

# **Modeling the Most Suitable Locations for Wetland Restoration within Bevens and Carver Creek Watersheds, Carver County, Minnesota USA**

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## **Abstract**

This project aimed to prioritize wetland restoration areas within the Bevens and Carver Creek Watersheds by applying a multi-variable analysis using a Geographic Information System (GIS). Three versions of the model were developed depending on the restoration's main objective: increase water quality, reduce flooding, or improve ecosystems by creating wetland continuity. First, constraints were applied to limit the study area to only land suitable for holding water. Secondly, a multi-criteria analysis was conducted with variables that indicate suitability for wetlands. Finally, to evaluate the strength of the model, a sensitivity analysis model was developed which studied the changes in the spatial distribution and size of the suitability classes when small changes were applied to the variables. GIS generated maps provide a visual representation of the model results and they contribute to improving the decision making process when prioritizing wetland restoration projects in Carver County.

## **Introduction**

The Minnesota Board of Water and Soil Resources (2009), in their Wetland Restoration Strategy Plan, defined wetlands as areas that are inundated frequently enough to support vegetation adapted to survive on saturated soils.

In the past, European settlers treated wetlands in the United States as wastelands and they found the most value in modifying and destroying them. Wetlands were drained and filled to become agricultural, residential, commercial, and recreational areas (Sands, n.d.).

The principal objective sought when restoring wetlands is to reestablish environmental services lost when the wetland was degraded. In an attempt to stop the loss of wetlands and restore them,

multiple programs (local, state, and federal) have been created (Minnesota Board of Water and Soil Resources, 2009). However, their effectiveness is limited due to the arduous work that is required to locate old drained wetlands within an altered landscape that is now occupied by agricultural land. It is expensive and requires people in the field as well as constant comparison between paper maps and on-site visits. This process often fails to take advantage of available planning and prioritization tools. Geographic Information Systems (GIS) have been used to evaluate natural resource management actions, including those related to land and water (Gatti and Richardson, 1999).

Some significant components of designing a wetland restoration strategy are to prioritize areas based on desired results

(improved water quality, increased habitat, decreased flood issues), better reconcile restoration efforts, and create restored wetlands that have beneficial functions and last a long time. Prioritizing is crucial because of financial constraints; resources must be spent where there are greatest investment returns (Minnesota Board of Water and Soil Resources, 2009).

A GIS model is a tool that helps professionals establish objectives for wetland restoration (White and Fennessy, 2005). A multi-criteria analysis provides a structured organization of the different elements that need to be analyzed as part of a complex decision-making process and establish relationships between them (Malczewski, 2006).

Wetland function, structure, and habitat will continue to be threatened if restoration measures are not taken, and consequently erosion, and the impacts of water scarcity, climate change, and natural disasters, will increase. An evaluation of multiple spatial datasets for potential restoration sites can be done using GIS tools. GIS can analyze large areas to prioritize sites from a landscape perspective, and then field-specific efforts can be limited to only those sites that match the criteria previously analyzed with GIS (Lin, Bourne, and Kleiss, 2006).

### ***Study Area***

Carver County Minnesota USA has an area of 218,330 acres, and it is geographically described by a flat landscape combined with gentle to steep hills, marshes, and lakes. The first settlers realized how fertile glacial till soil was for agriculture. To further increase agricultural productivity, they drained most of the hydric soils, first using surface ditches during the early 1800s and then replacing the ditches with drainage tile in the mid-1900s (Carver Soil and Water Conservation

District, 2010).

In its 2008 Annual Report, the Carver County Water Management Organization (2008) described wetlands as one of the most valuable ecosystems because of their biological and chemical functionality. Wetlands provide nutrient and sediment control within a watershed, filter contaminants, protect riverbanks and lakes from erosion, and provide habitat for a large variety of animals and plants. Carver County has lost up to 50% of the total pre-settlement area of wetlands, and the County Water Plan identifies the importance and necessity of protection and restoration of such ecosystems because of their influence on other water resources within a watershed (Carver Soil and Water Conservation District, 2010). This GIS research was developed for two watersheds located within Carver County: Carver Creek and Bevens Creek (Figure 1).

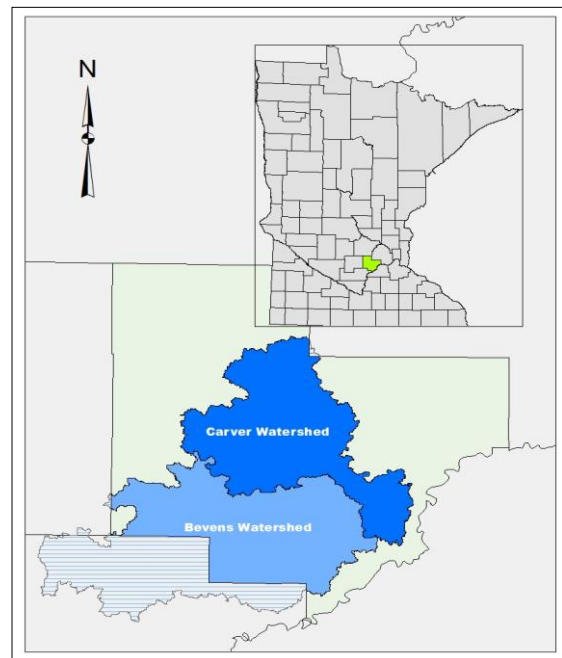


Figure 1. Carver and Bevens Creek Watersheds (blue) and Carver County (in green).

Bevens Creek Watershed is located in the southwestern part of the county with an area of 133 square miles and a length of

39 miles. It includes some urban areas, but it is comprised mostly of agricultural land and wetlands. The cities within the watershed are Green Isle, Hamburg, most of Norwood Young America, and a section of Cologne (Metropolitan Council, 2014a). For the purpose of this project, the study area only included the part of the watershed within Carver County, with an area of approximately 80 square miles. Carver Creek Watershed's area is 83 square miles, and it has a length of 31 miles. It is mostly agricultural but also includes developed areas, such as the city of Waconia, most of Cologne, and sections of Minnetrista and Carver (Metropolitan Council, 2014b). The extent of the watershed within Carver County is approximately 82 square miles.

### ***Purpose of Research***

The research objective was to identify the best areas for wetland restoration within Bevens Creek Watershed and Carver Creek Watershed and to provide a decision-making tool for the Hydrology Department of Carver County to use when prioritizing areas for restoration.

A GIS model has the potential to identify the most sensitive areas within the watersheds, where the restoration of a wetland would have the most effect on the overall watershed health. When budget is a constrained factor, identifying areas where restoration will have the greatest benefit helps to justify spending and determine the most effective use of funds.

First, environmental indicators were analyzed to identify the areas that can hold a wetland. A GIS multi-criteria analysis of variables that influence wetland effectiveness was then conducted. Three versions of the model were created depending on three primary restoration goals: (1) improve overall water quality in the watershed, (2) reduce flooding, and (3)

improve the watershed ecosystems by generating wetland connectivity. Finally, to evaluate the models, a sensitivity analysis was developed, modifying each variable one at a time, in 1% increments within a range of +/- 20%.

### **Methods**

There are four stages for creating a tool to prioritize wetland restoration: first, specify the restoration objectives; second, identify the variables/indicators to use; third, define how the indicators will be weighted; and fourth, specify how the variables relate to each other (Lin *et al.*, 2006). The goal of this analysis was to find potential sites that would benefit the health of the watershed the most, in terms of water quality, flood reduction, and habitat creation. Three versions of the model were created where each emphasized one goal over the others, and therefore the variables' weights shifted to prioritize one objective at a time.

### ***Selected Variables***

Identifying an area with an adequate hydrologic regime guarantees less economic effort and time spent modifying a site to reach the hydrological requirements needed (Lin *et al.*, 2006). Saturation index can be used as a hydrologic suitability indicator and describes the capacity of the soil to hold water based on the runoff concentration and potential for drainage. Flat raster cells (areas) surrounded by steep slopes score higher values (White and Fennessy, 2005). Slope and flow accumulation is used to calculate this variable, applying the following saturation index formula (White and Fennessy, 2005):

$$SI = \ln (\alpha / \tan \beta)$$

SI= Saturation Index

$\ln$  = Natural Logarithm  
 $\alpha$  = Upslope Drainage Area  
 $\beta$  = Local Slope (°)

This equation was applied using the ArcGIS Raster Calculator to obtain a saturation index raster layer (Appendix A). The upslope drainage area and local slope were calculated from a digital elevation model provided by the Carver County hydrology department.

When selecting restoration sites, it is important to analyze the soil properties. It is recommended to restore within existing hydric soils since it may take years for a hydric soil to develop in a natural way (Lin *et al.*, 2006). A hydric soils dataset was downloaded from the Soil Survey Geographic (SSURGO) online database and used to select only those areas with hydric soils for further analysis of restoration potential (Appendix A).

Other variables included in the model were stream order and overland flow length. Stream order emphasized the benefits of restoring areas around the watershed head in order to improve downstream water quality. The flow length variable measured the distance that water from a raster cell travels to reach the nearest waterbody; the farther from a stream, the fewer wetland restoration benefits (White and Fennessy, 2005). Wetlands located near a stream network have an effect on water quality, decrease flooding, and create aquatic habitat (Mitsch, Zhang, Anderson, Altor, and Hernandez, 2005). To obtain the stream order variable, the Strather Stream Order was calculated using the ArcGIS Stream Order tool, and streams of order 1 were extracted from the resulting layer. Then, the Euclidean Distance tool was applied. The resulting layer scored each cell in terms of distance to a stream of order 1, with small cell values equivalent to small travelling distances to the stream segment.

The Euclidean Distance tool was also used to obtain the flow length variable, and as in the previous raster, a small value is equivalent to a small distance to travel to reach a waterbody (Appendix A).

Restoring a wetland near impaired water has potential for greater benefit in terms of water quality for the watershed. Proximity to impaired waters was another variable included in the analysis. A spatial data layer containing impaired streams and lakes within Carver County was available to the public by the Minnesota Pollution Control Agency's Environmental Data Access System. Euclidean distance was then calculated to obtain a raster where a cell with a low value was close to an impaired water source (Appendix A).

Restoring wetlands in proximity to others creates wetland corridors for plants and wildlife, improving the habitat. The National Wetland Inventory shapefile for Minnesota was downloaded from the Minnesota Geospatial Commons and used to calculate a Euclidean distance raster layer. Cells with low values were close to current wetlands.

Finally, to analyze the land use along the watershed, the Minnesota Land Cover Classification System shapefile (MLCSS) was provided by Carver County. Current urban areas and water were excluded from further analysis, and the rest of the land uses were grouped into two final classes. The classification assigned a value of 0 or 1 based on the cost required to restore a site, depending on its current land use. For example crops and grasslands were assigned a value of 1, but forested areas obtained values of 0 because of the high cost to remove trees during a wetland restoration project (Appendix A).

### ***Data Normalization***

Prior to weighting each variable and

producing model results, all variables were normalized to a standard scale of 0 (least suitable) to 1 (most suitable). All the variables except land use were normalized to the 0 to 1 scale using the Fuzzy Membership tool. The ArcGIS Resource Center website (Esri, n.d.) explains that the fuzzy linear transformation function creates a linear function between the maximum and minimum values chosen by the user. For each variable, the minimum and maximum values present in the data were used as inputs to the tool, thus rescaling all values in between to fit the 0 to 1 scale. For this project, a direct linear function was assigned to describe the data for criteria rasters where a low value meant low suitability and high value meant high suitability. For those variables where a low raster cell value meant high suitability, an inverse linear function was chosen. For instance, the saturation index raster layer had values between -4.16276 and 22.7249 for one watershed, and -14.4533 and 23.2277 for the second watershed. Because low values represent low saturation index, and thus low suitability, a linear function was assigned (Figure 2).

For the other criteria (flow length, water quality, wetland proximity, and distance to stream segments of order 1), raster results with a low cell value were preferred, and therefore an inverse linear function was applied to normalize the results with values between 0 and 1 (Figure 3).

### ***Multi-Variable Analysis and Analytical Hierarchy Process (AHP)***

To identify the most suitable areas to be restored, a multi-criteria analysis was conducted. The studied variables were multiplied by their assigned weight and then added together. Each criterion's importance (weight) was determined based upon a list of

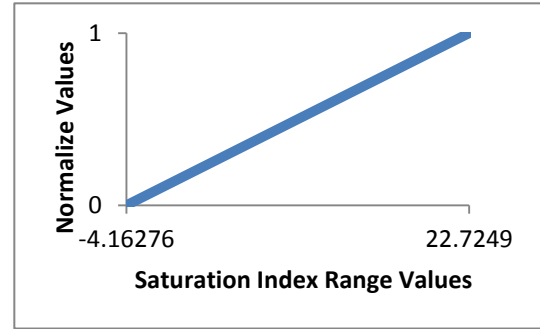


Figure 2. Bevens Creek Watershed; Saturation index raster values and normalized values resulting from the Fuzzy Membership-Linear function.

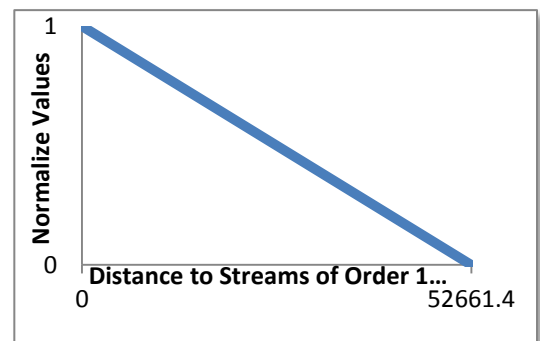


Figure 3. Bevens Creek Watershed; Distance to streams of order 1 raster values and normalized values resulting from the Fuzzy Membership- Inverse Linear Function.

interest and priorities provided by the Hydrology Department of Carver County. The importance of one variable over another was obtained by pairwise comparisons following the AHP methodology (Saaty, 1980).

The AHP is a popular approach when deciding weights of variables within a multi-criteria decision (Chen, Yu, and Khan, 2010). The method consists of ranking each criterion's importance in comparison to the rest of the variables in order to generate a normalized matrix. Then, a consistency ratio is calculated and compared to a random inconsistency index (RI) to evaluate each variable's level of consistency. The RI is obtained from a table and depends on the matrix order. Since this model evaluated 6 different variables, a matrix of order 6 was

obtained, and therefore RI=1.24. To facilitate calculations, an online AHP calculator was used, and the weight of the variables were adjusted until the consistency criterion was met (Klaus, 2013). Table 1 illustrates the resulting weights for each variable and restoration goal.

Table 1. Weights applicable to the variables for each restoration goal. SI= Saturation Index, FL= Flow Length, SO= Proximity to Stream Order 1, IW= Proximity to Impaired Waters, WP= Wetland Proximity and LU= Land Use.

| Variables | Flood Reduction | Improve Water Quality | Improve Wetland Ecosystem |
|-----------|-----------------|-----------------------|---------------------------|
| SI        | 0.4025          | 0.0499                | 0.0377                    |
| FL        | 0.1394          | 0.1140                | 0.1620                    |
| SO        | 0.1131          | 0.1626                | 0.0631                    |
| IW        | 0.0422          | 0.4402                | 0.0862                    |
| WP        | 0.0699          | 0.0381                | 0.4092                    |
| LU        | 0.2329          | 0.1953                | 0.2417                    |

When the main goal is to reduce flooding, the criterion assigned the most weight was saturation index, so areas that can easily hold water in the event of a flood would be prioritized when choosing restoration sites. Proximity to impaired waters and proximity to wetlands were the criteria that were weighed the most for the other two model goals (improved water quality and wetland ecosystem, respectively). Land use was always assigned a high value because of the budget constraint for any restoration project. Regardless of the main objective, selecting an easier/less expensive location to restore is always important.

### Sensitivity Analysis

A Sensitivity Analysis (SA) was used to evaluate the stability of the model by applying small changes to the assigned weights of the input data and analyzing the resulting variations in the output results. This process helped to decrease the level of

uncertainty in the application of the Multi-Criteria Decision Making process and evaluated how stable the results were when changing the values of the inputs slightly (Crosetto and Tarantola, 2001). The SA evaluated the stability of the resulting suitability class sizes and identified which variables registered the largest changes. The results of the SA were also mapped to study modifications in the location of the suitable cells within the watershed.

The one-at-a-time procedure was followed; a total change of +/- 20% with increments of 1% were applied to the weights of the criteria. The first simulation was -20%, and the 41st run was +20%. Position 21 was the base run with 0% change. On each run, the 1% modification was applied to one criterion, and the weights of the other variables were adjusted so that the addition of all weights remained equal to 1. The following formula was applied to adjust the weight values (Chen *et al.*, 2010):

$$W(c_i, pc) = (1 - W(c_m, pc)) * W(c_i, 0) / (1 - W(c_m, 0)),$$

$$i \neq m, 1 \leq i \leq n$$

$W(c_i, pc)$  = Weights of other criteria

$W(c_m, pc)$  = Weight of the criterion being adjusted

$W(c_i, 0)$  = Weight of the i-th criterion  $c_i$  at the base run

$W(c_m, 0)$  = Weight at the main criterion  $c_m$  being adjusted at the base run

To automate the process, ArcGIS Model Builder was used to create a model that iterated through a list of values that reflected the 1% changes in the selected variable weights and applied the modification to the formula within the Raster Calculator (Figure 4). These lists were previously calculated in Microsoft Excel using the adjusted weights formula previously mentioned and then loaded into the variable as a list of values. The final

result of each model run was 41 raster layers per variable per model objective.

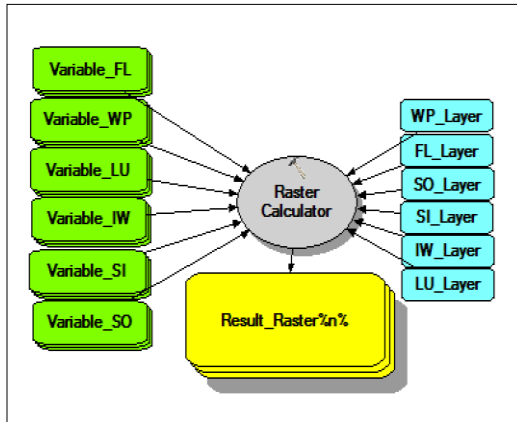


Figure 4. The model that created 41 rasters with 1% changes in the selected variable weight and adjusted the rest of the weights accordingly.

To better analyze the results, the layers were reclassified, and after testing multiple alternatives for the number of classes, four classes determined using the Jenks natural breaks method was the option that best represented the continuous raster suitability layers (Figure 5). When the number of classes differed from four, it created skewed spatial representations of the areas that scored high for wetland suitability.

The classes ranged from 1, representing low suitability, up to 4, representing high suitability. Finally, a Python script was developed to extract and organize the number of cells per suitability category for each raster to facilitate further analysis and graph creation in Excel.

The Sensitivity Analysis resulted in a total of 246 simulation runs per model, each of them with its own suitability map result and a table per variable that displayed the distribution per suitability class for each run.

Also, a sensitivity index (SI) was calculated by applying the following formula to each of the suitability classes for each of the variables (Pannell, 2015).

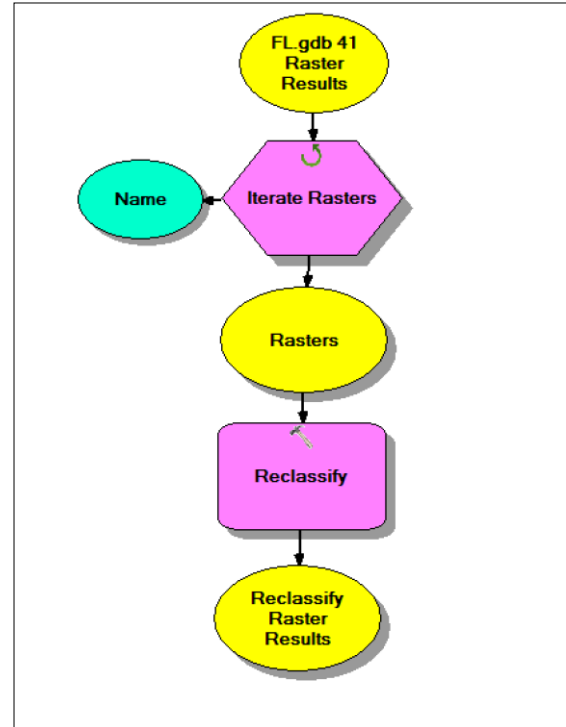


Figure 5. Reclassify model that iterated through each of the 41-raster layers for each variable and restoration goal to create the four suitability classes.

$$SI = (D_{\max} - D_{\min})$$

SI= Sensitivity Index

$D_{\max}$ = Result when the parameter is set to max values

$D_{\min}$ = Result when the parameter is set to min values

The SI produced a numeric measure of the difference between the smallest and largest values of each run per suitability class and criterion. SI measured the number of cells that changed between run #1 and run #41.

## Results and Discussion

### *The Suitability Analysis*

First, constrained areas were calculated and excluded from further analysis by retaining only land comprised of hydric soils with land cover areas that were classified as non-urban and non-water. A total of 38.6 square



miles for Bevens Watershed and 14.2 square miles for Carver Watershed remained that could potentially be selected for wetland restoration.

Three maps, one per restoration objective, were generated showing the suitability classification of the two watersheds. The total area per suitability class for each model was calculated to assist with describing the results (Table 2).

Table 2. Total area (square miles) per suitability class for each of the three model runs.

| Model             | Watershed | Suitability Analysis Classes |      |      |                    |
|-------------------|-----------|------------------------------|------|------|--------------------|
|                   |           | 1 Low Suitability            | 2    | 3    | 4 High Suitability |
| Flow Reduction    | Carver    | 1.56                         | 4.12 | 5.68 | 2.7                |
|                   | Bevens    | 3.09                         | 10   | 17.4 | 8.11               |
| Water Quality     | Carver    | 1.28                         | 2.56 | 5.54 | 4.69               |
|                   | Bevens    | 4.63                         | 7.72 | 10.4 | 16.2               |
| Wetland Proximity | Carver    | 1.7                          | 3.12 | 6.53 | 2.98               |
|                   | Bevens    | 2.7                          | 6.56 | 15.4 | 13.5               |

### Flood Reduction Model

For the flood reduction model, a total area of 2.7 square miles was identified as most suitable for wetland restoration within the Carver Creek Watershed. Starting in the southern part of the watershed, the high suitability class areas were mainly found at the headwaters of small tributaries, where slopes are gentle and land was not forested (Figure 6).

When moving upstream towards the headwaters of Carver Creek Watershed, a concentration of high suitability class areas were found around Lake Patterson, on the western border of the watershed. Two of the characteristics that made this area highly suitable for wetland restoration were the mostly agriculture land use and the high saturation index values.

Figure 7 depicts the distribution of the suitability classes across land cover types. Areas classified as lower suitability (Class 1 representing the lowest) were generally distributed within forested areas or

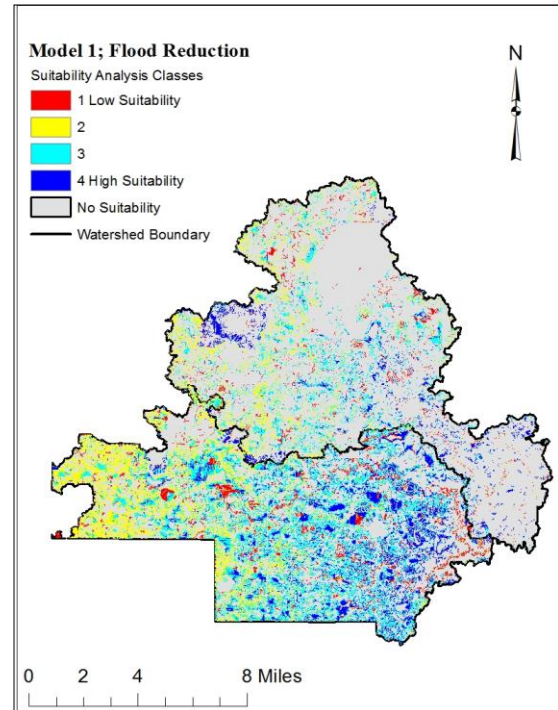


Figure 6. Model 1: Flood Reduction Model suitability map.

in locations far from a waterbody.

Bevens Creek Watershed had 8.11 square miles of land in the highest suitability class for wetland restoration, mostly found in the downstream area of the watershed. These areas are characterized by agricultural land and high saturation index values. The northwest section of the Bevens Creek Watershed, where distance to streams or lakes is greatest, was almost exclusively considered lower suitability.

### Water Quality Model

Figure 8 represents the spatial distribution of the suitability classes for the watersheds according to the water quality model. The Carver Creek Watershed had 4.69 square miles and Bevens Creek Watershed had 16.21 square miles classified as most suitable, when the main restoration objective was water quality.

The most suitable locations were near the impaired water bodies within both



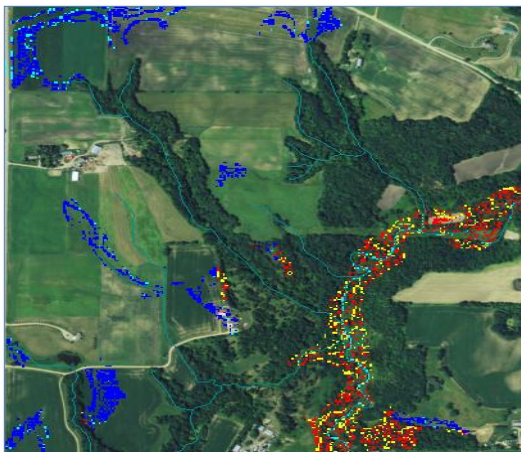


Figure 7. Example of suitability class distribution within different land uses.

of the watersheds, and where land cover was not forest. The Carver Creek watershed has 8 impaired lakes and multiple polluted stream segments distributed throughout the watershed. The Bevens Creek Watershed only contained one polluted lake, and the majority of impaired streams are located in the downstream area of the watershed.

### Wetland Ecosystem Improvement

When the main goal was to improve wetland ecosystems, a total of 2.98 square miles for the Carver Creek Watershed and 13.51 square miles for the Bevens Creek Watershed were classified with highest suitability for restoration. Figure 9 represents how the suitability classes were spatially distributed between the two watersheds.

The highly suitable locations in the Carver Creek Watershed were distributed throughout the entire watershed, with two areas of concentration, one near the border with the Bevens Creek Watershed and a second area on the western part of the watershed surrounding Lake Patterson. The most suitable locations were distributed surrounding current wetlands in both watersheds. Even though wetlands are distributed throughout the study area, the

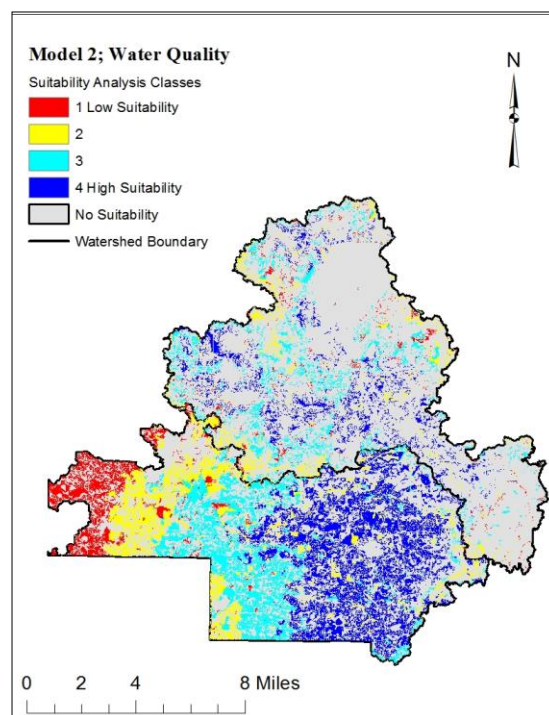


Figure 8. Model 2: Water Quality Model suitability map.

most suitable classes (dark blue on Figure 8) were found almost exclusively in those areas with the highest values of flow length (in close proximity to a water source, lake or river).

### *The Sensitivity Analysis*

The SA resulted in 41 model variations per variable. Graphs that represent how the distribution of the area within the four suitability classes (number of cells per suitability class) changed through the 41 trials were created (Appendix B). The SA also resulted in a sensitive index calculation for each suitability class for each variable in each model. A table summarizing the results was calculated for each model, representing the total area (in square miles) that changed between the first and the last run within each individual class and each variable.

### Model 1 - Flood Reduction Goal

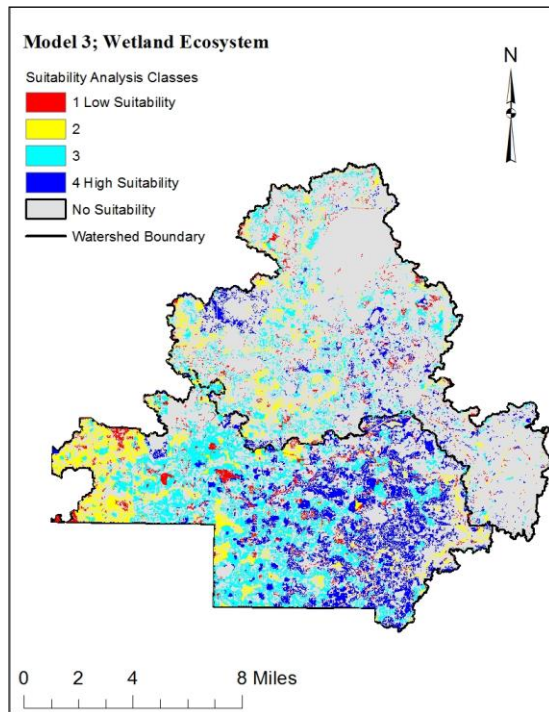


Figure 9. Model 3: Wetland Ecosystem Improvement Model suitability map.

The saturation index criterion was the most sensitive of all criteria in the flood reduction model (Table 3). The greatest changes occurred in class 4 (high suitability) and 3 (medium high suitability), where class 3 consistently decreased from run 1 to 41 and class 4 increased (Appendix B).

The second most sensitive criterion was land use. Proximity to streams of order 1 was the least sensitive to the simulation run variations

Table 3. Sensitive index results table for the Flood Reduction Model.

|                   | Flood Reduction Model- SI Results (Square Miles) |            |             |                  |                           |
|-------------------|--|------------|-------------|------------------|---------------------------|
|                   | Low suitability                                  | Low-Medium | Medium-High | High suitability | Total square miles change |
| Flow length       | 0.07   | 0.13       | 1.98        | 2.17             | 4.35                      |
| Land Use          | 0.64   | 1.01       | 3.47        | 3.84             | 8.96                      |
| Saturation Index  | 0.11   | 0.62       | 4.17        | 4.69             | 9.59                      |
| Stream Order 1    | 0.28   | 0.21       | 0.93        | 1.00             | 2.42                      |
| Wetland Proximity | 0.20   | 0.10       | 1.48        | 1.55             | 3.32                      |
| Impaired Waters   | 0.08   | 0.05       | 1.26        | 1.32             | 2.69                      |

Figure 10 illustrates how the location of the suitability classes changed when the saturation index variable was adjusted. To show the most dramatic contrast between resulting maps, the suitability maps depicted are from simulation run #1, where a -20% change was applied to the weight of the criterion, and simulation run #41, where a +20% change was applied. Most of the areas that started in run #1 classified within the high suitability class changed to medium-high suitability class by the end of the simulation. A small number of cells were identified as high suitability throughout the 41 simulation runs.

The saturation index criterion was the most sensitive of all; small changes had dramatic impact on the suitability classes. Most of the watershed's topography is flat or almost flat. High saturation index values were restricted to areas with the highest slopes. These areas can be identified on the map as those constantly classified as high suitability throughout the 41 runs.

When comparing runs #1 and #41 for the proximity to streams of order 1, no significant changes in the spatial distribution of the suitability class 4 (high suitability) occurred. This indicates modifying weights of the proximity to stream order 1 criterion had low influence over the results when flood reduction was the main restoration goal.

## Model 2 - Water Quality Goal

Flow length was the most sensitive criterion when water quality was the main goal for restoring wetlands (Table 4). The second most sensitive criterion was land use. The graphs in Appendix B.2 show how all four suitability classes changed as the simulation runs occurred, with the most dramatic changes in classes 3 and 4. Figure 11 represents the resulting maps from simulation runs #1 and #41 for the flow

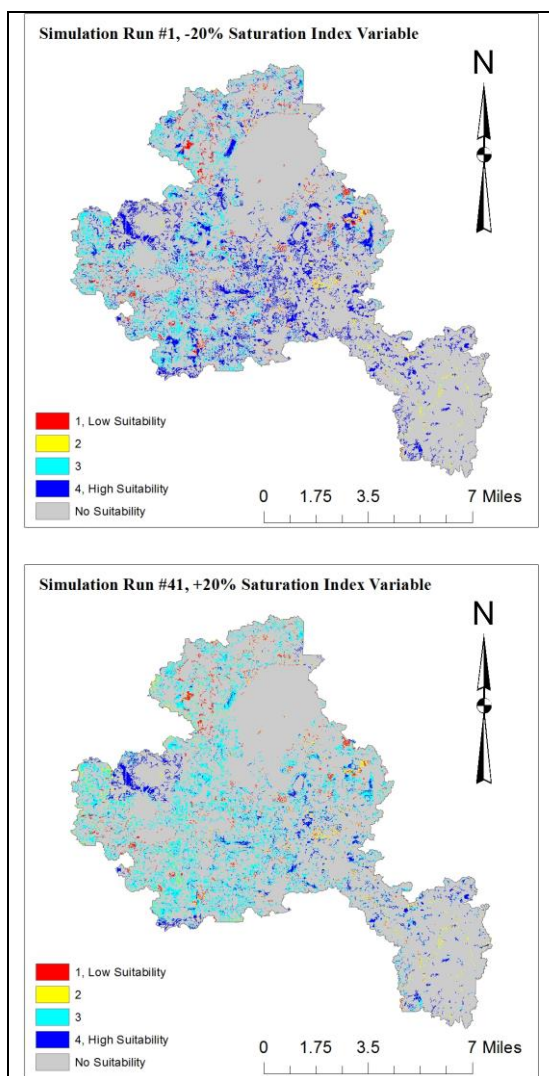


Figure 10. Sensitivity Analysis example: Flood Reduction Model, land use variable.

variable. The location of the suitability classes was the same between run #1 and run #41; the difference was not a change in general location but rather a change in the extent of the suitability classes, especially between class 3 (medium high suitability) and class 4 (high suitability).

The variable with the smallest sensitive index value was wetland proximity. Each of the suitability classes experienced small changes during the 41 simulation runs (Appendix B.2). When comparing run #1 and #41 in the most stable of all the variables, wetland proximity, there were no

noticeable changes in the location of the suitability classes; only small shifts in the total area of the classes occurred.

When water quality was the priority, flow length was the most influential criterion; variation of its weight had great consequence on the area occupied by the high suitability class.

### Model 3 - Wetland Ecosystem Improvement

The sensitive index results in Table 5 show that the flow length variable was the most sensitive criterion in the wetland ecosystem improvement model. The graphs in Appendix B.3 illustrate the variability of the four suitability classes, and how the number of cells changed from the first simulation run to the last run.

Table 4. Sensitive index result table for the Water Quality Model.

|                   | Water Quality Model- SI Results (Square Miles) |            |             |                  |         |
|-------------------|--|------------|-------------|------------------|---------|
|                   | Low suitability                                | Low-Medium | Medium-High | High suitability | Average |
| Flow length       | 0.55   | 1.07       | 1.45        | 1.97             | 5.03    |
| Land Use          | 0.12   | 0.39       | 1.51        | 2.02             | 4.04    |
| Saturation Index  | 0.02   | 0.10       | 0.48        | 0.61             | 1.22    |
| Stream Order 1    | 0.20   | 0.12       | 0.19        | 0.51             | 1.02    |
| Wetland Proximity | 0.05   | 0.03       | 0.09        | 0.17             | 0.34    |
| Impaired Waters   | 0.60   | 0.95       | 0.73        | 0.38             | 2.66    |

Proximity to impaired waters was the criterion with the smallest sensitive index. Its four suitability classes changed little between simulation runs. Analyzing the spatial distribution of the suitability classes for the flow length.

Table 5. Sensitive index result table for the Wetland Ecosystem Improvement Model.

|                   | Wetland Proximity Model- SI Results (Square Miles) |            |             |                  |                           |
|-------------------|--|------------|-------------|------------------|---------------------------|
|                   | Low suitability                                    | Low-Medium | Medium-High | High suitability | Total square miles change |
| Flow length       | 0.50   | 1.95       | 1.19        | 1.26             | 4.91                      |
| Land Use          | 0.45   | 1.93       | 1.21        | 1.17             | 4.76                      |
| Saturation Index  | 0.06   | 0.26       | 0.04        | 0.29             | 0.66                      |
| Stream Order 1    | 0.12   | 0.08       | 0.14        | 0.05             | 0.39                      |
| Wetland Proximity | 0.05   | 0.59       | 0.06        | 0.60             | 1.30                      |
| Impaired Waters   | 0.01   | 0.07       | 0.03        | 0.10             | 0.21                      |



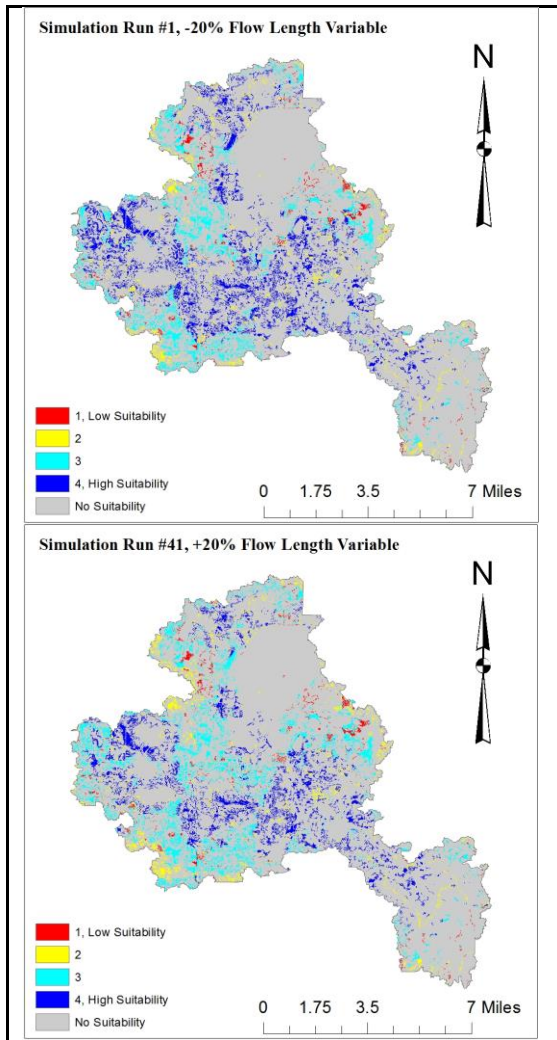


Figure 11. Sensitivity Analysis example: Water Quality Model, flow length variable.

criterion (Figure 12), the most suitable areas decreased from run #1 to #41, but the general location of the suitable areas was the same.

### *Comparing the Three Models*

There was variability in the size of the area classified as the most suitable when the variables were weighted differently for each of the three models. When water quality was the main objective, the two watersheds had the most area in the highest suitability class. For this model, the highest weight was assigned to the distance to

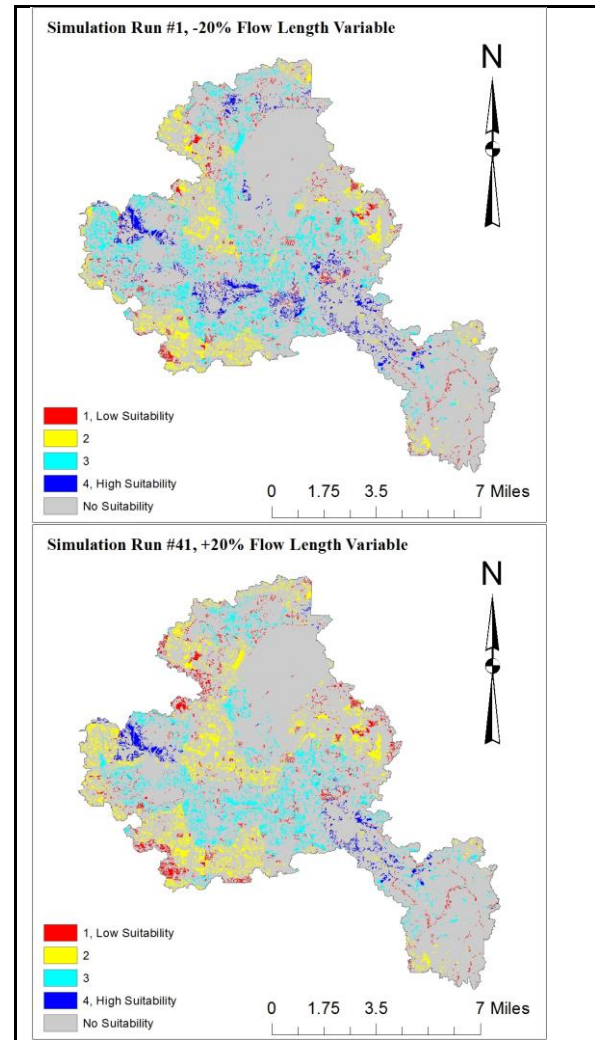


Figure 12. Sensitivity Analysis example: Wetland Ecosystem Improvement Model, flow length variable.

impaired water criteria. Two areas to highlight are (1) the northwest portion of the Carver Creek Watershed boundary and (2) the lowest part of Bevens Creek Watershed. Both areas maintained high concentrations of high suitability areas among the three models.

The suitability classes were highly influenced by land use (always the second most variable criterion in the sensitive index), which was divided into two classes: forested and non-forested. For future research, it would be interesting to analyze the MLCSS layer with a different approach

and, for example, create more than two classes, or even consider land cover not as a criterion but rather as a constraint.

Also, this research focused on analyzing 6 variables, and the only difference between the models was the weight assigned to each of them. Other criterion not included in this analysis may be equal to or even more influential for a specific restoration goal and results may be shifted in a different direction if other variables were included. It would be interesting to include an economic impact criterion to measure the potential economic benefit of a wetland restoration in a specific area.

## Conclusion

This paper identified the most suitable locations for wetland restoration by applying a multi-variable criteria evaluation within three different restoration goal models. Each of the models analyzed the same variables; the difference was in the importance weight assigned to each of the criterion. Three maps were obtained as a result of this procedure, and variation in the area and spatial distribution of the most suitable location for wetland restoration was observed. Within the two studied watersheds, a total of 10.8 square miles were classified as most suitable when the main goal was flood reduction, 20.9 square miles when targeting a water quality improvement goal, and 16.5 square miles when the model goal was to improve wetland connectivity. Regardless of the model, two areas were constantly identified as most suitable, one located at the headwaters of Carver Creek Watershed and the other in the downstream portion of Bevens Creek Watershed.

Finally, following the AHP methodology, a sensitivity analysis was developed using a combination of ArcGIS Model Builder and Python scripts. For each

criterion 41 maps were created as a result of 1% changes to the weight of the selected variable, and a Sensitivity Index was calculated based on the changes in the number of cells for each suitability class. This sensitivity analysis methodology not only analyzed the sensitivity of the criteria, but also evaluated the changes in spatial distribution of suitability.

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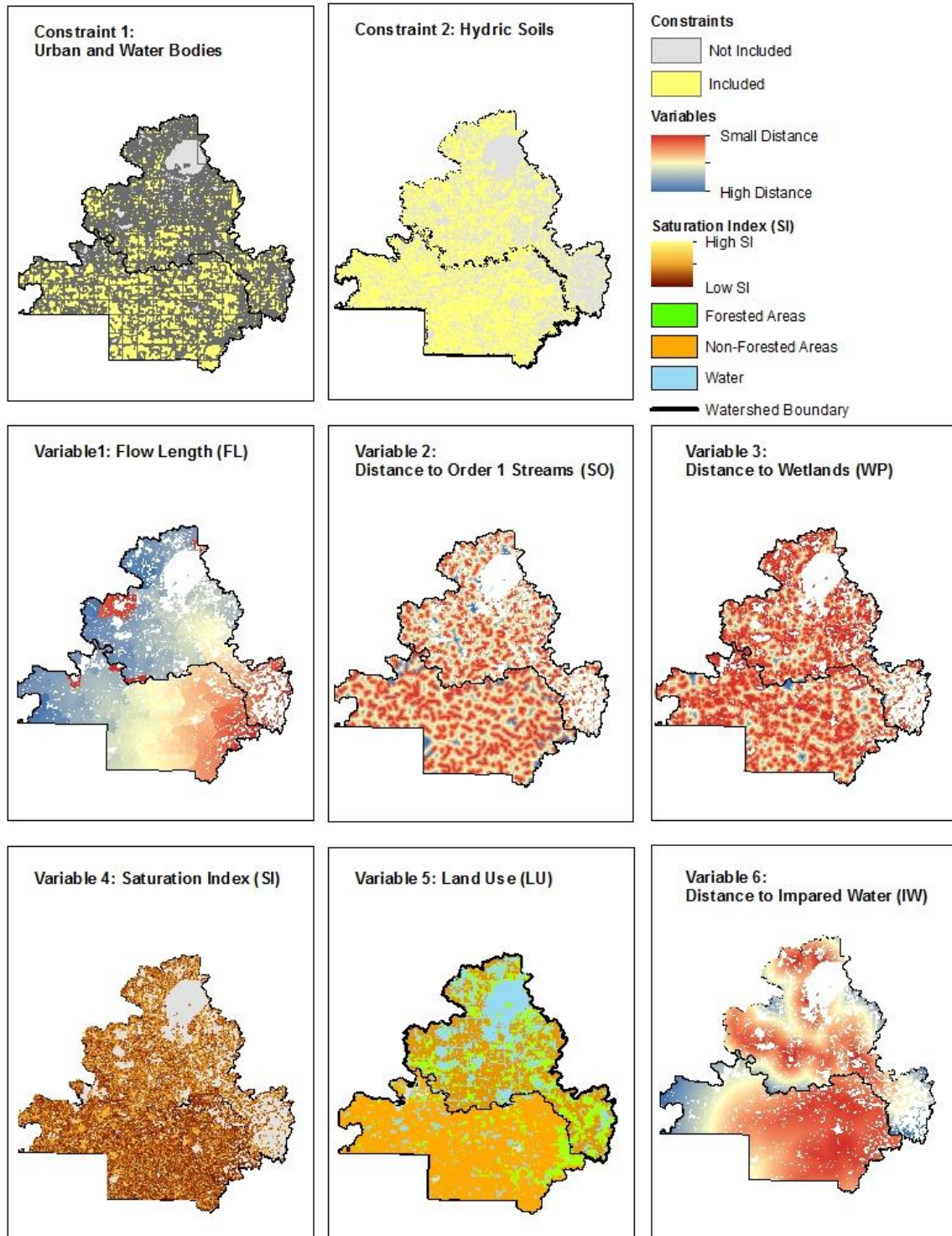
Last, but not less important, thanks to John and Ines for their unconditional love and support.

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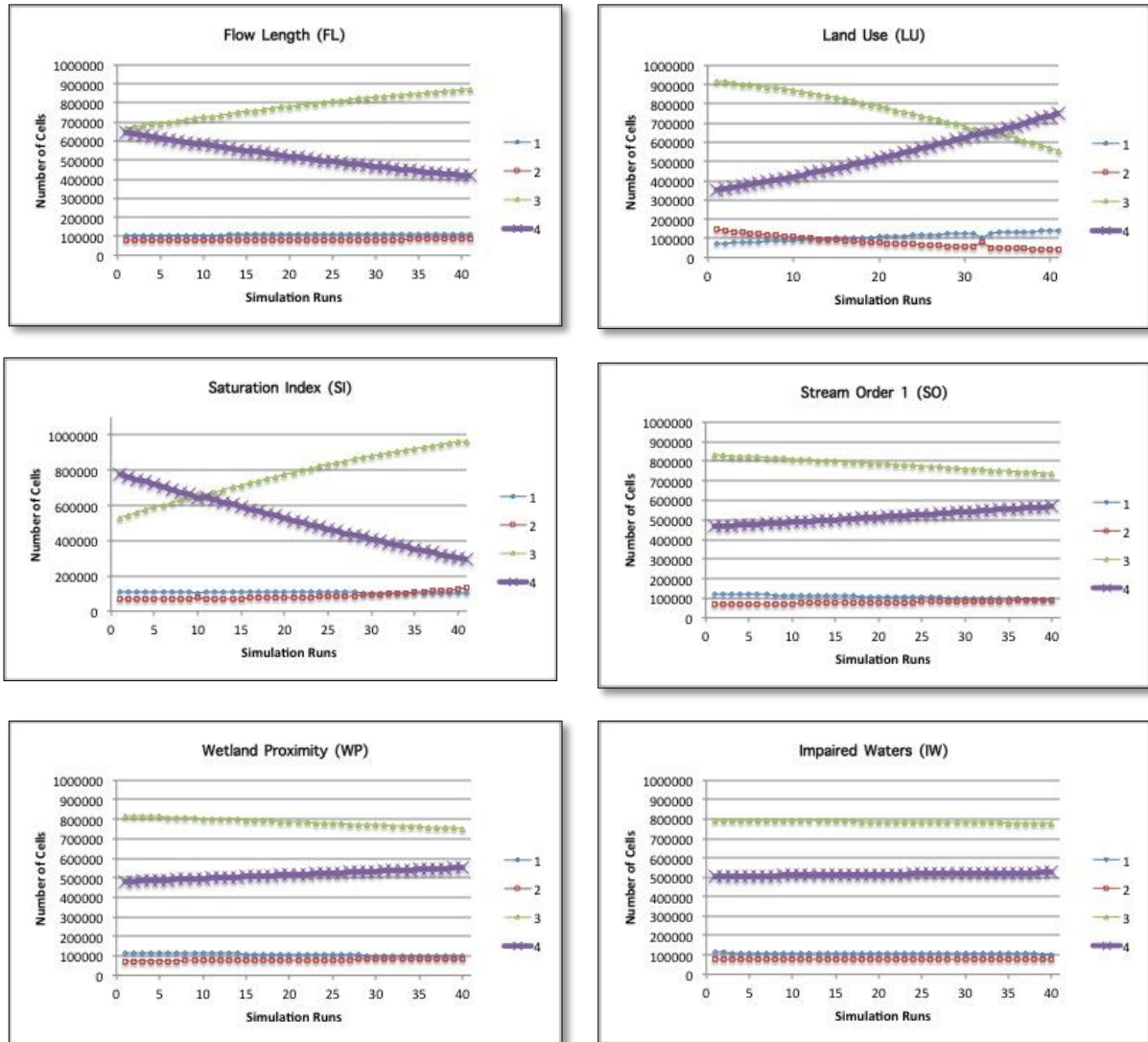
Appendix A. Constraints and Studied Variables.



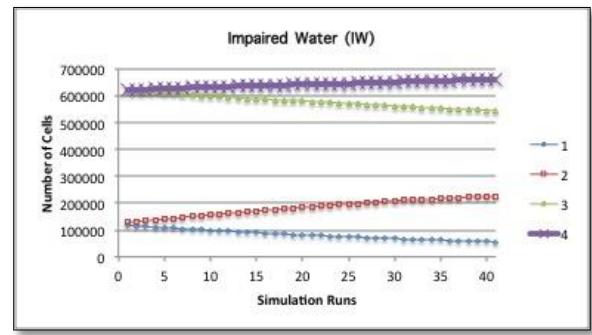
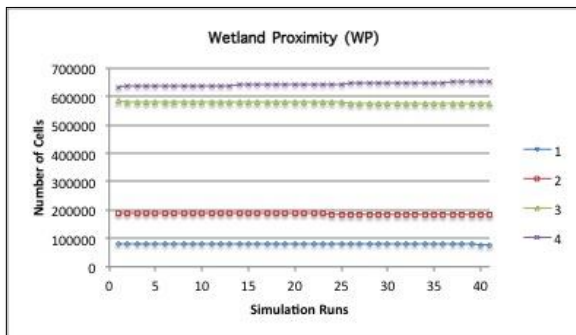
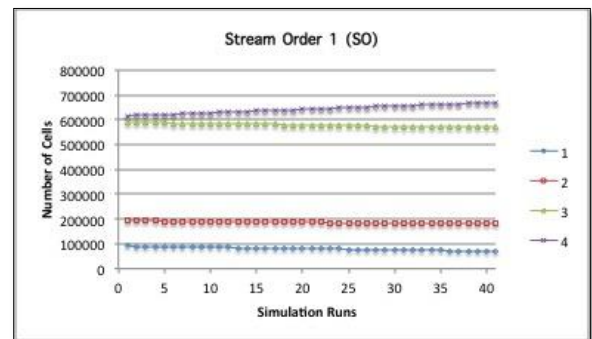
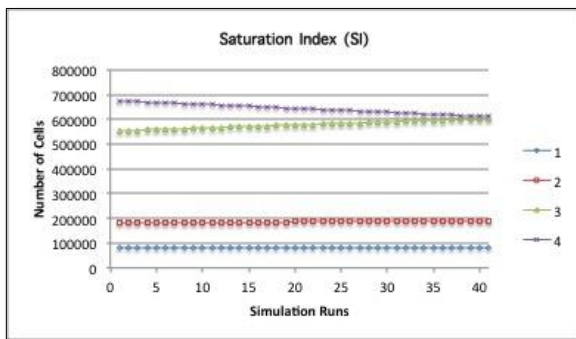
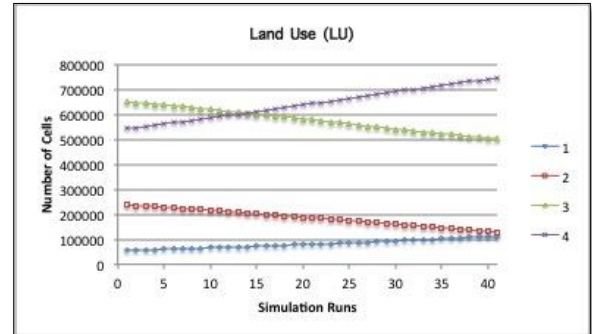
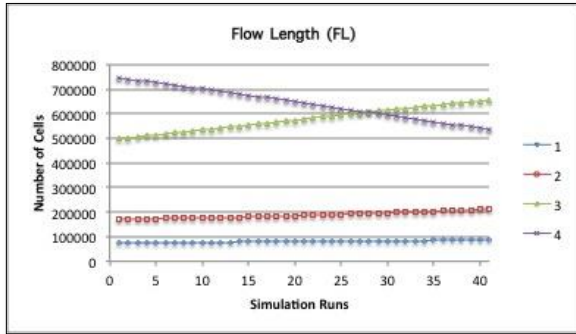


## Appendix B. Sensitivity Analysis Results.

B.1. Flood Reduction Model Graphs (Number of raster cells per suitability class 1-4 (1 = Low Suitability, 4 = High Suitability)).



B.2. Improved Water Quality Model Graphs (Number of raster cells per suitability class 1-4 (1 = Low Suitability, 4 = High Suitability)).



B.3. Wetland Continuity and Improved Ecosystems Model Graphs (Number of raster cells per suitability class 1-4 (1 = Low Suitability, 4 = High Suitability)).

