-cost ratio could be interpreted as the “benefits per dollar”. Ranking the benefit-to-cost ratio from the highest to the lowest enable us to select WRS parcels with the largest marginal benefits, and therefore will generate the lowest costs by enrolling the WRS parcels from the top of the ranking until the environmental goal is achieved.

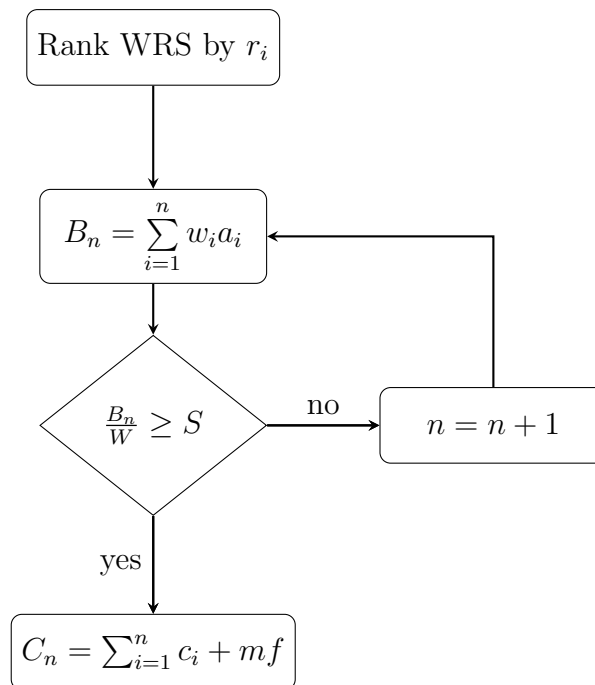


Figure 3.2: Flow Chart for Benefit-to-Cost Ratio Ranking

One thing that needs to be noticed is that the costs we applied in the benefit-to-cost ratio did not include the transaction (fixed) costs, which was associated with the land ownership. Moreover, since the ratio ranking method itself ignores the implicit “interdependence” of parcels induced by their membership to the same owner, we have to figure out the numbers

of landowners involved in our program according to the land ownership information after we got the placement plan suggested by ratio ranking. The total costs for WRS implementation, therefore, should be the cumulative costs got from ratio ranking plus the total amount of transaction costs.

Figure 3.2 shows the procedures for ratio ranking. The ratio r_i is determined by $\frac{w_i a_i}{c_i}$, where w_i is the sediment reduction coefficient for WRS parcel i ; a_i represents the area of each parcel i . So $w_i a_i$ indicates the amount of sediment reduction by each parcel i . B_n represents the total sediment reduction by all of the selected WRS parcels; c_i is the variable costs estimation for parcel i ; and the sum of c_i is the cumulative variable costs for achieving the given sediment reduction goal. mf indicates the total amount of fixed costs under ratio ranking method, where m is the number of landowners and f is the transaction costs need to be paid to each landowner. W is the baseline of sediment loads which equals to 49733.4(Mg/yr); S is the sediment reduction constraints, and $S \in \{5\%, 10\%, 15\% \dots 95\%, 100\%\}$;

3.4 Spatial Optimization Model

Our proposed 0-1 programming model aims to minimize the total costs of WRS implementation with the constraint of sediment reduction level and land ownership. The following notation was used for clarification:

Parameters:

a_i = the area in acres of each WRS parcel i . Source: the attribute of the geographic area in each county's GIS shapefile.

v_i = the variable cost of wetlands restoration(\$). This is the cost associated with each WRS parcel i , including the opportunity costs and construction costs. Source: Estimated from Hansen wetland costs model for Prairie Pothole Region and real options analysis.

t = the fixed cost for land conversion(\$). This is viewed as the transaction cost that will only be assigned to each landowner cluster j . As we discussed in the literature review, the actual value of transaction costs is complicated to decide, but according to the previous study (Conrad et al.(2012)[15]) and the Le Sueur River Watershed PMZI project report[14], we assume the cost is \$5000. Source: Literature review and official report.

w_i = the sediment reduction coefficient (Mg/yr/acre). It is associated with each WRS parcel i under certain scenarios. Source: Estimated from the simplified hydrological model created by Mitchell(2015)[46].

W = the baseline sediment loading rate (Mg/yr), which equals 49733.40. Source: The estimation of Mitchell's model(2015)[46] in the baseline scenario.

S = the sediment reduction rate. It is the objective of achieving a given percent rollback of the initial (baseline) sediment loading rate. Source: set as $S = \{5\%, 10\%, 15\%, \dots, 95\%, 100\%\}$

I = the set of all WRS parcels. The pool of all WRS candidates contains 7619 parcels in all the zones delineated by subbasins upstream. After comparing with each county's GIS shapefile, we excluded those without landowner information and got a set including 7589 WRS parcels. Source: WRS GIS shapefile from Mitchell(2015)[46] and GIS shapefile from each county.

J = the set of landowner clusters. Source: the attribute of the landowner information in each county's GIS shapefile.

Variables:

$x_i = 1$ if the WRS parcel i is selected, 0 otherwise;

$y_j = 1$ if the cluster of landowner j has been selected to restore wetlands, 0 otherwise;

The model is formulated as follows:

$$\text{Min } \sum_i v_i x_i + \sum_j t y_j \quad (3.15)$$

Subject to:

$$\sum_i w_i a_i x_i \geq WS \quad \forall i \in I \quad (3.16)$$

$$\sum_i x_i \geq y_j \quad \forall i \in I, \quad \forall j \in J \quad (3.17)$$

$$y_j \geq x_{ij} \quad \forall i \in I, \quad \forall j \in J \quad (3.18)$$

$$x_i, y_j \in \{0, 1\} \quad \forall i \in I, \quad \forall j \in J \quad (3.19)$$

Equation 3.15 minimize the total costs of WRS implementation, including the opportunity costs, construction costs, and fixed costs. Constraint 3.16 demonstrate the lower threshold of sediment reduction requirement, which means the selected WRS should at least achieve the S percent rollback of baseline sediment loading rate W . The constraint 3.17 says a cluster can only be selected once, which means for each landowner, we only need to pay the transaction costs once. Inequality 3.18 means that a cluster must be selected if one parcel that belongs to the cluster has been selected for wetland restoration. In other words, we must pay the transaction costs if $\forall x_{ij} = 1$; Constraint 3.19 defines the WRS parcels and landowner clusters as binary variables.

Chapter 4

RESULTS**4.1 Benefits Estimation Results**

The linear relationship estimation between WRS extend and sediment loading rates shows that the ability of sediment reduction varies among different scenarios (Hydraulic conductivity, design depths, and placement locations). Although both hydraulic conductivity and design depth have a positive correlation with the sediment reduction coefficients, the former has more significant effects than the latter one. The coefficients shift up/down drastically with the increase/decrease of hydraulic conductivity while the changing is not so obvious with the variation of design depth. The comparison of sediment reduction rates indicates that the total sediment reduction will be maximized when hydraulic conductivity is 6×10^{-10} m/s, and the design depth is 2m. On the contrary, those scenarios when hydraulic conductivity is 8×10^{-10} m/s have the poorest sediment reduction effects and therefore will not be considered in the further discussion.

	V=0.5m	V=1m	V=2m
K= 6×10^{-10} m/s	Scenario K6V05	Scenario K6V10	Scenario K6V20
K= 7×10^{-10} m/s	Scenario K7V05	Scenario K7V10	Scenario K7V20
K= 8×10^{-10} m/s	Scenario K8V05	Scenario K8V10	Scenario K8V20

Table 4.1: WRS Implementation Scenarios

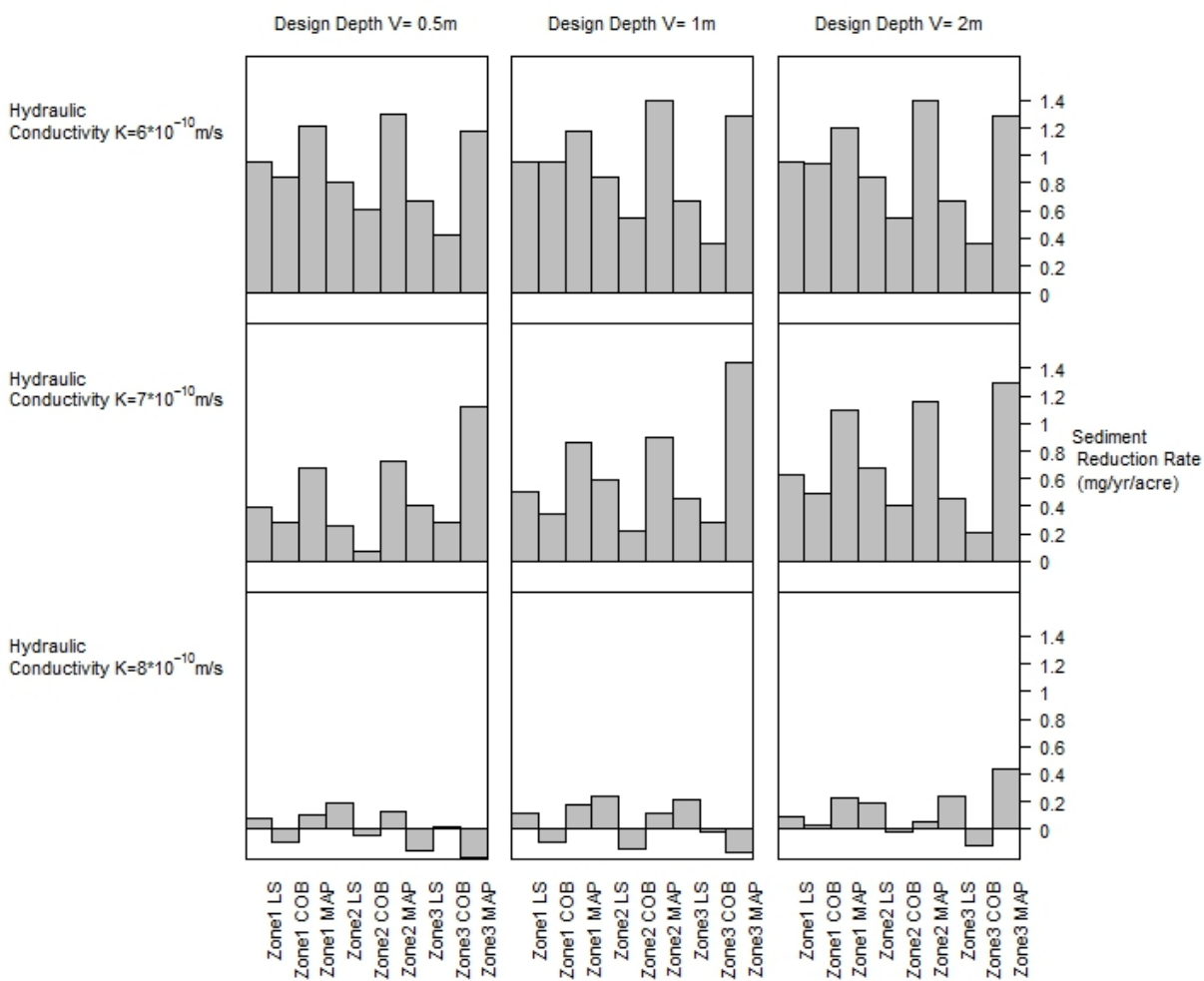


Figure 4.1: Sediment Reduction Coefficient.

Figure 4.1 shows the sediment coefficients for each zone in different scenarios.

From the perspective of spatial comparison at the sub-basin level, the average of sediment reductions at Cobb River sub-watershed is obviously lower than others in any scenarios. On the opposite, Maple River sub-watershed performs the best at reducing sediment. Meanwhile, with high hydraulic conductivity (ie. $K=6 \times 10^{-10}$ m/s), Zone1 and Zone2 offer better sediment reduction performance for Le Sueur River sub-watershed and Cobb River sub-watershed. When the hydraulic conductivity is lower (ie. $K=7 \times 10^{-10}$ m/s), Zone3 will also be a good place for WRS placement for these two sub-watershed. But for Maple River sub-watershed, WRS in Zone3 and Zone2 have more sediment reduction than the other Zone1.

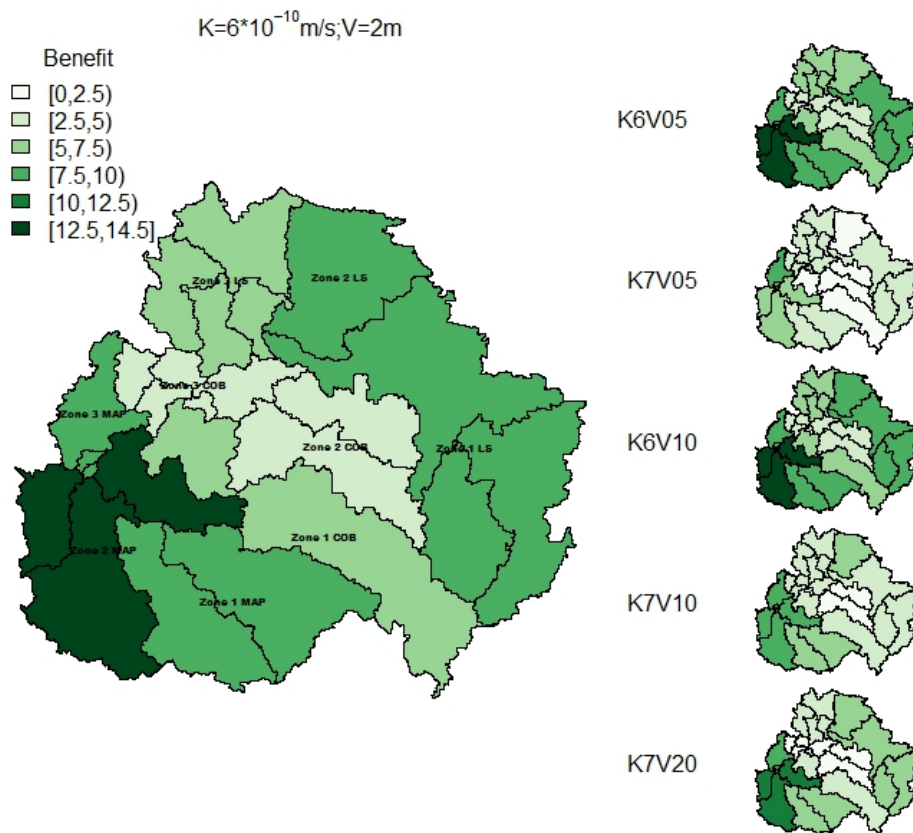


Figure 4.2: Sediment Reduction Difference at Zone Level

Figure 4.2 is the spatial display of the sediment reduction differences at zone level for the scenarios that have positive sediment reduction effects.

4.2 Cost Estimation Results

4.2.1 Hansen costs model (Model based on static net returns to agriculture)

In Hansen wetland costs model, the independent variables are the cash rental rates and areas in acres. The cash rental rates are various by each county, and the areas represent the actual size of each WRS parcel. The estimated average costs at zone level show that implementing WRS at Zone2 Maple River sub-watershed and Zone2 Le Sueur River sub-watershed is the most expensive, while at Zone2 Cobb River sub-watershed and Zone1 Maple River sub-watershed are most economically appealing. At the county level, implementing WRS at Freeborn County are most expensive in average while at Waseca County can save more.

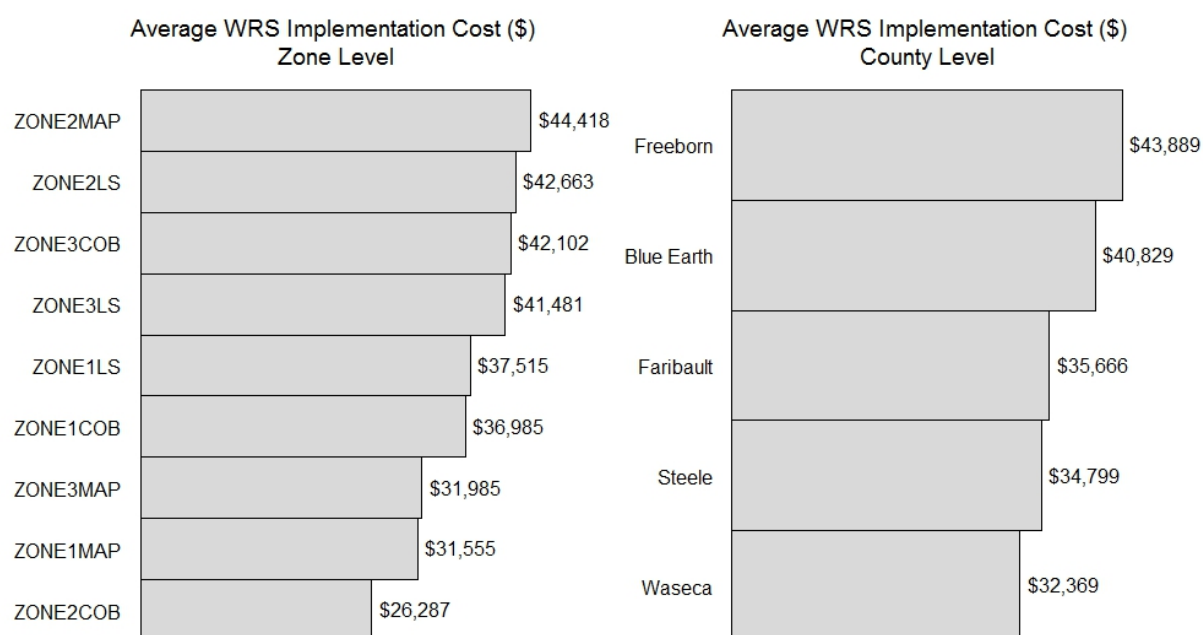


Figure 4.3: Average Cost of WRS Implementation

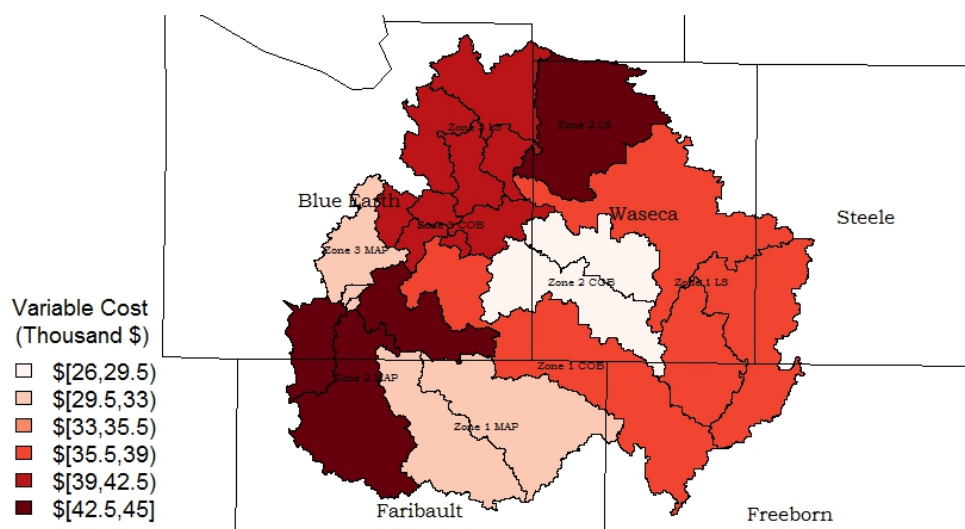


Figure 4.4: WRS Variable Cost Difference at Zone Level

Figure 4.3 and figure 4.4 shows the average variable costs for WRS implementation at the zone and county level.

4.2.2 Real Options Analysis Results

We use the county level's cropland cash rental rates data (1996-2016), which is available at University of Minnesota Extension Website¹, to create the time series as a proxy for the process of net returns to agricultural production. And we convert all dollars to the year of 1996 by assuming an inflation rate of 5%. According to the information in the extension website, the cash rental rates at 2015 and 2016 are calculated based on a decreased income by 5 percent in 2015 and another 10 percent in 2016. As a result, the cash rental rates for Blue Earth, Faribault, Freeborn, Steele, and Waseca in 2016 are \$205/acre, \$208/acre, \$227/acre, \$204/acre, and \$202/acre respectively. In our analysis, we take these 2016 cash

¹<http://www.extension.umn.edu/agriculture/business/land-economics/county-average-cropland-rental-rates/index.html>

rental rates as the critical value of NPV, which means without a forward-looking behavior component, farmers will sign the contract for land conversion only when the profits of WRS are at least equals to the current cash rental rates, or they will not join the WRS project.

The statistical PP test² shows a non-stationarity feature of the logarithm of agricultural net revenues for all the five counties within the Le Sueur Watershed, which implies that we can apply the geometric Brownian motion assumption to estimate those critical parameters for real options model.

County	PP.test P-value (Alternative hypothesis: stationary)
Blue Earth	0.7207
Faribault	0.7553
Freeborn	0.7355
Steele	0.6446
Waseca	0.7156

Table 4.2: The Results of PP Test

²The Phillips–Perron test is used in time series analysis to test the null hypothesis that x has a unit root against a stationary alternative.

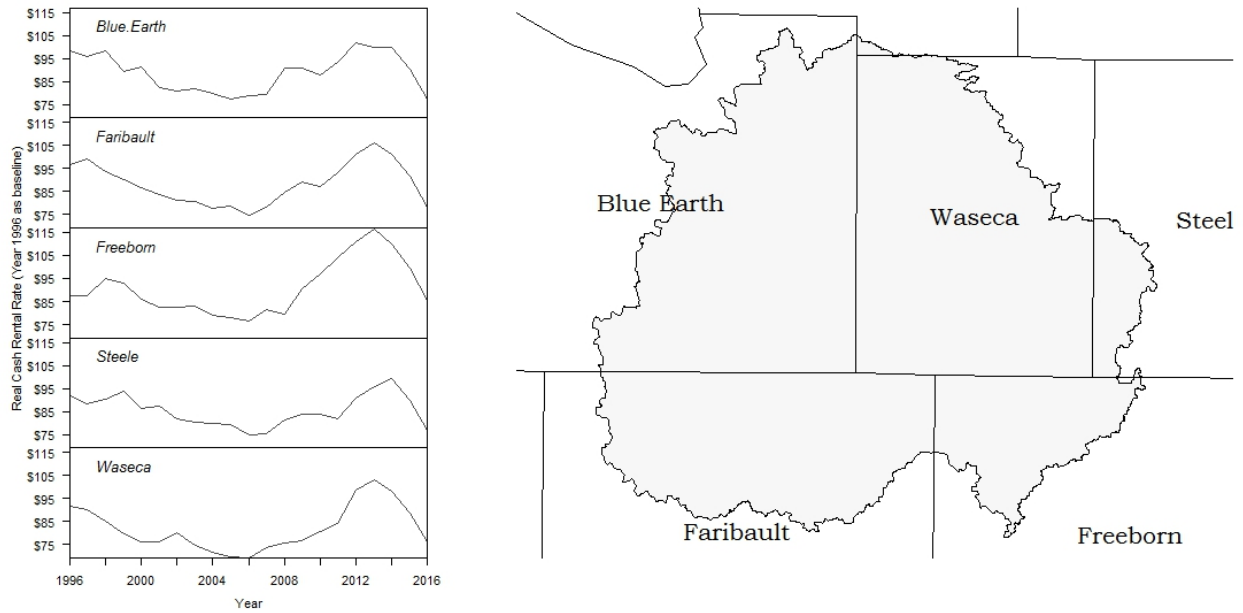


Figure 4.5: Cash Rental Rates (1996-2016)

Figure 4.5 shows the location of the five counties relative to Le Sueur Watershed and the time series of cash rental rates for the five counties .

The result table shows the parameter estimates and critical threshold for signing the contract based on a set of 50 years leasing duration, 5% discount rate and 50% sunk costs.

County	α	σ	β_2	π^{NPV}	π^*	p^{NPV}	p^*
Blue Earth	-0.0048	0.0291	-6.36	205	177	282	312
Faribault	0.0170	0.0266	-50.13	208	204	369	375
Freeborn	0.0212	0.0300	-48.16	227	222	433	440
Steele	-0.0035	0.0271	-7.53	204	180	281	307
Waseca	0.0176	0.0302	-40.26	202	197	358	364

Table 4.3: Estimation of Parameters and Critical Thresholds

The uncertainty about the agricultural profits translates into the uncertainty about land value and determines the critical values of land conversion strategies. From Figure 4.6 we can see that the critical cash rental threshold π^* is lower than with the critical NPV values π^{NPV} , which indicates that farmers have the tendency to postpone their decision of land conversion from t^{NPV} to t^* under uncertainty: they won't stop agricultural cultivation until the agricultural profits fall down below the π^* .

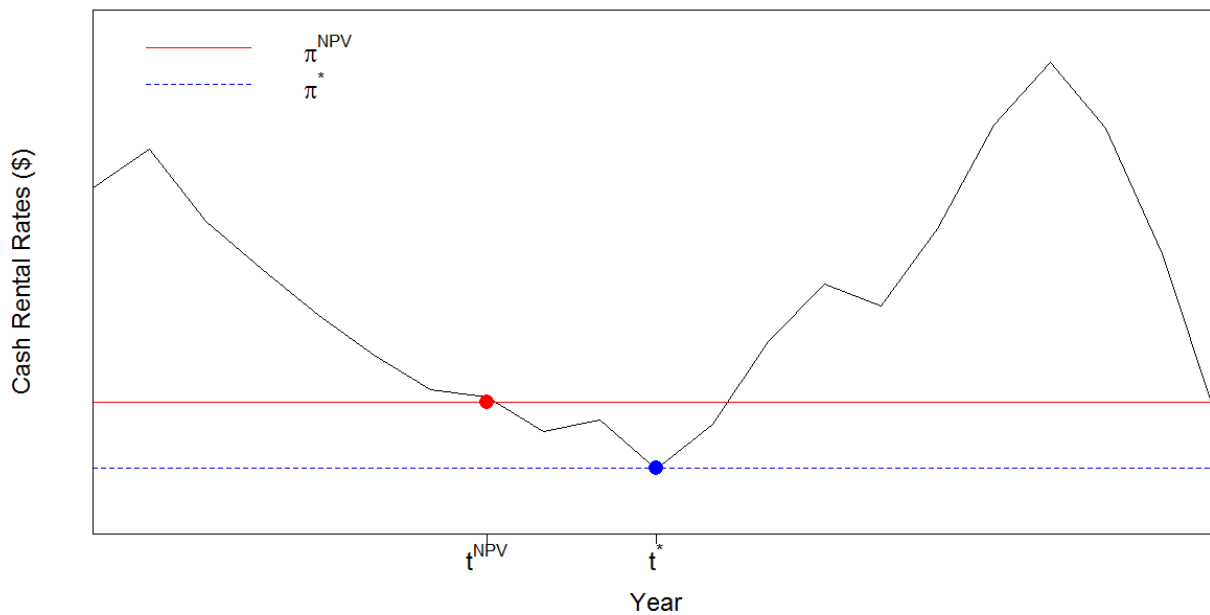


Figure 4.6: Critical Threshold Comparison

Figure 4.6 shows how the uncertainty can influence decision strategy.

Based on π^* , the critical payments to the farmers (p^*) are \$312/acre, \$373/acre, \$440/acre, \$307/acre and \$364/acre for Blue Earth County, Faribault County, Freeborn County, Steele County and Waseca County respectively, which means that at these payment levels, signing the contract to convert lands for WRS is more profitable compared with agricultural production.

To illustrate the effects of a change in the contract duration, discount rate, and the

percentage of construction costs on the critical payment p^* , we provide a sensitivity analysis.

		T=20			T=50			T=80		
		r=2%	r=5%	r=8%	r=2%	r=5%	r=8%	r=2%	r=5%	r=8%
L=0	Blue Earth	227	228	229	215	221	225	207	218	224
	Faribault	250	246	242	312	283	263	379	304	268
	Freeborn	284	279	273	377	334	304	487	368	313
	Steele	224	224	225	215	219	222	209	217	221
	Waseca	245	241	237	308	279	258	377	301	264
L=50%	Blue Earth	329	360	397	268	312	361	249	303	358
	Faribault	352	379	410	365	375	400	421	390	403
	Freeborn	402	432	468	439	440	462	535	467	468
	Steele	322	352	387	266	307	354	249	299	351
	Waseca	340	365	394	358	364	386	416	381	390
L=100%	Blue Earth	430	493	564	321	403	498	291	388	492
	Faribault	454	512	579	418	466	537	463	476	538
	Freeborn	520	586	663	500	546	621	584	566	624
	Steele	420	480	549	317	395	485	290	381	480
	Waseca	436	489	552	408	450	514	456	461	516

Table 4.4: Sensitivity Analysis for Payment p^* (\$)

Since L represents the fraction of WRS construction costs that need to be paid by the farmers, a higher L level means a lower agricultural profit critical threshold. In other words, if the sunk costs are high, the landowner is likely to exercise the option to lease later and ask for a higher leasing payment to sign the land conversion contract.

For the counties like Blue Earth and Steele, which have a negative drift(α), an increase in the contract duration has a positive impact on the timing of the option to lease. As the contract lasts longer, the critical threshold π^* becomes higher. Hence, the landowner exercises the option to convert land earlier, and for a lower leasing payment. However, for the counties with a positive drift value (α), like Faribault, Freeborn, and Waseca, increasing the leasing duration induce a raise of the leasing payment, which means with a longer contract duration will the landowner postpone the decision to lease. It could be explained as a consequence of the value attached to the flexibility which is implicitly given up by leasing[26].

When L is high, (in our case when $L=100\%$), an increase in the discount rate has a negative impact on the timing. In other words, the landowner would need a higher payment

to induce the decision of land conversion. When L is 0, a higher discount rate still leads to a delayed decision for counties have a negative drift (α) on cash rental rates; but has a positive impact on the timing and has lowered the payment level for those counties with positive drift (α). When L is 50%, only when the contract duration is long enough ($T=80$), an increasing of discounting rate will induce an early decision for the counties with positive drift value. However, for the situations with shorter contracts duration or negative drift value, the payment will increase with the improvement of discounting rate.

4.3 Benefit-to-Cost Ratio Ranking Results

The average benefit-to-cost ratio at zone level is quite consistent with the benefits estimation. Basically, Maple River sub-watershed and Le Sueur River sub-watershed are more cost efficient than Cobb River sub-watershed for WRS placement. At the zone level, Zone1 is more cost efficient for Le Sueur River sub-watershed and Cobb River sub-watersheds, while Zone3 is better for Maple River sub-watershed.

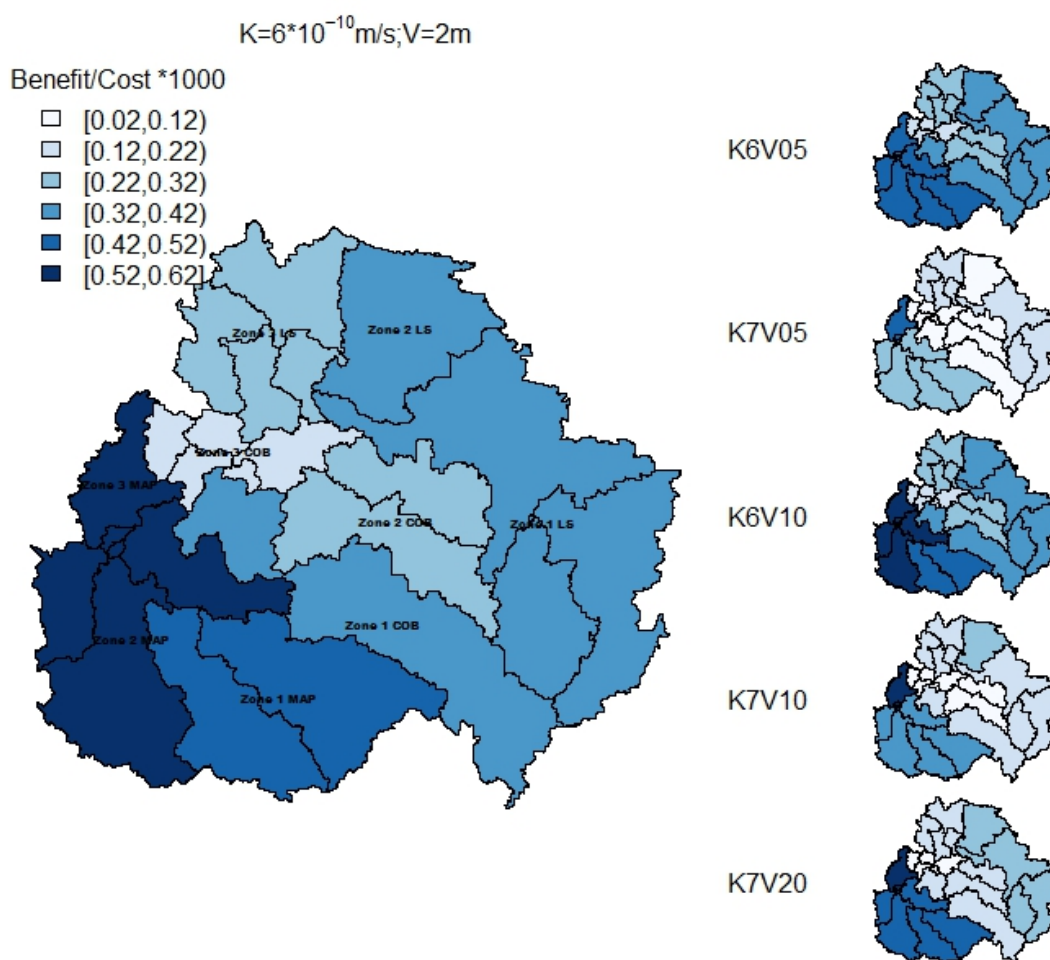


Figure 4.7: Benefit-to-Cost Ratio at the Zone Level

Figure 4.7 is the spatial display of the benefit-to-cost ratio at zone level for the scenarios that have positive sediment reduction effects.

In the individual WRS level, based on the results of benefit-to-cost ratio ranking, we can select those parcels that are more cost-efficient at certain sediment reduction level. For the scenario K6V20, we display the selected parcels in maps as follows, while the selection for other scenarios are showed in Appendix. Notice that in Scenario K7V05, K7V10 and K7V20, because of the limits in sediment reduction ability, the upper threshold for sediment reduction is 50%, 69%, 85% respectively.

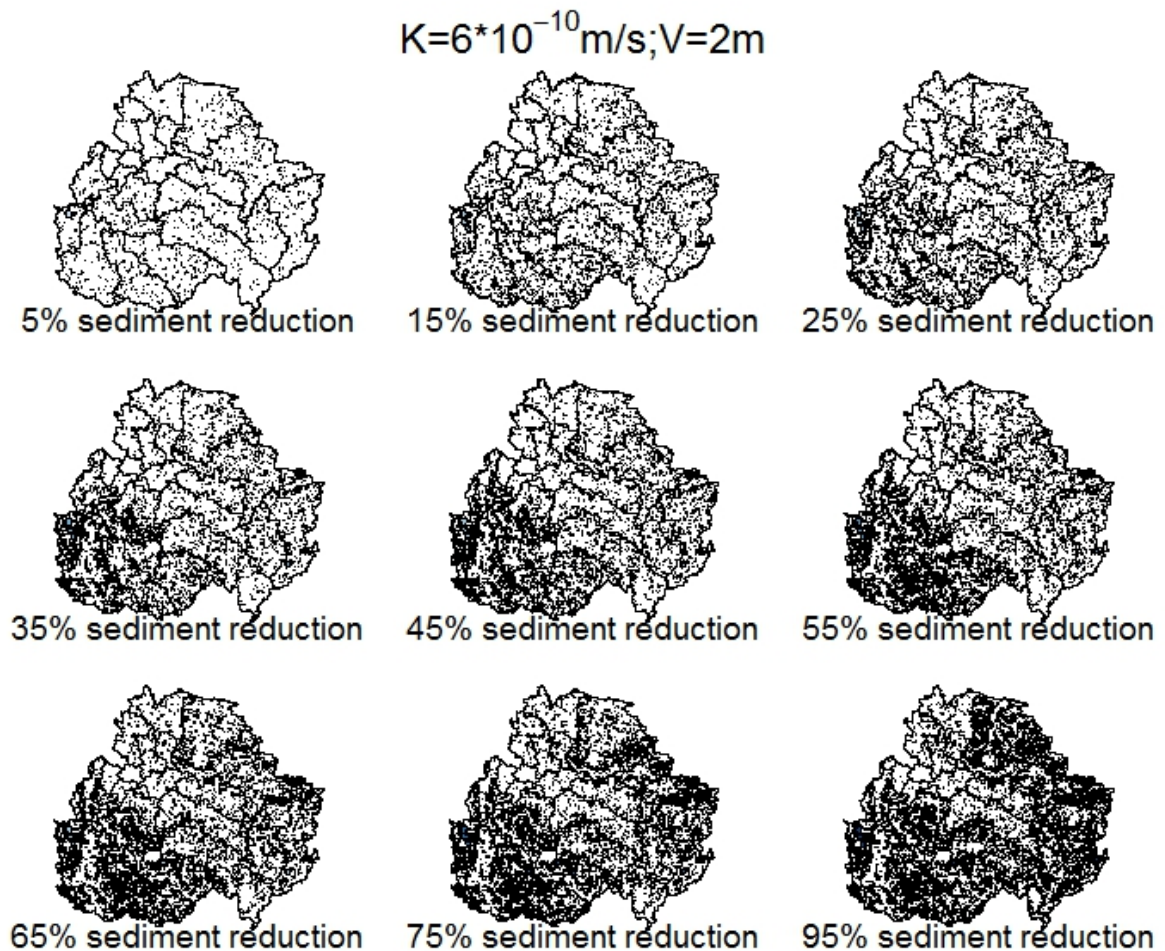


Figure 4.8: WRS Cost-Efficient Selection by Ratio Ranking

Figure 4.8 shows the spatial display of selected WRS parcels by benefit-to-cost ratio ranking method under the scenario K6V20.

From these maps, we can see that with the increase of sediment reduction level, the general pattern of WRS selection is from Maple River sub-watershed to Le Sueur River sub-watershed and then to Cobb River sub-watershed; and from Zone1 to Zone2 and then to Zone3.

The results also indicate that the increases of involved parcels and landowners are at a decline rate with the increase of sediment reduction. Meanwhile, for those scenarios with lower sediment reduction ability (Scenario K7V05, K7V10, and K7V20), the increases are more conspicuous than those that have better performance in sediment reduction (Scenario K6V05, K6V10, and K6V20). It is because more WRS parcels are needed for achieving the additional reduction when the sediment reduction coefficients are smaller.

Sediment Reduction	Scenario K6V05		Scenario K7V05		Scenario K6V10		Scenario K7V10		Scenario K6V20		Scenario K7V20	
	Total parcels	Total Landowners	Total parcels	Total Landowners	Total parcel	Total Landowners	Total parcels	Total Landowners	Total parcels	Total Landowners	Total parcels	Total Landowners
5%	1329	972	1566	1066	1204	905	1547	1062	1200	901	1454	1015
10%	2204	1451	2442	1472	2122	1409	2037	1318	2086	1388	2143	1360
15%	2790	1669	2895	1643	2814	1683	2827	1635	2758	1666	2690	1578
20%	3334	1877	3182	1747	3096	1799	3162	1771	3080	1792	2890	1659
25%	3566	1968	3496	1843	3369	1891	3380	1841	3356	1882	3146	1759
30%	3790	2046	4261	2154	3556	1956	3586	1906	3551	1949	3293	1807
35%	3945	2096	5074	2437	3731	2021	3774	1951	3714	2009	3528	1882
40%	4137	2153	5484	2573	3935	2080	4643	2293	3893	2067	3679	1921
45%	4384	2221	6092	2744	4348	2211	5091	2448	4288	2192	4099	2077
50%	4523	2252	6672	2917	4600	2283	5536	2581	4527	2259	4844	2335
55%	4767	2318	7590	3162	4752	2310	5832	2672	4678	2294	5273	2491
60%	5211	2458	7590	3161	5103	2414	6258	2812	5082	2409	5639	2590
65%	5465	2524	7590	3161	5358	2493	6934	3006	5338	2489	5881	2657
70%	5644	2581	7590	3161	5548	2543	7555	3147	5535	2539	6274	2773
75%	5841	2636	7590	3161	5739	2600	7590	3161	5722	2598	6685	2892
80%	6055	2694	7590	3161	5857	2620	7590	3161	5850	2622	7047	3000
85%	6271	2758	7590	3161	5983	2652	7590	3161	5968	2649	7483	3121
90%	6419	2802	7590	3161	6213	2737	7590	3161	6200	2734	7590	3161
95%	6573	2848	7590	3161	6394	2793	7590	3161	6385	2790	7590	3161
100%	6868	2930	7590	3161	6529	2824	7590	3161	6525	2827	7590	3161

Table 4.5: Number of Selected WRS Parcels and Involved Landowner

Table 4.5 shows number of selected WRS parcels and involved landowner within sediment reduction constraints by benefit-to-cost ratio ranking for each scenario.

The total costs of Scenario K6V05, K6V10, and K6V20 are quite close to each other and are more cost efficient than the other scenarios at lower sediment reduction levels, although their differences with Scenario K7V20 is not so obvious for sediment reduction lower than 50%. The Scenario K7V05 and K7V10 have the most expensive costs according to benefit-to-

cost ratio ranking and the costs increase rapidly with the sediment reduction improvement.

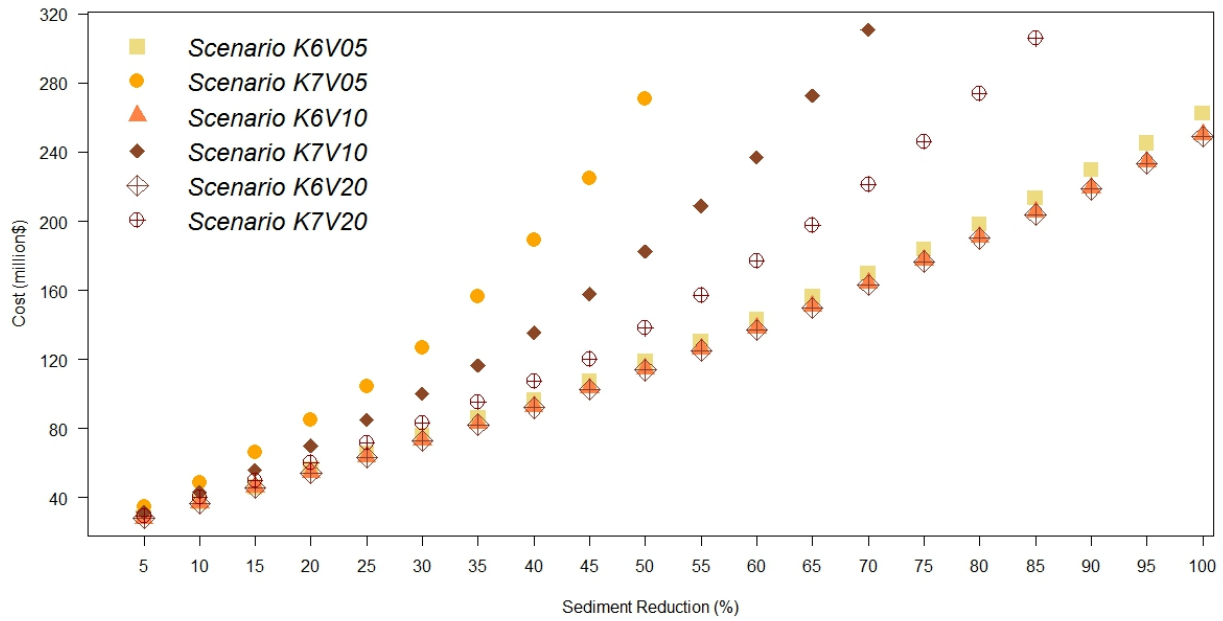


Figure 4.9: Abatement Cost for Sediment Reduction

Figure 4.9 shows the abatement costs got from benefit-to-cost ratio ranking under sediment reduction constraints for each scenario.

4.4 Spatial Optimization Model Results

For the given scenarios and sediment reduction requirement, the spatial optimization problems could be solved by the optimization software IBM-CPLEX12.1 and the computation took a few seconds.

Sediment Reduction	Scenario K6V05		Scenario K7V05		Scenario K6V10		Scenario K7V10		Scenario K6V20		Scenario K7V20	
	Total parcels	Total Landowners	Total parcels	Total Landowners	Total parcel	Total Landowners	Total parcels	Total Landowners	Total parcels	Total Landowners	Total parcels	Total Landowners
5%	238	46	271	75	141	26	230	57	133	24	138	26
10%	671	156	1067	330	629	151	871	268	724	175	825	220
15%	1217	312	1434	442	1019	265	1346	412	995	255	1045	291
20%	1481	395	1816	577	1260	337	1600	483	1312	349	1333	388
25%	1698	458	2054	672	1526	411	1870	571	1522	410	1546	453
30%	1915	525	3091	1170	1732	483	2050	622	1733	484	1812	551
35%	2264	646	3896	1418	1974	581	2603	938	2000	594	1947	603
40%	2443	709	4426	1600	2475	773	3367	1243	2441	762	2174	715
45%	2607	763	5512	2216	2799	881	3854	1424	2718	852	2996	1125
50%	2974	920	6280	2527	3031	955	4355	1585	2942	919	3617	1305
55%	3550	1175	7589	3161	3416	1114	4847	1794	3402	1124	4047	1441
60%	3887	1300	7589	3161	3807	1275	5445	2115	3772	1272	4877	1751
65%	4170	1399	7589	3161	4068	1369	6550	2640	4066	1371	4877	1751
70%	4445	1511	7589	3161	4357	1458	7466	3049	4345	1456	5423	2000
75%	4685	1620	7589	3161	4522	1507	7589	3161	4523	1516	6033	2271
80%	5022	1747	7589	3161	4684	1573	7589	3161	4684	1580	6561	2484
85%	5250	1834	7589	3161	4962	1705	7589	3161	4957	1704	7409	3052
90%	5489	1938	7589	3161	5243	1839	7589	3161	5235	1834	7589	3161
95%	5865	2152	7589	3161	5444	1914	7589	3161	5453	1929	7589	3161
100%	6346	2401	7589	3161	5721	2102	7589	3161	5715	2098	7589	3161

Table 4.6: Number of Selected WRS Parcels and Involved Landowner by Spatial Optimization Model

Compared with the benefit-to-cost ratio ranking method, the spatial optimization model significantly reduced the number of WRS parcels and the involved landowners for WRS implementation. For the first 30% of sediment reduction level, both the number of WRS parcels and landowners can be reduced by 70%-90%. Although the decreasing rate declined with the increase of sediment reduction constraints, at 50% of sediment reduction level for scenario K6V05, K6V10, and K6V20, the number of WRS parcels and landowners can still be decreased by about 60%. When the sediment reduction level rises continuously, the differences between the two methods become more and more inconspicuous. It is not too surprising because the available land for each landowner is given. After we have included those landowners with large amounts of WRS, we will meet the limit of the area and have

to add new landowners to our project even though they might only have a few or even just a single parcel for WRS.

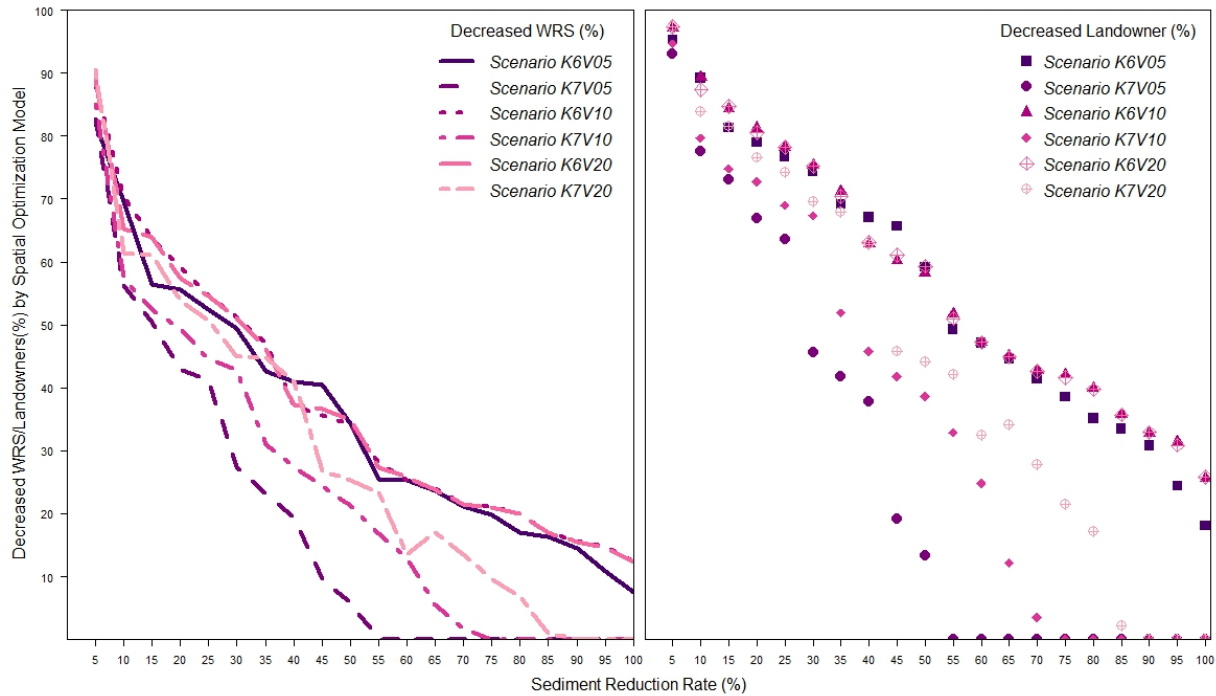


Figure 4.10: Reduced WRS and Landowners by Spatial Optimization Model

Figure 4.10 shows the reduced number of selected WRS parcels and landowners by spatial optimization model.

The spatial display of the results of spatial optimization model also shows a decreasing WRS selection trend and somewhat clustered WRS pattern compared with the benefit-to-cost ratio ranking method.

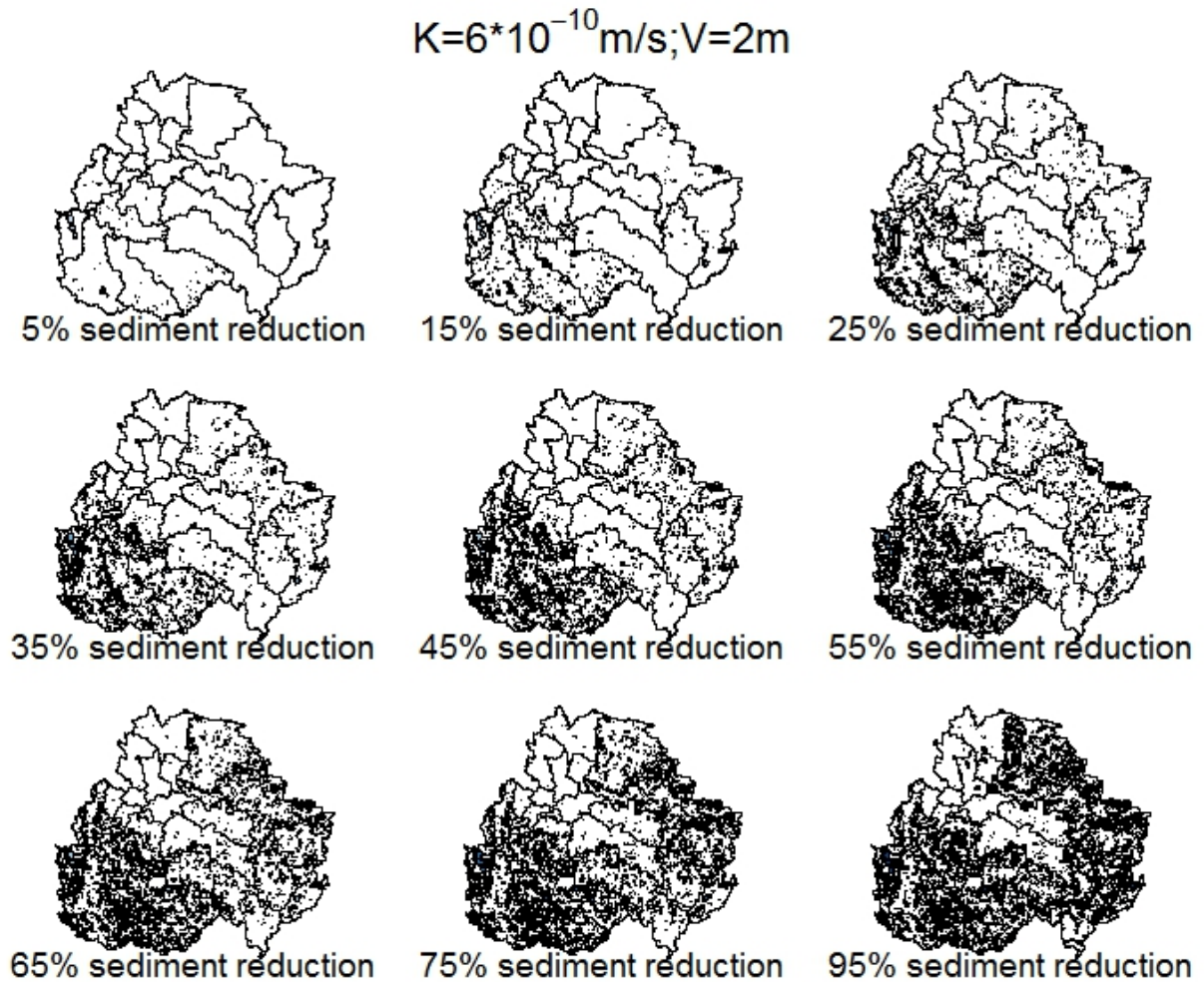


Figure 4.11: Spatial Optimization Model Selection K6V20

Figure 4.11 shows the spatial display of selected WRS parcels by spatial optimization model under the scenario K6V20.

To test if the spatial optimization model does lead to different WRS selection in spatial term, we did a statistical test for the average distance between each participating parcel and their neighbors under the spatial optimization model versus the benefit-to-cost ratio ranking method. If we can reject the null hypothesis that the differences in mean are random, then the spatial divergence between the two methods could be viewed as significant.

Welch Two Sample t-test for distance divergence

Scenario	Sediment Reduction	mean distance under ratio ranking	mean distance under spatial optimization	P-Value
K6V05	5%	671.145	673.904	0.9627
	15%	476.139	673.904	0.0008***
	35%	404.945	406.223	0.8899
	55%	377.698	373.009	0.4250
	75%	354.004	355.016	0.8164
	95%	344.075	345.139	0.7541
K7V05	5%	608.045	593.689	0.8207
	15%	457.933	408.838	0.0025**
	25%	422.890	383.446	0.0003***
	35%	366.822	361.717	0.3249
	45%	348.346	345.569	0.4435
	50%	342.765	339.150	0.2526
K6V10	5%	710.107	802.141	0.2913
	15%	472.989	490.083	0.4214
	35%	415.042	414.682	0.9719
	55%	376.634	369.372	0.2065
	75%	353.551	352.300	0.7787
	95%	348.601	347.186	0.6980
K7V10	5%	625.146	592.103	0.6408
	15%	463.168	430.285	0.1050
	25%	432.420	389.030	0.0002***
	35%	417.952	430.285	0.5354
	55%	417.952	357.435	0.0000***
	69%	332.481	332.726	0.9250
K6V20	5%	705.664	764.560	0.4869
	15%	478.801	487.340	0.6815
	35%	414.843	411.862	0.7669
	55%	380.130	373.360	0.2489
	75%	354.054	352.644	0.7521
	95%	346.978	347.172	0.9572
K7V20	5%	639.855	729.433	0.2750
	15%	483.083	437.121	0.0859
	35%	427.184	390.506	0.0020**
	55%	365.155	363.274	0.7089
	75%	341.493	342.813	0.6868
	85%	332.877	332.827	0.9848

*Note: * $p \leq 0.1$, ** $p \leq 0.05$, *** $p \leq 0.001$*

Table 4.7: Distance Divergence of Selected WRS Parcels by Two Optimization Models

The results of t-test show some significant distance differences in mean especially for the scenarios K7V05, K7V10, and K7V20, indicating that the clustering pattern might be more obvious when the sediment reduction ability is relatively low. However, since the spatial clustering is not the top priority for our model, the clustering is primarily associated with the selection of landowners whose parcels are presumably close to each other. Moreover, even the spatial clustering pattern is not significant, it is not surprising because the ownership structure in agricultural landscapes might not necessarily be adjacent to each other, and could be patchy instead.

The total costs comparison between spatial optimization and benefit-to-cost ratio ranking within 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, 95% sediment reduction constraints are as follows:

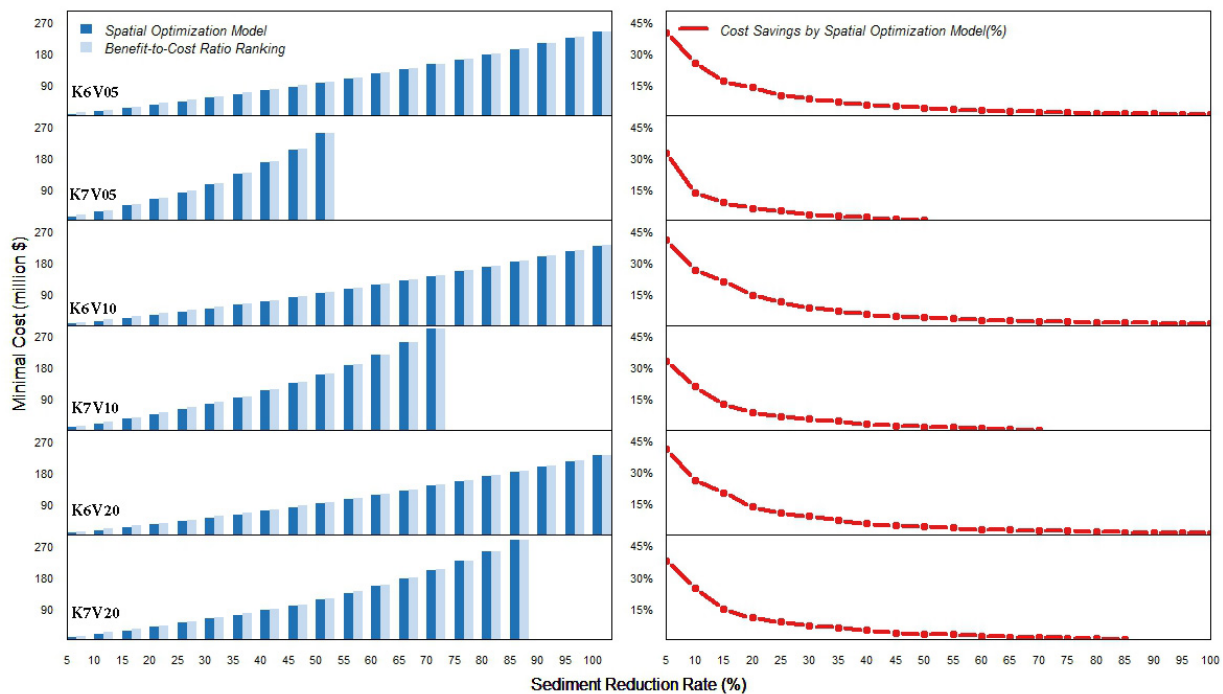


Figure 4.12: Cost Comparison Between Ratio Ranking and Spatial Optimization Model

Figure 4.12 shows the comparison of total costs between benefit-to-cost ratio ranking and spatial optimization model.

The advantage of the spatial optimization model to ratio ranking method in cost saving declines with the increase of sediment reduction level. It is consistent with the comparison of selected number of WRS and involved landowners by these two methods. With a \$5000 fixed cost per landowner, spatial optimization model can save about 30%-40% of costs with the first 10% of sediment reduction for all scenarios. As the increase of sediment reduction requirement, more land needs to be included into WRS system. Since the total area for a certain landowner is given, the rule of “choosing WRS belonging to the same landowner” is unable to play a crucial role within a high sediment reduction constraints.

The cost-saving effects of the spatial optimization model will be more significantly with a higher fixed cost. Take the situation in scenario K6V20 for example: when the fixed cost is

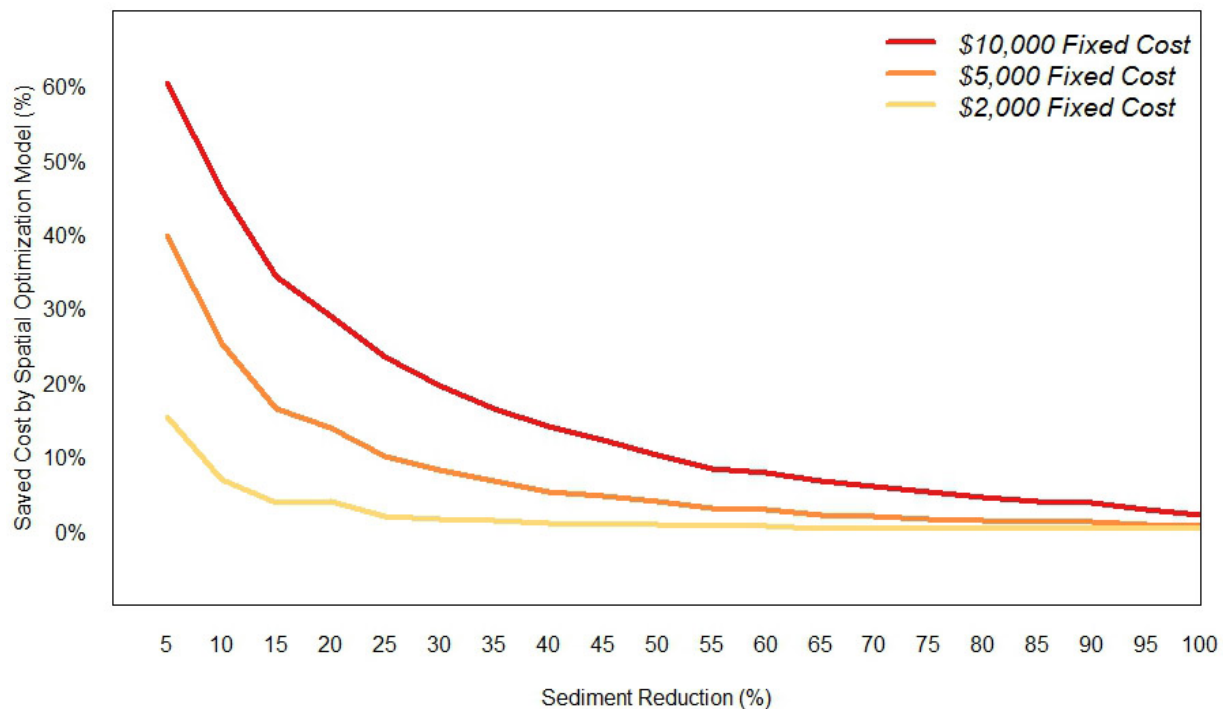


Figure 4.13: Cost Saving by Spatial Optimization Model under Different Fixed Cost Setting

Figure 4.13 shows the advantage of spatial optimization is more obvious with a higher fixed cost setting (Scenario K6V20).

\$10,000 per landowner, the total costs saving by spatial optimization model could be almost 60% with the first 10% of sediment reduction level. The cost saving percentage decreased to 20% and 10% at the 40% and 95% sediment reduction level respectively. When the fixed cost is \$2000 however, the spatial optimization model can save at most 15% of the total cost with the first 5% sediment reduction constraint, and in general, the differences between the two methods are very small.

The total costs comparison between the spatial optimization model and benefit-to-cost ratio ranking method with the real options assumption for costs estimation is consistent with the one we obtained from Hansen costs model for costs estimation.

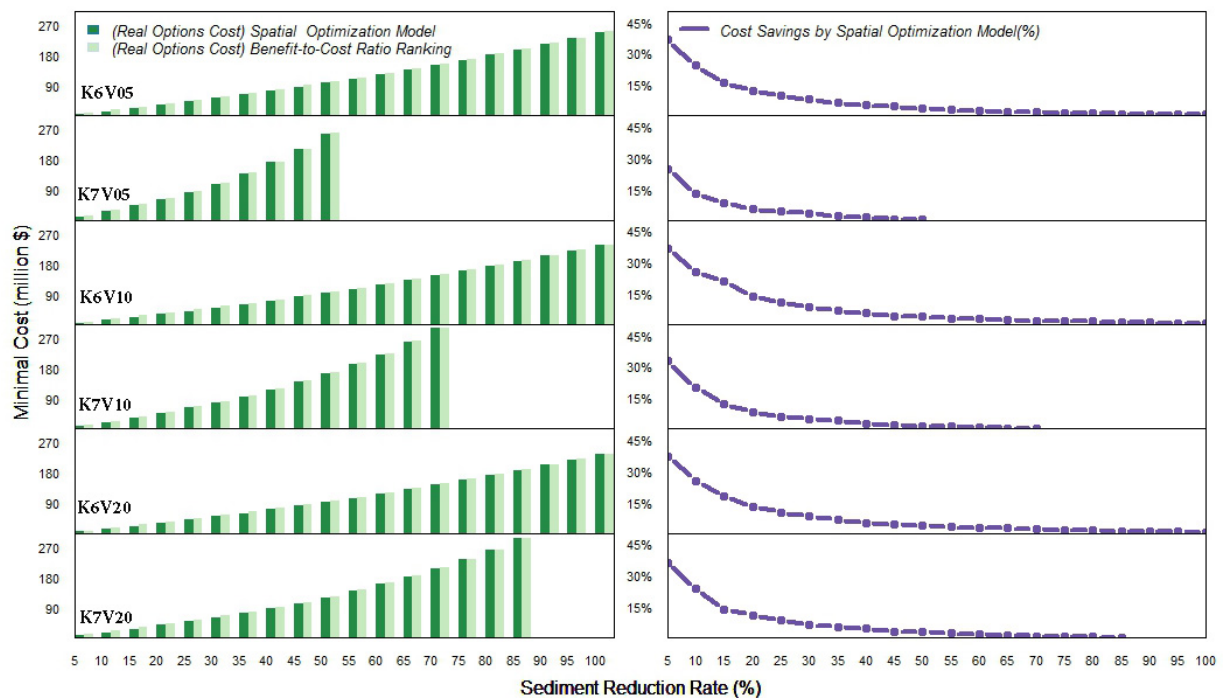


Figure 4.14: Saved Cost by Spatial Optimization Model with Real Options Cost Assumption

Figure 4.14 shows the comparison of total costs between benefit-to-cost ratio ranking and spatial optimization model within the real options costs assumption.

For the spatial optimization model itself, the uncertainty of agricultural profits will increase the total costs by 3%–4.6% since the critical payments p^* that we obtained from real options analysis are higher than the current cash rental rates.

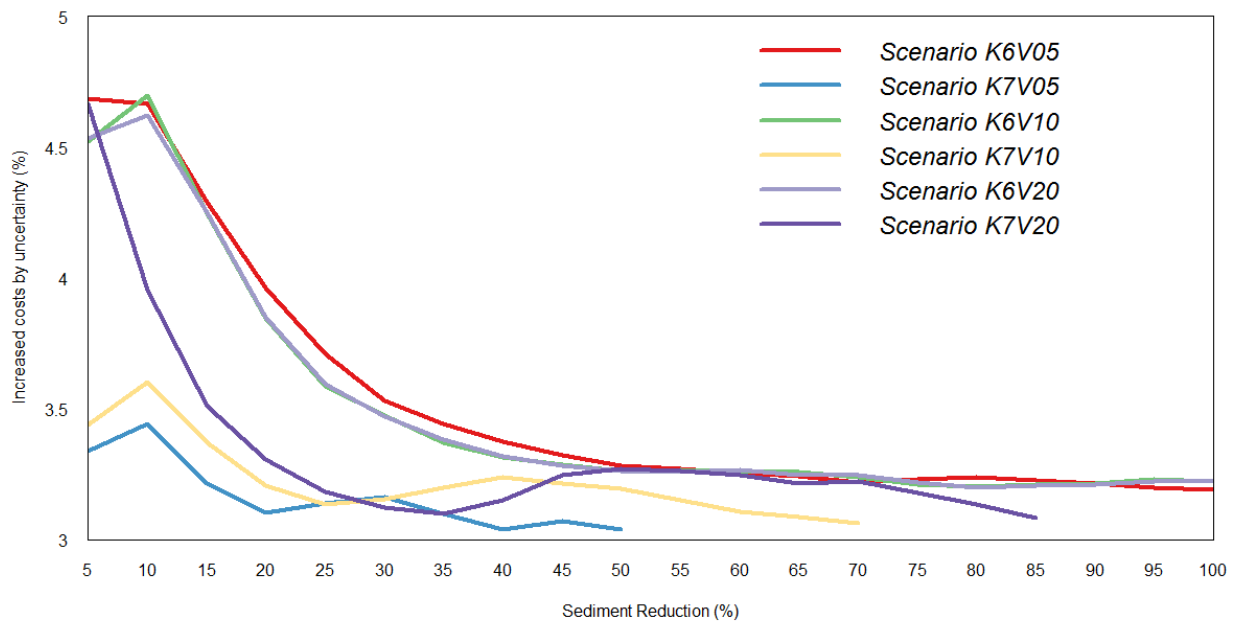


Figure 4.15: Increased Costs (in percentage) of Spatial Optimization Model from the Perspective of Forward-looking Farmers

Figure 4.15 shows the increased costs of spatial optimization model when applying the critical payment p^* to modify Hansen costs model for the variable costs estimation.

Chapter 5

DISCUSSION

5.1 Sediment Reduction Estimation

The estimation of sediment reduction coefficient shows that the sediment abatement goals could be achieved at different rates with some scenarios are more effective than others. A high hydraulic conductivity K has a dominating advantage in decreasing peak flow and sediment loading rates because it allows sites to empty their storages more effectively between precipitation events and to absorb more of the water associated with the upcoming event. A low hydraulic conductivity, on the opposite, will cause the precipitation landing on the site to overflow from the site rather than infiltrating into the soil. Although geomorphic history determines the hydraulic conductivity to some extent and our study region—the Le Sueur River Watershed has a relatively low hydraulic conductivity[46], in Mitchell’s generalized model it is taken as a controllable variable. Theoretically, we can set K at different scenarios for an optimal sediment reduction results.

Compared with K , the effects of design depth V to sediment reduction coefficient are less significant, especially when K is high ($K=6 \times 10^{-10}$ m/s). However, when the K is lower ($K=7 \times 10^{-10}$ m/s or $K=8 \times 10^{-10}$ m/s), we can still see improvements in sediment reduction ability with the increase of design depth. For example, in the scenarios when $K=8 \times 10^{-10}$ m/s, most of the negative coefficients at $V=0.5$ m and $V=1$ m could be converted to positive when $V= 2$ m. Moreover, in the scenarios when $K=7 \times 10^{-10}$ m/s, a higher design depth ($V=2$ m) can increase the sediment reduction ability to the level that nearly match the performances when $K=6 \times 10^{-10}$ m/s but with a lower design depth. And since in practice the design depth could be changed more handily by engineering techniques, it could be as a compensation to the low hydraulic conductivity deficiency to some degree.

Besides hydraulic conductivity and design depth, the spatial location will also influence the sediment reduction ability. With a high K value ($K=6 \times 10^{-10}$ m/s) combined with any design depths level, WRS in Le Sueur River sub-watershed and Cobb River sub-watershed will have the best performance in Zone1, where is the upper region in this watershed. However, for the WRS in the Maple River sub-watershed, there are no distinct differences in sediment reduction among different locations. Mitchell(2015)[46] explained this as the model might be capturing unique traits of the Maple sub-watershed or the models portrayal of Maple River sub-watershed could be lacking. When $K=7 \times 10^{-10}$ m/s, Zone1 is still the optimal location for WRS in the Cobb River sub-watershed for all design depths. Zone2 is the better choice for WRS in Le Sueur River sub-watershed when design depths is 1m or 2m, although when design depths is 0.5m, Zone1 offers a higher sediment reduction coefficient. For WRS in the Maple River sub-watershed, Zone3 performs best in sediment reduction, but the reduction becomes insensitive to location when design depth is relatively high (i.e., $V=2$ m). When $K=8 \times 10^{-10}$ m/s, the impacts of location might be offset by the drastic influence from hydraulic conductivity and therefore do not have a very clear pattern for all the sub-watersheds.

Based on the analysis above, for a better sediment reduction ability, we should first consider a high hydraulic conductivity (i.e., $K=6 \times 10^{-10}$ m/s) for all WRS. Meanwhile, a higher design depth could be a compensation for low hydraulic conductivity at some scenarios. However, the current spatial placement scenario for estimation is at the zone and sub-watershed level, which is not a high-precision magnitude compared with the large amount of individual WRS parcels. In the future study, we would like to apply simulation optimization approach like evolutionary algorithms to find the optimal hydraulic conductivity and design depth for individual WRS parcels in the watershed. Related research could be found at Rabotyagov et al.(2010)[57], Liu et al. (2013)[39],Babbar-Sebens et al.(2013)[4]. Moreover, the spatial interdependencies among WRS parcels could also be included into our consideration, especially for those parcels that have upslope and downslope relationships.

5.2 *Variable Costs Estimation*

We applied the Hansen costs model for Prairie Pothole Region as the primary method for variable costs estimation. We think this estimation is appropriate for our WRS project since their model is built on a big database and has comprehensive consideration of easement payments. Also, if we use their model to estimate the variable costs, we only need the data of cash rental rates and land area, which makes things much more practical and convenient especially when we do not have enough construction costs data to run the econometric process by ourselves, whereas Hansen et al.'s study already included this part of costs in their model.

However, we have to admit there is always a trade-off between convenience and accuracy. Since the cash rental rates data we used in Hansen costs model is at the county level, the scale is too large to be accurate for accessing the land value of individual WRS parcel. The land value varies in the same county not only because of the land productivity, but also the geographic characteristics will significantly influence the costs for wetlands construction. For example, filling channels, eliminating tile drainage, and restoring flow impediments can be much less costly than excavating filled wetlands. The actions taken to restore wetlands' hydrology would be expected to differ substantially across wetlands in the watersheds, but our estimations are unable to reflect these distinctions among WRS candidates. Also, simply taking the current cash rental rates as the easement payment ignores the uncertainty of agriculture net revenues in reality.

For improving the accuracy of costs estimation, some feasible proposals include:(1)Applying the property assessment data at the parcel level as the easement payment. (2)Incorporating detailed GIS data that reflects the spatial and physical heterogeneity to improve the costs estimation. For example, we could take the attribute of nearby existing wetlands as a weight coefficient for construction cost evaluation of each WRS parcel. (3)Capitalizing the uncertainty through contracts and view farmers' options as contingent decisions, which is what we did in the real options analysis.

5.3 Real Options Analysis

From the view of real options analysis, an option is the opportunity to make a decision based on how events unfold. In our WRS example, the farmers decision whether or not to sign a land leasing contract depends on the agricultural net revenues and the level of easement payment. If on the decision date, the agricultural production is more profitable, they will not assign the contracts; but if the agricultural market turns out poorly at that time, they will make the opposite decision. The data of county level's cash rates obtained from the agricultural extension website conforms to the non-stationary assumption and therefore one can apply the geometric Brownian motion to calculate the critical threshold. We show that the critical threshold of agricultural profits π^* is lower than the value we got from the net present value π^{NPV} , which indicates that the decision to lease land for WRS will be postponed on the timing resulting from taking the current cash rental rates to calculate the easement payment. It is consistent with the standard result in the real options analysis literature that it is recommended to postpone the exercise of the option under uncertainty. Based on the values of π^* , it is more profitable for farmers to sign the WRS contract if the easement payment p^* is \$312/acre, \$373/acre, \$440/acre, \$307/acre, and \$364/acre for Blue Earth County, Faribault County, Freeborn County, Steele County and Waseca County respectively.

According to the sensitivity analysis, higher construction costs borne by farmers will cause a delayed decision and higher payments, which is a straightforward result; A longer the contract duration T is expected to bring a higher payment level to trigger the leasing agreement because of the loss of land flexibility for the farmers. Although Blue Earth County and Steele County in our case have the opposite consequence as the increase of contract duration, it is be related to their negative drift value which indicates a declined land value¹. The effects of increased discounting rate to timing and leasing payment are combined with construction costs, contract duration and also the drift of cash rental rates data. However,

¹The cash rental rates of 2015 and 2016 in the extension website are estimated by decreasing income by 5% in 2015 and another 10% in 2016.

higher discounting rates should induce an earlier decision and lower leasing payment in general.

The real options analysis could also be improved if we can apply detailed information about site specific characteristics like land productivity, or use the property assessment data to build the time series. Also, we might need to adjust the option valuation model by capturing the land-price feedbacks to the underlying parcels for land conversion since many real assets experience leakage in value, and the leakage will affect the value of the option and the timing of the optimal investment decision. Kulatilaka et al.(1998)[2] demonstrated the ways of adjusting for leakage in real options analysis by applying several forms of cash flows and calculating the convenience yield from future prices. Tóth et al.(2011)[66] incorporated the land-price feedbacks model with spatial optimization model to capture the effects of land value spillover on optimal conservation strategy, which is a good example for our future study improvement.

5.4 Benefit-to-Cost Ratio Ranking

Benefit-Cost Analysis provides with a straightforward view to see whether the advantages of a particular action are likely to outweigh its drawbacks(Portney, 2008)[55]. In the U.S., the federal government is required to assess the benefits and costs of all major federal regulations, and most of these regulations examined under the requirements are environmental rules(Robinson, 2010)[60].

In our WRS program, the heterogeneity in both the sediment reduction capability and the potential costs indicated that we can get the least costs allocation strategy for sediment abatement by benefit-to-cost ratio ranking, which is one of the basic methods of Benefit-Cost Analysis. The results show that the heterogeneity in benefit has influenced the ratio ranking more than the variety of costs because the spatial placement of selected WRS by ratio ranking is quite consistent with the sediment reduction distribution.

One thing has to be noticed is that usually it has an attempt to identify and express the benefits in dollar terms when doing the Benefit-Cost Analysis. On one hand, only if

we can convert the benefits to the monetary value can we get the benefit-to-cost ratio for projects that have different kinds of benefits. For example, besides the benefit of sediment reduction, restoring WRS also has positive effects on nitrogen and phosphorus removal, as well as providing habitats for wildlife and then the corresponding benefits like duck hunting. If we want to evaluate the WRS from the perspective of total benefits, we need first to estimate the economic value of each kind of benefit and then add them together. On the other hand, it would be more considerate if we can also take timing into consideration. In our benefit-to-cost ratio ranking method, we assume the benefits occurred in the present since the timing is not very important for spatial cost-efficient strategy, but we need to do the discounting for economic benefit value if we want to evaluate whether the sediment reduction in the next 20 years outweighs the costs spent in this year.

5.5 *Spatial Optimization Model*

The spatial optimization model is for minimizing the total costs by selecting WRS that belongs to the same landowner as more as possible within sediment reduction constraints. The idea is based on the current problem that negotiation with farmers about land conversion for wetland restoration is both money and time consuming. The results of this approach for WRS implementation in the Le Sueur River Watershed confirm that the model can significantly reduce the number of selected WRS and involved landowners under sediment reduction constraints, in particular for the scenarios with high hydraulic conductivity value (i.e., $K=6 \times 10^{-10}$ m/s). As a consequence, it can be more cost-efficient compared with the benefit-to-cost ratio ranking methods. For example, for scenarios K6V05, K6V10, and K6V20, spatial optimization model can decrease the number of involved landowner by 70%-90% at the first 30% sediment reduction level, and save the total costs more than 30%, up to \$4,500,000. At a 50% sediment reduction level, the number of selected landowners by the spatial optimization model is still 60% lower than ratio ranking method, saving total costs about \$3,700,000. When the sediment reduction level increased to 90%, the spatial optimization model can still decrease 30% of the number of landowners and save costs more

than \$1,800,000 in total. For the scenario K7V05, K7V10, and K7V20, although the effect of spatial optimization model is not as significant as for the scenarios with a high K value, we can still achieve total costs saving in average by \$2,773,928, \$2,800,000, and \$2,855,757 respectively. And the advantage of spatial optimization model will be enlarged with the increase in fixed costs level.

In this project, the primary purpose of the spatial optimization model is to minimize the fixed costs. But as mentioned in the previous discussion, the model could be further improved by incorporating more complex interdependencies among WRS parcels from both physical and economic perspectives. Physically, more detailed information about the off-site sediment loadings could be included in the formation of sediment reduction constraint, since the sediment reduction coefficient of a WRS parcel depends not only on the geographical and hydrological characteristics of itself but also on the volume of runoff flowing in from the upland parcels. A good example is the study by Khanna et al.(2003)[34]. Meanwhile, the physical interdependencies would also make a difference to the construction costs because of the hydrological connectivity of the flow path(Trepel,2010)[45]. Therefore, we could embed more spatial constraints like incorporating spatial contiguity (Önal et al.,2006[53]), or by minimizing the total external perimeter or the sum of pairwise distances among each pair of selected WRS parcels for the concern of compactness(Tóth et al.,2008)[67]. Economically, the interdependencies could be reflected by the land-price feedbacks effects which indicate that the conservation actions on one reserve parcel have the impact on the price of land, and therefore on the risk of development, outside the reserves(Tóth et al.,2011)[66]. And since the environmental goal of this program is the total sediment reduction in the watershed, the heterogeneity of the land value implies the opportunity of establishing a cap-and-trade system to create incentives for enrollment potential WRS candidates with low opportunity costs. A potentially useful illustration of how the tradable abatement action credit system works for nonpoint-source water pollution could be found at Rabotyagov et al.(2013)[58].

Chapter 6

CONCLUSION

The main purpose of this study was to design, evaluate and promote cost-efficient policies to address the problem of sediment overloading through restoring Water Retention Sites (WRS) in the region of Le Sueur River Watershed. For this purpose, we integrated natural and social science knowledge to build two kinds of optimization systems: one is the benefit-to-cost ratio ranking, and the other is the spatial optimization model.

The meta-modeling results from a generalized hydrological model are applied as the index for measuring the benefits. It can clearly represent the heterogeneity in sediment reduction ability at different scenarios; but for a more accurate and comprehensive benefit-to-cost analysis, we might need to convert the sediment reduction into economic value in the future study.

The way we estimate the variable costs is under two assumptions: with or without uncertainty. When the uncertainty of agricultural net return is not considered, we apply the Hansen cost model directly. When assuming the farmers' decision whether or not to sign the land conversion contract for WRS depends on the changes of agricultural net revenues along with time and the level of easement payment, we do the real options analysis and use the results to modify the part of opportunity costs in Hansen costs model. According to the real options analysis, the easement payment to the landowners should be higher than the value under the NPV rule or the agreement of land conversion will be delayed. For improving the accuracy of costs estimation, we may need to look at the parcel level's property assessment data for opportunity costs and the engineering details for construction costs evaluation. For adjusting the spillover effects of the selected WRS parcels, we should pay attention to the land-price feedback effects.

The benefit-to-cost ratio is an important criterion for Benefit-Cost Analysis. It can generate the minimum costs at the certain sediment reduction level by ranking the benefit-to-cost ratio from the highest to the lowest and then enrolling the WRS parcels from the top of the ranking until the environmental goal is achieved. These results can provide with a direction for WRS cost-efficient spatial placement. In general, the benefit-to-cost ratios in Le Sueur River sub-watershed and Cobb River sub-watershed are higher if the WRS are placed at the upper part (Zone1 and Zone2) of the watershed; while the benefit-to-cost ratio in the Maple River sub-watershed will be higher when the WRS are installed near the outlet (Zone3). For a better application of the benefit-to-cost ratio ranking method in the future, it might be necessary to convert the benefits to economic value so we can evaluate more than one kind of WRS benefits and take the timing into consideration.

However, the benefit-to-cost ratio ranking ignores the implicit “interdependencies ” of parcels induced by their membership to the same landowner. Recognizing the problem of high transaction costs correlated with land ownership, we built the spatial optimization model by creating landowner cluster to reduce the transaction costs further. Compared with the results got from benefit-to-cost ratio ranking, the spatial optimization model can substantially save the total costs by selecting WRS belonging to the same landowner as more as possible. To upgrade the spatial optimization model, we could embed more physical interdependencies like spatial contiguity, and economic interdependencies like land value spillover among WRS parcels in the future studies.

The primary methodological contribution of this project is that we incorporated both spatial and temporal, natural and social considerations in our optimization models for cost-efficient site placement of the WRS program. The results of our project would provide help for dealing with the conflicts between sediment reduction and economic development, and the negotiation problems with landowners.

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Appendix A

APPENDIX

A.1 Linear Estimation for Sediment Reduction Coefficient

Zone1 LS			Zone1 COB			Zone1 MAP		
Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	Baseline	0	13137.77532	Baseline	0	18466.84829
0.2%	2.3294234	17554.32192	0.2%	1.5657036	12678.78109	0.2%	1.7749076	17847.18577
0.5%	5.8235585	16468.81698	0.5%	3.914259	12187.34873	0.5%	4.437269	17026.76441
1%	11.647117	15076.07208	1%	7.828518	11323.51417	1%	8.874538	15585.13642
2%	23.294234	12594.06955	2%	15.657036	9850.947638	2%	17.749076	13127.21899
Zone2 LS			Zone2 COB			Zone2 MAP		
Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	Baseline	0	13137.77532	Baseline	0	18466.84829
0.1%	1.1647117	17913.91534	0.1%	0.7828518	12960.00685	0.1%	0.8874538	18243.09075
0.2%	2.3294234	17699.05468	0.2%	1.5657036	12872.20601	0.2%	1.7749076	17871.02676
0.4%	4.6588468	17269.33335	0.4%	3.1314072	12623.52935	0.4%	3.5498152	17297.18326
0.8%	9.3176936	16269.34333	0.8%	6.2628144	12169.60166	0.8%	7.0996304	16219.54533
Zone3 LS			Zone3 COB			Zone3 MAP		
Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	Baseline	0	13137.77532	Baseline	0	18466.84829
0.1%	1.1647117	17954.09264	0.1%	0.7828518	12987.98125	0.1%	0.8874538	18235.61424
0.2%	2.3294234	17779.40928	0.2%	1.5657036	12928.15481	0.2%	1.7749076	17888.15802
0.4%	4.6588468	17430.04256	0.4%	3.1314072	12753.08495	0.4%	3.5498152	17369.86259
0.8%	9.3176936	16586.78016	0.8%	6.2628144	12461.79107	0.8%	7.0996304	16423.82953

Table A.1: Scenario K6V05: WRS Extent & Sediment Reduction

Zone1 LS			Zone1 COB			Zone1 MAP		
Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	Baseline	0	13137.77532	Baseline	0	18466.84829
0.2%	2.3294234	17904.51583	0.2%	1.5657036	13029.3119	0.2%	1.7749076	18194.90727
0.5%	5.8235585	17568.12558	0.5%	3.914259	12866.61676	0.5%	4.437269	17658.81489
1.0%	11.647117	17007.47515	1.0%	7.828518	12595.4582	1.0%	8.874538	16911.87253
2.0%	23.294234	15886.17429	2.0%	15.657036	12053.14109	2.0%	17.749076	15499.17675
Zone2 LS			Zone2 COB			Zone2 MAP		
Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	Baseline	0	13137.77532	Baseline	0	18466.84829
0.1%	1.1647117	18056.37086	0.1%	0.7828518	13122.53887	0.1%	0.8874538	18322.08454
0.2%	2.3294234	17983.96572	0.2%	1.5657036	13107.30241	0.2%	1.7749076	18177.3208
0.4%	4.6588468	17839.15544	0.4%	3.1314072	13076.8295	0.4%	3.5498152	17887.7933
0.8%	9.3176936	17549.53487	0.8%	6.2628144	13015.88368	0.8%	7.0996304	17196.71672
Zone3 LS			Zone3 COB			Zone3 MAP		
Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	Baseline	0	13137.77532	Baseline	0	18466.84829
0.1%	1.1647117	18010.74103	0.1%	0.7828518	13083.33289	0.1%	0.8874538	18274.92177
0.2%	2.3294234	17892.70606	0.2%	1.5657036	12958.67366	0.2%	1.7749076	18082.99524
0.4%	4.6588468	17656.63611	0.4%	3.1314072	12869.53962	0.4%	3.5498152	17595.39723
0.8%	9.3176936	17184.49622	0.8%	6.2628144	12691.27154	0.8%	7.0996304	16744.61749

Table A.2: Scenario K7V05: WRS Extent & Sediment Reduction

Zone1 LS				Zone1 COB				Zone1 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.2%	2.3294234	18082.6238	18082.6238	0.2%	1.5657036	13175.56544	13175.56544	0.2%	1.7749076	18420.55718	18420.55718
0.5%	5.8235585	18013.3955	18013.3955	0.5%	3.914259	13232.25062	13232.25062	0.5%	4.437269	18351.12052	18351.12052
1.0%	11.647117	17898.01499	17898.01499	1.0%	7.828518	13326.72592	13326.72592	1.0%	8.874538	18235.39274	18235.39274
2.0%	23.294234	17667.25397	17667.25397	2.0%	15.657036	13515.67652	13515.67652	2.0%	17.749076	18003.93718	18003.93718
Zone2 LS				Zone2 COB				Zone2 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.1%	1.1647117	18072.31673	18072.31673	0.1%	0.7828518	13145.86294	13145.86294	0.1%	0.8874538	18439.13618	18439.13618
0.2%	2.3294234	18015.85746	18015.85746	0.2%	1.5657036	13153.95055	13153.95055	0.2%	1.7749076	18411.42406	18411.42406
0.4%	4.6588468	17902.93892	17902.93892	0.4%	3.1314072	13170.12578	13170.12578	0.4%	3.5498152	18355.99982	18355.99982
0.8%	9.3176936	17677.10184	17677.10184	0.8%	6.2628144	13202.47625	13202.47625	0.8%	7.0996304	18245.15135	18245.15135
Zone3 LS				Zone3 COB				Zone3 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.1%	1.1647117	18172.25771	18172.25771	0.1%	0.7828518	13137.2447	13137.2447	0.1%	0.7828518	18505.20066	18505.20066
0.2%	2.3294234	18215.73941	18215.73941	0.2%	1.5657036	13136.71409	13136.71409	0.2%	1.5657036	18543.55303	18543.55303
0.4%	4.6588468	18302.70282	18302.70282	0.4%	3.1314072	13135.65286	13135.65286	0.4%	3.1314072	18620.25777	18620.25777
0.8%	9.3176936	18476.62963	18476.62963	0.8%	6.2628144	13105.66864	13105.66864	0.8%	6.2628144	18773.66725	18773.66725

Table A.3: Scenario K8V05: WRS Extent & Sediment Reduction

Zone1 LS				Zone1 COB				Zone1 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.2%	2.3294234	17571.67645	17571.67645	0.2%	1.5657036	12642.80607	12642.80607	0.2%	1.7749076	17873.78311	17873.78311
0.5%	5.8235585	16508.87406	16508.87406	0.5%	3.914259	12018.00227	12018.00227	0.5%	4.437269	16955.81925	16955.81925
1.0%	11.647117	15089.35146	15089.35146	1.0%	7.828518	11075.71216	11075.71216	1.0%	8.874538	15592.72457	15592.72457
2.0%	23.294234	12661.84591	12661.84591	2.0%	15.657036	9405.56439	9405.56439	2.0%	17.749076	13293.59264	13293.59264
Zone2 LS				Zone2 COB				Zone2 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.1%	1.1647117	17904.97095	17904.97095	0.1%	0.7828518	12971.09032	12971.09032	0.1%	0.8874538	18235.99433	18235.99433
0.2%	2.3294234	17681.1659	17681.1659	0.2%	1.5657036	12894.37294	12894.37294	0.2%	1.7749076	17856.83631	17856.83631
0.4%	4.6588468	17082.62058	17082.62058	0.4%	3.1314072	12667.86423	12667.86423	0.4%	3.5498152	17268.8305	17268.8305
0.8%	9.3176936	16207.54212	16207.54212	0.8%	6.2628144	12263.6639	12263.6639	0.8%	7.0996304	16040.05979	16040.05979
Zone3 LS				Zone3 COB				Zone3 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.1%	1.1647117	17954.21873	17954.21873	0.1%	0.7828518	13000.55084	13000.55084	0.1%	0.8874538	18215.034	18215.034
0.2%	2.3294234	17779.66146	17779.66146	0.2%	1.5657036	12953.29399	12953.29399	0.2%	1.7749076	17846.69424	17846.69424
0.4%	4.6588468	17430.54691	17430.54691	0.4%	3.1314072	12803.08716	12803.08716	0.4%	3.5498152	17287.158	17287.158
0.8%	9.3176936	16587.29075	16587.29075	0.8%	6.2628144	12560.90379	12560.90379	0.8%	7.0996304	16219.29162	16219.29162

Table A.4: Scenario K6V10: WRS Extent & Sediment Reduction

Zone1 LS				Zone1 COB				Zone1 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.2%	2.3294234	17840.38539	17840.38539	0.2%	1.5657036	13005.16234	13005.16234	0.2%	1.7749076	18114.6482	18114.6482
0.5%	5.8235585	17407.79948	17407.79948	0.5%	3.914259	12806.24287	12806.24287	0.5%	4.437269	17458.21889	17458.21889
1.0%	11.647117	16686.82295	16686.82295	1.0%	7.828518	12474.71042	12474.71042	1.0%	8.874538	16407.1562	16407.1562
2.0%	23.294234	15244.8699	15244.8699	2.0%	15.657036	11811.64552	11811.64552	2.0%	17.749076	14698.45398	14698.45398
Zone2 LS				Zone2 COB				Zone2 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.1%	1.1647117	17959.53174	17959.53174	0.1%	0.7828518	13011.50818	13011.50818	0.1%	0.8874538	18301.3168	18301.3168
0.2%	2.3294234	17790.28747	17790.28747	0.2%	1.5657036	12975.20866	12975.20866	0.2%	1.7749076	18135.7853	18135.7853
0.4%	4.6588468	17451.79895	17451.79895	0.4%	3.1314072	12902.60961	12902.60961	0.4%	3.5498152	17670.0241	17670.0241
0.8%	9.3176936	16774.82189	16774.82189	0.8%	6.2628144	12757.41153	12757.41153	0.8%	7.0996304	16921.49435	16921.49435
Zone3 LS				Zone3 COB				Zone3 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.1%	1.1647117	17996.14121	17996.14121	0.1%	0.7828518	13005.29575	13005.29575	0.1%	0.7828518	18217.67188	18217.67188
0.2%	2.3294234	17863.50642	17863.50642	0.2%	1.5657036	12962.78381	12962.78381	0.2%	1.5657036	17850.20253	17850.20253
0.4%	4.6588468	17598.23684	17598.23684	0.4%	3.1314072	12877.75991	12877.75991	0.4%	3.1314072	17291.45649	17291.45649
0.8%	9.3176936	17067.69768	17067.69768	0.8%	6.2628144	12658.41886	12658.41886	0.8%	6.2628144	16255.26028	16255.26028

Table A.5: Scenario K7V10: WRS Extent & Sediment Reduction

Zone1 LS				Zone1 COB				Zone1 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.2%	2.3294234	18061.02637	18061.02637	0.2%	1.5657036	13173.21083	13173.21083	0.2%	1.7749076	18387.5682	18387.5682
0.5%	5.8235585	17959.40191	17959.40191	0.5%	3.914259	13226.3641	13226.3641	0.5%	4.437269	18268.64805	18268.64805
1.0%	11.647117	17790.02781	17790.02781	1.0%	7.828518	13314.95288	13314.95288	1.0%	8.874538	18070.44781	18070.44781
2.0%	23.294234	17451.27961	17451.27961	2.0%	15.657036	13492.13044	13492.13044	2.0%	17.749076	17674.04733	17674.04733

Zone2 LS				Zone2 COB				Zone2 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.1%	1.1647117	18061.51084	18061.51084	0.1%	0.7828518	13166.27838	13166.27838	0.1%	0.8874538	18442.19969	18442.19969
0.2%	2.3294234	17994.24568	17994.24568	0.2%	1.5657036	13194.78144	13194.78144	0.2%	1.7749076	18417.55109	18417.55109
0.4%	4.6588468	17859.71535	17859.71535	0.4%	3.1314072	13251.78756	13251.78756	0.4%	3.5498152	18368.25389	18368.25389
0.8%	9.3176936	17590.65469	17590.65469	0.8%	6.2628144	13365.79981	13365.79981	0.8%	7.0996304	18269.65948	18269.65948

Zone3 LS				Zone3 COB				Zone3 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.1%	1.1647117	18065.23461	18065.23461	0.1%	0.7828518	13145.38819	13145.38819	0.1%	0.7828518	18499.33229	18499.33229
0.2%	2.3294234	18001.69322	18001.69322	0.2%	1.5657036	13153.00106	13153.00106	0.2%	1.5657036	18532.41828	18532.41828
0.4%	4.6588468	17874.61043	17874.61043	0.4%	3.1314072	13168.2268	13168.2268	0.4%	3.1314072	18597.98827	18597.98827
0.8%	9.3176936	17620.44485	17620.44485	0.8%	6.2628144	13170.08907	13170.08907	0.8%	6.2628144	18729.12825	18729.12825

Table A.6: Scenario K8V10: WRS Extent & Sediment Reduction

Zone1 LS				Zone1 COB				Zone1 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.2%	2.3294234	17571.3216	17571.3216	0.2%	1.5657036	12646.37769	12646.37769	0.2%	1.7749076	17865.18996	17865.18996
0.5%	5.8235585	16508.0078	16508.0078	0.5%	3.914259	12026.93131	12026.93131	0.5%	4.437269	16934.33292	16934.33292
1.0%	11.647117	15087.6479	15087.6479	1.0%	7.828518	11093.57024	11093.57024	1.0%	8.874538	15549.73747	15549.73747
2.0%	23.294234	12658.49939	12658.49939	2.0%	15.657036	9446.56591	9446.56591	2.0%	17.749076	13207.616	13207.616

Zone2 LS				Zone2 COB				Zone2 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.1%	1.1647117	17904.6462	17904.6462	0.1%	0.7828518	12971.054	12971.054	0.1%	0.8874538	18234.6677	18234.6677
0.2%	2.3294234	17680.5164	17680.5164	0.2%	1.5657036	12894.3003	12894.3003	0.2%	1.7749076	17854.1833	17854.1833
0.4%	4.6588468	17081.35763	17081.35763	0.4%	3.1314072	12667.71894	12667.71894	0.4%	3.5498152	17263.525	17263.525
0.8%	9.3176936	16205.01622	16205.01622	0.8%	6.2628144	12263.37331	12263.37331	0.8%	7.0996304	16029.452	16029.452

Zone3 LS				Zone3 COB				Zone3 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.1%	1.1647117	17954.54233	17954.54233	0.1%	0.7828518	13000.40568	13000.40568	0.1%	0.8874538	18214.82791	18214.82791
0.2%	2.3294234	17780.30867	17780.30867	0.2%	1.5657036	12953.00366	12953.00366	0.2%	1.7749076	17846.28206	17846.28206
0.4%	4.6588468	17431.84133	17431.84133	0.4%	3.1314072	12802.5065	12802.5065	0.4%	3.5498152	17286.35713	17286.35713
0.8%	9.3176936	16589.9093	16589.9093	0.8%	6.2628144	12559.74421	12559.74421	0.8%	7.0996304	16217.85822	16217.85822

Table A.7: Scenario K6V20: WRS Extent & Sediment Reduction

Zone1 LS				Zone1 COB				Zone1 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.2%	2.3294234	17770.26567	17770.26567	0.2%	1.5657036	12869.85192	12869.85192	0.2%	1.7749076	17890.19951	17890.19951
0.5%	5.8235585	17232.50018	17232.50018	0.5%	3.914259	12602.91826	12602.91826	0.5%	4.437269	17134.33986	17134.33986
1.0%	11.647117	16336.22435	16336.22435	1.0%	7.828518	12101.26793	12101.26793	1.0%	8.874538	15800.21347	15800.21347
2.0%	23.294234	14543.6727	14543.6727	2.0%	15.657036	11184.4813	11184.4813	2.0%	17.749076	13674.58214	13674.58214

Zone2 LS				Zone2 COB				Zone2 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.1%	1.1647117	17933.41348	17933.41348	0.1%	0.7828518	12991.53066	12991.53066	0.1%	0.8874538	18258.06424	18258.06424
0.2%	2.3294234	17738.05096	17738.05096	0.2%	1.5657036	12935.25362	12935.25362	0.2%	1.7749076	18049.28019	18049.28019
0.4%	4.6588468	17347.32591	17347.32591	0.4%	3.1314072	12749.70607	12749.70607	0.4%	3.5498152	17497.10021	17497.10021
0.8%	9.3176936	16565.87582	16565.87582	0.8%	6.2628144	12486.88336	12486.88336	0.8%	7.0996304	16459.04704	16459.04704

Zone3 LS				Zone3 COB				Zone3 MAP			
Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate	Extent	Entered WRS	Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	18128.776	Baseline	0	13137.77532	13137.77532	Baseline	0	18466.84829	18466.84829
0.1%	1.1647117	17996.33756	17996.33756	0.1%	0.7828518	13021.22496	13021.22496	0.1%	0.8874538	18218.05566	18218.05566
0.2%	2.3294234	17863.89911	17863.89911	0.2%	1.5657036	12994.64223	12994.64223	0.2%	1.7749076	17852.67588	17852.67588
0.4%	4.6588468	17599.02221	17599.02221	0.4%	3.1314072	12886.05314	12886.05314	0.4%	3.5498152	17295.46683	17295.46683
0.8%	9.3176936	17069.26841	17069.26841	0.8%	6.2628144	12786.13537	12786.13537	0.8%	7.0996304	16215.83386	16215.83386

Table A.8: Scenario K7V20: WRS Extent & Sediment Reduction

Zone1 LS			Zone1 COB			Zone1 MAP		
Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	Baseline	0	13137.77532	Baseline	0	18466.84829
0.2%	2.3294234	18077.6013	0.2%	1.5657036	13125.90908	0.2%	1.7749076	18366.0233
0.5%	5.8235585	18000.83925	0.5%	3.914259	13108.10971	0.5%	4.437269	18214.78582
1.0%	11.647117	17872.9025	1.0%	7.828518	13078.44411	1.0%	8.874538	17962.72334
2.0%	23.294234	17617.02899	2.0%	15.657036	13019.11289	2.0%	17.749076	17458.59838
Zone2 LS			Zone2 COB			Zone2 MAP		
Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	Baseline	0	13137.77532	Baseline	0	18466.84829
0.1%	1.1647117	18075.17036	0.1%	0.7828518	13140.84983	0.1%	0.8874538	18454.26509
0.2%	2.3294234	18021.56472	0.2%	1.5657036	13143.92434	0.2%	1.7749076	18441.68189
0.4%	4.6588468	17914.35345	0.4%	3.1314072	13150.07336	0.4%	3.5498152	18416.51548
0.8%	9.3176936	17699.93089	0.8%	6.2628144	13162.37141	0.8%	7.0996304	18366.18267
Zone3 LS			Zone3 COB			Zone3 MAP		
Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate	Extent	Entered WRS Extent (km^2)	Sediment loading rate
Baseline	0	18128.776	Baseline	0	13137.77532	Baseline	0	18466.84829
0.1%	1.1647117	18059.45971	0.1%	0.7828518	13164.85712	0.1%	0.8874538	18372.27293
0.2%	2.3294234	17990.14341	0.2%	1.5657036	13191.93893	0.2%	1.7749076	18277.69757
0.4%	4.6588468	17851.51082	0.4%	3.1314072	13192.79801	0.4%	3.5498152	18088.54684
0.8%	9.3176936	17574.24564	0.8%	6.2628144	13337.78832	0.8%	7.0996304	17710.24539

Table A.9: Scenario K8V20: WRS Extent & Sediment Reduction

Region	Subbasin	V=0.5m		V=1m		V=1m		V=1m		V=2m		V=2m		V=2m	
		K=6 × 10 ⁻¹⁰ m/s	K=7 × 10 ⁻¹⁰ m/s	K=8 × 10 ⁻¹⁰ m/s	K=6 × 10 ⁻¹⁰ m/s	K=7 × 10 ⁻¹⁰ m/s	K=8 × 10 ⁻¹⁰ m/s	K=6 × 10 ⁻¹⁰ m/s	K=7 × 10 ⁻¹⁰ m/s	K=8 × 10 ⁻¹⁰ m/s	K=6 × 10 ⁻¹⁰ m/s	K=7 × 10 ⁻¹⁰ m/s	K=8 × 10 ⁻¹⁰ m/s	K=6 × 10 ⁻¹⁰ m/s	K=7 × 10 ⁻¹⁰ m/s
Zone1 LS	18, 24, 26	-234.48	-96.27	-19.81	-235.13	-123.8	-29.08	-235.28	-153.91	-21.97					
Zone1 COB	27	-207.08	-69.28	24.14	-235.39	-84.7	22.63	-232.77	-123.01	-7.58					
Zone1 MAP	28, 30	-300.11	-167.91	-26.08	-290.65	-214.21	-44.67	-295.5	-269.96	-56.81					
Zone2 LS	9	-199.56	-62.17	-48.48	-209.43	-145.31	-57.75	-209.7	-167.73	-46.03					
Zone2 COB	17, 20	-151.18	-19.46	10.33	-136.16	-54.99	36.41	-136.21	-100.51	3.93					
Zone2 MAP	23, 25, 29	-320.1	-178.9	-31.23	-345.38	-221.46	-27.78	-346.87	-286.6	-14.18					
Zone3 LS	1, 4, 5, 10	-165.49	-101.34	37.33	-165.44	-113.88	-54.36	-165.16	-113.71	-59.51					
Zone3 COB	12, 13, 14, 15, 16	-103.96	-70.66	-5.13	-88.14	-70.79	5.52	-88.33	-52.72	30.23					
Zone3 MAP	19, 21, 22	-289.34	-278.31	48.99	-318.15	-355.06	41.88	-318.35	-318.74	-106.57					

Table A.10: Sediment Reduction Coefficients by Linear Estimation(mg/yr/km²)

A.2 WRS Cost-Efficient Spatial Placement Comparison

Scenario $K=6 \times 10^{-10}$ m/s, $V=0.5$ m:

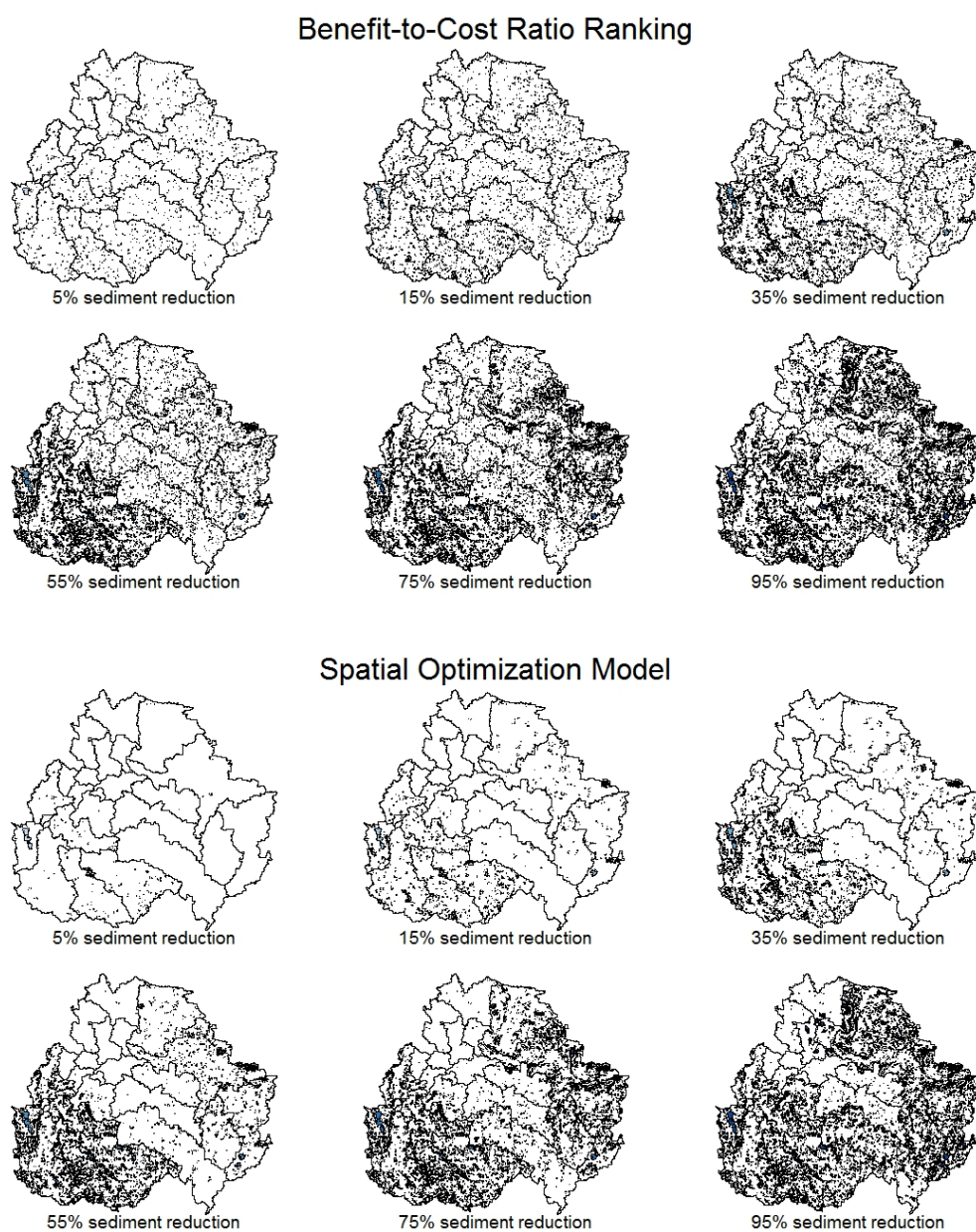


Figure A.1: Scenario K6V05 Spatial Placement Comparison

Scenario $K=7 \times 10^{-10}$ m/s, $V=0.5$ m:

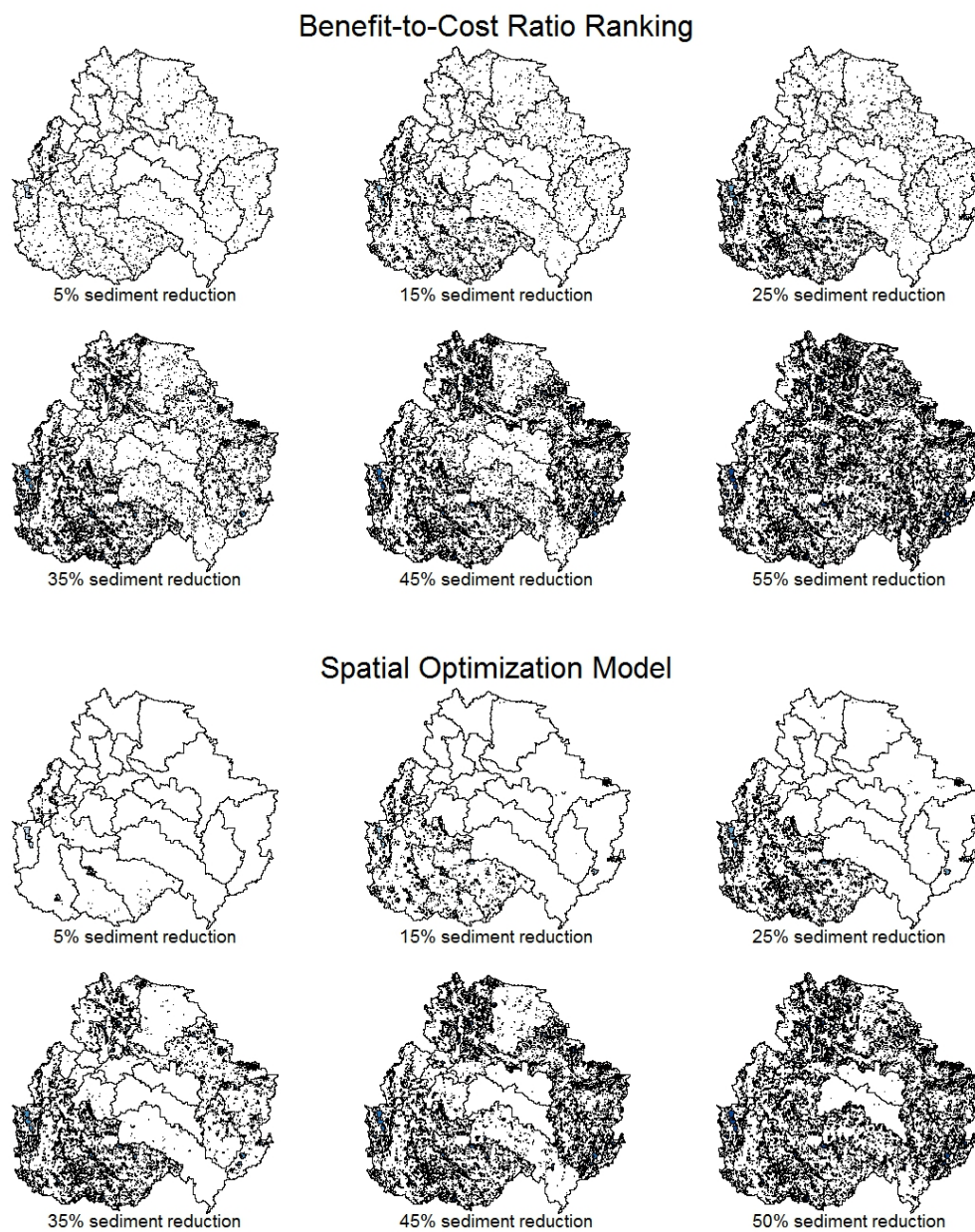


Figure A.2: Scenario K7V05 Spatial Placement Comparison

Scenario $K=6 \times 10^{-10} \text{ m/s}, V=1\text{m}$:

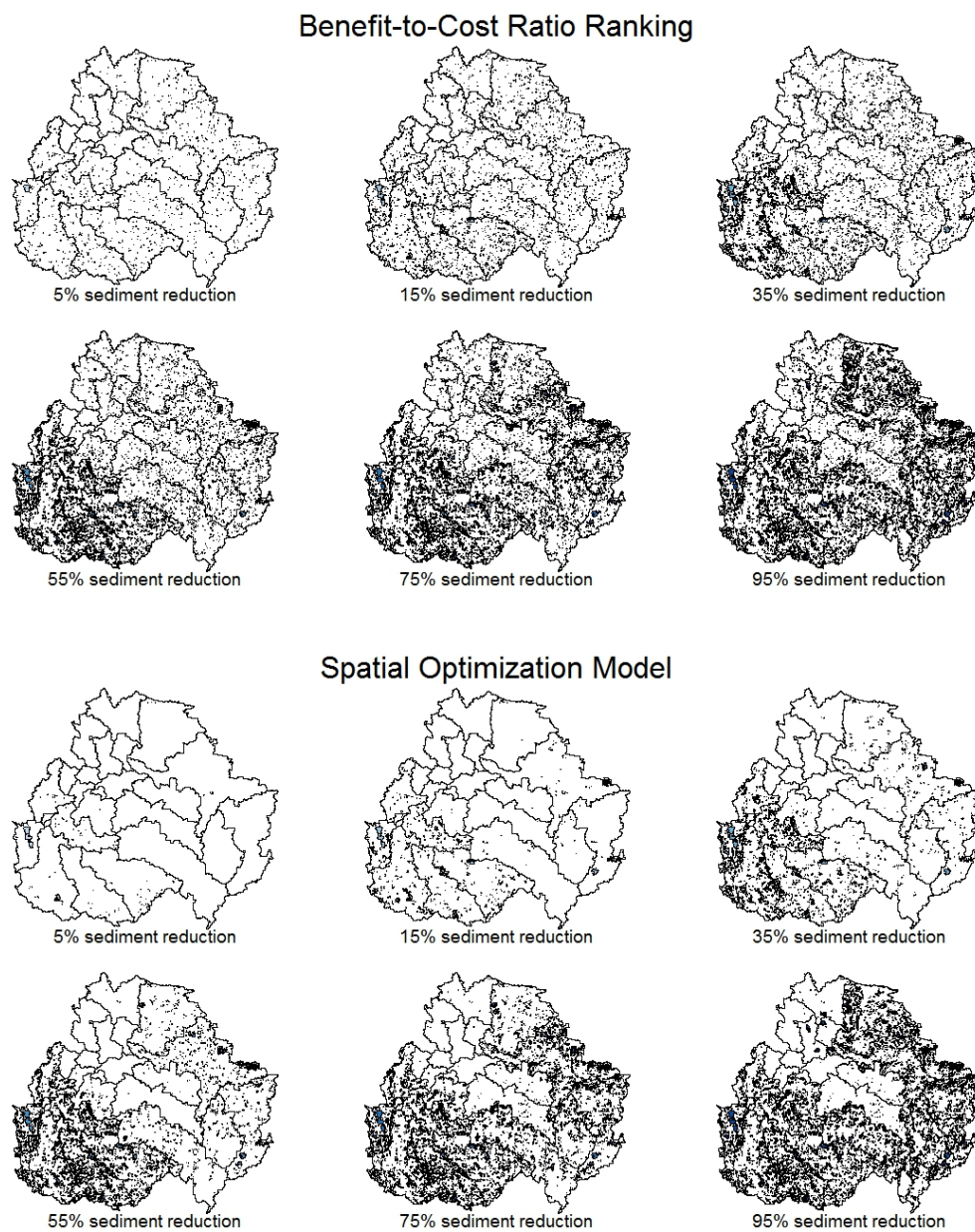


Figure A.3: Scenario K6V10 Spatial Placement Comparison

Scenario $K=7 \times 10^{-10} \text{ m/s}, V=1\text{m}$:

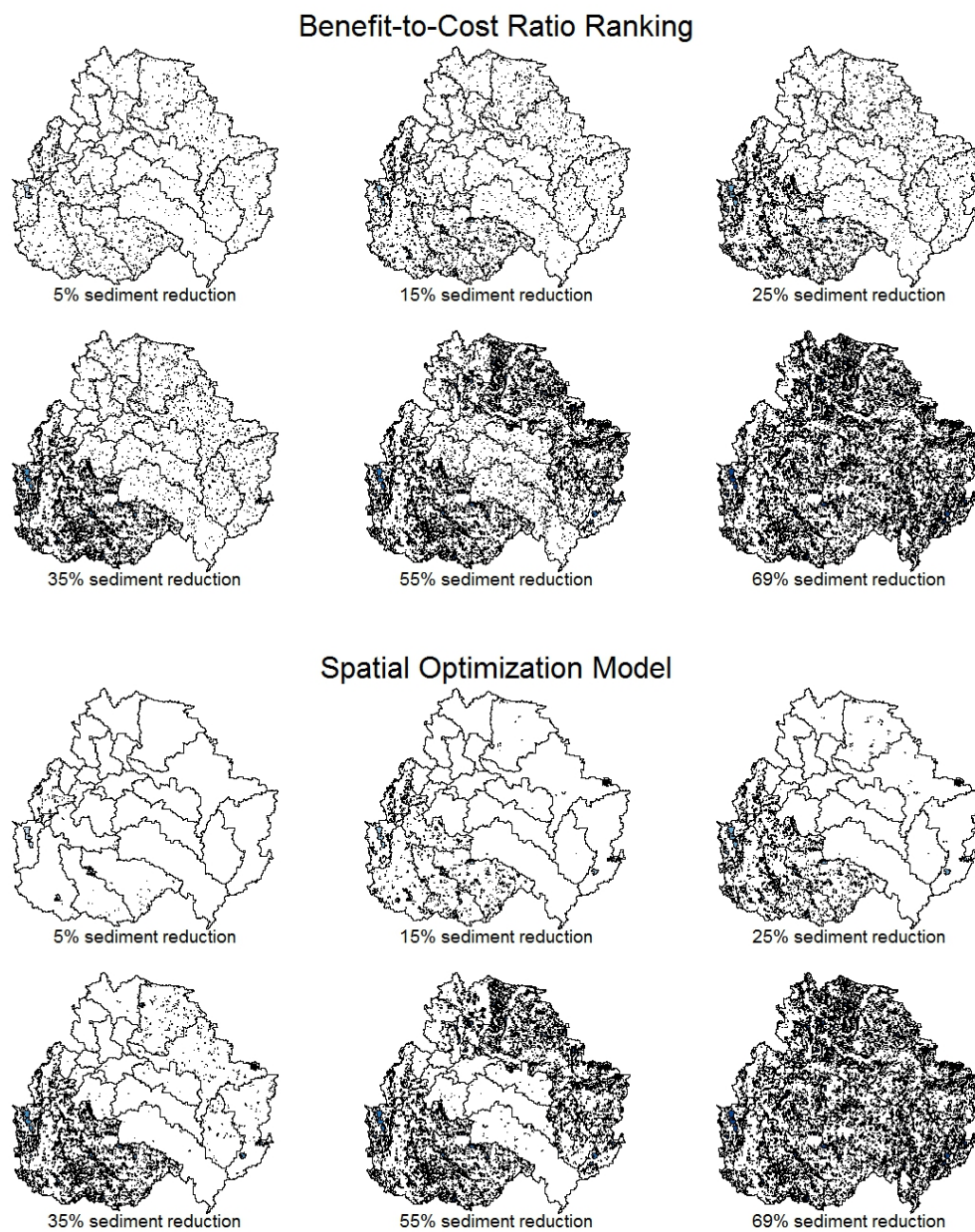


Figure A.4: Scenario K7V10 Spatial Placement Comparison

Scenario $K=7 \times 10^{-10}$ m/s, $V=2$ m:

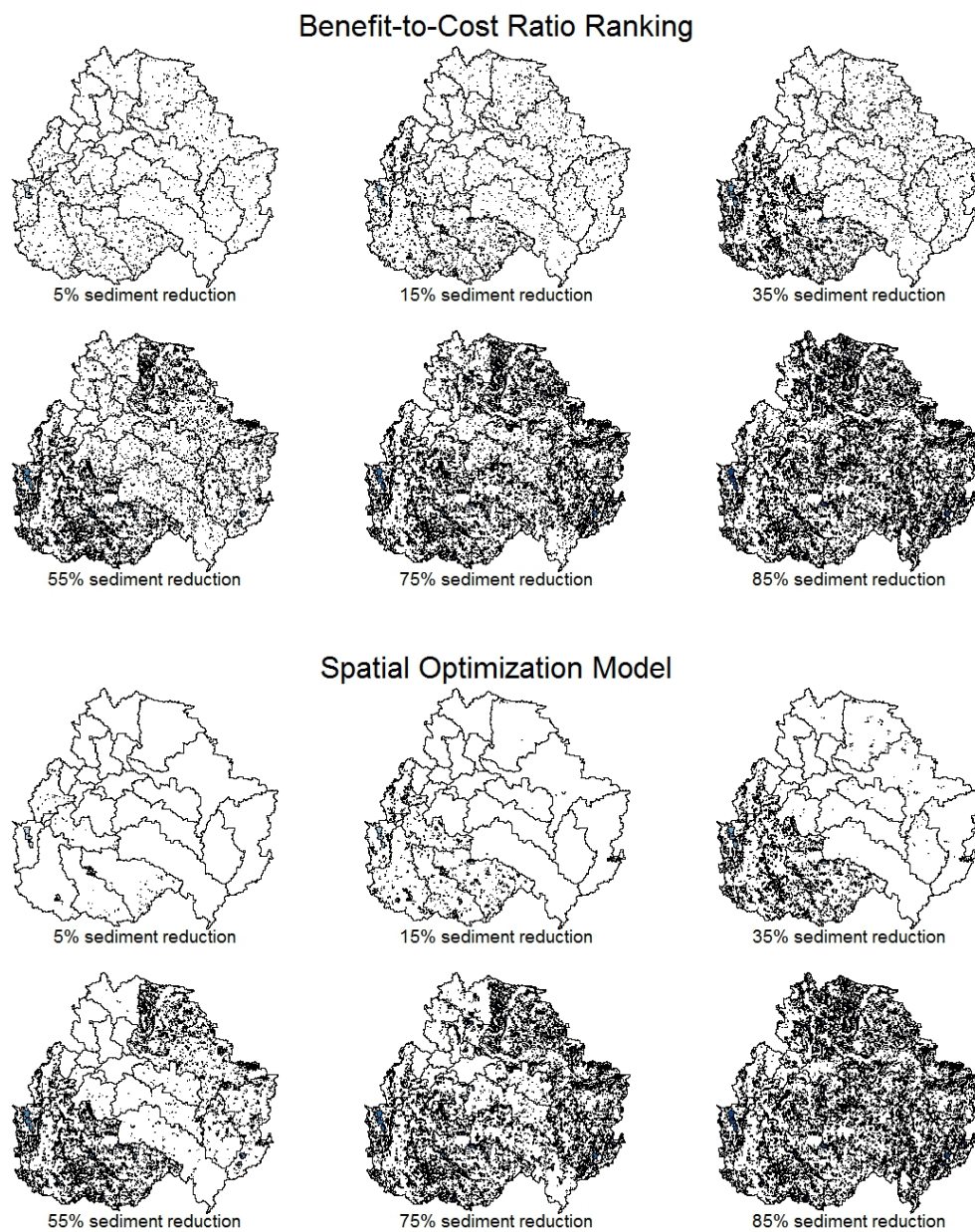


Figure A.5: Scenario K7V10 Spatial Placement Comparison

A.3 Total Cost Comparison

Total cost comparison between spatial optimization and benefit-to-cost ratio ranking within 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, 95% sediment reduction constraints:

Scenario K6V05:

Sediment reduction	Hansen Cost		Real Options Cost	
	Spatial Optimization Model	Ratio Ranking	Spatial Optimization Model	Ratio Ranking
5%	5,217,479.46	8,656,132.12	5,461,910.26	8,590,252.79
10%	12,879,152.36	17,218,814.59	13,480,128.48	17782521.59
15%	21,794,223.65	26,073,569.06	22,729,328.63	26,999,267.60
20%	31,293,152.08	36,270,655.24	32,533,167.16	37,044,751.03
25%	41,182,605.52	45,707,333.94	42,709,964.03	47,244,346.87
30%	51,326,034.65	55,881,181.96	53,137,400.90	57,667,250.84
35%	61,766,453.91	66,130,312.45	63,893,540.12	68,173,955.17
40%	72,529,368.42	76,537,548.90	74,976,418.97	779,083,668.61
45%	83,453,245.15	87,499,424.83	86,224,212.96	90,310,635.73
50%	94,728,867.29	98,566,038.55	97,836,531.32	101,580,800.20
55%	106,857,843.90	110,104,056.90	110,352,373.00	113,659,157.20
60%	119,766,945.70	123,110,347.30	123,663,191.20	126,741,750.20
65%	133,178,528.10	136,029,478.80	137,494,969.30	140,317,291.00
70%	146,874,926.40	149,708,526.40	151,604,141.40	154,412,805.40
75%	161,136,781.00	163,735,718.20	166,341,464.60	168,740,816.30
80%	175,978,165.40	178,167,343.30	181,675,763.20	184,237,502.00
85%	191,332,691.20	193,442,433.30	197,503,595.40	199,579,941.60
90%	207,053,147.20	209,538,272.80	213,704,412.50	215,641,304.60
95%	223,456,597.40	225,051,269.20	230,601,379.10	232,132,205.50
100%	241,098,795.10	242,486,361.90	248,789,610.80	250,421,873.60

Table A.11: Spatial Optimization Model VS. Benefit-to-Cost Ratio Ranking (K6V05)

Scenario K7V05:

Sediment reduction	Hansen Cost		Real Options Cost	
	Spatial Optimization Model	Ratio Ranking	Spatial Optimization Model	Ratio Ranking
5%	10,163,930.93	15,023,343.73	10,503,133.48	13,922,315.71
10%	25,040,843.55	28,868,461.67	25,902,288.72	29,664,278.67
15%	42,530,417.69	46,486,935.80	43,896,616.87	47,972,727.46
20%	61,048,361.37	64,890,807.98	62,941,527.22	66,639,303.62
25%	80,470,718.62	84,326,081.91	82,995,054.20	86,619,392.62
30%	103,576,209.50	106,646,087.10	106,852,802.20	110,767,061.20
35%	133,800,769.90	136,588,152.10	137,943,932.60	140,738,523.90
40%	166,541,141.00	169,124,767.80	171,604,331.40	174,001,605.10
45%	203,739,885.50	205,142,313.50	209,995,383.00	211,266,034.20
50%	249,963,833.00	250,817,950.70	257,555,787.00	258,483,049.40

Table A.12: Spatial Optimization Model VS. Benefit-to-Cost Ratio Ranking(K7V05)

Scenario K6V10:

Sediment reduction	Hansen Cost		Real Options Cost	
	Spatial Optimization Model	Ratio Ranking	Spatial Optimization Model	Ratio Ranking
5%	4,807,226.68	8,090,354.35	5,024,634.05	7,932,578.92
10%	12,321,095.84	16,743,244.24	12,899,700.00	17,314,407.38
15%	20,763,810.34	26,286,454.89	21,645,535.45	27,424,981.70
20%	29,718,211.94	34,708,094.03	30,860,719.12	35,749,505.19
25%	38,989,179.62	43,848,200.65	40,387,633.55	45,247,816.17
30%	48,486,217.59	52,969,468.44	50,171,145.86	54,764,846.58
35%	58,332,480.33	62,672,406.44	60,298,489.65	64,582,803.28
40%	68,685,625.09	72,507,046.98	70,962,748.72	75,021,626.63
45%	79,692,569.73	83,315,723.07	82,311,278.34	85,921,958.54
50%	90,952,294.53	94,662,577.36	93,918,565.04	97,593,917.23
55%	102,655,439.10	105,968,288.80	106,006,977.50	109,362,850.00
60%	115,065,981.60	118,024,636.10	118,816,310.10	122,415,307.50
65%	127,925,513.40	130,821,880.90	132,094,084.10	135,080,858.90
70%	141,198,156.00	143,908,202.40	145,769,661.60	148,511,956.20
75%	154,712,557.00	157,450,621.90	159,678,476.20	162,431,227.20
80%	168,410,114.60	170,983,923.20	173,799,786.30	176,457,949.80
85%	182,556,633.00	185,315,957.50	188,418,967.00	1190,603,200.80
90%	197,407,359.60	199,342,652.30	203,750,117.40	205,661,599.60
95%	212,614,617.20	214,528,293.70	219,483,343.50	221,284,865.60
100%	228,274,736.40	229,998,004.70	235,628,655.30	237,249,904.40

Table A.13: Spatial Optimization Model VS. Benefit-to-Cost Ratio Ranking(K6V10)

Scenario K7V10:

Sediment reduction	Hansen Cost		Real Options Cost	
	Spatial Optimization Model	Ratio Ranking	Spatial Optimization Model	Ratio Ranking
5%	7,700,041.25	11,476,222.04	7,964,859.90	11,815,459.88
10%	18,214,049.53	22,963,103.06	18,869,997.21	23,531,051.73
15%	31,630,159.15	36,075,338.94	32,695,799.41	37,256,698.55
20%	45,958,259.90	50,145,098.38	47,432,285.51	51,498,083.69
25%	60,796,672.25	65,098,161.24	62,703,086.87	66,809,090.95
30%	76,014,626.21	80,196,136.97	78,413,528.05	82,555,406.20
35%	92,171,659.96	96,470,846.33	95,119,751.19	99,189,815.13
40%	112,361,447.60	115,528,066.60	116,001,422.90	119,116,346.40
45%	134,988,156.50	137,863,243.70	139,327,359.50	142,222,400.90
50%	159,839,155.00	162,429,934.50	164,941,726.10	167,521,261.80
55%	186,294,853.50	188,813,093.70	192,162,466.50	194,672,246.30
60%	215,143,276.30	216,809,813.80	221,829,813.60	223,477,601.10
65%	251,762,019.50	252,560,056.60	259,532,746.70	260,897,417.60
70%	290,751,530.30	290,970,845.60	299,654,171.50	299,867,943.30

Table A.14: Spatial Optimization Model VS. Benefit-to-Cost Ratio Ranking(K7V10)

Scenario K6V20:

Sediment reduction	Hansen Cost		Real Options Cost	
	Spatial Optimization Model	Ratio Ranking	Spatial Optimization Model	Ratio Ranking
5%	4,778,395.60	8,066,399.74	4,994,942.20	7,933,706.11
10%	12,206,124.67	16,513,583.22	12,770,390.95	17,106,621.03
15%	20,604,540.25	25,812,537.02	21,479,880.82	26,058,098.42
20%	29,509,432.30	34,029,574.70	30,645,318.47	35,165,208.63
25%	38,728,975.11	43,231,524.09	40,120,509.78	44,665,386.47
30%	48,169,505.80	52,788,393.17	49,841,213.32	54,346,643.53
35%	57,939,545.42	62,239,614.58	59,898,097.81	64,200,523.07
40%	68,205,804.98	71,997,029.33	70,468,606.42	74,275,712.89
45%	79,051,422.46	82,719,880.11	81,645,680.21	85,310,993.57
50%	90,124,609.20	93,870,033.57	93,063,507.28	96,813,429.86
55%	101,713,845.30	105,157,397.00	105,028,416.40	108,359,660.40
60%	114,091,459.90	117,056,670.90	117,816,667.60	120,810,727.40
65%	126,955,523.20	129,865,491.00	131,075,491.00	134,395,437.00
70%	140,218,290.40	143,137,733.20	144,772,312.50	147,811,780.10
75%	153,742,423.20	156,658,442.00	158,689,603.50	161,437,134.80
80%	167,485,738.50	170,074,919.40	172,843,737.70	175,364,721.60
85%	181,629,578.70	183,882,015.20	187,454,024.60	189,633,268.60
90%	196,461,284.70	198,583,637.20	202,768,925.00	204,868,176.70
95%	211,703,025.70	213,564,183.50	218,528,637.00	220,375,229.40
100%	227,362,829.60	228,992,855.90	234,685,430.40	236,323,542.50

Table A.15: Spatial Optimization Model VS. Benefit-to-Cost Ratio Ranking(K6V20)

Scenario K7V20:

Sediment reduction	Hansen Cost		Real Options Cost	
	Spatial Optimization Model	Ratio Ranking	Spatial Optimization Model	Ratio Ranking
5%	5,997,539.73	9,603,084.40	6,277,316.05	9,777,761.82
10%	15,090,236.83	20,015,060.54	15,686,962.05	20,555,275.50
15%	25,389,197.86	29,676,867.74	26,279,937.01	30,437,588.16
20%	36,216,296.48	40,381,980.10	37,413,930.97	42,013,098.72
25%	47,432,307.06	51,739,793.09	48,941,814.33	53,389,365.56
30%	59,033,189.15	63,114,817.09	60,876,970.12	64,864,116.62
35%	71,028,725.54	75,258,914.57	73,230,729.57	77,346,607.30
40%	83,268,149.64	87,253,851.37	85,890,141.88	89,814,811.57
45%	97,271,156.21	100,306,514.50	100,428,113.60	103,465,462.70
50%	114,885,611.40	118,095,871.20	118,641,426.80	122,037,927.80
55%	134,014,238.80	137,250,747.00	138,385,059.10	141,387,265.10
60%	154,300,473.30	156,940,590.30	159,306,883.90	161,920,919.30
65%	175,635,868.60	177,835,809.40	181,280,273.60	183,369,528.00
70%	198,935,938.90	201,442,900.10	205,346,939.30	207,162,750.70
75%	224,541,069.00	226,170,818.30	231,677,563.10	233,611,698.10
80%	252,720,245.20	253,748,019.30	260,637,142.70	261,619,234.30
85%	285,600,108.60	285,767,981.90	294,407,067.80	294,580,372.90

Table A.16: Spatial Optimization Model VS. Benefit-to-Cost Ratio Ranking(K7V20)

A.4 Landowner Information

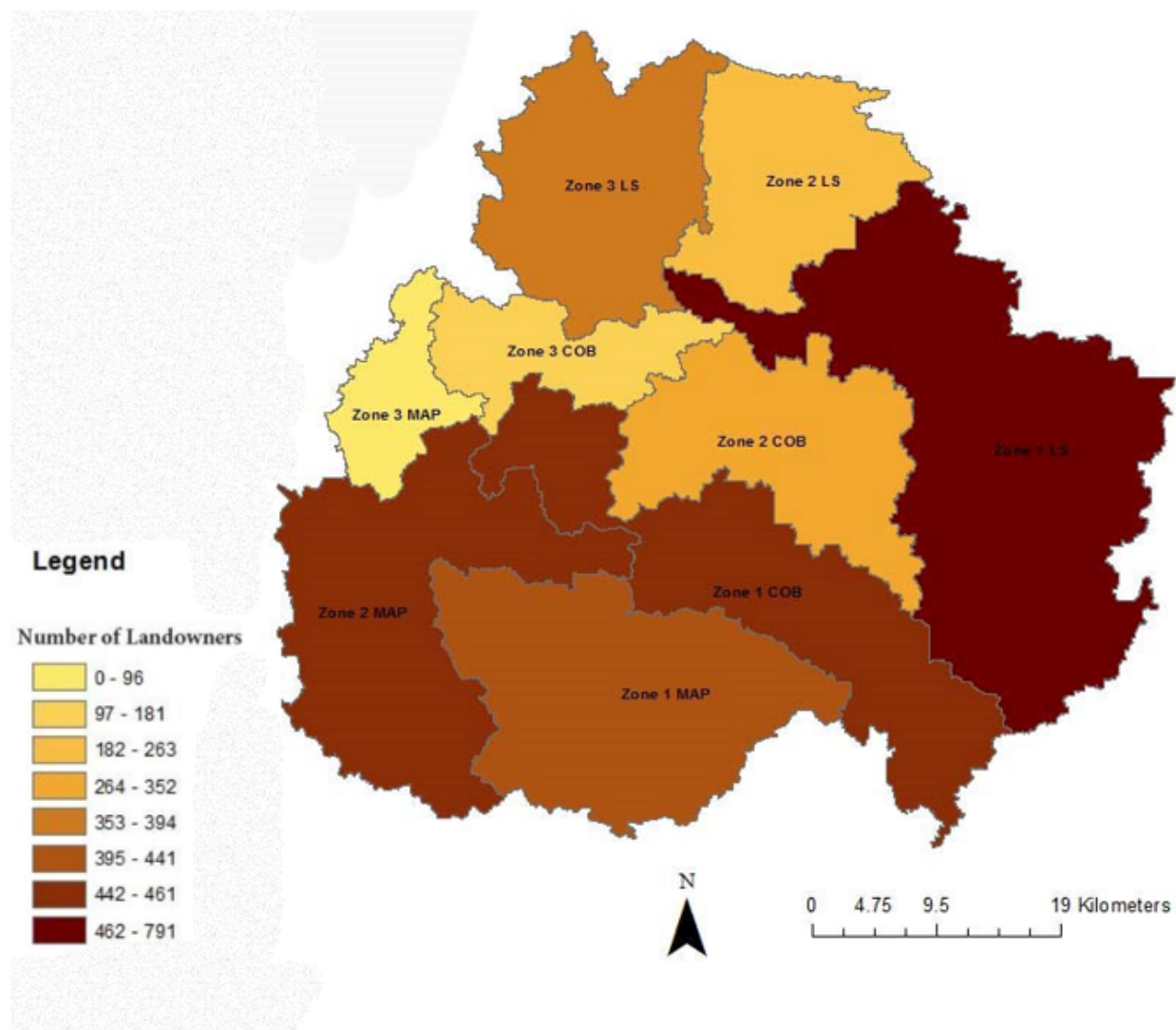


Figure A.6: Number of Landowners

Legend

Number of WRS parcels
each landowner has

- 1 - 2
- ◆ 3 - 5
- ◆ 6 - 11
- ◆ 12 - 29
- ◆ 30 - 77

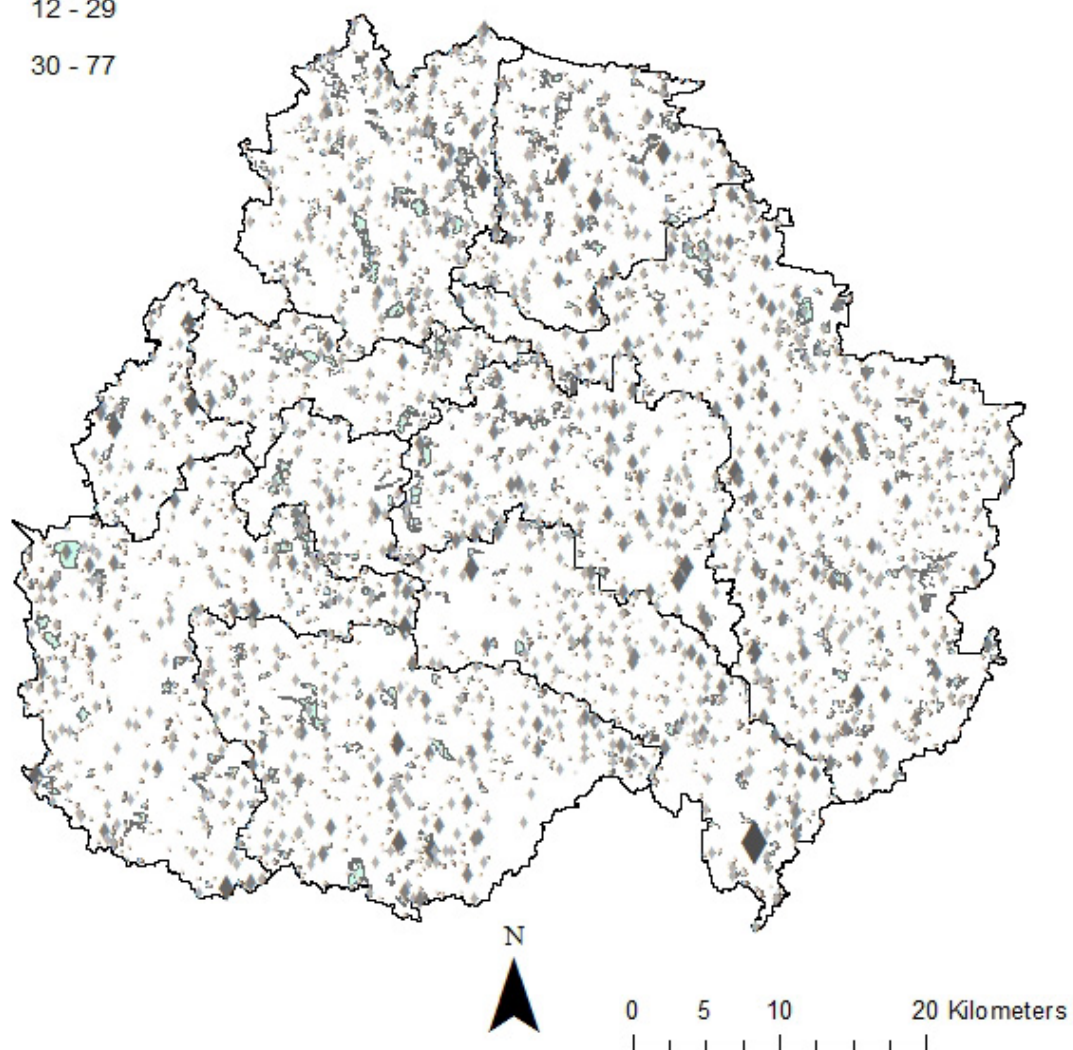


Figure A.7: Number of WRS Parcels by Each Landowner