THESIS

QUANTIFYING THE RELATIONSHIP BETWEEN IRRIGATION ACTIVITIES AND WETLANDS IN A NORTHERN COLORADO WATERSHED: ASSESSING THIS ADDED VALUE OF IRRIGATION

Submitted by

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ABSTRACT

QUANTIFYING THE RELATIONSHIP BETWEEN IRRIGATION ACTIVITIES AND WETLANDS IN A NORTHERN COLORADO WATERSHED: ASSESSING THIS ADDED VALUE OF IRRIGATION

The construction over the past 130 years of an extensive canal system throughout Colorado has allowed for the spread of irrigated agriculture further and further from the water source. Irrigation activities and associated return flows serve multiple benefits to the surrounding ecosystem health and function, specifically the creation and maintenance of wetlands that would otherwise not exist. This research aims to quantify the relationship between cropland irrigation and down gradient "incidental" wetlands, to allow for the valuation of ecosystem services provided by water in agriculture. Non-linear and multiple-linear regression analyses were used in combination to explain the variability in the size of "incidental" wetlands in a northern Colorado watershed, in response to irrigation application and infrastructure within the contributing areas of each wetland. The explanatory variables included amount of area under flood and sprinkler irrigation, irrigation conveyance structures, and controls for heterogeneities in the landscape, including runoff potential and shallow groundwater flow potential. The analyses were performed using aggregated landscape properties at various distances from the edge of the wetlands, from 50 m to 500 m, in an attempt to identify a spatial area of influence for irrigation activities in the study area. Further analyses included evaluating the impact of changing irrigation scenarios on the size of "incidental" wetlands. The simulated scenarios included increasing application efficiency by converting all flood irrigated lands to sprinkler irrigation; and increasing conveyance efficiency by lining all existing canals. Research findings include (i) the most significant explanatory variables, irrespective of distance from wetland, were amount of flood-irrigated lands and length of irrigation conveyance structures, (ii) irrigation activities within 200 m of a wetland explained the greatest variability in wetland size ($R^2_{adj} = 0.50$), (iii) increasing runoff potential in the contributing areas, represented by area-weighted curve number values, increased the impact of irrigation variables on the size of “incidental” wetlands, and (iv) increasing irrigation efficiencies in the study area consistently resulted in decreasing total wetland area. Furthermore, an ecosystem benefits transfer model was utilized to estimate the dollar value of the ecosystem services provided by the “incidental” wetlands in the study area. At an estimated value of $5,647/ha, the ability to evaluate the impact of changing irrigation practices on nearby wetlands may influence the decision process of both landowners and water planners.

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1 INTRODUCTION

The success of agricultural production depends greatly on an adequate, dependable water supply. In arid environments, such as the western U.S., it is unlikely that crop water demands will be met by direct precipitation. For Colorado farmers, this has meant securing water for their crops from one of the many headwater rivers draining snow melt from the Rocky Mountains. This irrigation water must then be conveyed through a series of canal systems en route to field application.

The construction over the last 130 years of an extensive conveyance network throughout Colorado has allowed for the spread of irrigated agriculture further and further away from the water source. This has resulted in a unique environmental interdependence on irrigation, and its associated return flows, with the surrounding ecosystem health and function, specifically the creation and maintenance of wetlands that would otherwise not exist (Lovvorn and Hart 2004; Peck and Lovvorn 2001). In many cases, these "incidental" wetlands have come to function comparably to naturally occurring ones, providing ecosystem benefits including wildlife habitat, water filtration, flow control, recreational opportunities and even carbon sequestration.

Continued rapid population growth throughout much of the West, however, is increasing the competition between agriculture and municipal and industrial (M&I) uses for the limited available water resources. The population in Colorado is projected to nearly double by 2050; resulting in an estimated increase in M&I water demand of between 600,000 and 1 million acre-feet/year (CWCB 2010). Water supply managers anticipate closing the gap between municipal supplies and demand through new water supply development, conservation, reuse, and the reallocation of water from agriculture to urban uses.

When assessing water management options, planners must strike a balance between socioeconomic and environmental considerations. With the extremely high cost of developing new water supplies and the uncertainty of the approval process, planners are likely to rely heavily on other in-basin management options. While conservation and reuse are valuable tools, the amount of "new" water that can be generated is limited based on current technology, social acceptability and strict guidelines within the Doctrine of Prior Appropriation. Combining this with the fact that more than 85% of Colorado's freshwater supplies are currently used in agriculture sheds light as to why many planners are likely to turn to agricultural water transfers to fill a large portion of their anticipated supply gap (CWCB 2010). These probable transfers are expected to result in irrigated acreage losses in nearly every river basin in Colorado. The South Platte River Basin alone is projected to lose as many as 108,000 irrigated hectares (267,000 acres) by 2050, more than 32% of the lands under irrigation in 2005 (CWCB 2010).

In recent years, agricultural water transfers have received considerable attention due to the economic and social impacts associated with the permanent dry-up of irrigable lands. While the direct and indirect production impacts associated with permanent transfers have been well documented (Howe and Goemans 2003; Howe, Lazo, and Weber 1990; Young 1983), the potential loss of other public benefits of agriculture have received considerably less attention. These benefits include access to locally produced foods and open space, as well as the many ecosystem services provided by irrigation dependent, or "incidental" wetlands. With no current means of internalizing the public goods aspect of these environmental benefits, market transactions do not reflect the true value of water in agriculture.

The goal of this study is to evaluate the ecosystem benefits of incidental wetlands in the Boxelder Creek Watershed in Northern Colorado. This evaluation necessitates an increased understanding of the relationship between irrigated agriculture and the ecosystems it creates and/or maintains, allowing for a more complete valuation of all aspects of transferring water out of agriculture, not just those associated with changes in production.

The main objectives of this study include (i) developing a GIS and statistical methodology to quantify the relationship between the size of incidental wetlands and surrounding irrigated agriculture, while controlling for geo-spatial characteristics of the contributing areas, (ii) quantifying the dollar value of these wetlands utilizing an ecosystem benefits transfer model created by Loomis and Richardson (2008), and (iii) investigating the impact to incidental wetlands of increasing both conveyance and on-farm application efficiencies.

In order to make informed decisions, and to fully understand their repercussions, planners and land owners must have an indication of all of the effects of changing irrigation practices, including permanent water transfers, water leasing arrangements, and increased efficiency practices. Non-market valuation techniques, together with a better understanding of the physical relationship between irrigation and incidental wetlands can provide a method to gage the previously unaccounted for environmental benefits of irrigated agriculture. As water marketing becomes more common in Colorado, being able to identify the irrigated lands which provide the most ecosystem services can help mitigate the environmental impacts associated with increased water conservation or the reallocation of agricultural water.

2 STUDY AREA

Boxelder Creek, a tributary of the Cache la Poudre River, drains 739 km^2 (285 mi^2) along the Front Range of northern Colorado and a small portion of southeastern Wyoming. The creek originates in Wyoming and flows southeast through Larimer County, including the towns of Wellington and Fort Collins, before reaching its confluence with the Cache la Poudre River along the eastern edge of Fort Collins. The watershed contains a mix of land use types, consisting predominantly of irrigated agriculture, open grasslands, and natural shrub land (NLCD 2001). Evergreen forests can also be found in the upper reaches of the watershed, where the elevation reaches 2,250 m (7,380 ft), compared to 1,500 m (4,920 ft) in the lower reaches. It is important to note that most of the topographic variability occurs in the northern half of the watershed, where there is little to no irrigation. Areas dominated by irrigated agriculture in the southern half of the watershed have very little topographic variability.

The Boxelder Creek watershed was chosen for this study due, in part, to the complex network of irrigation infrastructure which both traverses the watershed, taking irrigation water to fields in Weld County, as well as serves the watershed, irrigating nearly 11,320 hectares (28,000 acres) within the basin. With more than 215 km of irrigation canals crisscrossing the southern half of the basin, it is not surprising that Boxelder Creek is drained and recharged by these canals several times before reaching its confluence with the Cache la Poudre River. This intertwining of natural habitat with man-made structures has created a very unique environmental interdependence on irrigation and its associated return flows with the ecology of the area. It is this very interdependence, created over the preceding 130 years of irrigation in the region that led us to choose this watershed for quantifying the relationship between irrigation and wetlands.

Figure 2-1A depicts the basin, including irrigated fields, the main stem of Boxelder Creek and the many irrigation canals which intersect the area.

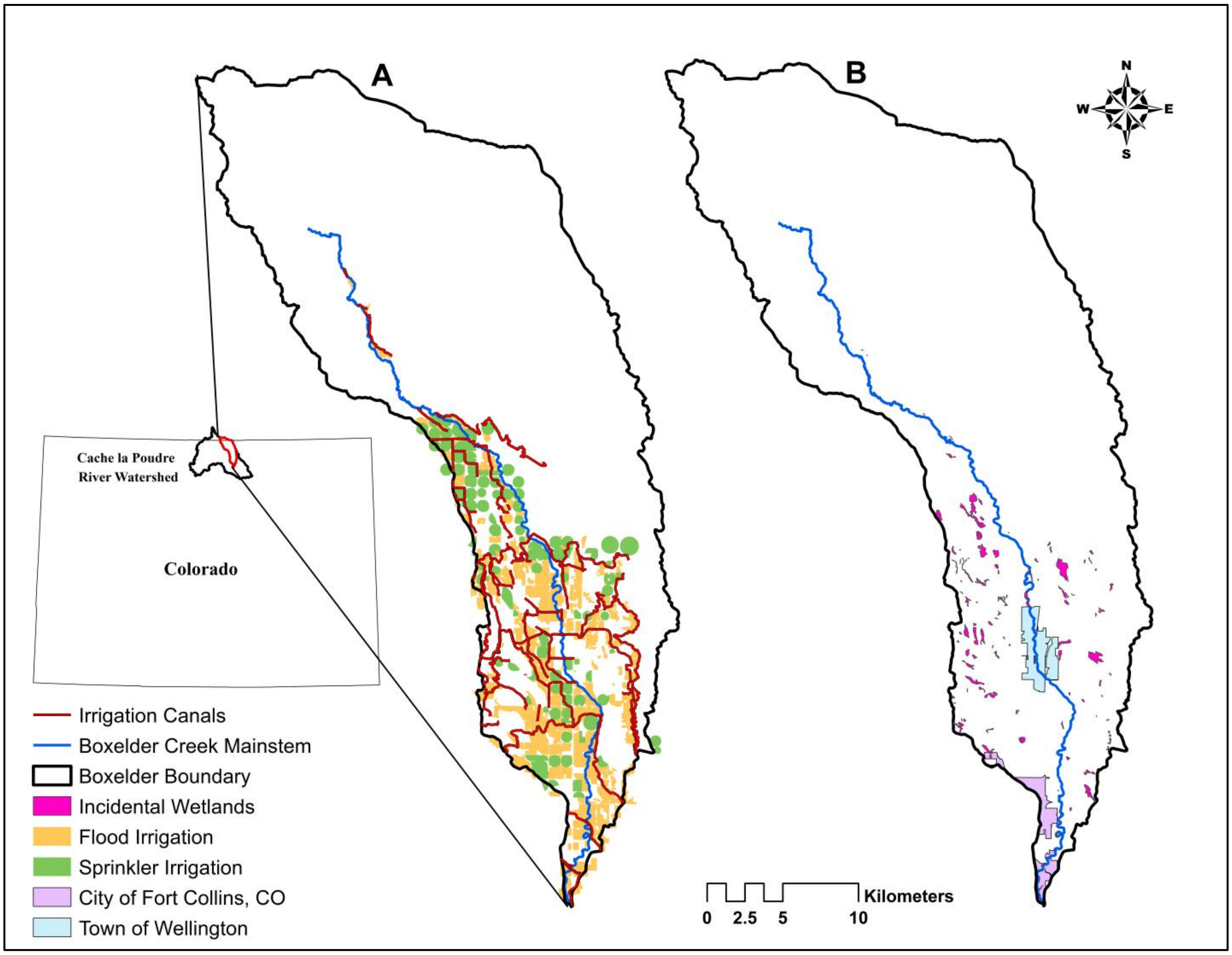

Figure 2-1 - Location of Boxelder Creek wateshed within the Cache la Poudre River watershed and Colorado. (A) Mainstem of Boxelder Creek, flood and sprinkler irrigated lands, and the complex irrigation network through the basin. (B) Map of incidental, or irrigation dependent wetlands, also depicting Wellington and Fort Collins, for reference.

3 METHODS

3.1 Geographic Analyses

3.1.1 Wetlands

A current digital map of jurisdictional wetlands does not exist for the state of Colorado. As such, the first part of this research entailed generating a detailed map of wetlands for the Boxelder Creek Watershed. This map was created by starting with a digital riparian and wetland mapping layer produced by the Colorado Department of Wildlife (CDOW, 2005). As defined by the CDOW, "riparian areas are those plant communities adjacent to and affected by surface or ground water of perennial or ephemeral water bodies…" Furthermore, the CDOW states their riparian mapping is "inclusive of jurisdictional wetland areas."

As a result of the all-inclusive nature of the CDOW wetlands mapping, the dataset includes not only the incidental wetlands of interest to this study, but also the many managed reservoirs in the basin, most of the irrigation canals, all irrigated fields in the basin, as well as the riparian wetlands (often bare stream bottom) along Boxelder Creek and its many small tributaries. Alterations to this data layer included removing those areas which were created intentionally, not as a byproduct of conveyance or application. This resulted in eliminating all irrigated fields, irrigation canals, and managed reservoirs. The data layer was further verified against National Wetlands Inventory maps, dating from the late 1970s, which were digitized for this project by the Colorado Natural Heritage Program, and recent aerial imagery of the region, obtained from Esri, which is updated continuously. Further areas excluded from this study included wetlands depicting bare, natural stream channel and adjacent riparian areas to Boxelder Creek and its tributaries. Again, the intention of this study is to quantify a relationship between irrigation and wetlands, not natural stream flow and wetlands. At this point, the resulting layer was further altered by merging wetland polygons which were adjacent to each other, or which, by visual inspection, were clearly hydraulically connected. This pared down wetland dataset was then merged with a digital layer of wetlands for southeast Wyoming (USFWS, 1998).

3.1.2 Drainage Areas

In order to quantify the relationship between the geospatial factors under consideration and the size of wetlands, the scope of influence was first limited to the contributing area for each wetland. These areas were defined using the Watershed Tool within the Hydrology Toolbox function in ArcGIS 9.3.2. Input data included a 10-meter Digital Elevation Model (DEM) from the U.S. Geological Survey (USGS) National Elevation Dataset and the wetlands layer created for this study.

The only alteration made to this process was in regards to the creation of the pour points, or watershed outlets. In typical watershed delineations, the user defines one pour point for each watershed by digitizing a point along the flow path of the Stream Raster dataset, which is created as a step in the delineation process. The watershed is then delineated based on the terrain provided, and includes all areas which drain to the defined point on the stream. For this study, however, we are interested in defining the area draining into a wetland, which often has more than one inlet point and is typically not located directly on the stream network. This necessitated a modification of the standard process.

To define the area draining into a wetland, multiple pour points were generated for each wetland. A 10 m buffer was created around each wetland and converted to a wetland boundary raster. A buffer width of 10 m was chosen based on the resolution of the input DEM. The wetland boundary raster was then combined with the Flow Accumulation Raster, created from a previous step in the delineation process. The pour points for each wetland were defined by then selecting only those cells with a flow accumulation value greater than zero. This resulted in a pour point grid with multiple pour points for each wetland. A batch watershed delineation function was executed using this pour point grid, creating multiple drainage areas for each wetland. These drainage areas were then merged for each wetland, resulting in one contributing area for each.

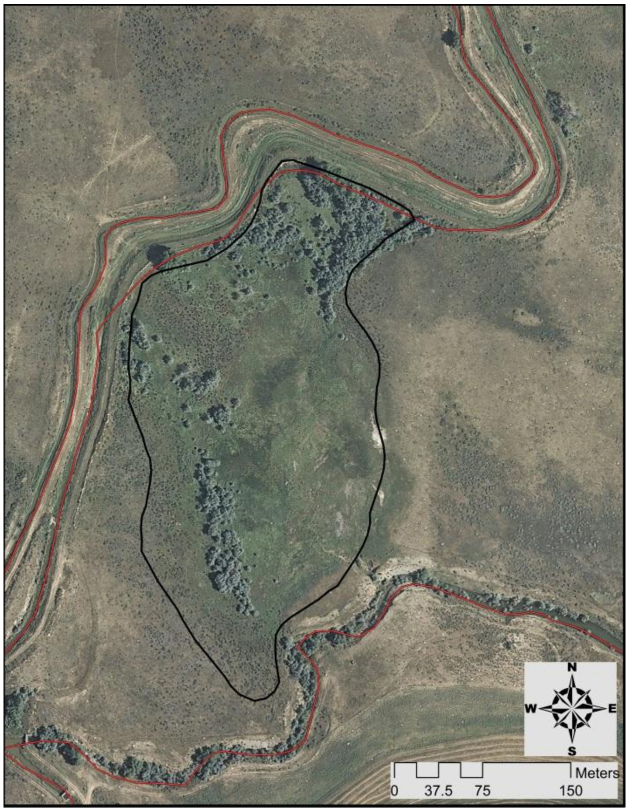

Figure 3-1 - A nearly 7 ha wetland, outlined in black, in the Boxelder Creek watershed. The irrigation canals passing adjacent to the wetland appear to be its main water source.

The delineated contributing areas were then used in conjunction with current aerial imagery to further limit the wetlands dataset to only those wetlands attributable to irrigation infrastructure or application. The imagery was visually inspected, to isolate wetlands adjacent to, or otherwise hydraulically connected to irrigated fields or irrigation canals. The defined contributing areas were used to limit the spatial scope of influence to those areas with topographical drainage impact. If surface runoff or shallow groundwater flow was evident within the contributing area through altered vegetation patterns from irrigation infrastructure or application to a wetland, then it was attributed to irrigation (Figure 3-1). Finally, wetland polygons which were adjacent to one another, or were hydraulically connected through visual inspection of aerial imagery, were combined as one wetland.

3.1.3 Geo-Spatial Characteristics

The geo-spatial characteristics anticipated to impact wetland size included length of irrigation canal, area under irrigation, surface runoff potential, and shallow groundwater flow potential. Heeding Tobler's first law of geography (Tobler 1970) which states "everything is related to everything else, but near things are more related than distant things," these characteristics were assessed at increasing distances from the edge of wetlands. ArcGIS 9.3.2 was utilized to define multiple overlapping distance buffers for each wetland (0-50 m, 0-100 m, 0-150 m, 0-200 m, 0-250 m, 0-300 m, 0-350 m and 0-500 m). The distance buffers were intersected with the delineated contributing areas, generating eight areas of influence (Figure 3-2). This method allowed us to investigate the concept of an optimum area of influence, or a distance from the wetland within which the geo-spatial characteristics explain the greatest variability in wetland size (King et al. 2005, Houlahan and Findlay 2004).

Considering the limited seasonal precipitation in this region, it was hypothesized that the volume of water available to sustain a wetland is a function of the amount water applied for irrigation and seepage from irrigation canals. Amount of water applied is a direct function of amount of land under irrigation and amount of seepage is a direct function of the length of canal used to convey water through the system. Therefore, the irrigation related geo-spatial characteristics included as explanatory variables for this analysis are length of irrigation canals, amount of flood irrigated lands, and amount of sprinkler irrigated lands. The irrigated lands were divided between irrigation types, anticipating that each would have differing effects on wetland size. It was anticipated that the inefficiencies of flood irrigation would inherently lead to more water available for losses to runoff and shallow groundwater percolation.

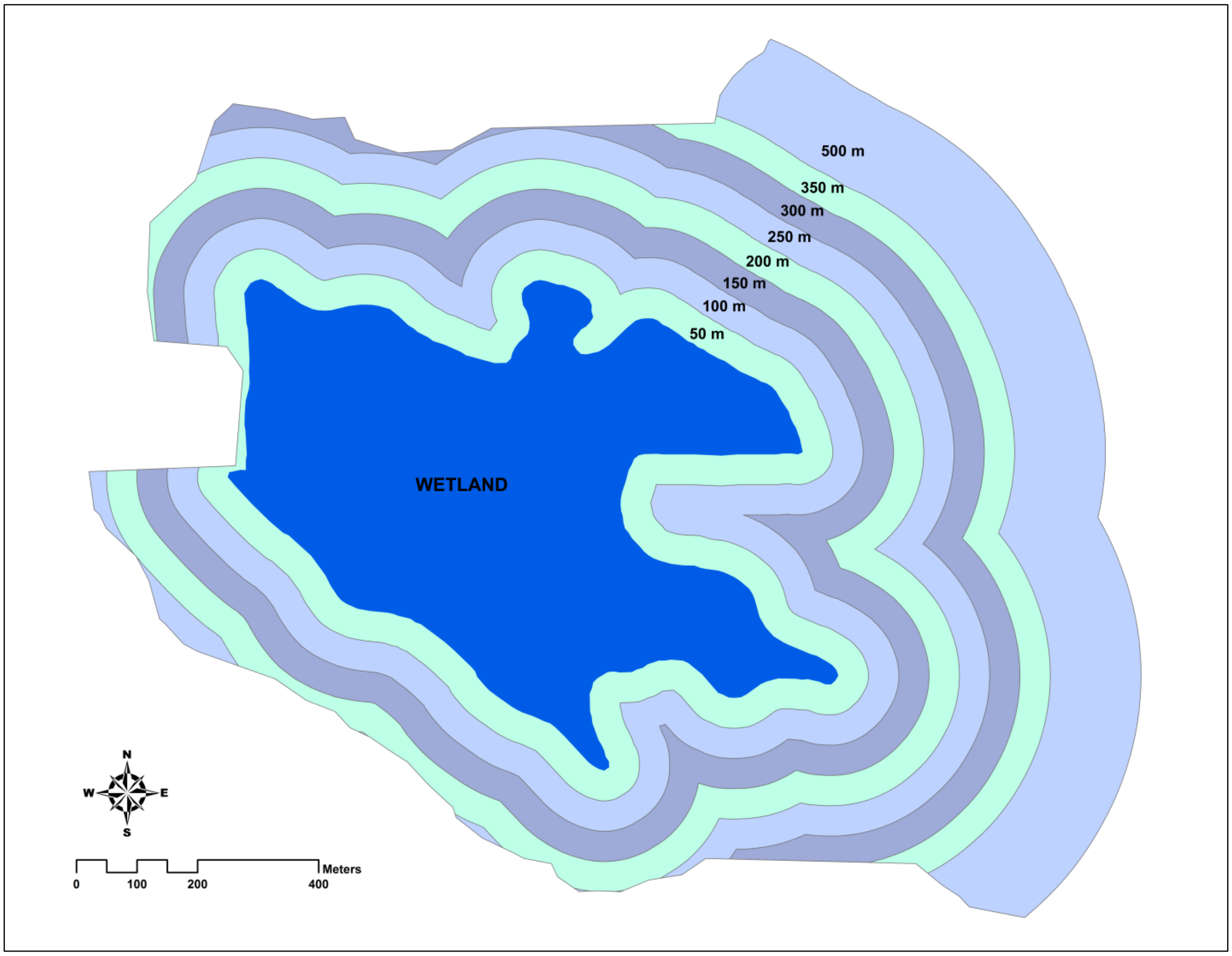

Figure 3-2 –Wetland with eight overlapping areas of influence. Distance buffers were intersected with the wetland contributing area to create the areas of influence.

Literature values for canal conveyance in this region estimate losses to seepage at roughly 15% of total diversions (LRE 2010). Understanding that canal seepage is a direct function of canal length, combined with soil permeability and canal flows, length of irrigation canals is included as an explanatory variable in the analysis, serving as a proxy for canal seepage and referred to as canal-seepage contributing length. This proxy was chosen based on the data being readily available and the assumption that permeability for earth lined canals is fairly constant across the study area. All irrigation related data was obtained through the Colorado Decision Support System (CDSS), in the form of digital GIS layers for the South Platte River Basin. The digital layers were clipped to the Boxelder Creek watershed and then further compiled based on the eight areas of influence described above.

Other geo-spatial factors considered for this analysis include runoff potential and shallow groundwater flow potential. As previously stated, it was anticipated that the majority of water available to maintain wetlands in the region is from irrigation application and conveyance. Including a variable for runoff potential allowed us to capture the impact of varying land uses across the basin, as well as the heterogeneity of soil types in the area.

The Natural Resources Conservation Service (NRCS) runoff curve number (CN) was used to characterize the runoff potential in the areas of influence. The runoff curve number is a parameter of the NRCS method for runoff prediction from rainfall excess (NRCS 2004). It is an empirically based parameter which takes into account the hydrologic soil group (HSG) of a site specific soil type, as well as land use at that site. To assign curve numbers, soils data from the USDA NRCS Soil Survey Geographic (SSURGO) Database were merged in ArcGIS with National Land Cover Dataset (NLCD 2001) from the USDA NRCS National Cartography and Geospatial Center, creating a soil type-land cover type combination for each grid cell in the NLCD. Each soil type-land cover type combination was assigned a curve number based on the best match between the NLCD land use descriptions and the NRCS curve number land use descriptions. The curve number values were then area weighted for each of the eight areas of influence defined above. Table 3-1 shows how the NLCD land use descriptions are related to the NRCS curve number land use descriptions, as well as the associated curve number values according to HSG .

Table 3-1 - Land use descriptions from 2001 NLCD with corresponding NRCS land cover descriptions and curve number values for each hydrologic soil group (NRCS 2004).

Land Use/Land Cover Descriptions		Hydrologic Soil Group			
NLCD	NRCS	A	B	C	D
Developed, Open Space	Open Space - Fair Condition	49	69	79	84
Developed, Low Intensity	Residential District - 1/3 acre lot size	57	72	81	86
Developed, Medium Intensity	Residential District - 1/8 acre lot size	77	85	90	92
Developed, High Intensity	Commercial and business district	89	92	94	95
Barren Land (Rock/Sand/Clay)	Bare Soil	77	86	91	94
Deciduous Forest	Woods - Fair condition	36	60	73	79
Evergreen Forest	Woods - Fair condition	36	60	73	79
Mixed Forest	Woods - Fair condition	36	60	73	79
Shrub/Scrub	Brush - Fair condition	35	56	70	77
Grassland/Herbaceous	Meadow	30	58	71	78
Pasture/Hay	Pasture - Fair condition	49	69	79	84
Cultivated Crops	Row crops - Average of treatment and conditions	66.5	75.5	82.5	85.5

Due to most of the wetlands identified as irrigation dependent being located outside of the Boxelder Creek alluvial plain, we expected groundwater interactions to play a limited role in the maintenance of these wetlands. However, in order to investigate this theory, and in an attempt to capture the possible effect of shallow interflow from canal seepage, saturated hydraulic conductivity (K_{sat}) was included as an explanatory variable in the analysis. K_{sat} is a measure of the ease of water movement through saturated soil, and is a function of soil type, including pore size, grain size distribution and soil texture. For this study, K_{sat} values were obtained from the SSURGO Database. For each soil polygon in the data layer, the K_{sat} values were depth weighted and then area weighted within each of the eight areas of influence.

The geo-spatial characteristics data were then extracted and compiled for each of the eight areas of influence. Table 3-2 summarizes the geo-spatial characteristics considered for the analyses.

Table 3-2 - Summary of geo-spatial characteristics considered for the analyses, including source of data and description of modifications.

Variable	Geo-spatial Characteristic	Data Source	Modifications
Flood Irrigation	Number of hectares under flood irrigation	CDSS GIS Data - Division 1 Irrigated Lands 2005	Data layer intersected with each defined area of influence
Sprinkler Irrigation	Number of hectares under sprinkler irrigation	CDSS GIS Data - Division 1 Irrigated Lands 2005	Data layer intersected with each defined area of influence
Canal-Seepage Contributing Length	Meters of irrigation canals	CDSS GIS Data - Division 1 Structures	Data layer intersected with each defined area of influence
K_{sat}	Saturated Hydraulic Conductivity, used as proxy for shallow groundwater flow potential	USDA NRCS Soil Survey Geographic Database (SSURGO)	K_{sat} values were depth weighted for each soil polygon, then area weighted within defined areas of influence
CN	NRCS curve number, used to estimate runoff potential	USDA NRCS National Cartography & Geospatial Center Land Use Data	Land use layer intersected with SSURGO layer (soils data) and CN assigned for each intersection (NEH 2004). CN area weighted within defined areas of influence

3.2 Statistical Analyses

3.2.1 Multiple-Linear Regression Analysis

Regression analysis can be used as a tool to explore the predictors, or explanatory variables, that have the most control or influence on the dependent variable. It can also be used as a predictive tool, used to estimate the value of the dependent variable to changing conditions of the predictor variables (Kutner et al. 2004). For this study, multiple-linear regression was employed for both purposes; exploring the relationship between the size of wetlands and irrigation in the area, as well as estimating the possible change in wetlands due to changing irrigation practices.

Prior to the regression analysis, an initial data exploration, involving scatterplots of the data, was performed in order to verify linearity between wetland size and the explanatory variables. This resulted in using a natural log transformation of wetland size for the data to best meet the linearity assumption. Inspection of the scatterplots also provided an opportunity for verification that the explanatory variables were uncorrelated. The Variance Inflation Factor (VIF) was used to further verify there were no multicollinearity issues between explanatory variables within the eight defined areas of influence (Kutner et al. 2004).

A step-wise multiple-linear regression analysis was then performed for each area of influence. In forward selection step-wise regression, the model is first assessed testing each individual predictor variable and progresses with the addition of one predictor variable at a time, culminating in the full-model, which includes each of the predictor variables. This allows for comparison of the goodness-of-fit of each model created for each possible combination of predictor variables, as well as confirmation of the most significant variables, and determination of how well these variables explain the variation in wetland size within the areas of influence. The general equation for the MLR model is:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_p X_{ip} + \varepsilon_i$$

where i corresponds to the number of observations of the dependent variable and p is the number of explanatory variables used in the model.

To determine the goodness of fit of for each of the 32 models fitted for each of the buffered distances, three main criteria were analyzed; (i) R^2_{adj}, the adjusted coefficient of multiple determination, (ii) *AIC*, Akaike's information criterion, and (iii) *SBC*, Schwarz' Bayesian criterion (Kutner et al. 2004). Although R^2 is the typical measure cited for goodness of fit of a regression model, using this criterion alone can result in over-fitting of the model since the R^2 value will increase as more variables are added to the model. For this reason R^2_{adj}, *AIC*, and *SBC* were calculated. All three criteria “penalize” the statistic with each additional predictor variable, therefore favoring more parsimonious models. As with R^2, $\mathrm{R}^2_{\mathrm{adj}}$ will have a value between zero and one with the best fit model having the highest $\mathrm{R}^2_{\mathrm{adj}}$. For the *AIC* and *SBC* criteria, the smaller the value, the better the fit.

As with the initial data exploration, a residuals analysis allowed further confirmation of the appropriateness of the linear regression models. This analysis included confirming the residuals were uncorrelated with the individual explanatory variables, as well as confirming a normal distribution of the residuals.

In an attempt to control for unobserved heterogeneity that was likely correlated with both CN and $\mathrm{K}_{\mathrm{sat}}$, further regression analyses were performed on the data set. Two separate analyses were completed; including (i) sorting the data by CN values and (ii) sorting the data by $\mathrm{K}_{\mathrm{sat}}$ values. The data were then grouped into three classes for each sorting; the lowest third of CN or $\mathrm{K}_{\mathrm{sat}}$, the middle third, and so on. Multiple-linear regression analysis was performed on each ranked set of data, for each area of influence. For these analyses, the explanatory variables included area under flood irrigation, area under sprinkler irrigation and canal-seepage contributing length.

3.2.2 Classification and Regression Tree Analysis

To supplement the findings of the MLR analysis, a classification and regression tree regression (CART) analysis was also performed. This method of regression allows quick visualization of the predictor variables which affect wetland size the most for each of the eight areas of influence.

The CART analysis was executed in conjunction with bootstrap aggregation (Breiman et al. 1984; Breiman 1996) for each of the eight areas of influence. All CART analyses were performed in MATLAB R2012a.

CART is a conceptually simple method of non-parametric regression, which does not require the extensive list of assumptions needed for other regression models. There is no assumed distribution of the underlying data, nor any assumptions made regarding the residuals. In this non-linear method, the data space is partitioned into smaller regions, where the interactions between predictors are more manageable. The sub-divisions are partitioned over and over until the data within the smallest space can be represented by the simplest model. In order to assure the stability of the tree regression model, bootstrap aggregation was used to grow multiple regression trees based on 1000 independently drawn bootstrap replicas of the input data. The importance of each predictor was then averaged over the 1000 replicas.

3.3 Scenario Analysis – Changing Irrigation Practices

To investigate the possible impacts of changing irrigation practices in the Boxelder Creek watershed on the size of incidental wetlands, two scenarios were considered; (i) all flood irrigated lands were converted to sprinkler irrigation (increased application efficiency, and (ii) all canals in the watershed were lined (increased conveyance efficiency). Both scenarios were explored using the regression models fitted for the CN sorted datasets for each area of influence. The simulations entailed altering the input data to reflect the respective scenario changes; (i) adding all areas of flood irrigation to sprinkler irrigation and (ii) eliminating all canals from the input data. Each model was run separately, providing the mean response of the system to the designated scenario changes.

3.4 Benefits Transfer Analysis

As previously stated, economic impact studies on agriculture-to-urban water transfers have historically only considered the direct and indirect financial impacts associated with the resulting change in agricultural production. In order to see the entire economic picture associated with the value of water in agriculture, the value provided by irrigation dependent wetlands must be considered. To allow for this, the ecosystem services value of incidental wetlands in the Boxelder Creek watershed was estimated utilizing a benefits transfer economic model created by Loomis and Richardson (2008). The benefits transfer method of economic valuation refers to transferring available information from studies completed in another location to the context and location of the study at hand (Loomis 1992).

The model, based on a meta-analysis by Borisova-Kidder (2006), evaluates nine possible ecosystem services provided by wetlands, while controlling for measures that account for geographic location within the United States, overall scarcity of wetlands in the region, type of wetlands being evaluated, and local household income. The services are valued based on user willingness-to-pay, which is defined as "the maximum amount the user would pay to continue to have access to a given natural resource" (Loomis and Richardson 2008). The ecosystem services quantified by the model are outlined and defined in Table 3-3.

For this study, the ecosystem services included for valuation are (i) water quality, (ii) bird watching, (iii) amenity, and (iv) habitat. The other five ecosystem services available in the model were not used in this study for various reasons, including the assumption that fishing and bird hunting are not viable activities in the majority of the study wetlands, given their typically small size, shallow depth, and variable location. Also, with the majority of the irrigation dependent wetlands located outside of the assumed flood plain, their ability to serve as flood prevention areas and their capability to augment water supplies is limited. It should be noted that including only a conservative subset of the available parameters when determining the ecosystem services value of the irrigation dependent wetlands results in a lower-bound of this estimated value.

The model, which is designed as an interactive spreadsheet, allows the user to select the services to be valued and enter the total number of wetland acres. For this study, it was assumed that all identified wetlands were providing the same ecosystems services. The benefits transfer model was used first to ascertain the ecosystem services value of the entire set of irrigation dependent wetlands. Further valuation included investigating the extent to which a reduction in wetland size affects the ecosystem service value it provides. The range of changes in wetland size was obtained from the scenario analyses, based on changes resulting in increased on-farm and conveyance efficiencies.

Table 3-3 - Definitions of the ecosystem services valued by the Loomis and Richardson (2008) ecosystem benefits transfer model.

Ecosystem service	Definition of service provided
Flood Prevention	Reduced damage due to flooding and/or stabilization of the sediment for erosion reduction
Water Quality	Reduced costs of water purification
Water Supply	Increased water quantity
Recreational Fishing	Improvements in recreational fisheries either on or off site
Commercial Fishing	Improvement in commercial fisheries either on or off site
Bird hunting	Hunting of wildlife
Bird watching	Recreational observation of wildlife
Amenity	Amenity values provided by proximity to the environment
Habitat	Nonuse appreciation of the species

4 RESULTS AND DISCUSSION

4.1 Geographic Analysis

As previously stated, the drainage areas delineated for each wetland were used in conjunction with current aerial photos to classify the wetlands based on apparent water source, specifically isolating those wetlands attributable to irrigation infrastructure or application. The result of the classification was a subset of 100 irrigation dependent wetlands (Figure 2-1) totaling more than 598 hectares (1,478 acres). The delineated contributing areas, combined with the distance buffers, allowed for the extraction and compilation of the geo-spatial characteristics for each defined area of influence for each wetland. Table 4-1 presents summary statistics, by area of influence, on the total number of irrigated hectares (both flood and sprinkler) and total meters of canal, as well as the range of K_{sat} and CN values within each area. It can be seen from this table that as the area of influence increases, total number of irrigated hectares and total meters of canal increases as well. The ranges for the values of K_{sat} and CN decrease as the area over which they are averaged increases.

Table 4-1 - Summary of geo-spatial characteristics by area of influence.

Area of Influence	Total Flood Irrigation (ha)	Total Sprinkler Irrigation (ha)	Total Length of Canals (m)	Range of K_{sat}	Range of CN
50 m	180	25.5	13,213	1.8 - 314.7	15.3 - 82.8
100 m	316	64.8	34,398	1.72 - 257.6	23.6 - 81.4
150 m	445	112	41,147	1.74 - 190.5	21.2 - 81.6
200 m	565	162	46,826	1.98 - 180.7	18.6 - 81.6
250 m	676	208	50,781	2.48 - 185	19.7 - 81.2
300 m	783	248	53,830	2.79 - 194.7	22.5 - 80.9
350 m	886	284	56,468	2.95 - 192.4	26.6 - 80.7
500 m	1,164	380	65,520	3.13 - 167.2	24.3 - 79.8

4.2 Statistical Analysis

4.2.1 Multiple-Linear Regression Analysis (MLR)

Results of the initial data exploration, as well as the residuals analysis are found in Appendix A. This includes draftsman's plots of the natural log of wetland size and the five explanatory variables for each area of influence, as well as scatterplots and histograms of the residuals. These results support the initial assumptions necessary for multiple-linear regression, including the residuals being uncorrelated with the explanatory variables and the residuals being normally distributed.

Before assessing the results from the step-wise regression, the full model was evaluated for each area of influence. The various goodness of fit criteria were analyzed, showing the 200 m area of as explaining the most variability in wetland size (Figure 4-1).

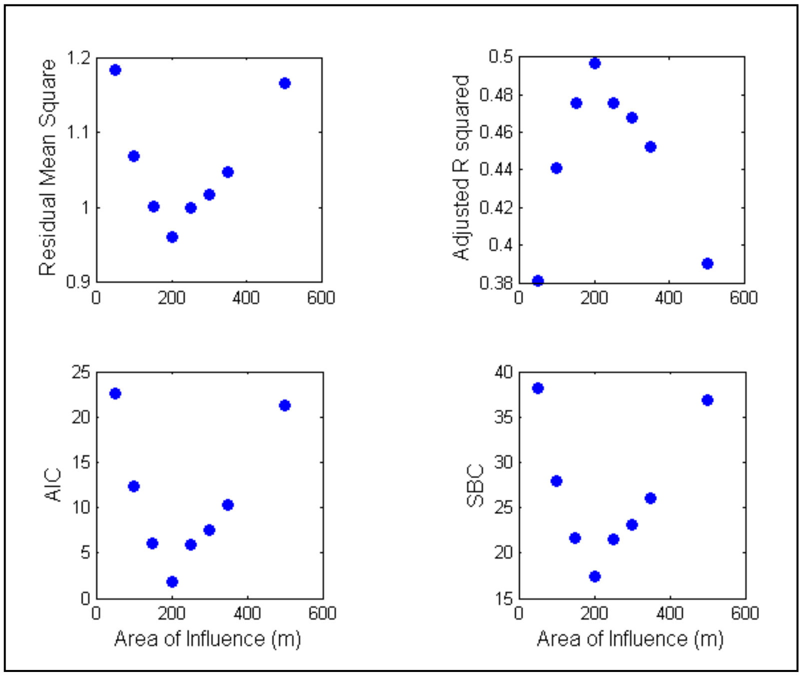

Figure 4-1 - Goodness of fit criteria for the optimum full models for each area of influence, showing the 200 m area of influence as the overall optimum model.

The step-wise multiple-linear regression analysis consistently showed canal-seepage contributing length and area under flood irrigation to be significant ($p < 0.001$) explanatory variables for each area of influence, regardless of the number of variables included in the model.

Table 4-2 depicts the full model generated for each area of influence, as well as a reduced model, comprised of only the variables showing as most significant ($p < 0.05$ or $p < 0.001$). Of the 32 models generated by the step-wise regression for each area of influence, the reduced models depicted in Table 4-2 are the optimal. This is to be expected, considering the models are comprised of only the significant variables for each area of influence.

The significance of canals and flood irrigation in the relationship to wetland size is not surprising, considering these are the main sources of water in the region. It is surprising however, that CN is negatively correlated to wetland size. This negative correlation was constant across all areas of influence, regardless of the number of variables included in the model. This implies that as CN increases, wetland size is decreasing. Seeing as a higher CN results in greater runoff potential, this is counter-intuitive to what we expect in the physical environment. In view of the fact that checks for multicollinearity in the explanatory variables were performed prior to analysis, and given there are no radical changes in coefficients with the addition or removal of this or other variables, it is anticipated that this negative coefficient indicates that CN is highly correlated with a variable not considered in the analysis, which is in turn negatively correlated with wetland size.

Table 4-2 – The optimum full and reduced multiple-linear regression models generated for each area of influence.

Area of Influence	Flood Irrigation	Sprinkler Irrigation	Canal-Seepage Contributing Length	K_{sat}	CN	Constant	R^2_{adj}	AIC	SBC
50 m	0.1424***	0.1099	0.00091***	3.65E-04	-0.0267***	1.8423***	0.381	22.58	38.21
	0.1418***		0.00097***		-0.0251***	1.7767***	0.388	19.63	30.05
100 m	0.103***	0.0534	0.00085***	-3.85E-05	-0.0328***	2.1917***	0.441	12.37	28.01
	0.1034***		0.00092***		-0.0306***	2.0621***	0.447	9.37	19.79
150 m	0.0815***	0.0412	0.00084***	-1.27E-04	-0.0367***	2.3868***	0.476	6.02	21.65
	0.0815***		0.00091***		-0.0335***	2.1965***	0.478	3.61	14.03
200 m	0.0665***	0.0371	0.00081***	-1.70E-04	-0.0403***	2.5929***	0.497	1.85	17.48
	0.0661***		0.00089***		-0.0361***	2.3478***	0.495	0.40	10.82
250 m	0.0561***	0.0326*	0.00078***	-6.93E-06	-0.0383***	2.4463***	0.476	5.86	21.50
	0.0551***		0.00086***		-0.0337***	2.1873***	0.471	4.94	15.36
300 m	0.0474***	0.0301*	0.00078***	9.04E-05	-0.0386***	2.4608***	0.468	7.50	23.14
	0.0461***		0.00086***		-0.0335***	2.1755**	0.460	7.13	17.55
350 m	0.0402***	0.0277*	0.00077***	2.14E-05	-0.038***	2.4217***	0.452	10.36	25.99
	0.0386***		0.00085***		-0.0324**	2.1097**	0.442	10.30	20.73
500 m	0.0268***	0.0227*	0.00073***	8.81E-04	-0.0299**	1.9027**	0.390	21.20	36.83
	0.025***		0.0008***		-0.0243**	1.6176**	0.396	19.27	32.30

*, **, *** indicates $p < 0.1$, $p < 0.05$, $p < 0.001$, respectively

Although K_{sat} did not show as one of the dominant variables in the CART analysis, it did compete with the level of importance of CN within areas of influence less than 200 m (Figure 4-1; Appendix E). For this reason, it was surprising that K_{sat} proved to be insignificant in every model generated by the step-wise regression analysis. This result is in line, however, with the original hypothesis that groundwater interactions play a limited role in the creation and maintenance of irrigation dependent wetlands.

Considering the lack of importance of sprinkler irrigation in the CART analysis, combined with the initial assumption that it would play a lesser role than flood irrigation in the support of wetlands, it is not surprising that it also shows as insignificant or the least significant in every model generated by the step-wise regression.

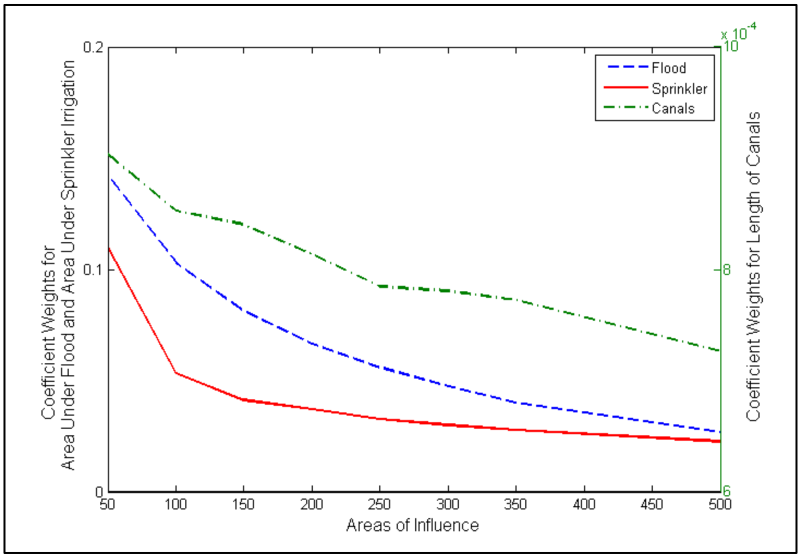

Figure 4-2 – Showing decreasing trend in coefficient weights for all three irrigation related variables as the areas of influence increase. Coefficients are for the full models.

One noticeable pattern that is consistent in both the full and reduced models is the decreasing trend in the coefficient values of the irrigation variables as the area of influence increases (Figure 4-2). Although it is the 200 m area of influence which generates models best able to explain the variation in wetland size, according to the R^2_{adj}, it is at the closest buffer widths that the variables have the greatest impact on wetland size. This trend makes sense in the physical environment; the closer an irrigation canal or irrigated field is to a wetland, the greater the impact it has on that wetland. The increasing trend in the goodness of fit of the models up to 200 m with a decreasing trend for larger areas tends to suggest there is an optimum area of influence that provides the maximum amount of water from irrigation application and infrastructure while still applying that water close enough to a wetland to explain the greatest variability.

4.2.2 Classification and Regression Tree Analysis

Results of the classification and regression tree analysis, in conjunction with bootstrap aggregation for the 200 m area of influence are shown in Figure 4-3 (results for the remaining areas of influence are found in Appendix E). For this analysis, the entire dataset was utilized and no data transformations were made. The explanatory variables included were (i) area under flood irrigation, (ii) area under sprinkler irrigation, (iii) canal-seepage contributing length, (iv) K_{sat}, and (v) CN. Although 1,000 bootstrap replicas were drawn from the eight datasets, with regression trees grown for each replica, all models seemed to stabilize after 200 grown trees, as seen in Figure 4-3A. The importance of the explanatory variables was then averaged over the 1,000 grown trees. The level of importance of each variable for the 200 m area of influence is depicted in Figure 4-3B. This analysis shows canal-seepage contributing length and area under flood irrigation to be the dominant variables across each of the eight areas of influence. Another telling result of this analysis is that for areas of influence less than 300 m from the edge of the wetlands, the variable with the least effect on wetland size is the amount of area under sprinkler irrigation. This result changes slightly for the 350 m and 500 m areas of influence, when Ksat becomes the least important explanatory variable.

Although it was anticipated that flood irrigation would have a dominant impact on the size of wetlands over sprinkler irrigation, it was not expected that sprinkler irrigation would seem to have no effect. This is presumably due to two main factors; (i) the inefficiencies of flood versus sprinkler irrigation, which allow for the loss of more water to runoff and percolation, and (ii) the dominance of flood irrigation in landscape. There are more than 2.5 times as many hectares under flood irrigation in the Boxelder basin as under sprinkler irrigation, 3,298 ha (8,150 ac) and 1,255 ha (3,101 ac), respectively.

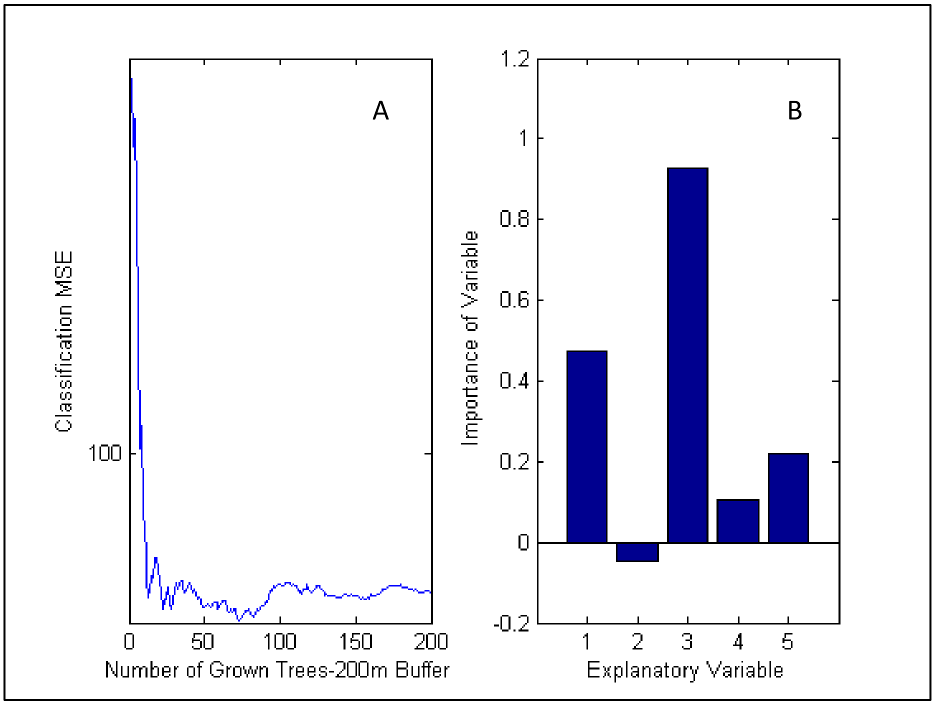

Figure 4-3 - Results of the classification and regression tree (CART) bootstrap aggregation analysis of the 200 m area of influence. Classification MSE represents the out-of-bag classification error (the number of observations not included in the replica) associated with the number of grown trees. Explanatory variables are (1) area under flood irrigation, (2) area under sprinkler irrigation, (3) canal-seepage contributing length, (4) K_{sat}, (5) CN.

The most telling result of this analysis is the stability of the level of importance of both flood irrigation and canal-seepage contributing length across all eight areas of influence (Appendix E). This is consistent with our expectations and with the results of the MLR analysis.

4.2.3 MLR Sorted on Curve Number (CN)

Anticipating that CN was having an effect that could not be deciphered from the negative weights of the coefficients in the full and reduced models, further analyses were performed. The data was sorted by increasing CN, split into three groups (lowest 1/3, middle 1/3, highest 1/3) and regressed separately. As previously stated, the explanatory variables included in this regression were area under flood irrigation, area under sprinkler irrigation and canal-seepage contributing length. Sprinkler irrigation was included in this regression with the anticipation that CN would have an impact on its effect of wetlands.

Results of this analysis showed exactly the trend one would expect in the physical environment, across nearly every area of influence. For every area of influence except 50 m, both area under flood irrigation and canal-seepage contributing length showed as significant ($p < 0.05$ or $p < .001$) regardless of CN value. For the data subsets with the highest CN values, area under sprinkler irrigation becomes significant ($p < 0.1$) across every area of influence. This makes sense, as there is a greater potential for runoff at the higher CN values. There is also an increasing trend in the coefficient weights for the significant variables as CN increases within the same area of influence. It was shown that although the coefficient weights are typically greater for the data with the highest CN values, there is still an overall decreasing trend in coefficient weights as the area of influence increases (Figure 4-4).

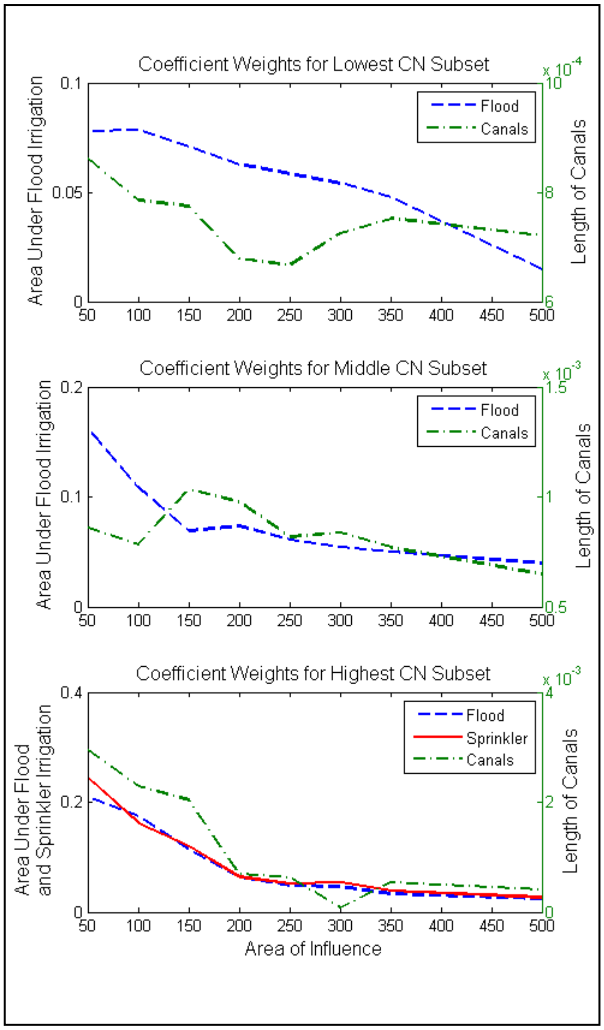

Figure 4-4 - Decreasing trends in coefficient weights for significant variables in CN sorted subsets regression models, as areas of influence increase in size.

This supports the idea that the closer the irrigation application or infrastructure is to the wetland, the greater the impact it has on wetland size. However, of note is that the coefficient weights for area under flood irrigation and area under sprinkler irrigation are very nearly the same for the highest CN subset across all areas of influence. See Appendix B for a detailed list of all models fitted to the CN ranked data

As with the results of the unsorted models from the step-wise regression, it may be the nearest areas of influence show the greatest magnitude of impact of each variable, but it is after getting to the mid-range areas of influence that the greatest variability in wetland size is explained (Figure 4-5). This pattern holds true regardless of CN value.

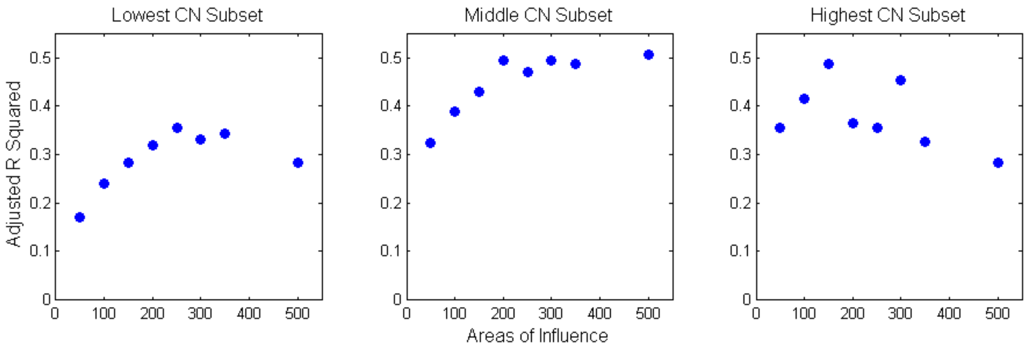

Figure 4-5 - Adjusted R squared values for CN subset fitted models using area under flood irrigation, area under sprinkler irrigation and length of canals as explanatory variables. R^2_{adj} are shown for each area of influence.

4.2.4 MLR Sorted on Saturated Hydraulic Conductivity (Ksat)

Although K_{sat} proved to be insignificant in every model created by the step-wise regression, it was surprising, considering its level of importance for areas of influence less than 200 m in the CART analysis (Figure 4-3; Appendix E). In order to further investigate the possible effects of K_{sat}, the same analysis was performed as for CN. The data was sorted by increasing K_{sat} values, split into three groups for each area of influence and regressed separately.

A pattern emerged from this analysis, as well, centering around the mid-range group of K_{sat} values. Instead of increasing across the K_{sat} groupings, from lowest to highest, the coefficient weights were highest for all three irrigation variables corresponding with the regression of the middle 1/3 of the ranked data set. This held true for every area of influence. Consistent with all other analysis, the coefficient weights are highest at the closest areas of influence and decrease as the areas of influence increase.

These results tend to suggest there may be an optimum range of K_{sat} values that are high enough to allow for the greatest amount of shallow, sub-surface flow from both canal seepage and irrigation application, but low enough to limit the amount of deep percolation. However, there were some inconclusive results, both within and across many areas of influence from the K_{sat} analysis, including negative coefficient weights when the physical environment suggests they should be positive. For this reason, combined with the consistency of the results from the CN sorted data, subsequent analysis focused only on the models generated from the CN ranked data set.

4.3 Scenario Analysis

4.3.1 Increased Application Efficiency

The models fitted using the CN sorted dataset were utilized to investigate the impact of increased on-farm application efficiencies on the size of incidental wetlands. The simulations were performed for each area of influence by altering the input dataset to reflect all areas under flood irrigation being converted to sprinkler irrigation. These simulations consistently predicted a decrease in the size of wetlands for the lowest and middle CN subsets, across every area of influence except the 500 m area of influence. There is essentially no change in wetland size when moving from flood to sprinkler irrigation for data with the highest CN values (Figure 4-6). (Graphs for remaining areas of influence are located in Appendix C).

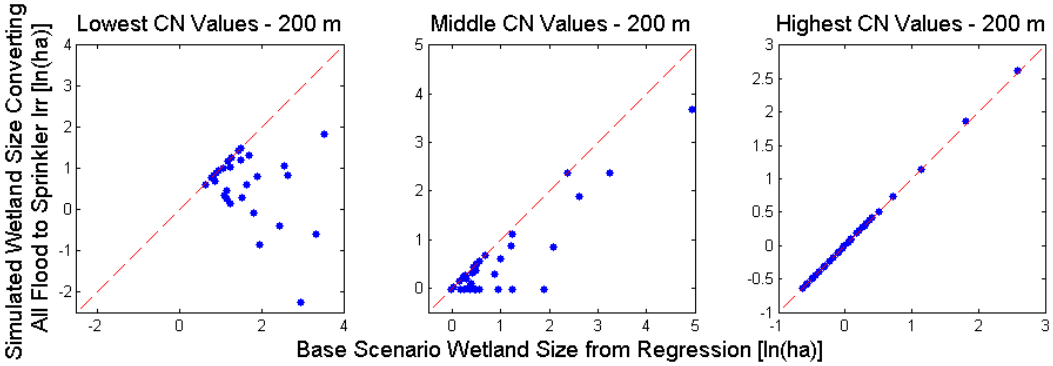

Figure 4-6 - – Scatterplot of base scenario wetland size versus simulated wetland size when converting all flood irrigated lands to sprinkler irrigation for the 200 m area of influence.

As previously noted, the coefficient weights for area under flood and area under sprinkler irrigation were virtually the same for the highest CN values, hence it was expected there would be no change in this simulation for this data subset. However, it should be noted that of the nearly 598 ha of irrigation dependent wetlands in the study area, roughly 10% fall in the highest CN category. Consequently, while there is little change in this subset across the eight areas of influence, changing from flood to sprinkler irrigation still results in a substantial decrease in total wetland area for every area of influence except the 500 m area of influence. There is an estimated loss of between 156 ha and 286 ha, depending on the area of influence in which the change is being assessed (Table 4-3). This is between 26% and 48% of the total irrigation dependent wetlands in the study area.

Table 4-3 – Base scenario total wetland areas generated by the fitted models for each CN subset and then summed for each area of influence, compared with the simulated total wetland areas for increased application efficiency scenario of converting all flood irrigation to sprinkler, run for each CN subset and summed for each area of influence.

Area of Influence	Base Scenario Total Wetlands (ha)	Simulated Total Wetlands (ha)	Change in Total Wetlands (ha)
50 m	417.0	160.6	-256.4
100 m	446.9	174.4	-272.5
150 m	460.0	195.7	-264.2
200 m	524.5	238.7	-285.9
250 m	522.9	291.6	-231.3
300 m	517.9	317.1	-200.8
350 m	504.2	347.8	-156.4
500 m	475.4	823.3	347.9

Conversely, for the 500 m area of influence, there shows to be an estimated *increase* in wetland size, resulting in a net addition of nearly 348 ha of wetlands. This is a result of the coefficient weight for area under sprinkler irrigation for the lowest CN subset of the 500 m area of influence being 10 times larger than the coefficient weight for area under flood irrigation (Appendix C). It should be noted, however, that the only variable showing as significant in this particular regression is canal-seepage contributing length. As this scenario does not make sense in the physical environment, (we would not expect to see total wetland area double due to a *decrease* in water application) the simulated result for this area of influence will not be considered for the benefits transfer analysis.

One interesting result of this scenario analysis is in the pattern of overall change in total wetland area across the areas of influence. As previously noted, the coefficient weights for the fitted models decrease as the areas increase, however the goodness of fit of the models tend to be best in the mid-range areas of influence. This pattern is depicted in Table 4-3, where there is a substantial loss of wetland area at the closest areas of influence; however the maximum loss occurs at the 200 m area of influence.

4.3.2 Increased Conveyance Efficiency

The models fitted using the CN sorted dataset were further utilized to investigate the impact of increased conveyance efficiencies on the size of incidental wetlands. The simulations were performed by altering the input dataset to reflect all irrigation canals as being lined. These simulations consistently resulted in a decrease in the size of wetlands across each area of influence, regardless of CN subset (Figure 4-7; Appendix D).

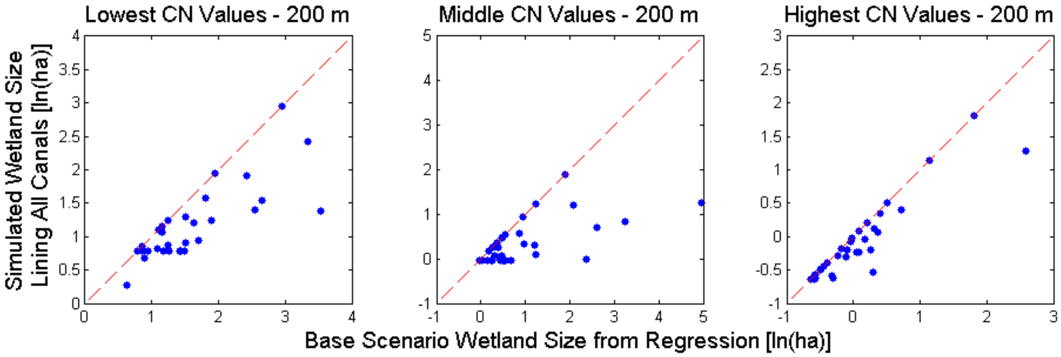

Figure 4-7 – Scatterplot of base scenario wetland size versus simulated wetland size of lining all irrigation canals for the 200 m area of influence.

For the highest CN data subsets for areas of influence greater than 200 m, there is very little impact from removing irrigation canals from the analysis (Appendix E). The coefficient weights for the canal-seepage contributing length variable for these subsets are not only insignificant in the fitted models, but are also nearly zero in value (Appendix C). This increased conveyance efficiency simulation resulted in an overall estimated total loss of wetland area of between 191 ha and 307 ha, depending on the area of influence in which the change is being assessed (Table 4-4). This is between 32% and 51% of the total irrigation dependent wetlands in the study area.

A notable result from this scenario analysis is that an increase in total canal-seepage contributing length within a defined area of influence has an increasing impact on wetland size up to the 200 m area of influence, at which point the effect of canals seems to stabilize until reaching the 500 m area of influence, where the effect diminishes (Table 4-4). Although the total length of canals within the defined areas of influence increases as the areas increase, it is only at the nearest areas of influence that we see an increasing effect. For this study area, it appears that when accounting for irrigation application, irrigation canals located more than 200 m from the edge of a wetland have little to no effect on the size of that wetland.

Table 4-4 - Base scenario total wetland areas generated by the fitted models for each CN subset and then summed for each area of influence, compared with the simulated total wetland areas for increased conveyance efficiency scenario of lining all irrigation canals, run for each CN subset and summed for each area of influence.

Area of Influence	Base Scenario Total Wetlands (ha)	Simulated Total Wetlands (ha)	Change in Total Wetlands (ha)
50 m	417.0	226.3	-190.7
100 m	446.9	216.6	-230.3
150 m	460.0	209.3	-250.7
200 m	524.5	217.7	-306.8
250 m	522.9	220.9	-302.0
300 m	517.9	214.9	-303.0
350 m	504.2	203.2	-301.0
500 m	475.4	204.1	-271.3

4.4 Benefits Transfer Analysis

The benefits transfer model utilized in this analysis was developed by Loomis and Richardson (2008), based on a meta-analysis by Borisova-Kidder (2006). The model was utilized to estimate the annual dollar value of the ecosystem services provided by the irrigation dependent wetlands in the Boxelder Creek watershed. The model was further utilized to estimate a range of value potentially lost due to decreased total wetland areas from the scenarios under consideration for this study; (i) increased application efficiency (converting all flood irrigation to sprinkler) and (ii) increased conveyance efficiency (lining all irrigation canals).

The 598 ha (1,478 ac) of wetlands identified as irrigation dependent, results in approximately \$3.38 million/year of added value to agricultural water in the Boxelder Creek watershed, or \$5,647/ha (\$2,285/ac). According to the U.S. Department of Agriculture – National Agricultural Statistics Service (USDA-NASS 2011), the average value of of irrigated cropland in Colorado is \$7,880/ha (\$3,190/ac). Taking the additional value of irrigated wetlands into consideration when evaluating potential agricultural water reallocation arrangements could have a significant impact on the estimated value of water in agriculture. At the very least, planners and landowners should be aware of the potential value trade-offs when considering changing irrigation practices or water market strategies.

From the scenario analyses in this study, it was shown that increasing on-farm application efficiency resulted in an estimated loss of total wetlands between 156 ha (385 ac) and 286 ha (707 ac), or between 26% and 48% of the total irrigation dependent wetlands in the study area. This loss of wetland area results in an estimated economic loss of between \$880,000 and \$1.62 million. Increasing conveyance efficiency in this study resulted in an estimated loss of total wetlands between 191 ha (472 ac) and 307 ha (759 ac), or between 32% and 51% of the total irrigation dependent wetlands in the study area. This loss of wetland area results in an estimated economic loss of between \$1.08 million and \$1.73 million.

5 Conclusions

The results of this study suggest that area under flood irrigation and canal-seepage contributing length are the two driving variables for estimating wetland size in the Boxelder Creek watershed. This conclusion is supported by the multiple-linear regression (MLR) analysis, as well as the classification and regression tree (CART) analysis. Furthermore, by controlling for changing runoff potential we were able illustrate the impact of increasing curve number values on the effect of irrigation application in the Boxelder Creek watershed.

The consistency of both the MLR and CART analyses across the multiple areas of influence, and the strong physical correlations of the results, combine to give great confidence to the overall outcome of this study. The MLR analysis shows a consistent decreasing trend on the impacts of the irrigation variables as you move further away from the edge of a wetland, which is exactly what one would expect in the physical environment. The analysis also shows an increasing trend on the impacts of the irrigation variables when accounting for increasing runoff potential.

The analysis further suggests there is an optimum area of influence at approximately 200 m from the edge of a wetland. It is at this range where the MLR analysis was able to explain the greatest variability in wetland size. Furthermore, it was at the 200 m area of influence where the simulated scenarios showed the greatest overall decrease in total wetland area.

With agriculture to urban transfers of water rights anticipated to meet the majority of future municipal water needs in the West, this study provides an initial indication of the spatial scope of the impacts of altered irrigation practices. This knowledge can provide water planners and landowners the opportunity to anticipate an area of impact for things such as proposed water transfers, lining of canals for increased conveyance efficiencies, or possible change of use cases for water rights, including changing irrigation types.

While the framework within the doctrine of prior appropriation, combined with Colorado's no injury requirement, does an excellent job of protecting water rights holders from altered or diminished water supplies, it provides no protection for ecosystem function, whether natural or incidentally created. Moreover, with previous economic studies focusing only on the direct and indirect production impacts associated with transfers of agricultural water, the benefits associated with incidentally created habitat have received little attention. These benefits have historically not been reflected in estimates of the value of water in agriculture, leading to a possible value loss to farmers and society should these ecosystems be lost due to the reallocation of agricultural water rights.

The rising acceptance of non-market valuation techniques, such as ecosystems benefits transfer, combined with a better understanding of the physical relationship between irrigated agriculture and incidental wetlands, can help to shed light on the unaccounted values of water in agriculture. From this initial study in the Boxelder Creek watershed, there is an estimated $3.38 million of ecosystem services being provided by habitat that is partially, if not fully dependent on irrigation. At an estimated value of $5,647/ha, the ability to evaluate the impact of changing irrigation practices on nearby wetlands may influence the decision process of both landowners and water planners. This study helps to highlight the fact that irrigated agriculture in Colorado and beyond is worth more than just the price of a bushel of corn or bale of hay.

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Appendix A – Initial Data Exploration and Residuals Analysis

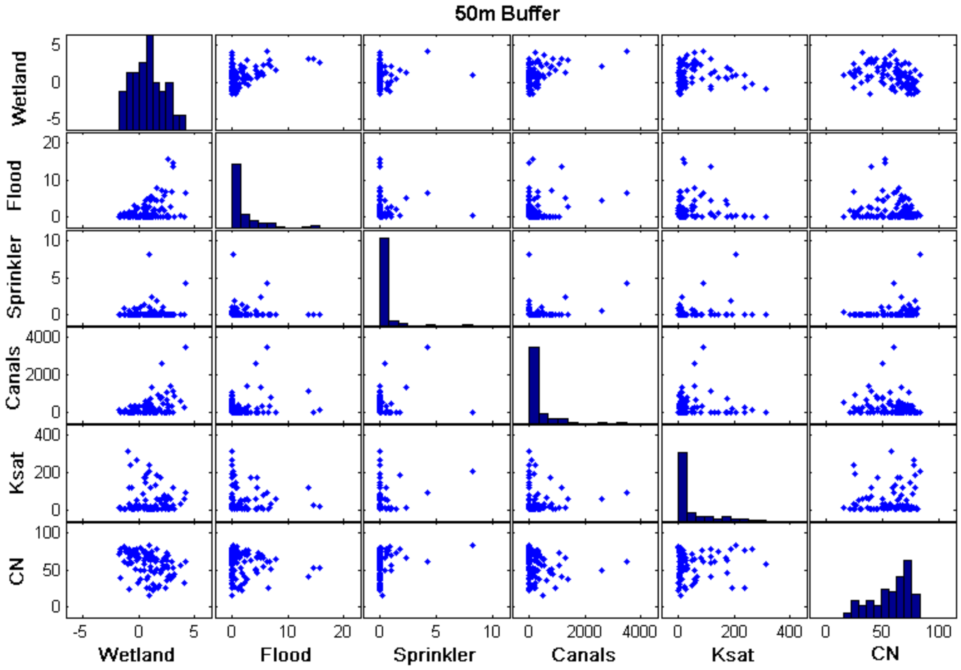
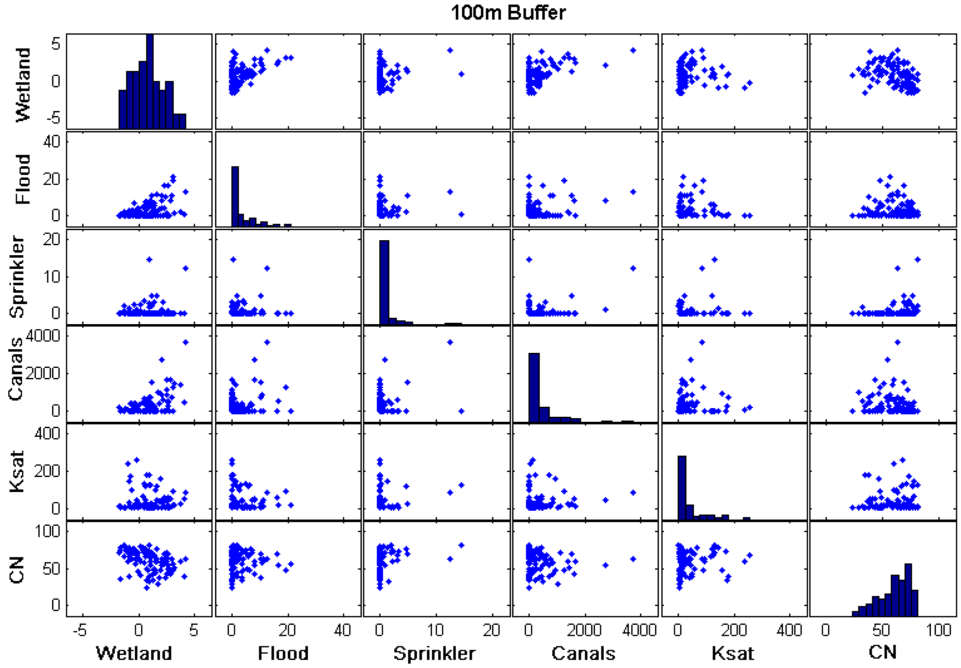


Figure A- 1 - Scatterplot of natural log of wetland size and all five explanatory variables for 50 m area of influence.



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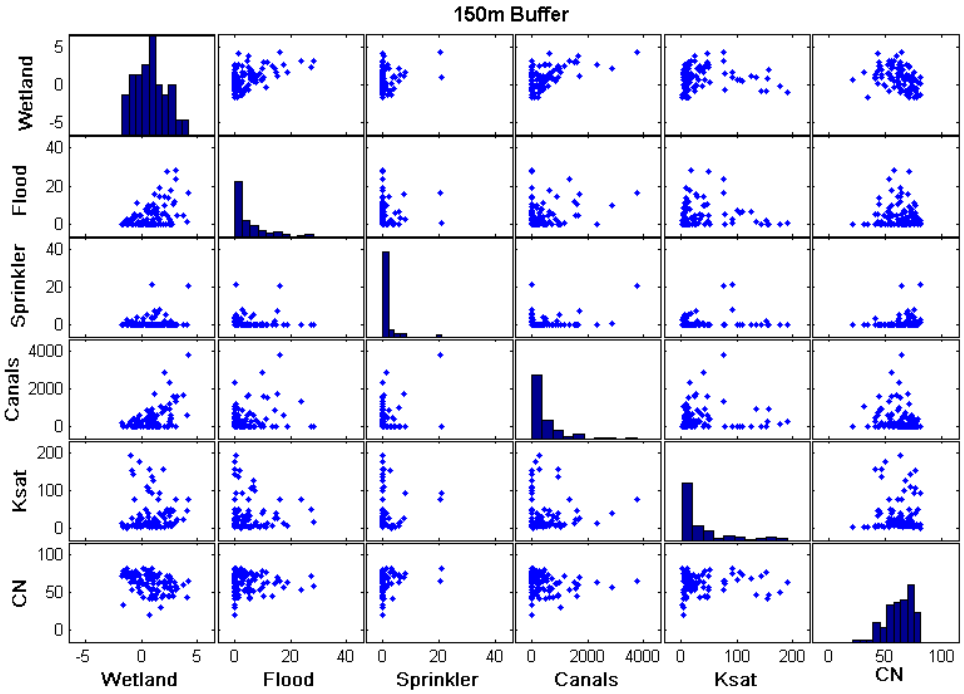
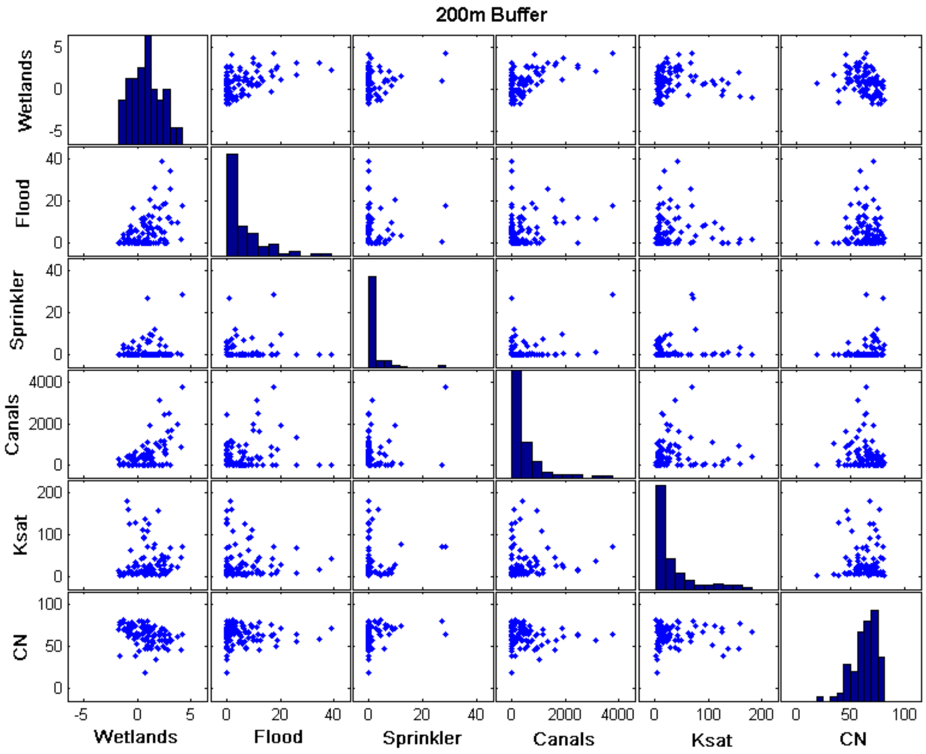


Figure A- 3 - Scatterplot of natural log of wetland size and all five explanatory variables for 150 m area of influence.



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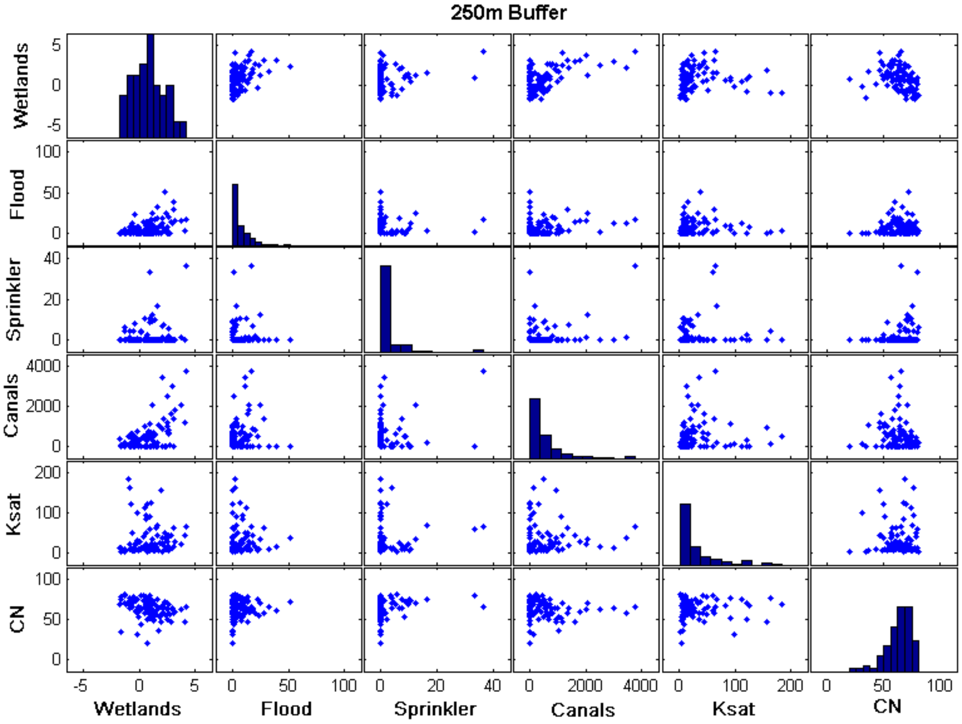

Figure A- 5 - Scatterplot of natural log of wetland size and all five explanatory variables for 250 m area of influence.

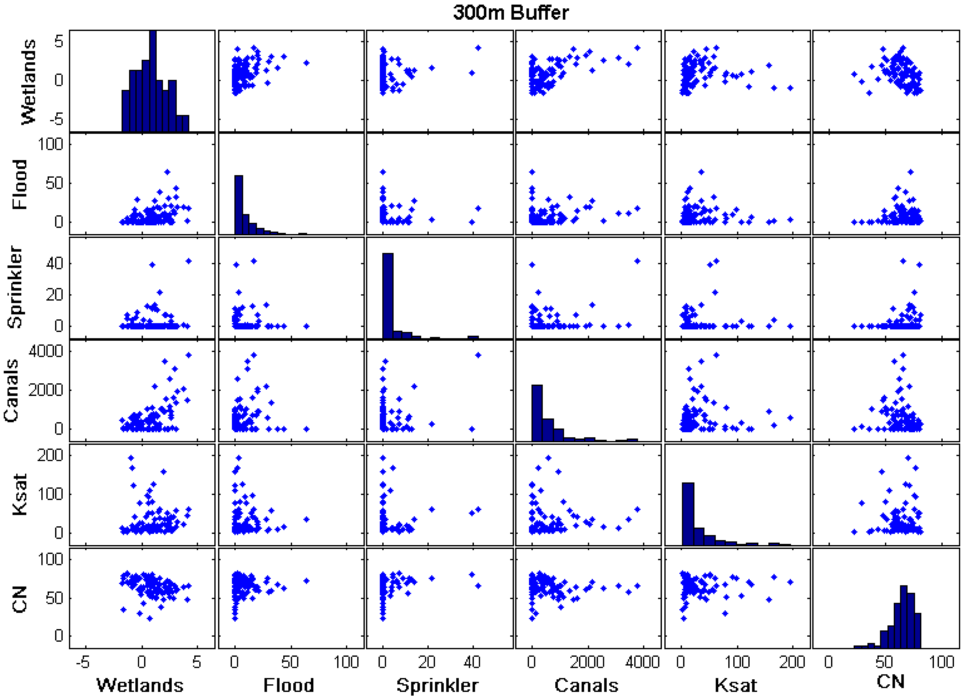

Figure A- 6 - Scatterplot of natural log of wetland size and all five explanatory variables for 300 m area of influence.

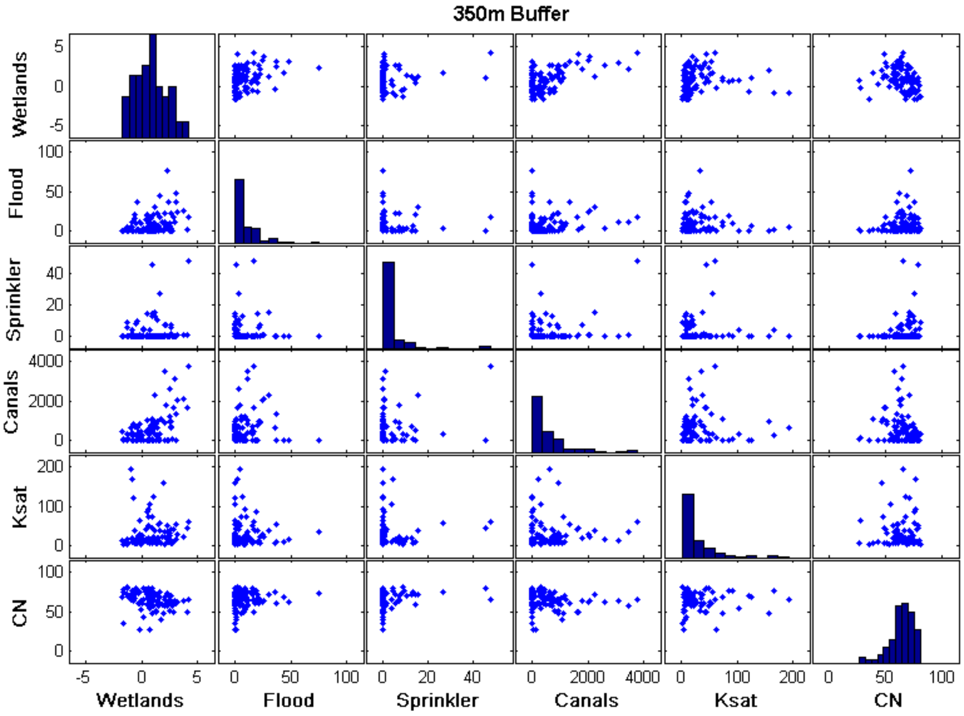

Figure A- 7 - Scatterplot of natural log of wetland size and all five explanatory variables for 350 m area of influence.

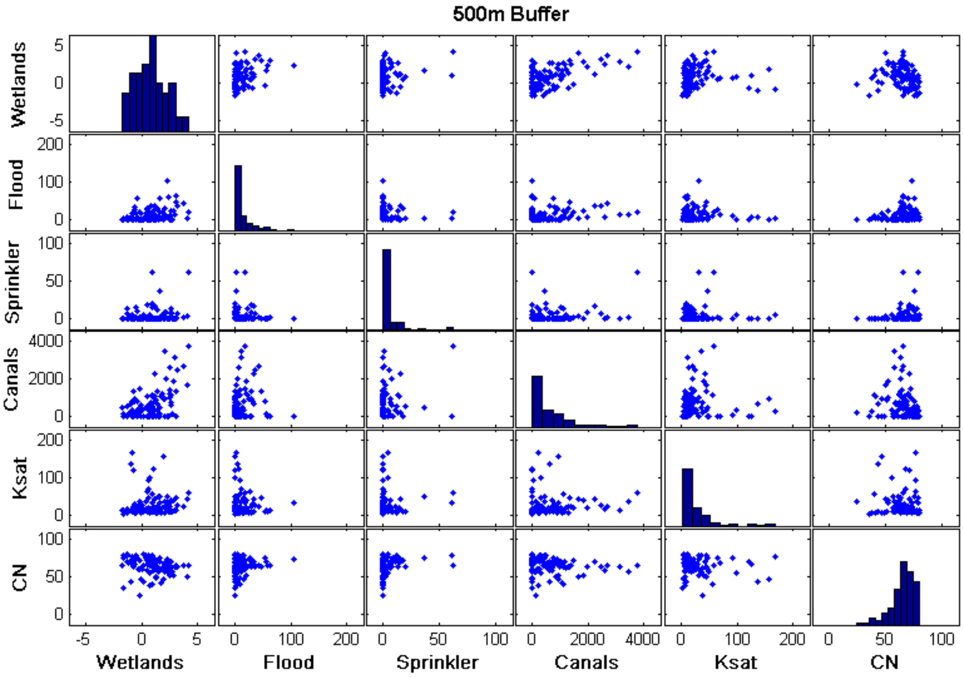

Figure A- 8 - Scatterplot of natural log of wetland size and all five explanatory variables for 500 m area of influence.

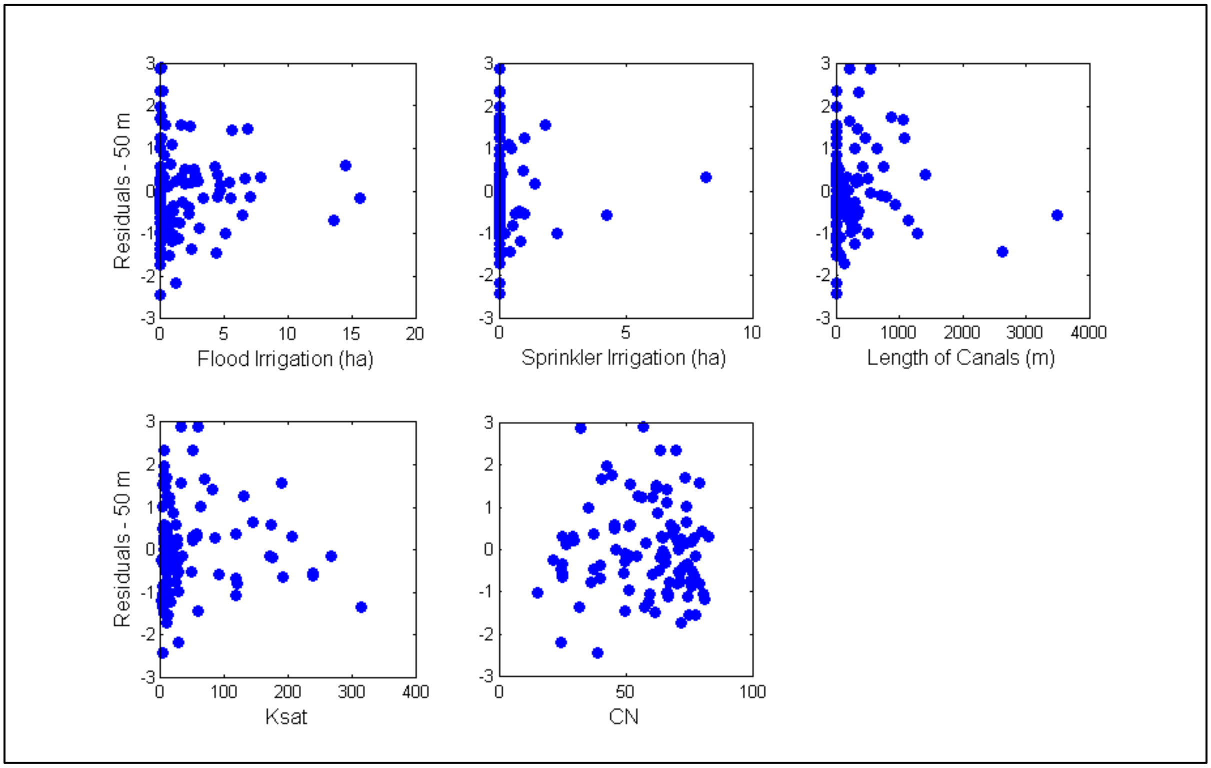

Figure A- 9 - Scatterplots of residuals against predictor variables for full model of 50 m area of influence.

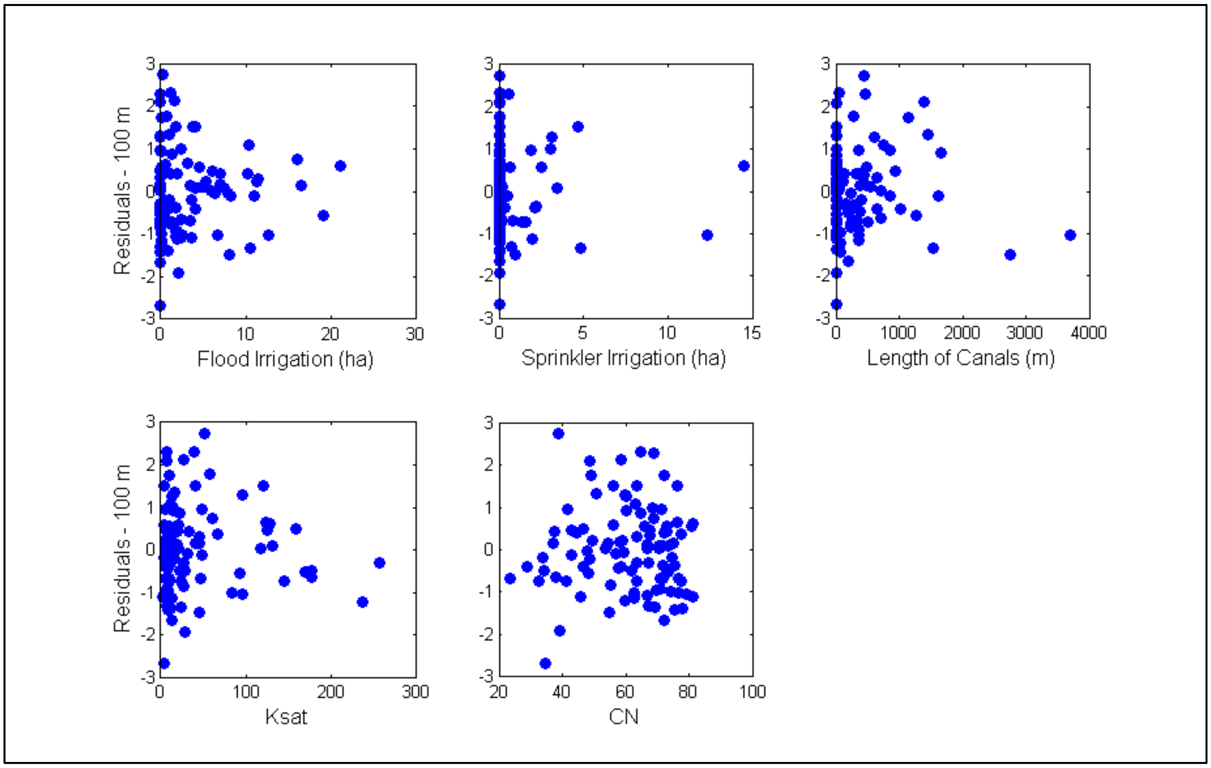

Figure A- 10 - Scatterplots of residuals against predictor variables for full model of 100 m area of influence.

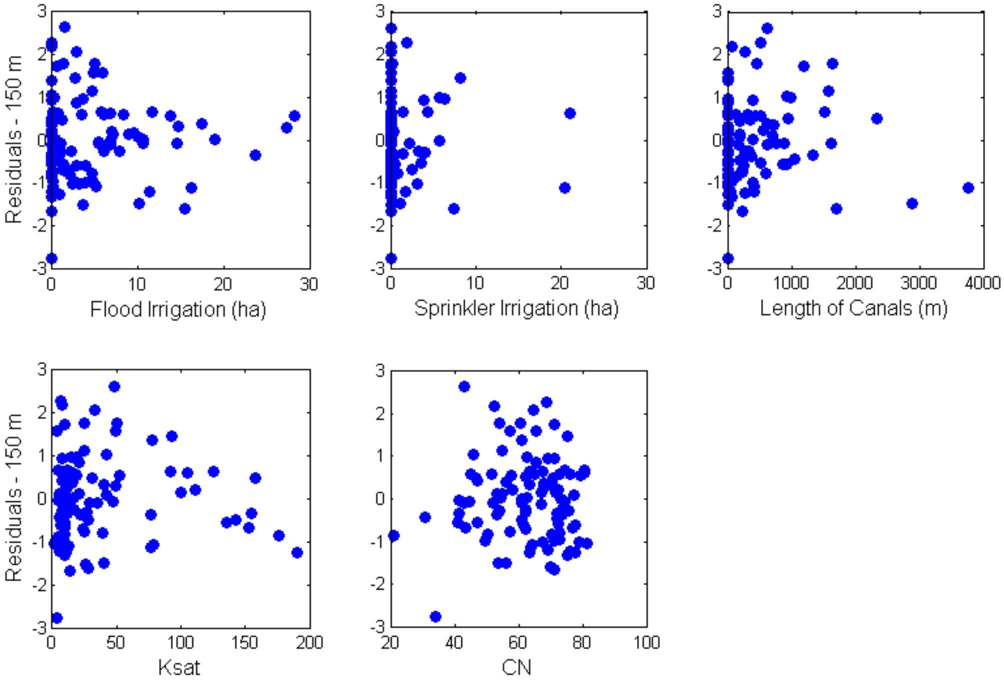

Figure A- 11 - Scatterplots of residuals against predictor variables for full model of 150 m area of influence.

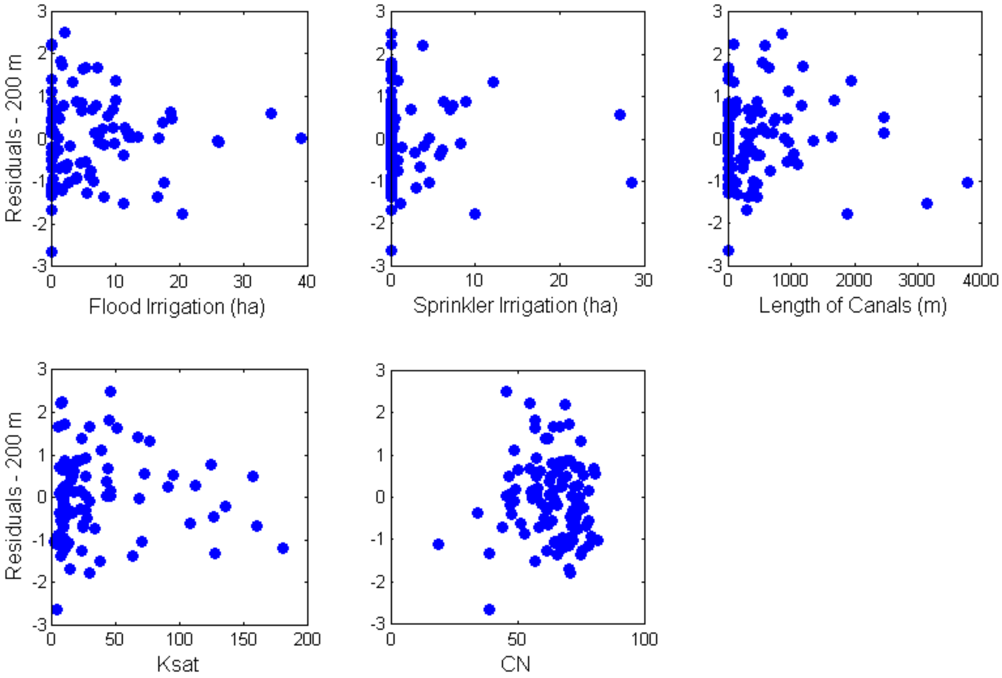

Figure A- 12 - Scatterplots of residuals against predictor variables for full model of 200 m area of influence.

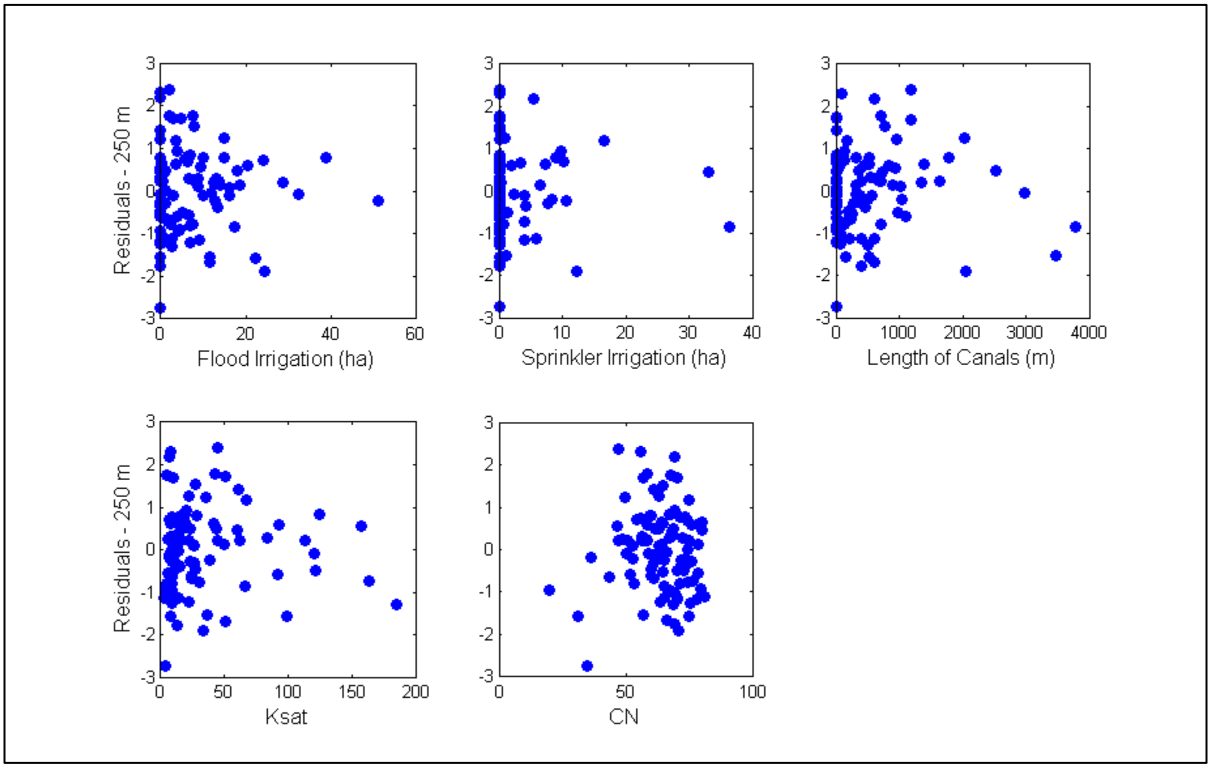

Figure A- 13 - Scatterplots of residuals against predictor variables for full model of 250 m area of influence.

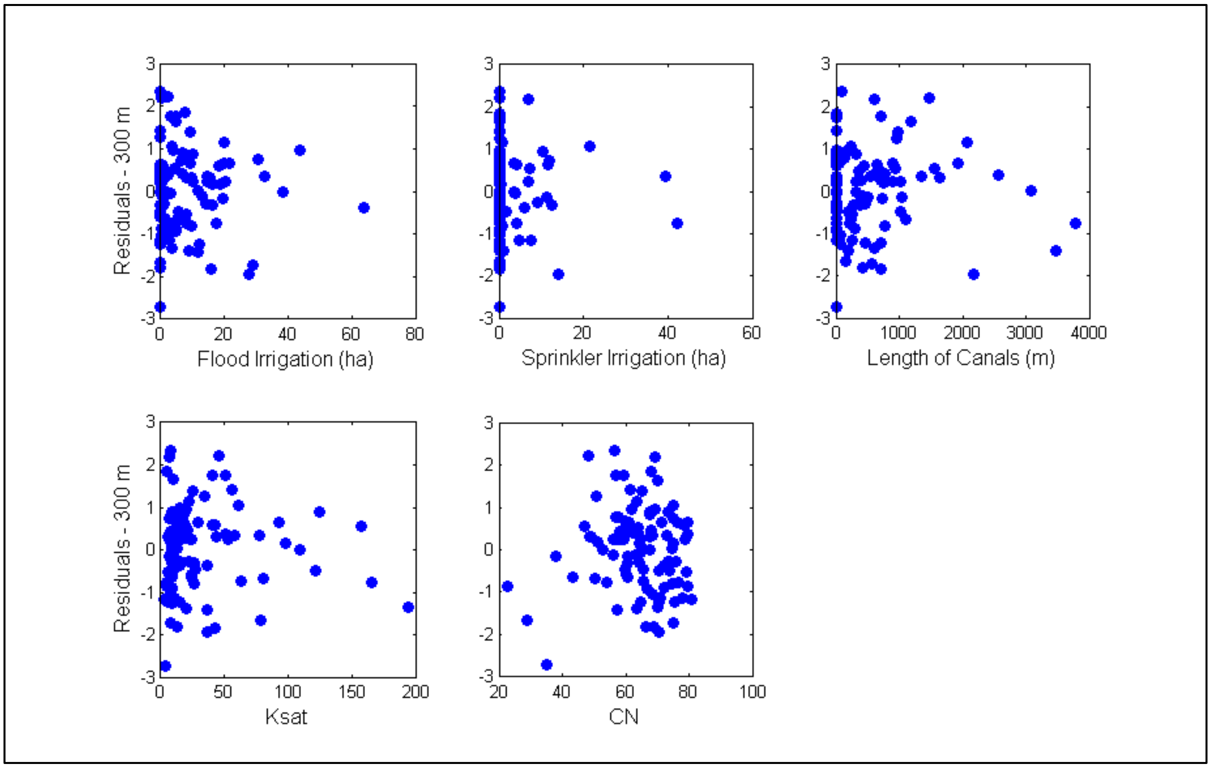

Figure A- 14 - Scatterplots of residuals against predictor variables for full model of 300 m area of influence.

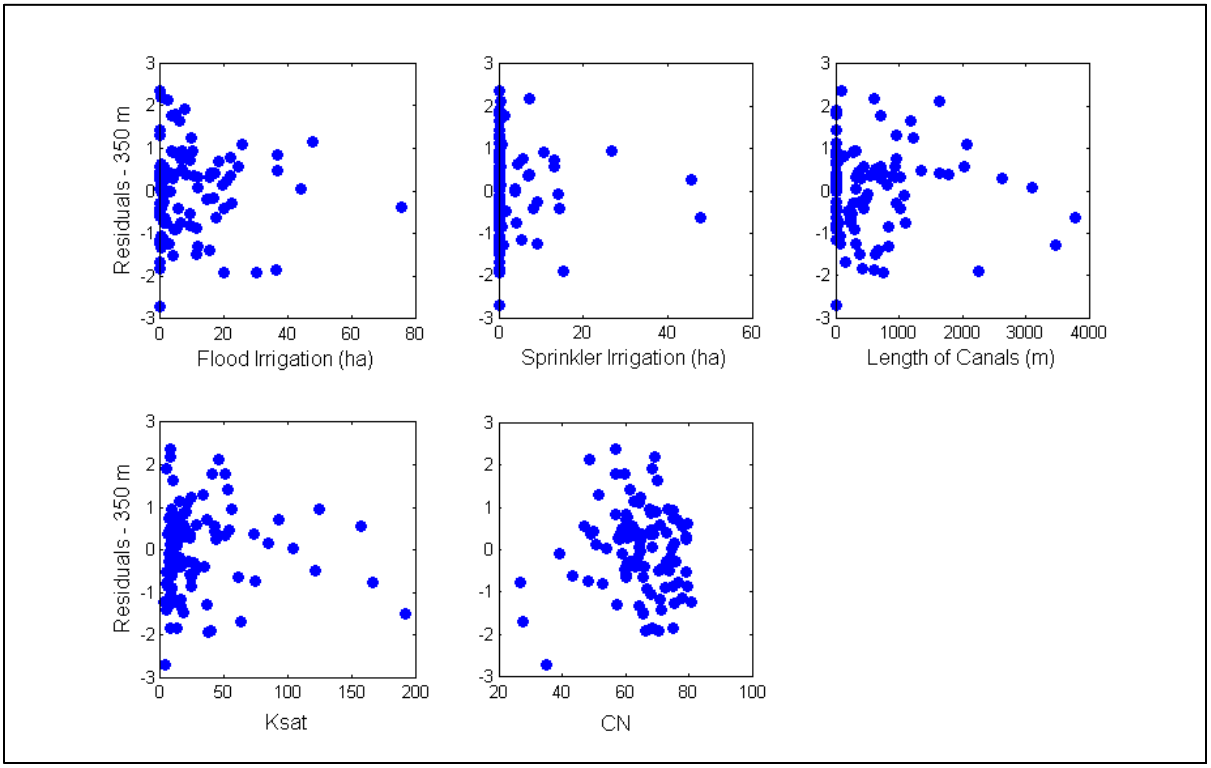

Figure A- 15 - Scatterplots of residuals against predictor variables for full model of 350 m area of influence.

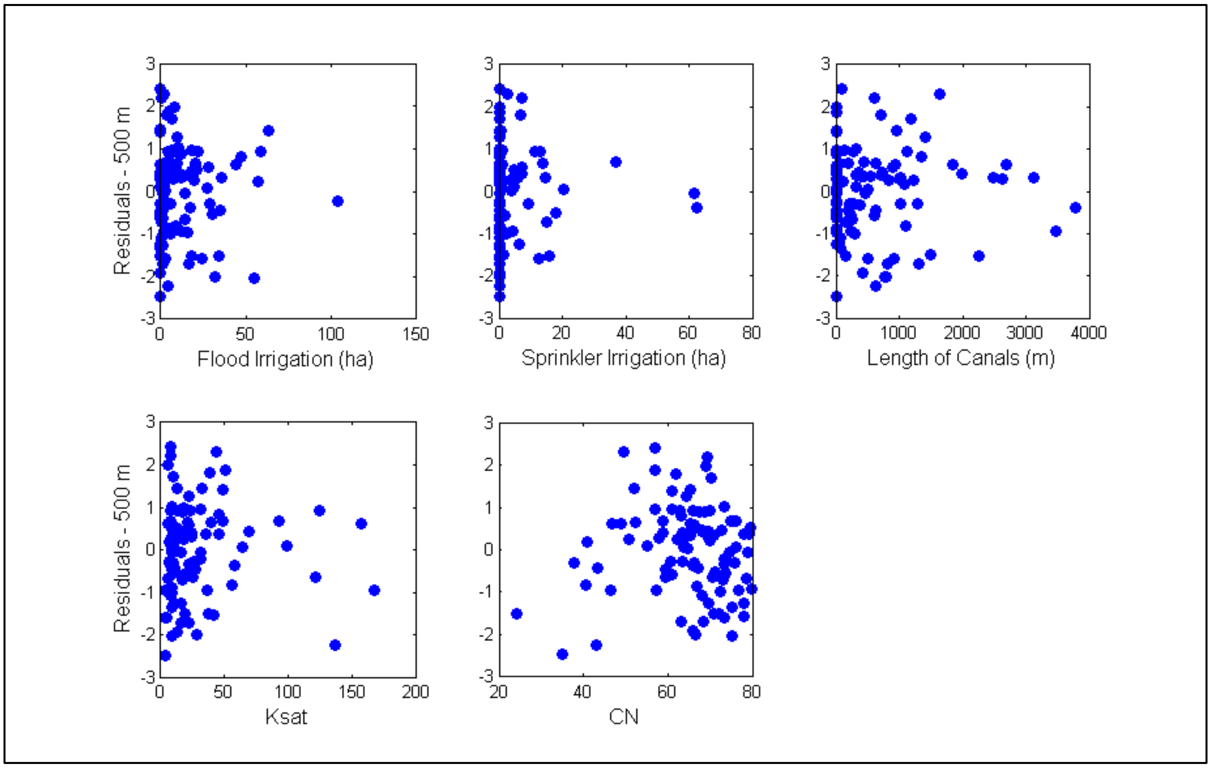

Figure A- 16 - Scatterplots of residuals against predictor variables for full model of 500 m area of influence.

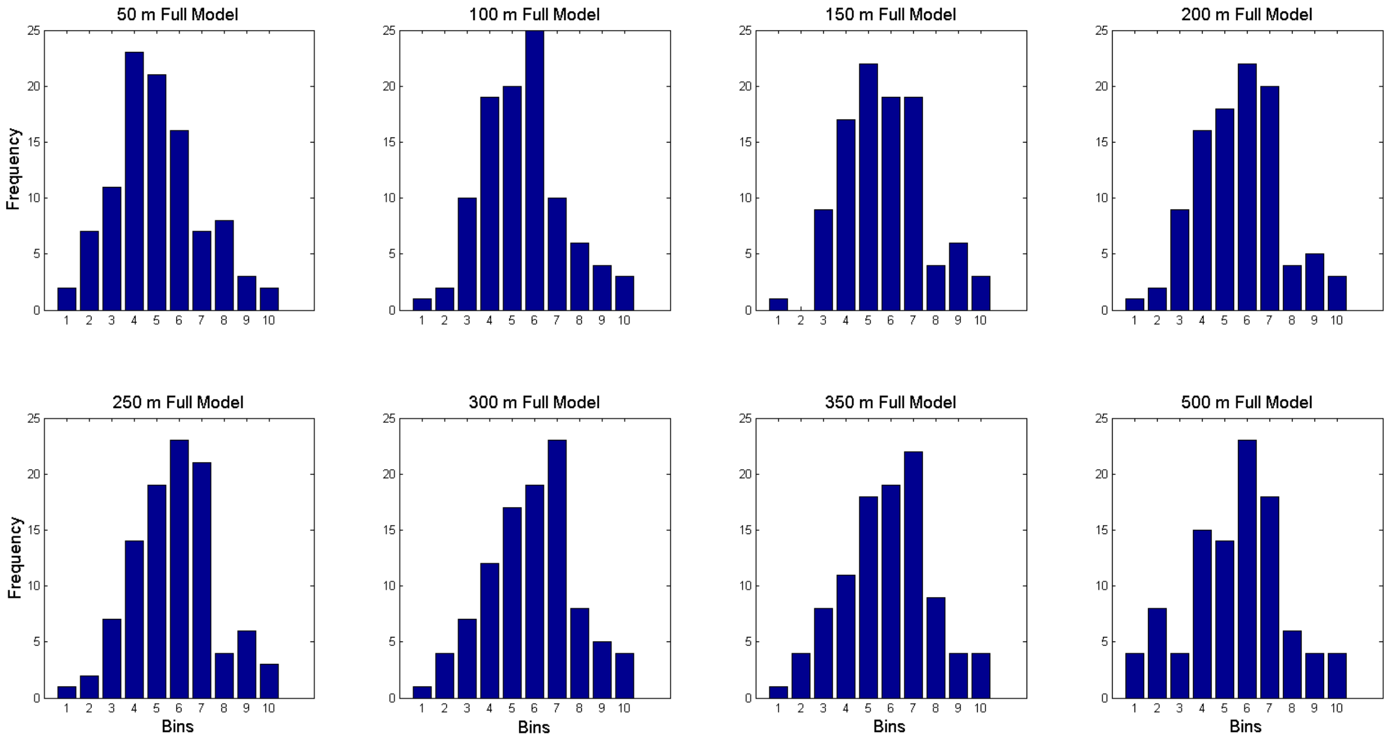

Figure A- 17 - Histogram of residuals for the various areas of influence for the full models. The frequency distribution shows the residuals are normally distributed.

Appendix B– Fitted Models for the CN Ranked Data Sets

Table B- 1 - Fitted models for CN ranked datasets, including confidence intervals for the coefficient weights.

Area of Influence	CN Range	Flood Irrigation	Sprinkler Irrigation	Length of Canal	Constant	R^2_{adj}
50	low	0.07783 (-0.06878, 0.22444)	-1.32101 (-3.50613, 0.86411)	0.00086 (7.8766E-05, 0.00164)	0.98884*** (0.47331, 1.5044)	0.171
	mid	0.16252** (0.0558, 0.26923)	-0.42087 (-1.4652, 0.62342)	0.00134** (9.667E-07, 0.00268)	0.41944 (-0.11568, 0.95457)	0.325
	high	0.20944* (-0.02535, 0.44422)	0.24458** (0.02084, 0.46832)	0.00295*** (0.00146, 0.00444)	-0.70670 (-1.1703, -0.2431)	0.355
100	low	0.07830** (0.0089, 0.14771)	-0.63656 (-1.9273, 0.6542)	0.00078** (8.502E-05, 0.00148)	0.93207** (0.39153, 1.4726)	0.241
	mid	0.10858** (0.01907, 0.19808)	-0.15335 (-0.42773, 0.12104)	0.00128** (4.421E-04, 0.00211)	0.23898 (-0.26899, 0.74695)	0.388
	high	0.17397* (0.05643, 0.2915)	0.16233** (0.05465, 0.27001)	0.00229*** (1.082E-03, 0.00349)	-0.90712*** (-1.362, -0.4522)	0.414
150	low	0.07074** (0.01362, 0.12787)	-0.20247 (-0.82927, 0.42433)	0.00077** (1.315E-04, 0.00142)	0.76713** (0.21255, 1.3217)	0.284
	mid	0.06907* (-0.00106, 0.13921)	-0.03815 (-0.17325, 0.09694)	0.00103** (4.219E-04, 0.00165)	0.19470 (-0.30295, 0.69235)	0.429
	high	0.11431*** (0.06134, 0.16727)	0.12012** (0.04657, 0.19367)	0.00204*** (9.015E-04, 0.00318)	-0.97786*** (-1.4319, -0.52374)	0.486
200	low	0.06268** (0.01799, 0.10736)	-0.08809 (-0.44111, 0.26491)	0.00068** (0.00013, 0.00123)	0.78741** (0.25648, 1.3183)	0.319
	mid	0.07355** (0.01533, 0.13178)	0.00044 (-0.08914, 0.09002)	0.00098*** (0.00045, 0.00151)	-0.03425 (-0.54009, 0.47158)	0.494
	high	0.06243** (0.0223, 0.10255)	0.0639* (0.00718, 0.12061)	0.00069* (-0.00011, 0.0015)	-0.63141** (-1.067, -0.19585)	0.365
250	low	0.05836** (0.01996, 0.09677)	-0.03939 (-0.27763, 0.19884)	0.00067* (0.00016, 0.00118)	0.71471** (0.18911, 1.24032)	0.356
	mid	0.06097** (0.01055, 0.11138)	0.0215 (-0.04866, 0.09166)	0.00082** (0.00032, 0.00132)	-0.01224 (-0.54561, 0.052113)	0.472
	high	0.0491** (0.01754, 0.08066)	0.05192** (0.00605, 0.09779)	0.00063 (-0.00014, 0.0014)	-0.63599** (-1.0802, -0.1918)	0.355
300	low	0.05411** (0.01106, 0.09716)	-0.00975 (-0.18529, 0.16578)	0.00072** (0.000195, 0.0013)	0.58174** (0.07259, 1.09089)	0.331
	mid	0.05439** (0.01948, 0.08929)	0.01577 (-0.04229, 0.07382)	0.00084*** (0.00037, 0.0013)	0.05991 (-0.50531, 0.62513)	0.494
	high	0.04682*** (0.02501, 0.06863)	0.05403** (0.02155, 0.0865)	0.000076 (-0.00059, 0.00074)	-0.69416*** (-1.0687, -0.3196)	0.454
350	low	0.04776** (0.00987, 0.08565)	0.00927 (-0.12652, 0.14506)	0.00075** (0.00024, 0.00127)	0.55267** (0.04535, 1.05999)	0.343
	mid	0.05012** (0.01889, 0.08135)	0.02304 (-0.02998, 0.07606)	0.00077** (0.0003, 0.00124)	-0.05881 (-0.641, 0.52338)	0.487
	high	0.03286** (0.0108, 0.05492)	0.03868** (0.00509, 0.07226)	0.00054 (-0.00017, 0.00125)	-0.61146** (-1.0656, -0.15731)	0.326
500	low	0.01507 (-0.05082, 0.08095)	0.11593 (-0.04686, 0.27871)	0.00072** (0.0002, 0.00124)	0.51129* (-0.02691, 1.04949)	0.283
	mid	0.03938*** (0.01757, 0.06118)	0.02518 (-0.01428, 0.06464)	0.00065** (0.00019, 0.00111)	-0.07087 (-0.64021, 0.49848)	0.506
	high	0.02402** (0.0086, 0.03944)	0.02731** (0.00102, 0.0536)	0.00041 (-0.00024, 0.00107)	-0.51557** (-1.0029, -0.02819)	0.284

*,**,*** indicates $p < 0.1$, $p < 0.05$, $p < 0.001$, respectively

Appendix C – Scatterplots of base scenario wetland size versus simulated wetland size with increased application efficiency

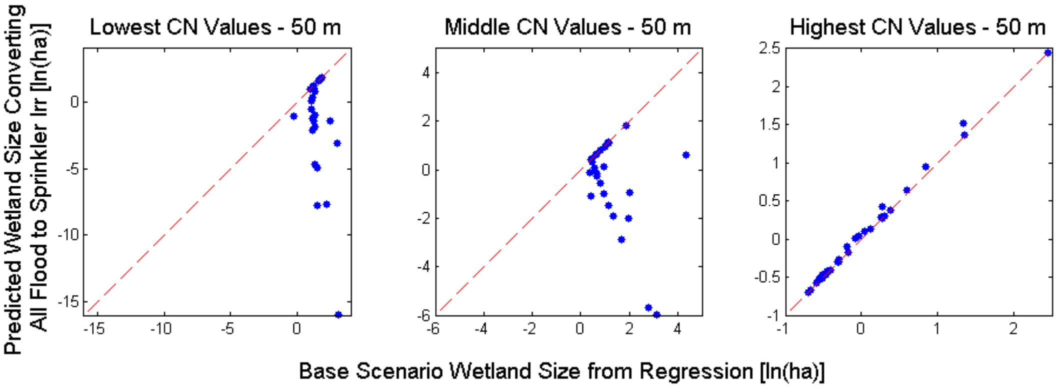

Figure C- 3 - Scatterplot of base scenario wetland size versus simulated wetland size when converting all flood irrigated lands to sprinkler irrigation for the 50 m area of influence.

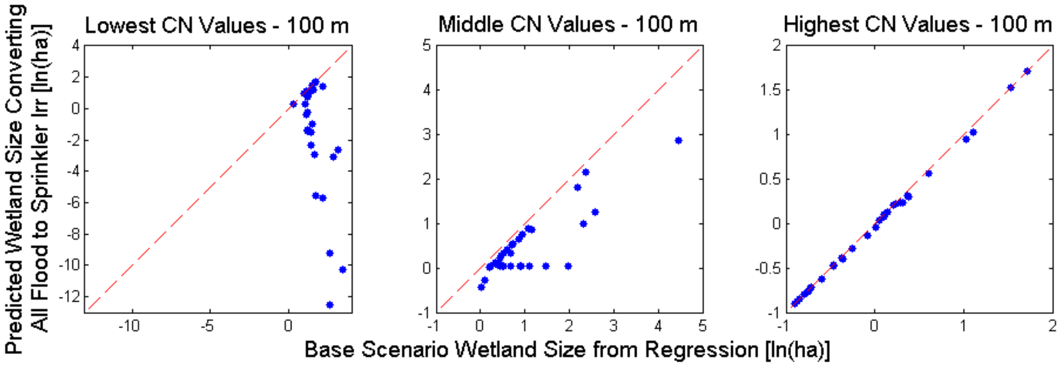

Figure C- 2 - Scatterplot of base scenario wetland size versus simulated wetland size when converting all flood irrigated lands to sprinkler irrigation for the 100 m area of influence.

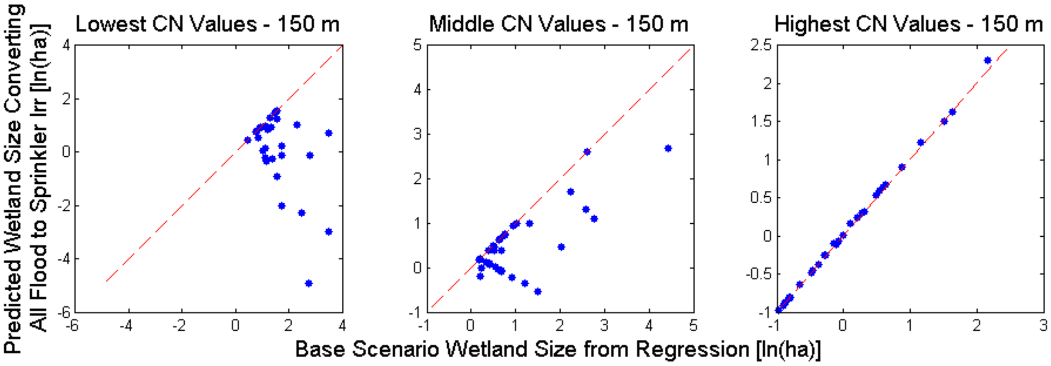

Figure C- 1 - Scatterplot of base scenario wetland size versus simulated wetland size when converting all flood irrigated lands to sprinkler irrigation for the 150 m area of influence.

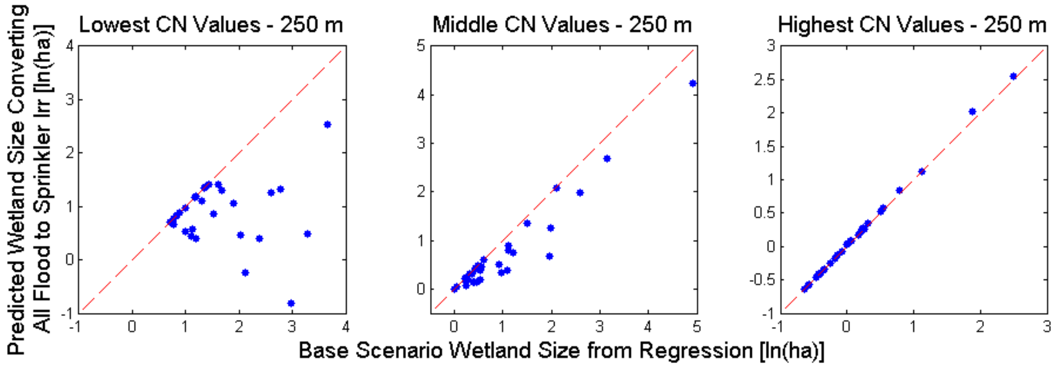

Figure C- 5 - Scatterplot of base scenario wetland size versus simulated wetland size when converting all flood irrigated lands to sprinkler irrigation for the 250 m area of influence.

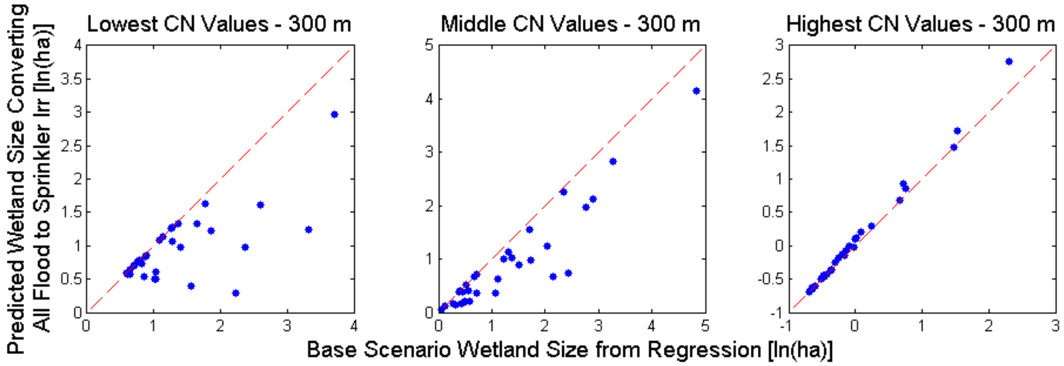

Figure C- 4 - Scatterplot of base scenario wetland size versus simulated wetland size when converting all flood irrigated lands to sprinkler irrigation for the 300 m area of influence.

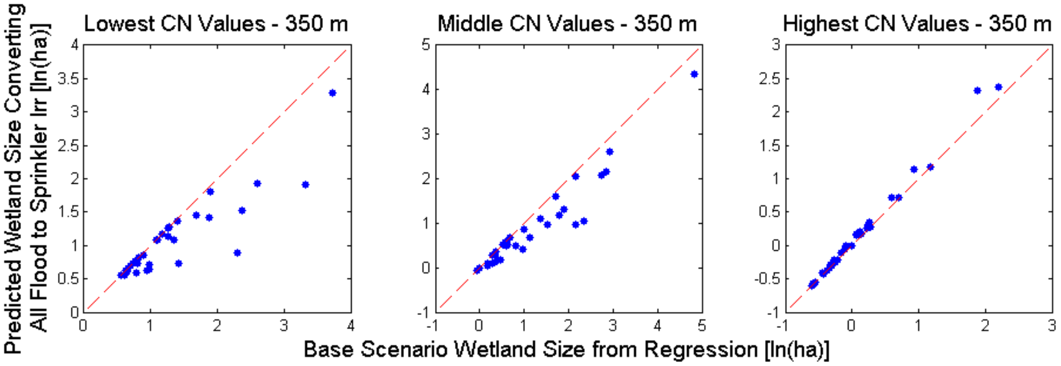

Figure C- 6 - Scatterplot of base scenario wetland size versus simulated wetland size when converting all flood irrigated lands to sprinkler irrigation for the 350 m area of influence.

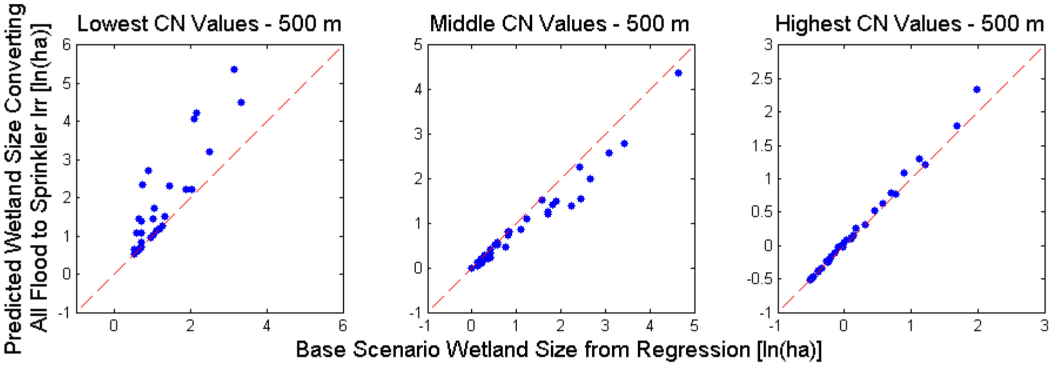

Figure C- 7 - Scatterplot of base scenario wetland size versus simulated wetland size when converting all flood irrigated lands to sprinkler irrigation for the 500 m area of influence

Appendix D – Scatterplots of base scenario wetland size versus simulated wetland size with increased conveyance efficiency

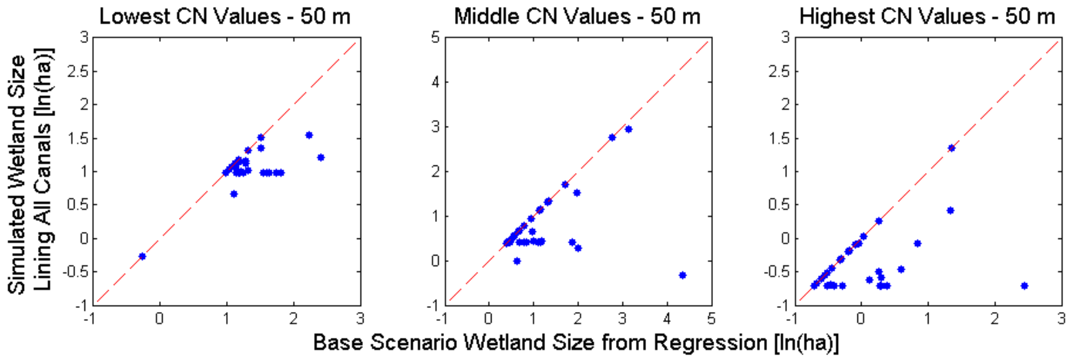

Figure D- 3 - Scatterplot of base scenario wetland size versus simulated wetland size when lining all irrigation canals for the 50 m area of influence.

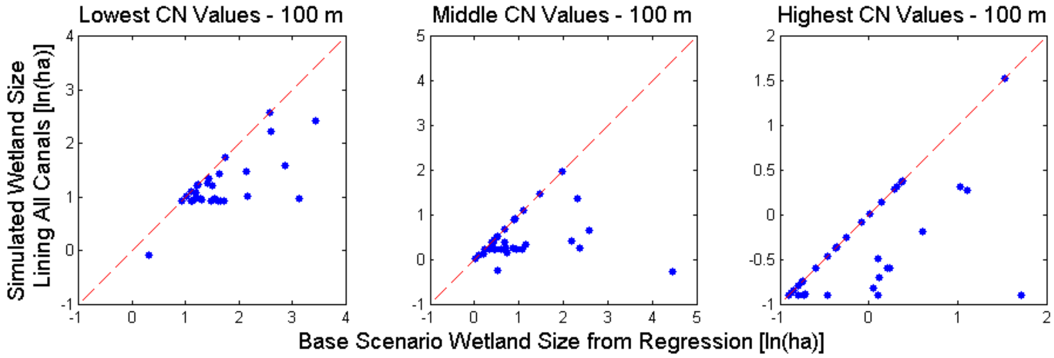

Figure D- 2 - Scatterplot of base scenario wetland size versus simulated wetland size when lining all irrigation canals for the 100 m area of influence.

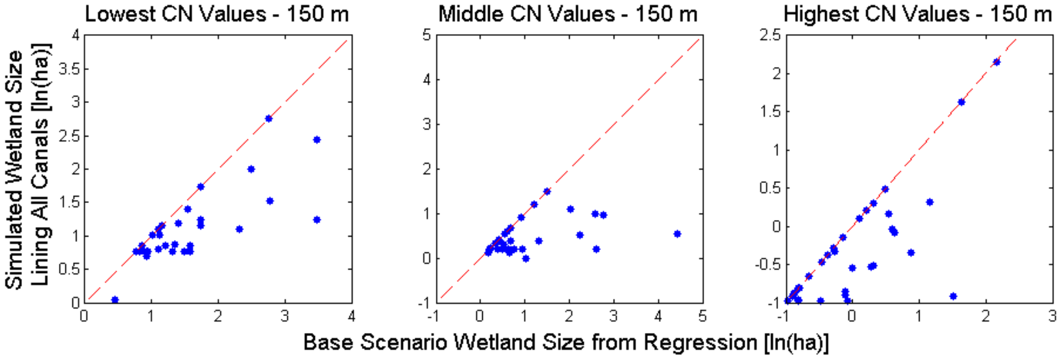

Figure D- 1 - Scatterplot of base scenario wetland size versus simulated wetland size when lining all irrigation canals for the 150 m area of influence.

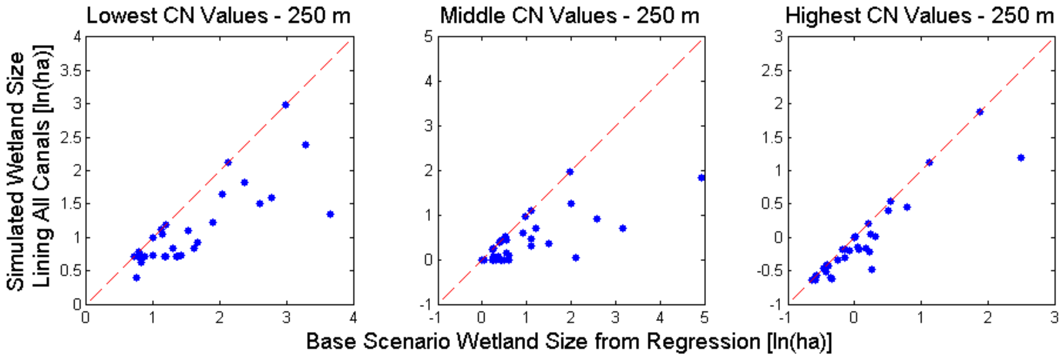

Figure D- 6 - Scatterplot of base scenario wetland size versus simulated wetland size when lining all irrigation canals for the 250 m area of influence.

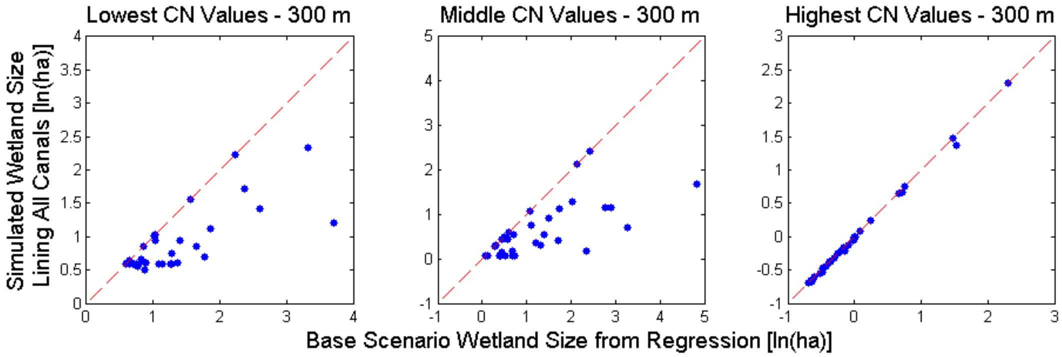

Figure D- 5 - Scatterplot of base scenario wetland size versus simulated wetland size when lining all irrigation canals for the 300 m area of influence.

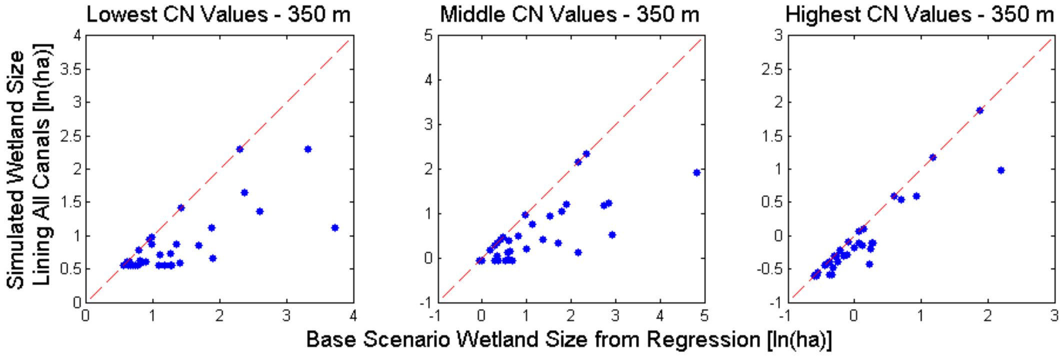

Figure D- 4 - Scatterplot of base scenario wetland size versus simulated wetland size when lining all irrigation canals for the 350 m area of influence.

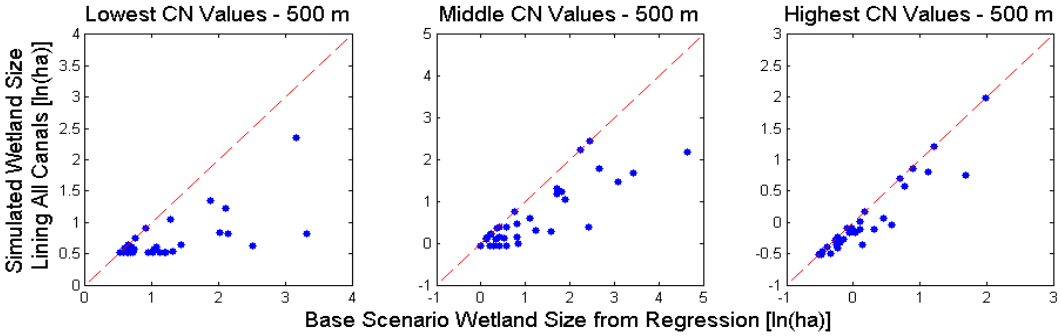

Figure D- 7 - Scatterplot of base scenario wetland size versus simulated wetland size when lining all irrigation canals for the 500 m area of influence.

Appendix E – Classification and Regression Tree Analysis (CART)

Results of the classification and regression tree (CART) bootstrap aggregation analysis of the eight areas of influence, as specified on the graphs. Classification MSE represents the out-of-bag classification error (the number of observations not included in the replica) associated with the number of grown trees. Explanatory variables are (1) area under flood irrigation, (2) area under sprinkler irrigation, (3) canal-seepage contributing length, (4) K_{sat}, (5) CN.

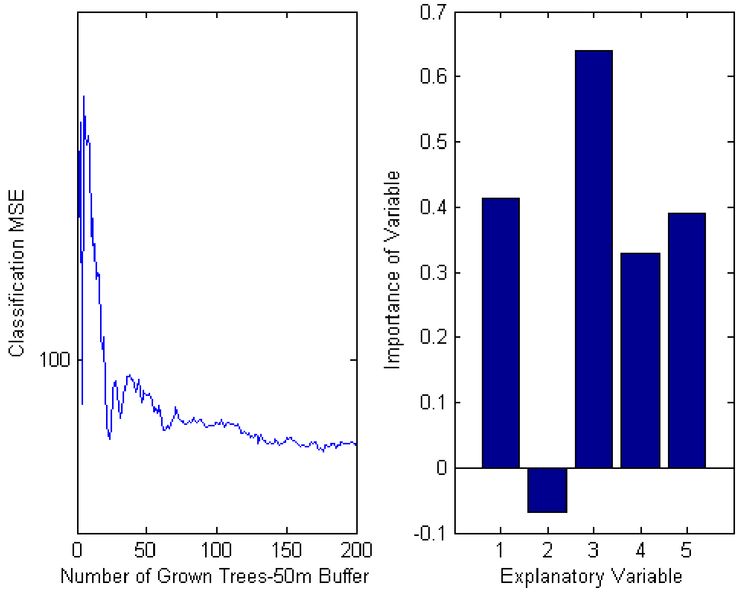

Figure E- 1 - Results of the classification and regression tree (CART) bootstrap aggregation analysis of the 50 m area of influence. Classification MSE represents the out-of-bag classification error (the number of observations not included in the replica) associated with the number of grown trees. Explanatory variables are (1) area under flood irrigation, (2) area under sprinkler irrigation, (3) canal-seepage contributing length, (4) Ksat, (5) CN.

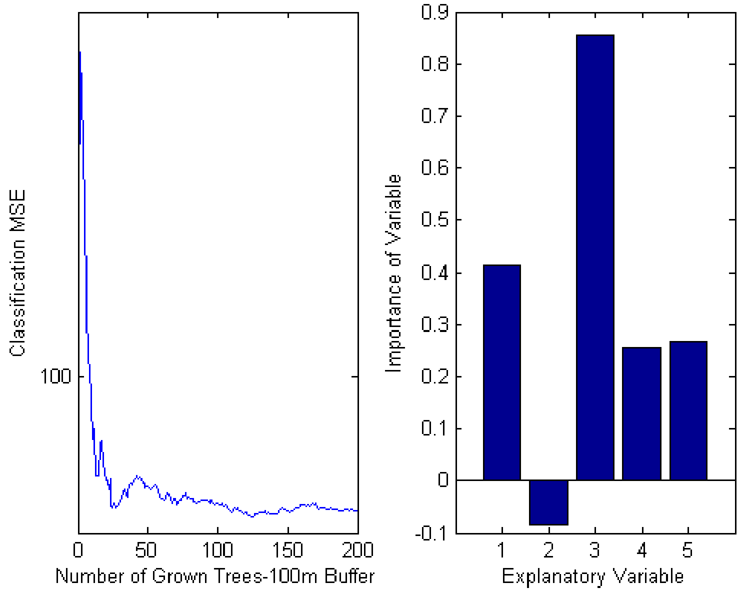

Figure E- 2 - Results of the classification and regression tree (CART) bootstrap aggregation analysis of the 100 m area of influence. Classification MSE represents the out-of-bag classification error (the number of observations not included in the replica) associated with the number of grown trees. Explanatory variables are (1) area under flood irrigation, (2) area under sprinkler irrigation, (3) canal-seepage contributing length, (4) Ksat, (5) CN.

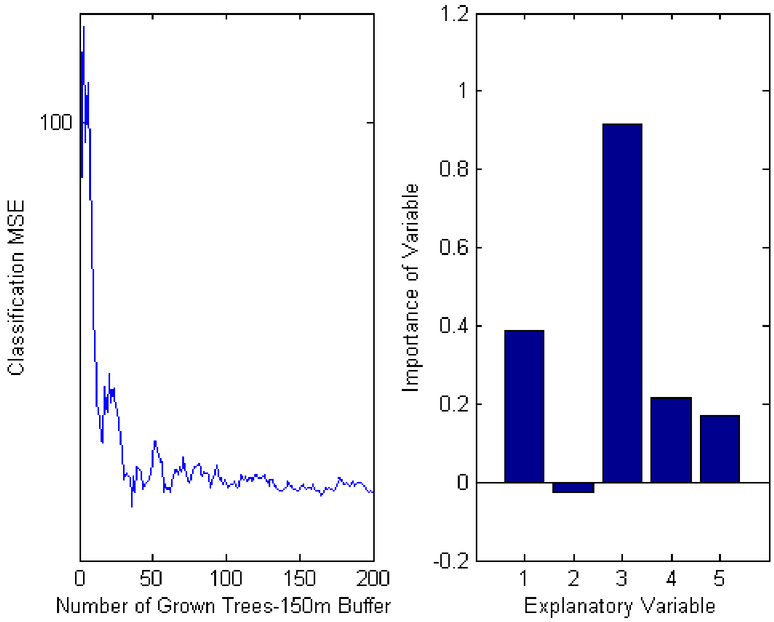

Figure E- 3 - Results of the classification and regression tree (CART) bootstrap aggregation analysis of the 150 m area of influence. Classification MSE represents the out-of-bag classification error (the number of observations not included in the replica) associated with the number of grown trees. Explanatory variables are (1) area under flood irrigation, (2) area under sprinkler irrigation, (3) canal-seepage contributing length, (4) Ksat, (5) CN.

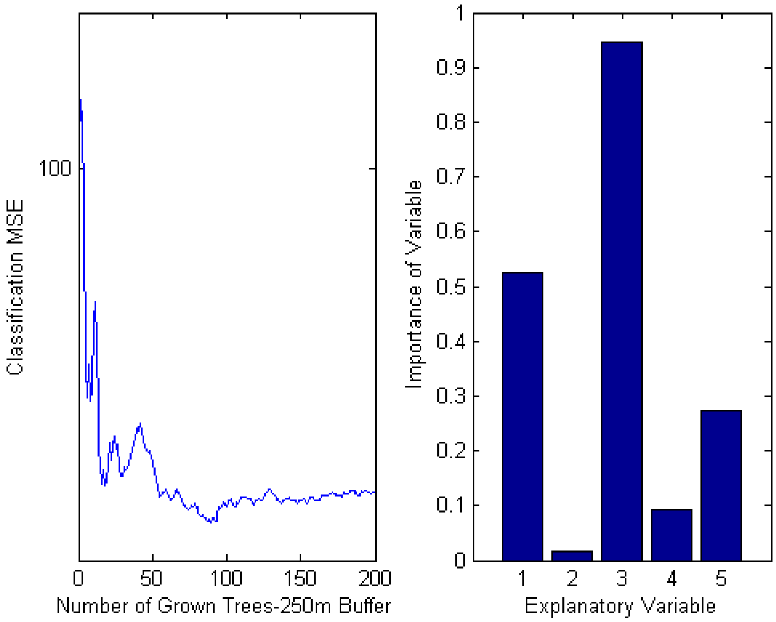

Figure E- 4 - Results of the classification and regression tree (CART) bootstrap aggregation analysis of the 250 m area of influence. Classification MSE represents the out-of-bag classification error (the number of observations not included in the replica) associated with the number of grown trees. Explanatory variables are (1) area under flood irrigation, (2) area under sprinkler irrigation, (3) canal-seepage contributing length, (4) Ksat, (5) CN.

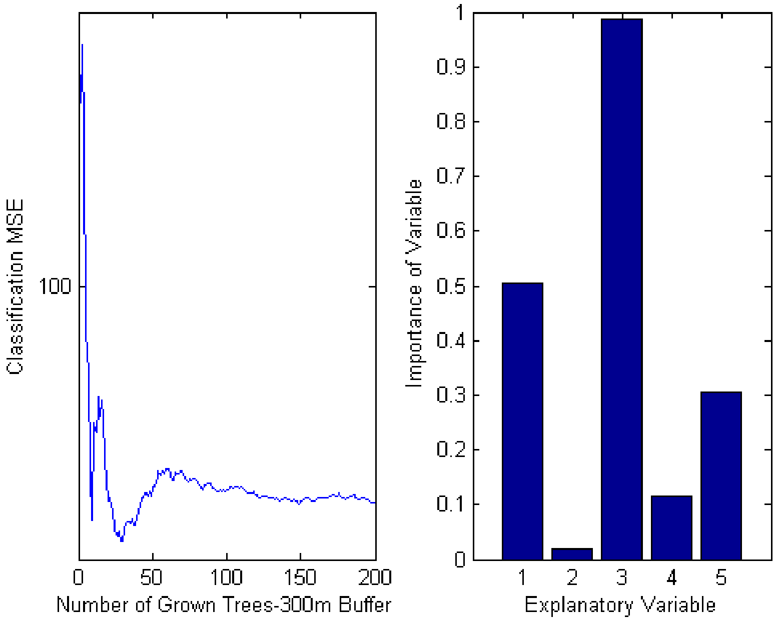

Figure E- 5 - Results of the classification and regression tree (CART) bootstrap aggregation analysis of the 300 m area of influence. Classification MSE represents the out-of-bag classification error (the number of observations not included in the replica) associated with the number of grown trees. Explanatory variables are (1) area under flood irrigation, (2) area under sprinkler irrigation, (3) canal-seepage contributing length, (4) Ksat, (5) CN.

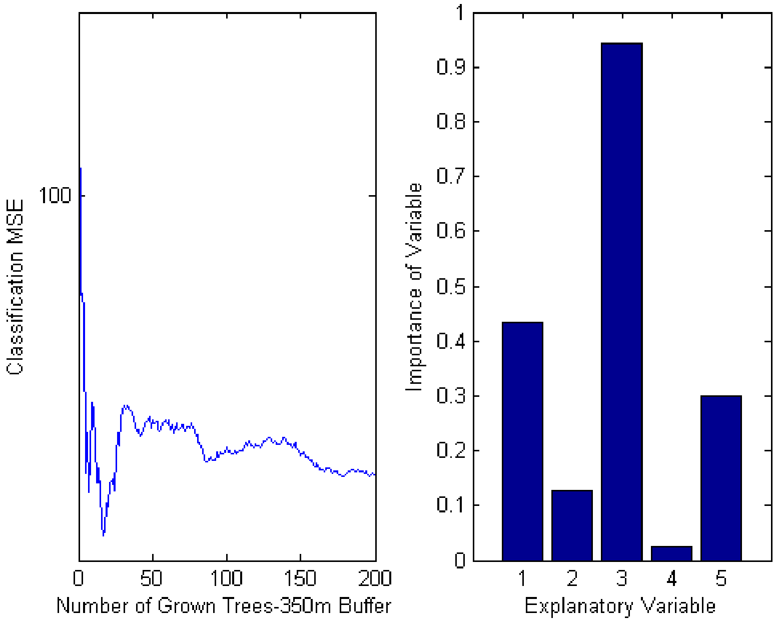

Figure E- 6 - Results of the classification and regression tree (CART) bootstrap aggregation analysis of the 350 m area of influence. Classification MSE represents the out-of-bag classification error (the number of observations not included in the replica) associated with the number of grown trees. Explanatory variables are (1) area under flood irrigation, (2) area under sprinkler irrigation, (3) canal-seepage contributing length, (4) Ksat, (5) CN.

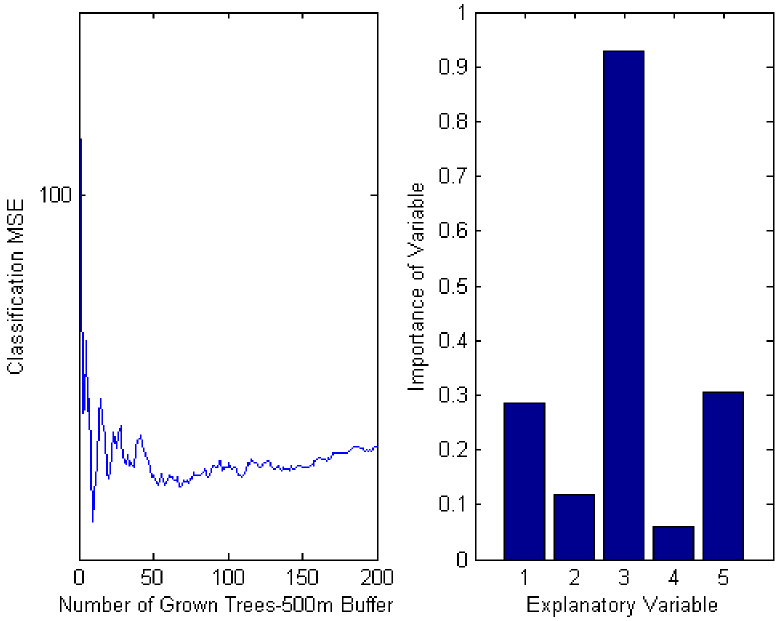

Figure E- 7 - Results of the classification and regression tree (CART) bootstrap aggregation analysis of the 500 m area of influence. Classification MSE represents the out-of-bag classification error (the number of observations not included in the replica) associated with the number of grown trees. Explanatory variables are (1) area under flood irrigation, (2) area under sprinkler irrigation, (3) canal-seepage contributing length, (4) Ksat, (5) CN.