

© 2011 Adam Tobias Bank Lentz

PHYSICAL CRITERIA FOR WETLAND TARGETING ON A WATERSHED SCALE

BY

ADAM TOBIAS BANK LENTZ

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Natural Resources and Environmental Sciences
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2011

Urbana, Illinois

Master's Committee:

Associate Professor Richard J. Brazee, Co-Chair
Assistant Professor Nicholas Brozović, Co-Chair
Associate Professor Amy W. Ando

Abstract

Wetlands are vital ecosystems that provide a wide range of services. Much attention has been focused on wetlands' ability to retain and remove pollutants, in particular nitrogen, from streams and waterways. For example, nitrogen runoff from tile-drained fields in the Upper Mississippi River Basin is considered a major cause of hypoxia and the dead zone in the Gulf of Mexico. Wetlands have been shown to be a cost-effective solution for reducing nitrate pollution in the Upper Mississippi River Basin. To improve wetlands' ability to remove nitrogen loads, research has suggested that sites should be targeted on a watershed scale. One method that has been applied in choosing wetland sites is the wetland-to-watershed ratio; for all suitable wetland sites, the upstream drainage area is calculated and the ratio is then calculated. The wetland's suitability is determined based on the specific ranking of the ratio. However, in the literature on nitrogen removal in wetlands, the recommended ratio varies by an order of magnitude; when the ratio is used to determine wetlands, it is important to assess which ratio is the most appropriate for a specific biophysical and physical setting. In this thesis I build on previous work on wetlands' ability to remove nitrogen and combine a biophysical and a physical model to target nitrogen removal on a watershed scale. I find that different wetland-to-watershed ratios should be used in different climatic settings. In areas of high stream discharge, wetlands should be located relatively farther upstream and have comparatively larger wetland-to-watershed ratios. The same is true for wetlands located in cold climates. If the nitrogen concentration increases or stays constant throughout a watershed, wetlands should be located in the bottom of the watershed (very small wetland-to-watershed ratios), but if the nitrate concentration decreases downstream, there may be an optimal location in a watershed, since lower wetland-to-watershed ratios mean a decrease in nitrogen removal. Lastly, given a choice between two sites with different nitrogen

concentrations, the site with the highest nitrogen concentration should be chosen to maximize the mass of nitrogen removed. In general, I find optimal wetland-to-watershed ratios that are smaller than those previously used and reported in the literature and policy reports.

Acknowledgements

I would like to thank the many people who have helped to make it possible for me to realize my dream of studying in the US and focus on improving environmental quality to better the future for all.

First and foremost I would like to thank the three professors who have spent countless hours advising me during my three years at the University of Illinois and without whom I would not have been able to complete this thesis and my other degree in Agricultural and Applied Economics. Prof. Richard Brazee helped me set the right course for my academic and professional path, always giving insightful input on the problems I was working on and supporting me beyond what anyone could ever have expected. Prof. Amy Ando taught me the importance of diligence to succeed in graduate school and how to be a better economist; Prof. Nicholas Brozović pushed my limits in improving my technical skills and taught me creative ways to analyze environmental problems.

I would like to thank my friends, whose friendship and support have been invaluable. I would especially like to thank Jae Han, Sahan Dissanayake and Kiyoshi Mino, whose patience and many helpful suggestions on my work have been immeasurable.

In a world of limited resources, I am most grateful for the economic support I have received from The Fulbright Commission, the EPA Targeted Watershed Grant (EPA-OW-OWOW-08-04) and The Wetlands Initiative to complete graduate school and this research project in particular. Jim Monchak and Jill Kostel from the Wetlands Initiative generously shared their knowledge on wetlands, helping me with everything from GIS advice to vital data. I would also like to thank Professor Crumpton, who provided me with estimates on wetlands nitrate removal potential – for

this I am very grateful. And finally I would like to thank Professor Greg McIsaac, who was very helpful in answering whatever questions I had on wetlands' ability to remove nutrients.

Last but not least I would like to thank, my family and my love in Denmark, to whom I long to return. Words cannot express what you mean to me!

Table of Contents

List of tables	vii
List of figures	viii
Introduction.....	1
Previous literature.....	4
Background	10
Nitrogen removal efficiency	10
Nitrogen flux	12
Watershed hydrology	13
Model.....	15
Graphical analysis	22
Application to an Illinois watershed.....	27
Study area	27
Data	28
Results from Big Bureau Creek Watershed	30
Discussion of results.....	33
Conclusion and policy implications	37
Tables and figures	40
Appendix A: Matlab code.....	58
Appendix B: Raw data.....	70
References.....	75

List of tables

1	Wetland-to-watershed ratios: Reported ratios, ratios used for prescreening and other wetland targeting recommendations	40
2	Calculated settling velocities for nitrate in subsurface wetlands	41
3	Limits of marginal change of nitrate removal with respect to drainage area	42
4	Descriptive statistics: Drainage area and nitrate concentrations	43
5	Regression results for nitrate concentration change in Big Bureau Creek Watershed	44
6	Descriptive statistics: Estimated marginal change in removal and change of nitrate removal for Big Bureau Creek Watershed	45

List of figures

1	Graphical analysis of the marginal change in nitrate removal with respect to drainage area	46
2	Variation in marginal influent concentration: Change in nitrate removal and nitrate removal per square meter	47
3	Graphs of nitrate removal and the change in marginal nitrate removal: Variation in wetness	48
4	Graphs of the change in marginal nitrate removal and nitrate removal: Variation in stream concentration	49
5	Graphs of the change in marginal nitrate removal and nitrate removal: Variation in wetland size	50
6	Wetland-to-watershed ratio	51
7	Study area: Big Bureau Creek Watershed and Bureau County, IL	52
8	Spatial distribution: Nitrate concentrations and drainage area sizes in Big Bureau Creek Watershed	53
9	Scatterplot: Influent concentration for different drainage areas in Big Bureau Creek Watershed	54
10	Graphs of the change in marginal nitrate removal and nitrate removal: Big Bureau Creek Watershed	55
11	Comparison of independent and author's estimates of nitrate removal for Big Bureau Creek Watershed (I)	56
12	Comparison of independent and author's estimates of nitrate removal for Big Bureau Creek Watershed (II)	57

Introduction

Constructed wetlands have a proven ability to improve water quality through biomass uptake, water filtration and chemical processes (Kadlec and Wallace 2008). One type of water quality improvement from wetlands that has received much attention is their capacity to retain and remove nitrogen from streams and rivers. Wetlands remove nitrogen through denitrification of nitrate from agricultural runoff and point sources (Crumpton et al. 2006, Kadlec and Wallace 2008). Wetlands retention of nitrogen loads may reduce hypoxia problems downstream in a cost-effective manner (Doering 2002) as well as reducing local water quality problems (Illinois Department of Natural Resources 2006).

One method to site constructed wetlands is applying rules of thumb for a wetland of a given size relative to its location in a watershed, or what is known in the literature as the wetland-to-watershed ratio. The Iowa Conservation Reserve Enhancement Program requires constructed wetlands to have a wetland-to-watershed ratio between 1:200 and 1:50, which means that a wetland of one hectare should have a drainage area between 50 and 200 hectares (U.S. Department of Agriculture and Iowa Department of Agriculture and Land Stewardship 2009). In Minnesota's wetland restoration strategy, wetlands with a wetland-to-watershed ratio of 1:5 are considered desirable to reduce nutrient pollution, while wetlands with a ratio of 1:20 and smaller are not recommended for wetland restoration (Minnesota Board on Water and Soil Resources 2009). As can be seen, these two programs apply very different rules of thumb to achieve the same policy objective: to reduce nutrient pollution from agricultural runoff.

Research has suggested that proper site selection of constructed wetlands may be the most important determinant of whether a wetland will be successful in achieving its design objective (Sonntag and Cole 2008). Looking exclusively at wetlands nitrogen removal potential, there can

be variation of a factor of ten within a small sub-watershed (Tomer et al. forthcoming), suggesting that targeting wetland sites for their removal potential is very important. Acknowledging the importance of targeting optimal wetland locations, several different attempts to evaluate site suitability and prioritize potential wetland sites have been made in recent years; much of this research has applied Geographical Information System (GIS) methods (e.g. Moreno-Mateos, Mander, and Pedrocchi 2010, Trepel and Palmeri 2002). But little research has been devoted to finding the right wetland-to-watershed ratio as a rule of thumb to site optimal locations for constructed wetlands to remove nitrogen. In order to achieve the policy objective of reducing nitrogen pollution, there is a need to understand how to set the rules of thumb for wetland-to-watershed ratios optimally when both biophysical and physical characteristics of a watershed are taken into consideration.

In this thesis, I analyze a general model for siting constructed wetlands for nitrogen removal, which is the amount of nitrogen a wetland of a given size can remove per year, and consider how biophysical characteristics of wetlands and physical watershed structures affect wetland placement criteria. The model utilizes simplified relationships among the basic determinants of nitrogen removal: wetland performance, watershed characteristics and land use and climatic variation with respect to both temperature and precipitation. In the model, these well established relationships are combined in a new way and extended to answer a different set of questions than they might have independently. Going back to the first principles, I analyze the basic properties of nitrogen removal by wetlands and the change in nitrogen removal with respect to the size of the drainage area. The model is then tested on real data from a typical agricultural watershed in the Upper Mississippi River Basin, and the model of nitrate removal is calibrated and compared to independent estimates of the nitrate removal potential of wetlands. For a wetland of a fixed

size, the wetland-to-watershed ratio can be seen as an approximation of its location on a wetland scale. The insights from this thesis can help wetland planners maximize benefits, represented by nitrogen removal, from constructed wetlands in different climatic and physical settings.

The main conclusion that can be drawn from this general model is that in watersheds where the nitrogen concentration increases or remains constant, wetlands should be located in the very bottom of the watershed, which means that the wetland can have as big a drainage area as possible. If the concentration decreases downstream, there may be an optimal location for a wetland of a given size other than the bottom of the watershed, assuming that the watershed is big enough; therefore there may be an optimal wetland-to-watershed ratio. It is, however, worth noting that when the concentration is constant or increasing downstream, the benefits from moving a wetland of a specific size farther down in a watershed may be very limited in terms of nitrogen removal per square meter of wetland because the additional removal as a function of the increased discharge downstream is negligible. Where this point is located in a watershed varies with climate and geographical location. Furthermore, this thesis provides a theoretical justification for some of the wetland ratios that have been used in the literature on wetlands removal of nitrogen. Additionally, this thesis also develops a simple model to estimate wetlands' ability to remove nitrate as a function of nitrate concentration flowing into a wetland and the change in stream concentration with respect to an increase in drainage area under different climatic and geographical settings.

As pointed out by Crumpton (2001) and Zedler (2003), one should locate wetlands in different places in a watershed depending on whether the wetlands are for storm flood abatement or water quality improvement. There may in fact be discrepancies between the best location and design for nitrogen and phosphorus removal (Hansson et al. 2005); therefore the

recommendations from this thesis only apply to reducing nitrogen pollution. Moreover, the focus of this thesis is to reduce loads of nitrogen to address regional water quality issues such as hypoxia in the Gulf of Mexico and other impaired waters. It is beyond the scope of this thesis to address the equally important question of local water quality problems that originate from high nitrogen concentrations, though the model could be adapted to address such issues as well.

The thesis is organized as follows. First I provide an overview of the literature on water quality improvements, focusing on best management practices for agriculture and wetland targeting. In the background section I first introduce the biophysical relationships that govern wetlands' nitrogen removal efficiency. Afterwards I present the geophysical aspects related to nitrogen concentrations in waterways as well as the basic watershed hydrological relationships that can describe discharge at any given point in a watershed as a function of the size of the drainage area. In the section on the model's development, I combine these basic relationships into a mathematical model that can explain a wetland's nitrogen removal potential as a function of the wetland's location in a watershed. In the section on graphical analysis, I use the general model to analyze optimal wetland locations on a watershed scale under different climatic and geophysical settings. I then apply the general model to a typical corn and soy producing tile-drained watershed in the Midwest. In the last two sections, I discuss the results and conclude the study with a summary of the policy implications for the design of future wetlands constructed to reduce nitrogen pollution.

Previous literature

I present two streams of research in this short review of the previous literature on wetland targeting. First I summarize the research on the targeting of wetlands and other best management

practices addressing water quality problems related to agriculture and how careful targeting can achieve higher levels of benefits. Second I present research on constructed wetlands specifically related to nitrogen removal potential and wetland-to-watershed ratios.

There is a great deal of scientific literature combining ecological, hydrological, soil and agronomic sciences to give recommendations on spatial targeting of various measures to reduce pollution from agriculture (Almendinger 1999, Diebel et al. 2009, Dosskey, Helmers, and Eisenhauer 2006, Newbold 2005, Qiu 2009, Tomer, James, and Isenhardt 2003, Tomer et al. 2009, Trepel and Palmeri 2002). Careful targeting of locations has been shown to increase the water quality benefits achieved from wetlands, riparian buffers and other best management practices at various levels, e.g. in a small sub-watershed (Tomer et al. 2011), a watershed (Dosskey, Helmers, and Eisenhauer 2006, Qiu 2009, Tomer, James, and Isenhardt 2003) and a large landscape scale covering an entire state (Diebel et al. 2009).

A common approach is to use geospatial data to target areas suited for conservation, preservation and restoration and use a Geographical Information System (GIS) as the analytical tool to find optimal locations. Some examples of the types of data used are digital elevation model (DEM) data (Tomer et al. 2009, Trepel and Palmeri 2002), soil survey databases (Diebel et al. 2009, Dosskey, Helmers, and Eisenhauer 2006, Tomer et al. 2009), land-use/cover data (Newbold 2005, Qiu 2009, Russell, Hawkins, and O'Neill 1997), maps of historical distribution of wetlands (Trepel and Palmeri 2002), water quality data (Diebel et al. 2009) and maps of the geomorphology (Moreno-Mateos, Mander, and Pedrocchi 2010); most recently, Light Detection And Ranging (LiDAR) data have been applied for precision conservation (Tomer et al. 2011). These different data types have been used to calculate the wetness index (Russell, Hawkins, and O'Neill 1997, Tomer, James, and Isenhardt 2003), erosion measures (Tomer, James, and Isenhardt

2003), the topographic index that predicts runoff (Qiu 2009) and sediment trapping efficiency measures (Dosskey, Helmers, and Eisenhauer 2006). In some studies these indicators have been used as standalone measures of site suitability (Qiu 2009, Tomer et al. 2009) while in other studies, they have been combined in different ways to achieve a holistic approach to siting (Dosskey, Helmers, and Eisenhauer 2006, Qiu 2010, Tomer, James, and Isenhardt 2003).

A common way to select the most suitable sites is defining specific thresholds required for some of the indicators mentioned above and then excluding sites that do not meet the requirement. Russell, Hawkins, and O'Neill (1997) excluded all sites that were smaller than 1 hectare, recognizing that the cutoff value was arbitrary but arguing that smaller areas would have a limited ability to attenuate floods. Restricting preservation and restoration to certain sites that are less suited without carefully evaluating the cost and benefits may lead to suboptimal site selection (Newbold 2005).

An alternative approach to excluding sites based on threshold values is to assign a weight to specific indicators and then prioritize the sites based on the relative value of the specific suitability index. Ranking sites is commonly used for both best management practices and wetland targeting. Qiu (2010) developed an algorithm that combined soil erodibility, hydrological sensitivity, wildlife habitat and impervious surface parameters. Each of the four parameters was weighted based on an expert panel's evaluation of their importance to site selection for riparian conservation. Similar approaches have also been used to prioritize wetland sites.

Moreno-Mateos, Mander, and Pedrocchi (2010) determined sites' suitability for constructed wetlands similar to already existing wetlands. They asked experts to define suitability criteria with respect to land use, geomorphology and soil classes. The sites chosen by the method were

predominately located in the lower third of large catchments and coincided with already existing wetlands, proving the model's usefulness in siting wetlands similar to existing wetlands (Moreno-Mateos, Mander, and Pedrocchi 2010). In a study of nitrogen retention in sited wetlands, Trepel and Palmeri (2002) used a suitability index similar in spirit to those described above. After overall suitability was determined, the site's nominal retention time was calculated: all sites with a shorter retention time than 5 days and a mean water level of less than 0.5 m were excluded due to their low expected denitrification ability. Of the remaining three sites, the wetland farthest downstream had the highest nitrogen removal but the lowest efficiency per square meter of wetland (Trepel and Palmeri 2002).

Diebel et al. (2009) used a different approach to determine site suitability and drew on previous statistical models to predict the load reduction potential of sediments and phosphorus from conservation. Point sources, urban runoff, soil type and erosion risk were some of the explanatory variables used to rank potential sites' suitability. Based on the predicted values, they suggested that wetlands be located downstream of sediment sources.

The exclusion and ranking criteria in all of the above mentioned studies achieve quite different targeting suggestions, and because of the differences in the studies' policy goals, they are not directly comparable with each other and provide little guidance on how to site wetlands to optimize nitrogen removal.

An alternative targeting approach that has been used in state policies as well as in theoretical papers is the wetland-to-watershed ratio. The first step in this approach is to identify potential wetland sites based on a number of criteria. When the size of a potential wetland has been calculated, the upstream drainage area and the wetland-to-watershed ratio are calculated; this

then serves as an indicator of a site's suitability as a nitrogen removing wetland (Tomer, James, and Isenhardt 2003, Tomer et al. 2011).

Empirical studies on wetlands' ability to remove nitrogen often report the wetland-to-watershed ratio (Table 1). The ratio is considered a simple indicator of retention time and therefore wetlands' ability to remove nitrogen (Woltemade 2000). However, there is little consensus on what the right ratio should be and it therefore varies from study to study. In a study of four wetlands in Iowa, Illinois and Maryland, Woltemade (2000) suggests that wetlands with a smaller ratio perform poorly with respect to nitrogen load reductions, due to short retention time in the wetlands, but fails to recommend an optimal ratio for any specific geographical location. Under low flow conditions, wetlands that are small compared to the drainage area can be very effective. Kovacic et al. (2000) suggest that the optimal ratio is between 1:15 and 1:20, based on a study of three wetlands in Champaign County, Illinois. Larson et al. (2000) studied wetlands in the same county and found that the wetland with the lowest wetland-to-watershed ratio (1:25) and shallowest water retained the smallest percentage of nitrogen.

The wetland-to-watershed ratio has been used in at least two statewide wetland policies (Table 1). The Minnesota Board on Water and Soil Resources (2009) outlined a GIS approach to prioritizing potential wetland restoration sites for nutrient removal and stated that a one-hectare wetland should preferably have a drainage area of less than five hectares, or a wetland-to-watershed ratio of one to five. Wetlands with a drainage area of more than 20 times their own size were deemed unsuitable for nutrient removal (Minnesota Board on Water and Soil Resources 2009). The report noted that the combination of the multiple benefit ranking complicates the site selection process (Minnesota Board on Water and Soil Resources 2009). In Iowa, Minnesota's neighbor state, it is a requirement that potential nitrogen-removing wetlands

that receive state funding from the CREP program have a wetland-to-watershed ratio between 1:200 and 1:50, meaning that a one-hectare wetland needs to have a drainage area between 50 and 200 hectares (U.S. Department of Agriculture and Iowa Department of Agriculture and Land Stewardship 2009). Applying these two criteria will obviously achieve quite different wetland sites.

Tomer et al. (2011) also used the size of the drainage area as a measure for prioritizing wetland sites for nitrogen removal. Potential wetlands with a drainage area of more than 200 times their own size were precluded from further analysis (wetland-to-watershed ratio of less than 1:200). The remaining potential wetland sites were ranked based on their relative size compared to their drainage area, and therefore the wetlands located farthest downstream were ranked as the most suitable wetlands for nitrogen removal. However, the rankings of wetlands based on the wetland-to-watershed ratio and on their estimated nitrogen removal potential differed from each other. Therefore the drainage area did not seem to be a sufficient measure for targeting optimal wetland locations for nitrogen removal (Tomer et al. 2011).

Without specifying a wetland-to-watershed ratio, Crumpton (2001) emphasizes the importance of wetlands being placed so that they inundate large drainage areas and therefore suggests that watershed endpoints should be considered optimal for nitrogen removal wetlands if these endpoints also receive substantial nitrogen loads. In addition to the wetland-to-watershed ratio, the actual size of a wetland is important as it affects the retention time (Woltemade 2000) and stillness of the water and thus the nutrients' ability to sediment and denitrify (Hansson et al. 2005). Generally there is more turbulence in larger wetlands due to wind disturbance, which favors phosphorus sedimentation rather than denitrification (Hansson et al. 2005). However, there seems to be consensus that wetlands are best placed for high reductions of nitrogen if there

is substantial agricultural runoff with high nitrate concentrations such as from tile drainage (Crumpton et al. 2006, Diebel et al. 2009).

Background

There is a trade-off between wetland efficiency and the mass of nitrogen removed (Woltemade 2000). A wetland that removes a high proportion of the incoming nitrogen (high removal efficiency) does not necessarily remove a large mass (Kovacik et al. 2000, Trepel and Palmeri 2002). Wetlands with high removal efficiency normally retain water for a long time, which requires that the water flux through a wetland be limited (Woltemade 2000). Mass removal is a function of both removal efficiency and the mass flux of nitrogen (Almindinger 1999). With little water flowing through a wetland, the mass of nitrogen flowing through will also be small, which may result in total removal being low even when a wetland is very efficient. Recall that the objective of this study is to maximize nitrogen removal, which depends on both the nitrogen removal efficiency of a wetland and the nitrogen amount flowing through the wetland.

Nitrogen removal efficiency

Total nitrogen (TN) is defined as the sum of organic and ammonia nitrogen (NH_3), nitrate (NO_3^-) and nitrite (NO_2^-). Wetlands reduce nitrogen chiefly from denitrification of nitrate; other ways wetlands can remove nitrogen include sedimentation and biomass sinks (Kadlec and Wallace 2008). Studies have found that 90 percent of total nitrogen removal in wetlands happens through denitrification (Xue et al. 1999). Wetlands' nitrogen denitrification efficiency primarily depends on 1) retention time and 2) the temperature of the soil and water.

Crumpton et al. (2006) found percent nitrate removal can be explained by the hydraulic loading rate $HLR = q = \frac{Q}{A}$ and the nitrogen concentration of influent waters (c_i), where Q is the water flow rate (m^3/d) and A is the wetland area (m^2). They found a nonlinear decreasing relationship between HLR and percent of nitrogen mass removed, as the retention time is negatively correlated with high HLR . The longer the retention time, the higher the removal percentage (Kadlec and Wallace 2008). Mitsch and Gosselink (2007) report that the optimal retention time is between 5 and 14 days for treatment wetlands.

Nitrogen removal is also positively influenced by the total biomass in a wetland because plants slow down the passage of water through wetlands and therefore increase retention time (Kadlec and Knight 1996). Additionally, plants absorb nitrogen as they grow; therefore the removal may in fact be greater than has been suggested in models of denitrification in wetlands. Many wetland plants prefer shallow water of around 30 cm (Mitsch and Gosselink 2007). Shallow water also leads to near-anaerobic conditions that are conducive to the macrophytes that are necessary for an efficient denitrification process (Mitsch and Gosselink 2007). Therefore Mitsch and Gosselink (2007) suggest that wetlands should be designed with an optimal depth of 30 cm. This finding is also supported by Hansson et al. (2005).

Denitrification generally occurs at higher rates during the summer and fall months when the temperature is higher (Kadlec and Wallace 2008) because microbial activity and plant growth are reduced at low sediment and water temperatures (Larson et al. 2000). This relationship has been shown empirically by Xue et al. (1999), who found that a wetland in Champaign County, IL removed five times as much nitrate in June, when the temperature of the water/sediment interface was 25 degrees Celsius, than in February, when the temperature was only 4 degrees Celsius.

The nitrate settling velocity k_A (m/yr) captures how sensitive wetlands' removal potential is to the temperature of the surrounding environment; i.e. the higher the temperature of water and soil, the higher the settling velocity and the higher the removal rate. Kadlec and Knight (1996) report that the settling velocity for nitrate in wetlands ranges from 10.3 -63.0 m/yr; the average value is 15 m/yr when adjusted for temperature and the average settling velocity for a wetland in an area with an average temperature of 20 Celsius is 35 m/yr (Table 2).

Nitrogen flux

The second component to consider when targeting sites for removal of nitrogen is the mass flux of nitrogen through a wetland (Almindinger 1999), which depends on nitrogen concentration and total discharge. Research has found that mass removal of nitrogen in wetlands depends on the concentration of nitrogen in the influent water (Kovacic et al. 2000, Mitsch and Gosselink 2007).

Because influent nitrogen concentrations into wetlands are so important in determining a wetland's removal potential, it is crucial to know the sources of nitrogen pollution in streams and waterways so that one can approximate the concentrations in streams and waterways. It is widely acknowledged that agriculture is a major contributor of nitrogen, primarily in the form of nitrate (NO_3^-), to the waterways in the Midwest, especially in Illinois and Iowa (Goolsby et al. 1999). Particularly high concentrations of nitrate can be found in tile drain effluent; David et al. (1997) found that tile drainage nitrate concentration ranged from 5 mg/L to 49 mg/L, compared to 8-10 mg/L at the reference point of the stream. Logan, Eckert, and Beak (1994) found runoff concentrations to be in the range of 0.3-4.0 mg/L compared to 0.1-17.8 mg/L in tile drainage. According to Fausey et al. (1995), as much as 37 percent of total cropland in the Midwest is tile drained. Tile drainage is especially prevalent in flat terrain, where the fields drain poorly (David

et al. 1997). In general, runoff can be expected to have lower nitrate concentrations than emissions from tile drains. Royer, Tank, and David (2004) suggest that there is a strong relationship between nitrate concentrations and discharge in the Midwest, where much of the agriculture is tile drained. The highest emissions of nitrogen in tile-drained areas have been found to occur during high flood events in the summer and winter (David et al 1997). Crumpton et al. (2006) found that the proportion of land in corn and soy production upstream of a potential wetland site can be used to approximate the nitrate concentration at a given point in a watershed. A nonlinear relationship with the percentage of cropland upstream of a wetland site provides a good fit to empirical flow-weighted nitrate concentrations (Crumpton et al. 2006).

Watershed hydrology

The third component of nitrogen removal from wetlands is the discharge of water at all potential wetland sites. Though river systems can differ with respect to precipitation, temperature and other location-specific characteristics, there are some general relationships that hold for most river systems. Leopold and Maddock (1953) describe some basic properties for stream channels and watersheds in the United States, or what is known as the hydraulic geometry of streams. These properties are still used to estimate values for stream geometry in a wide range of studies, including some that address denitrification in streams (Bernot and Dodds 2005, Böhlke et al. 2009, Melody and Dodds 2005, Wollheim et al. 2006). The basic idea is that the width (feet), mean depth (feet), mean velocity (feet/second) and mean suspended sediment loads at any point on a stream system can be described as a function of the discharge (cfs). Width, depth and velocity increase as discharge increases (Leopold and Maddock 1953).

Other studies have confirmed these general findings as a function of drainage area and frequency of discharge (Stall and Fok 1968) and stream order (Bhowmik 1984). In general,

discharge increases as drainage area increases. Dunne and Leopold (1978) found that it is an acceptable first generalization to consider annual average discharge, Q , as a linear function of drainage area, B (with a z -value, the scaling power, equal to 1):

$$Q = \alpha B^z \quad [1]$$

Galster (2009) reports that z values in many cases are close to 1, which represents a linear relationship between discharge and drainage area. Dunne and Leopold (1978) interpret α as the climate and flood frequency variable; it can be seen as the discharge scaling parameter and also serves to convert the units of discharge (cfs) and drainage area (square miles). In the original model of mean annual discharge [1], a value of α equal to one represents the general relationship for continental North America (Dunne and Leopold 1978)¹. High values of α imply that the drainage area is particularly wet or has a high proportion of impervious surface. Low values of α are found if the drainage area is located in an arid region or in a region where the soil has a high water storage capacity.

To summarize, the important concepts that govern a wetland's ability to remove loads of nitrogen are 1) the time the polluted water is retained in a wetland, 2) the temperature of the soil and water, 3) the nitrate concentration of the influent and 4) the discharge of water for a given wetland. If discharge is high, the retention time will be low, but mass removal may be greater due to the increased loads flowing through a wetland.

¹ To convert the original model of mean annual discharge [1] from the United States Customary System to metric units, one should use $\alpha = 0.3448 \text{ m year}^{-1}$ instead of $\alpha = 1$ to represent the general relationship in Dunne and Leopold (1978):

$$1 \text{ cfs} = 0.0283168466 \text{ m}^3, 1 \text{ cfs} = 893,000.0744 \text{ m}^3/\text{yr}, 1 \text{ square mile} = 2.589.988,11 \text{ m}^2, \text{ therefore } \alpha = \frac{893,000.0744}{2.589.988,11} = 0.3448 \text{ m}^3/\text{yr}$$

Model

In this section I develop a theoretical model to target wetland locations on a watershed scale. The model is an extension of the k - C^* model (Kadlec and Knight 1996, Mitsch and Gosselink 2007). The k - C^* model [2] is a first-order area-based model developed as a design tool to analyze wetlands' ability to remove different pollutants, e.g. total nitrate removal, total phosphorus sedimentation and reduction of suspended solids. One use of the model has been to calculate the size of a wetland required to remove a specific proportion of a pollutant (Mitsch and Gosselink 2007). Though the original k - C^* model was not specifically designed for nitrate (or nitrogen) removal, it can be used for this purpose with appropriate values of the parameters (Mitsch and Gosselink 2007). To keep my model as simple as possible, I use the version that captures the proportion of total nitrogen removal in the form of nitrate and removed through denitrification. Equation [2] is a differential equation that describes the change in nitrate concentration as a function of the time the water is retained in a wetland:

$$q \frac{dc}{dy} = k_A(C - C^*) \quad [2]$$

where k_A is the settling velocity of nitrate (m yr^{-1}) and C and C^* are the concentration and the irreducible background concentration of nitrate in the water (g m^{-3}).² Following Mitsch and Gosselink (2007), we can integrate over the fractional distance water travels through the wetland y (m) to get the change in nitrate concentration. When water enters a wetland, y is equal to zero and the nitrate concentration (C_i) is represented by the influent concentration. When the water exits a wetland, y is one and the nitrate concentration is represented by the effluent concentration (C_o)

² In the original k - C^* model, the concentration was measured in mg L^{-1} .

$$\begin{aligned}
\int_0^1 q \frac{dC}{dy} &= \int_0^1 k_A (C - C^*) \\
q \int_0^1 \frac{1}{(C - C^*)} dC &= k_A \int_0^1 dy \\
q [\ln(C - C^*)]_0^1 &= k_A \\
q (\ln(C(1) - C^*) - \ln(C(0) - C^*)) &= k_A \\
q (\ln(C_o - C^*) - \ln(C_i - C^*)) &= k_A \\
-\ln\left(\frac{C_o - C^*}{C_i - C^*}\right) &= \frac{k_A}{q} \\
\frac{C_o - C^*}{C_i - C^*} &= e^{(-\frac{k_A}{q})} \tag{3}
\end{aligned}$$

To get the concentration change of a wetland of a given size, one can substitute the hydraulic loading rate q (m day^{-1}), with $q = \frac{Q}{A}$, where Q is the discharge ($\text{m}^3 \text{ day}^{-1}$) and A is the wetland size in (m^2):

$$\frac{C_o - C^*}{C_i - C^*} = e^{\left(-\frac{k_A}{Q/A}\right)} \tag{4}$$

Assuming $C^* = 0$, meaning that all nitrate can be removed by a wetland, I obtain the proportion of the influent nitrate that remains in the effluent after exiting a wetland, denoted by γ . Several studies suggest that $C^* = 0$ is not an unreasonable assumption for nitrate removal (Kadlec and Knight 1996, Mitsch and Gosselink 2007).

$$\gamma = \frac{C_o}{C_i} = e^{\left(-\frac{k_A}{Q}\right)} \tag{5}$$

Now I take the model [5] as it was developed in Kadlec and Knight (1996) and Mitsch and Gosselink (2007), combine it with a mathematical relationship of discharge and extend the model's usage to analyze nitrate removal for wetlands located in different places in a watershed [6-8]. Subtracting γ from 1 gives the proportion of nitrate removed or retained of the nitrate flowing through a wetland. Substituting Dunne and Leopold's (1978) basic hydraulic geometry relationship for the average discharge (cfs) as a function of the size of drainage area B (square miles), we get

$$\begin{aligned}(1 - \gamma) &= 1 - e^{\left(\frac{k_A * A}{\alpha B^Z}\right)} \\ &= 1 - e^{\left(-\frac{k_A * A}{\alpha B}\right)}\end{aligned}\tag{6}$$

I have assumed the scaling power (z) to be 1, which is consistent with the literature; α represents the scaling relationship between the drainage area and the discharge.

To find R , the annual mass removal of nitrogen (represented by nitrate) as a function of a wetland's location in a watershed, I multiply the removal rate of nitrate [6] by the mass flowing through a wetland during a year. Here I assume nitrate removal to be a function of the proportion of nitrate that is retained in a wetland and the mass flux of nitrate flowing through a wetland:

$$R = (1 - \gamma)\alpha B * c_i(B)\tag{7}$$

where c_i , the inflow concentration (g m^{-3}), is a function of the proportion of drainage area B that is in agricultural production. As described in the background section, the greater the proportion in agricultural production, the higher the nitrate concentration in streams. Removal is a linear function with respect to the influent concentration but is nonlinear with respect to the size of the drainage area. The relationship governing the total removal can be denoted as

$$R = \alpha B c_i - \gamma \alpha B c_i\tag{8}$$

which is the total mass flowing into a wetland minus the amount leaving it. R captures the basic relationships that govern nitrate removal, including inflow of nitrate concentrations and mass flux, the amount of nitrate that settles in a wetland at different temperatures and the distance (and time) the polluted water travels through a wetland. Differentiating removal with respect to the drainage area, we can determine the optimal location in a watershed for a wetland of a given size. The derivative gives us the marginal change in nitrate removal for a one-unit change in the size of drainage area for a wetland of a given size A . As long as the derivative is positive, it is beneficial to construct a wetland farther downstream; if the derivative is negative, locating a wetland farther downstream would lead to reduced nitrogen reduction, and if the derivative is zero, moving a wetland farther downstream will not change its removal potential:

$$\begin{aligned}
\frac{dR}{dB} &= \alpha c_i + \alpha B c_i' - \left(\gamma \alpha c_i + \gamma \alpha B c_i' + \gamma \frac{k_A A}{\alpha B^2} \alpha B c_i \right) \\
&= (1 - \gamma) \alpha c_i + (1 - \gamma) \alpha B c_i' - \gamma c_i \left(\frac{k_A A}{B} \right) \\
&= (1 - \gamma) \alpha B c_i' + \alpha c_i \left[1 - \gamma \left(1 + \frac{k_A A}{\alpha B} \right) \right] \\
&= \left(1 - e^{\left(-\frac{k_A A}{\alpha B} \right)} \right) \alpha B c_i' + \alpha c_i \left[1 - e^{\left(-\frac{k_A A}{\alpha B} \right)} \left(1 + \frac{k_A A}{\alpha B} \right) \right] \tag{9}
\end{aligned}$$

Equation [9] is the relationship upon which the majority of my analysis relies. The relationship can be interpreted as the marginal change in removal of nitrate when nitrate concentration changes throughout a watershed, plus the change in the mass of nitrate passing through a wetland in a specific climate, minus the wetland's ability to retain nutrients for a given amount of nitrate flux through a wetland in a specific climate. An alternative interpretation would be that the two terms represent the marginal change in removal as the concentration changes with the drainage area, plus the marginal change in removal as the amount running through the wetland changes with drainage area for a given climate.

To analyze marginal change in removal with respect to the size of the drainage area, I have assumed that a wetland of size A can be constructed anywhere in a watershed, that the discharge is non-stochastic and that wetlands remove nitrate at their maximum rate at all times. Recall that $\gamma = e^{\left(-\frac{k_A A}{\alpha B}\right)}$, and since we know k_A (wetlands' ability to settle nitrate in a given climate), α (precipitation), B (drainage area) and A (wetland area) are all non-negative values, γ must belong to $[0,1]$; as the drainage area goes to infinity, the term $\frac{k_A A}{\alpha B}$ goes to zero and γ goes to one. The influent concentration (c_i) is non-negative. Therefore the second term $\left(\alpha c_i \left[1 - e^{\left(-\frac{k_A A}{\alpha B}\right)} \left(1 + \frac{k_A A}{\alpha B}\right)\right]\right)$ in equation [9] converges to zero (and remains non-negative) as the drainage area converges to infinity. The first term $\left(\left(1 - e^{\left(-\frac{k_A A}{\alpha B}\right)}\right) \alpha B c_i'\right)$ therefore determines whether the change in removal with drainage area is positive, negative or zero. As the drainage area increases, the removal rate, represented by the term $\left(1 - e^{\left(-\frac{k_A A}{\alpha B}\right)}\right)$, approaches zero, but at the same time the discharge at a given point in a watershed (αB) increases with the drainage area, so this term is positive. This leaves only one term that can be positive, negative or zero and thus determines if the entire equation [9] is positive, negative or zero: the marginal change in concentration for a one-unit change in drainage size (c_i'). If the change in nitrate removal with respect to a change in drainage area $\left(\frac{dR}{dB}\right)$ is negative, there may be an optimal wetland location in a watershed other than at the bottom of the watershed. In the limit, as the size of the drainage area (B) approaches zero, or more correctly the size of the wetland (A), the marginal change in nitrate removal with respect to the size of the drainage area $\left(\frac{dR}{dB}\right)$ attains its maximum value. The first term in equation [9] $\left(\left(1 - e^{\left(-\frac{k_A A}{\alpha B}\right)}\right) \alpha B c_i'\right)$ approaches zero, and the second term

$\left(\alpha c_i \left[1 - e^{\left(-\frac{k_A A}{\alpha B} \right)} \left(1 + \frac{k_A A}{\alpha B} \right) \right] \right)$ goes to (αc_i) , which is the highest change in removal with respect to the size of the drainage area. Therefore $\left(\frac{dR}{dB} \right)$ is continuous for the range of drainage areas between the wetland size and a potential zero crossing if the concentration change with drainage area (c'_i) , is negative.

From numerical analysis it can be confirmed that the second-order conditions for removal with respect to the size of the drainage area is always negative if c'_i is zero or positive. When the concentration decreases downstream, the second-order condition is negative for drainage areas smaller than the optimal drainage areas for a wetland of a given size; therefore the removal for the optimal drainage area size constitutes a global maximum.

With the above discussion in mind, consider the following three cases (Table 2):

Case 1) $c'_i > 0$

The nitrate concentration increases downstream ($c'_i > 0$). Consider a watershed where a larger share of the land is occupied by agriculture downstream than upstream and the proportion of land in agricultural production is therefore increasing downstream. Recalling that the proportion of upstream land in agricultural production is positively correlated with nitrate concentration, the nitrate concentration would increase downstream in a watershed such as the one just described. Some possible explanations for why a larger proportion of downstream areas in a watershed may be in agricultural production could be that downstream areas in a specific watershed may be less hilly and therefore less prone to erosion and easier to farm or simply because land downstream is sometimes more fertile.

When nitrate concentration increases downstream, the first term in equation [9] will never be negative and the marginal change in nitrate removal with area will never be negative. Moving a

wetland farther downstream will always increase its nitrate removal potential. It is therefore optimal to push a wetland to the bottom of a watershed, giving a corner solution.

Case 2) $c'_i = 0$

The nitrate concentration in streams may be constant throughout a watershed ($c'_i = 0$) if the proportion of agricultural land stays constant throughout the watershed. As in the case where the concentration increases downstream, a wetland located in the bottom of a watershed has the highest nitrate removal potential of any location in a watershed when nitrate concentration is constant throughout the watershed. The optimal location is therefore also a corner solution when the concentration is constant.

The important lesson from cases 1) and 2) is that if concentration stays constant or increases downstream, it is optimal to push wetlands to the bottom of a watershed, or as far down as possible. The intuition behind this result is that though a smaller proportion of nitrate coming through a wetland is retained downstream, the increase in nitrate load as a function of the larger discharge more than compensates for the reduced efficiency.

Case 3) $c'_i < 0$

The concentration would decrease downstream ($c'_i < 0$) in a watershed where the attractive agricultural lands are located upstream or if there are streams and sources that add water with lower nitrate concentrations to the streams and thereby dilute nitrate concentrations. An alternative situation would be if downstream areas are urban areas with little diffuse nitrate pollution, and so the nitrate concentration could decrease downstream.

In this case there may be an optimal location of a nitrate-removing wetland in a watershed. For small drainage areas, relative to the wetland size, there will be benefits to moving a wetland farther downstream; however, as the drainage area increases, the marginal change in removal

approaches a very small negative number. For drainage area sizes beyond a specific point, a wetland's ability to remove nitrate will be reduced. Determination of the point where marginal nitrate removal becomes negative is an empirical question and will depend on k_A , which is temperature dependent; α , which is dependent on precipitation; the target size for the wetland (A) and the marginal change in concentration (c'_i) in the specific setting.

Graphical analysis

In this section I will present the basic analytical results from stylized simulations of the marginal change in removal and the change in removal per square meter of wetland with respect to a change in the size of the drainage area. Only one parameter is changed at a time for the graphical simulations. I explore some different values for the parameters in the model reported in the literature and observed in nature. I simulated values for k_A ranging from 10.3 to 35 m/yr and the mean of 22.65 m/yr, which reflects the extremes of the most likely values from the settling velocity reported in the literature (Table 2). The scaling parameter for drainage area and discharge, α , was simulated for the general relationship between drainage area and discharge for the U.S., $0.3448 \text{ m}^3 \text{ yr}^{-1}$, half ($0.1724 \text{ m}^3 \text{ yr}^{-1}$) and twice the general relationship ($0.6896 \text{ m}^3 \text{ yr}^{-1}$). The low and high values of α were arbitrarily chosen to represent a very dry and very wet watershed. They could have been simulated for larger or smaller non-negative values, however, without providing further insights into the effect of precipitation and runoff. In the analysis I also varied the wetland size between 1000 square meters and 100 hectares. The stream nitrate concentrations reflect a wide range of average nitrate concentrations (Logan, Eckert, and Beak 1994) and range from a low of 2.2 mg/L to a high nitrate concentration of 13.2 mg/L. Increasing the highest concentration and lowering the lowest concentration would not alter the qualitative

results. Lastly, the values for the concentration change were of the same order of magnitude as the values estimated for Big Bureau Creek Watershed in Illinois, described in the next section.

The general pattern is that a wetland of a given size removes very little nitrate for very small drainage areas, but that the marginal increase in nitrate removal of moving a wetland downstream is largest when drainage areas are small. As a wetland is moved downstream and the discharge increases, the marginal change in removal decreases and goes to zero, suggesting that at some point there will be no or very limited additional benefits from moving the wetland farther downstream. In the base scenario there will be only limited additional benefits beyond a wetland to drainage area ratio of 1:400, which means that a one-hectare wetland does not need to have a larger drainage area than 400 hectares to approach its maximum removal potential (Figure 1a). In all three cases there will be a point in a watershed where the benefits from pushing a wetland farther downstream will be limited because the marginal change in nitrate removal with respect to the size of the drainage area is very close to zero. The exact point where there are limited benefits from moving a wetland downstream differs from watershed to watershed.

As previously explained, we can find c'_i to be greater than zero (case 1), equal to zero (case 2) and less than zero (case 3); regardless of the sign, the general shape of the curve of the marginal change in nitrate removal follows a similar pattern, with high removal rates for small drainage areas and a gradual decrease in the removal rate as the drainage area increases (Figure 1f). However, if the concentration decreases throughout a watershed ($c'_i < 0$) (case 3), there will be decreasing nitrate removal per square meter for drainage areas greater than 5,000 hectares (50 km²) (Figure 2), meaning that a one-hectare wetland should not have a larger drainage area than 5,000 hectares for the given set of parameters. For cases 1 and 2, the nitrate removal will not

decrease for any size of drainage area (Figure 2); therefore wetlands should be located at the bottom of the watershed in those cases. This can be considered a corner solution.

Wetlands should not be located in the same place in a watershed in two different precipitation zones or in watersheds where the soils have distinctly different abilities to retain water. Changing the discharge scaling parameter (α), which can be interpreted as a precipitation or soil moisture parameter, demonstrates this change in optimal sites for nitrate removal wetlands (Figures 1c and 3). When α is equal to 0.3448, the mean relationship between drainage and discharge is as previously described, α greater than 0.3448 means particularly wet areas or a watershed with many impervious surface areas or a high proportion of tile-drained agriculture, and α less than 0.3448 $\text{m}^3 \text{yr}^{-1}$ occurs in dry watersheds or watersheds where the soil retains a high proportion of the precipitation. Wetlands should be located relatively far upstream in a wet area watershed compared to a dry watershed as the wetland would need a smaller drainage area to be saturated with water (Figure 3). Furthermore, there will be very few additional benefits from pushing a wetland downstream in wet areas; therefore the recommended wetland-to-watershed ratio should be much smaller in a dry area, all else being equal, i.e., a wetland should be smaller relative to the drainage area in a dry watershed than in a wet watershed.

The location of a watershed is generally not sensitive to the influent nitrate concentration (Figures 1e and 4). However, given a choice between two streams in the same watershed with significantly different nitrate concentrations, a wetland designer should target the stream with the highest concentration as this would achieve most benefits in the form of substantially higher levels of mass removal of nitrate per square meter wetland, all else being equal. An interesting implication of this finding is that one should locate a wetland upstream of a point source, under the condition that the point source is tightly regulated and emits effluent with a lower

concentration than the stream water and that its emissions therefore dilute the stream concentration at the outlet.

Wetlands of different sizes should also be targeted in different locations in a watershed (Figures 1b and 5). Small wetlands should preferably be located upstream and larger wetlands should be located farther downstream. The intuition behind this result is that for the removal processes to occur, a wetland needs to be wet and nitrate needs to flow to the wetland; as an example, a wetland of 10 hectares should have a drainage area in excess of 4,000 hectares to achieve its maximum removal potential per square meter of wetland or a wetland-to-drainage area ratio of 1:400 (Figure 5a).

The settling velocity represents a wetland's ability to retain nutrients: in the case of nitrate, one would find high settling velocities in warmer areas ($k_A=35 \text{ m yr}^{-1}$) and lower values in colder climates ($k_A=10.3 \text{ m yr}^{-1}$). Wetlands in watersheds with a warm climate will be able to remove larger nitrate loads, but at the same time it is still more beneficial to increase the wetland-to-watershed ratio in warm areas than in a cold climate (Figure 1d). Intuitively, this result can be explained in that there will be additional benefits from adding more nutrients to a more effective wetland. To compare the wetland-to-watershed ratio from my model, I calculated and graphed the optimal ratio for case 3, where the nitrate concentration is decreasing downstream ($c'_i < 0$), for three different values of k_A (Figure 6). As can be seen, wetlands with a higher settling velocity (k_A) have a lower wetland-to-watershed ratio than do wetlands with a lower settling velocity; a high k_A can mean that a wetland located in a warmer climate is more conducive to denitrification. Therefore it is beneficial to construct wetlands farther downstream in a warmer climate as they remove nitrate more effectively (see also Figure 1d). If they are in an area with relatively high precipitation, wetlands should have relatively smaller drainage areas. In general

the ratios found in this simulation of wetland-to-watershed ratios are sensitive to the choice of parameters. When the nitrate concentration decreases downstream (case 3), larger wetlands should be designed and located so that their drainage areas are relatively smaller than those of small wetlands (Figure 6c). The wetland-to-watershed ratios ranged from approximately 1:2000 to 1:200, meaning that a wetland of one hectare needed 2,000 hectares of drainage area, but a wetland of 100 hectares only needed 20,000 hectares of drainage area in a watershed where the concentration was decreasing downstream. The wetland-to-watershed ratios in this study are substantially smaller than the ones reported in the literature (Table 1) though the largest ratios from this study do compare with some from the literature (Tomer et al. 2011, Woltemade 2000).

This variation in optimal wetland-to-watershed ratios for wetlands of different sizes under different stream nitrate concentration conditions further highlights that if wetland-to-watershed ratios are used to target optimal sites for nitrate removal, they should be carefully chosen for a specific watershed. The main insight from the simulations performed is that sites for wetlands should be targeted differently on a watershed scale in the following cases: 1) when wetlands vary in size, 2) when areas vary in precipitation and involve soils with varying capacities to retain water, 3) when wetland areas have different settling velocities (which can capture temperature differences) and 4) when stream nitrate concentration varies throughout a watershed (Figures 1a-f). Therefore there are good reasons to apply different wetland-to-watershed ratios depending on the targeting criteria; there is support for the various ratios that have been used in the literature (Table 1). However, the ratios I found do not support the large wetland-to-watershed ratios found in the literature. This result is of course sensitive to the choice of values for the additional parameters in the model and should therefore not be applied blindly; still, there may be benefits

from constructing wetlands with smaller wetland-to-drainage area ratios than those that have previously been suggested in the literature.

Application to an Illinois watershed

In the second part of this section I present and discuss an empirical application of the model to the Big Bureau Creek Watershed in Illinois. First I briefly describe the watershed, which is representative of many watersheds in the Upper Mississippi River basin, and then I describe the data used in the model. Finally I present and discuss the results from the site-specific application of the model.

Study area

The study area I chose was Big Bureau Creek Watershed, which is located in northeastern Illinois. The major waterway running through the watershed is Big Bureau Creek, a tributary to the Illinois River; the average drop of the creek is 7 feet per mile, and the steepest areas can be found in the bottom of the watershed (Figure 7). The watershed drains 499 square miles of land (129,240 hectares) that is primarily in corn and soybean rotation (U.S. Department of Agriculture 2009). Sugg (2007) estimated that approximately 60 percent of Bureau County, which covers the majority of Big Bureau Creek Watershed, is tile drained. The area has a sparse population, in the range of 40.9 persons per square mile (U.S. Department of Commerce 2000).

A report by the Illinois Department of Natural Resources (2006) found that the water quality here is of particular concern with respect to nitrogen, phosphorous, fecal coliform bacteria, flood frequencies, erosion and sediment transportation and poor riparian quality. Many of these problems originate from agriculture. The report gave a number of recommendations on how to

reduce the impact of agriculture on water quality, including restoring and constructing hundreds of acres of wetlands in the watershed (Illinois Department of Natural Resources 2006).

Data

Two kinds of data were used for this study: drainage area size calculated from geospatial data and modeled influent nitrate stream concentrations for the part of Big Bureau Creek Watershed within Bureau County, Illinois. Descriptive statistics can be found in Table 4, the spatial distribution of the nitrate concentrations and size of the drainage areas can be found in Figure 8 and the data are plotted in Figure 9. The geospatial data were provided by the Wetlands Initiative, and the nitrate concentrations were estimated by Dr. Crumpton at Iowa State University.

Before we calculated the drainage areas and estimated the nitrate concentrations, we used the Public Land Survey System (PLSS) to divide the entire study area into sections of one square mile; these sections served as our unit of observation of drainage areas and nutrient concentrations, which will now be referred to as receptor points. In total there were 211 potential receptor points suited for constructed wetlands within the study area. We selected the receptor points that were suited for wetlands using detailed DEM-10 meter data (U.S. Department of Agriculture 2010) containing information on the elevation of every 10-by-10 meter square in the study area. We applied three general criteria to assess the suitability of each 10-by-10 meter area for a wetland 1) there was a stream within 100 meters of the square point, 2) water was flowing to that point and 3) there were no land-use conflicts for the particular square. To test whether there was a stream within a 100-meter radius, we generated 100-meter-wide buffers around all the streams (National Atlas) and selected each 10-by-10 meter square within the buffer. For all of these squares we calculated the Topographical Positioning Index (TPI) and selected all of the

squares with a negative TPI, indicating that water was flowing to the square. From these squares, we excluded those that were located in areas classified as coniferous forest, low to high urban density or open urban areas. If all three requirements were fulfilled for at least one 10-by-10 meter square within a receptor point, it was considered suited for a wetland and we proceeded with the analysis by calculating the size of the drainage area and the nitrate concentration for the receptor point.

We selected the square with the lowest elevation within each section as the point at which to calculate the drainage area. The drainage area of each receptor point was also calculated from the DEM-10 data using the Arc Hydro extension packet for ArcMap (ESRI 2010). The size of the drainage areas ranged from 0.29 to 1270 million square meters (29-127,000 hectares) with a mean of 140 million square meters (14,000 hectares). All data and maps were projected to UTM-16.

The nitrate concentrations were provided by Crumpton, and estimated following the method described in Crumpton (Forthcoming) using current land-use data of areas in corn and soy rotations and the size of the upstream drainage areas for the wetland. The method is an extended and improved version of the one used in Crumpton et al. (2006) in which they found that the *HLR* does not explain mass reduction of nitrate very well and that there is a large variation in mass removal as a function of *HLR*. Instead, Crumpton et al. (2006) estimated mass removal as a function of the *HLR* and the flow-weighted average nitrate concentration. The same method of mass removal from wetlands was also used in Tomer et al. (2011), who estimated nitrogen removal to increase with higher nitrate concentrations and higher *HLRs* but found that the increase in removal as a function of *HLR* attenuated for higher *HLRs*. Other researchers have found that removal of nitrate is a function of the concentration of nitrate in the influent (Kovacic

et al. 2000, Mitsch and Gosselink 2007). I assumed that the concentration at a receptor point where 100 percent was in corn and soy rotation would be 15 mg/L. The 211 potential wetland sites I have data for cover a wide range of nitrate concentration and drainage area sizes (Table 4). The inflow nitrate concentrations ranged from 2.44-14.71 mg/L with a mean concentration of 12.23 mg/L, and the drainage areas ranged from 30 to 127,000 hectares.

Plotting the nitrate concentration in relation to the drainage area (Figure 9), we can see that there is great variation in both concentration and drainage area. For smaller drainage areas, there is particularly great variation in concentration, ranging the entire span from 2.44-14.71 mg/L; the larger the drainage area, the smaller the variation in the nitrate concentration. In Figure 9 there are six clusters of data points; these can be interpreted as receptor points in streams of different orders. To estimate the marginal change in nitrate concentration throughout the watershed (c'_i), I performed linear regressions for data points in the six clusters (Table 5).

After the concentration change was estimated for the six clusters of data in Figure 9, I calculated the nitrate removal and marginal change in nitrate removal with respect to a change in the size of the drainage area using equations [7] and [9]. As a scaling parameter between the drainage area and discharge, I used $\alpha = 0.3448$. The settling velocity was found by pairing independently observed estimates of removal from Crumpton (2011) with my estimates and minimizing the squared difference between the nitrate removal estimates. The minimum squared difference was found for a settling velocity of 15.50 m yr^{-1} .

Results from Big Bureau Creek Watershed

Analyzing the empirical data from Big Bureau Creek Watershed in a similar fashion to the graphical section, I found that targeting the location of a wetland on a wetland scale can have significant implications with respect to how much nitrate a similarly sized wetland can remove

(Figure 10). Because the concentration decreases downstream in Big Bureau Creek Watershed, it would be optimal to target wetlands upstream in the watershed. Installing a wetland at the optimal location upstream compared to the location farthest downstream with the largest drainage area can result in additional 20 g nitrate removal per square meter of wetland per year: for a wetland of 1 hectare, this means 200 kg nitrate per year (Figure 10b).

Because the concentration decreases downstream ($c'_i < 0$), the marginal change in nitrate removal with respect to drainage area is negative for large parts of the drainage area and therefore it is generally preferable to locate a wetland such that the drainage area is no larger than 5,107 hectares (51.07 km²). The turning point where there is a decreasing nitrate removal from larger drainage areas will of course change for wetlands in other settings with different values for the other parameters (wetland area A , α and k_A), but a wetland planner should take note of the possibility that putting a wetland too far downstream could have negative consequences for total nitrate removal. This reduced nitrate removal potential downstream can be explained by the reduced removal efficiency downstream due to the higher flux and therefore shorter retention time and concentration reductions downstream.

In addition to illustrating the effect of decreasing concentrations throughout a watershed, the data from Big Bureau Creek also provide another interesting result: the nitrate removal per square meter of wetland upstream can vary by a factor of six; the total nitrate removal can therefore be highly uncertain for small wetland-to-drainage area ratios (Table 6). The smallest variation in estimated nitrate removal is found for wetlands located with a drainage area between 10,500 to 20,000 hectares where the wetlands also are quite efficient compared with other ranges of drainage area. The highest nitrate removal, however, is found for very small drainage areas (Table 6). This is likely a function of the influent concentration at the potential wetlands sites

(compare Figures 9 and 10). Though Big Bureau Creek Watershed exhibits decreasing concentrations of nitrate downstream, some of the tributaries far upstream have low nitrate concentrations and therefore also remove very little nitrate as they have not only low discharges but also low nitrate concentrations. Therefore it is important to choose upstream sites with the highest influent concentrations in order to maximize nitrate removal in a watershed like Big Bureau Creek Watershed. Based on the data available, it appears that there is a trade-off between certainty in nitrate removal and maximization of removal.

Confirmation that the model presented in this thesis predicts nitrate removal quite well can be found in Figure 11a, where my results have been plotted against independent nitrate removal estimates (Crumpton 2011). For smaller drainage areas, my model systematically underestimates the nitrate removal potential for wetlands (positive differences in Figure 11b), but for drainage areas larger than 1,000 hectares, the two estimates are quite close. For drainage areas larger than 3,000 hectares, my model slightly overestimates the removal potential compared to the independent estimates (negative differences). There were no independent estimates available for drainage areas larger than 11,000 hectares (110 km²), but because the concentration decreases downstream in Big Bureau Creek Watershed, it would not be beneficial to construct a wetland that far downstream in any case. A further comparison of my estimates for nitrogen removal to the independent estimates can be seen in Figure 12, where the differences in the estimates have been plotted in three dimensions, with the influent concentration and size of the drainage as the explanatory variables. The greatest difference is found in the estimates for the highest influent concentrations in the smallest drainage areas.

Overall the nitrate removal potential that was estimated from the model in this thesis performed well relative to the independent estimates, and the general patterns of changes in

nitrate removal with respect to a change in drainage area were confirmed. This application to an agricultural watershed in the Upper Mississippi River Basin suggests that the model can have practical applications to site constructed wetlands and as a simple method for estimating the nitrate removal potential of wetlands for other management purposes.

Discussion of results

There are four major contributions from this thesis that can potentially lead to better wetland siting strategies on a watershed scale. First, a wetland should be relatively small compared to the size of the area that drains to it if the concentration of nitrate is increasing downstream or is constant. Only when the nitrate concentration decreases downstream may it be beneficial to locate a wetland so that it has a relatively small drainage area. Second, going back to the first principles in analyzing how removal of nitrate changes as a function of a wetland's location on a watershed scale, I showed how variation in climate and geophysical characteristics of a watershed determines the optimal location of a wetland. Therefore it is not always possible to transfer rules of thumb from one watershed to another. However, the third important finding from this research is that the model can be used to complement rules of thumb currently used to target wetland locations on a watershed scale. Fourth, the model of nitrate removal potential on a watershed scale performed quite well compared to independent estimates of nitrate removal for the same locations. The difference in nitrate removal between the two methods was largest for small drainage areas, but as the size of the drainage area increased, the difference between the estimates became smaller.

Of these four major results from this study, the first and fourth deviate particularly from previous research and therefore need to be discussed further. The wetland-to-watershed ratios I

found in this study were significantly smaller than those in previous research (Table 1), implying that wetlands should be constructed relatively further downstream than what had been recommended in the past. As in previous studies, I found that there can be a large variation in what the optimal ratio should be, but overall the ratios presented in this study are comparatively smaller than the ones from the literature. The specific ratios are sensitive to the choice of parameters. There can be several possible explanations for the discrepancy between the ratios in this study, the ratios used to target areas and the ratios reported in the literature on constructed wetlands. David et al. (1997) found that much of the nitrate runoff from fields occurs during high flood events and therefore cannot be taken as an annual average. If much of the nitrate is delivered as pulse inputs to wetlands when discharge is high and not as a continuous delivery, the wetland should be designed for treatment of the pulse events rather than for the annual average. All else being equal, building wetlands for pulse events would require relatively larger wetlands or that the wetlands be constructed upstream in a watershed, i.e. the wetland-to-watershed ratio would be greater than what has been suggested in this study. Two possible methods to improve the model's ability to target wetland locations for pulse events would be either to integrate over removal as a function of the annual distribution of both nitrate concentration and discharge or to use the maximum annual discharge instead of the annual mean discharge as a function of the drainage area. In either case the wetland-to-watershed ratios would be closer to the ratios in the literature. Another possible explanation for why I found that wetlands should be located relatively further downstream is that the extrapolation of the original $k-C^*$ -model to the application in this study does not predict load removal accurately enough. As was seen in the comparison with the independently estimated nitrate removal for Big Bureau Creek Watershed, my model estimates compared very well for drainage areas larger than 100

hectares. Below 100 hectares my model systematically underestimated the nitrate removal potential compared to the independent estimates, which could also impact the recommendations on optimal wetland locations. If the removal potential was in fact greater for smaller wetlands than what was found in this study, the recommendations on wetland-to-watershed ratios would change and wetlands should be constructed relatively larger to optimize nitrate removal.

The model's ability to predict mass removal of nitrate from wetlands compared quite well to independent estimates calculated from flow-weighted average concentrations and assumptions on the *HLRs* and the removal rate for potential wetland sites. However, the model developed in this thesis did not compare equally well in all ranges of drainage area. In particular for wetlands located in smaller drainage areas, there was a discrepancy between the results from the two models, where the results from my model were comparatively smaller than the independent estimates. In my model nitrate removal was a function of mass flux of nitrate flowing through a wetland and the removal efficiency at a given point in a watershed. Because the flux of nitrate is not very large for wetlands located upstream, the high influent nitrate concentrations in some of the wetlands may be insignificant because the discharge is so low, even though the removal efficiency will be high. Therefore the total nitrate removal estimated in my model may be small for polluted drainage areas located upstream (Figure 11).

In this thesis I have focused on targeting the benefits that accrue from installing wetlands at various locations in a watershed, but the cost of installing wetlands at these locations should also be considered to target the optimal location from a net benefit perspective that optimizes societal benefits (Babcock et al. 1996 and 1997). The total cost of installing wetlands consists primarily of three components: the opportunity cost of land taken out of production, design costs and construction costs of the wetland (Lentz 2011). The construction cost will vary with the

landscape. If there are natural inundations of a site, the construction cost may be lower than if a site does not have any natural borders and therefore requires levees and dams to contain the water. Furthermore, the opportunity cost of taking land out of production also depends on the landscape. More fertile fields will have higher opportunity costs, and fields with flatter slopes tend to have a higher opportunity cost (Lentz 2011). Therefore watersheds where nitrate concentration increases downstream (case 1), as a function of a higher proportion of land in agricultural production, will most likely also face higher opportunity costs downstream, and the construction cost will likely be higher as well. This will increase the optimal wetland-to-watershed ratio, and it will then no longer be optimal to push wetlands all the way to the bottom of a watershed. If nitrate concentration decreases downstream (case 3) as a function of a smaller proportion of the drainage area in agricultural production, the optimal site in a watershed may also change. If downstream areas are used for urban development, the opportunity cost will likely be higher downstream and wetlands should optimally be located higher in a watershed with a greater wetland-to-watershed ratio. If downstream areas are less attractive for farming, as in the Big Bureau Creek Watershed, it may be optimal to locate the wetland farther down than what is optimal from a biophysical perspective.

A few of the assumptions I used in the model development need discussion. In this study I assumed a linear relationship between nitrate removal and concentration and a nonlinear relationship between nitrate removal and drainage area. Research has suggested that mass retention as a linear function of mass load and retention rate overestimated mass removal for downstream wetlands (Trepel and Palmeri 2002). Similarly, Woltemade (2000) found that large drainage areas diminish the water quality improvements without specifying whether the improvements were due to smaller nitrate loads downstream or lower nitrate concentrations.

Assuming that nitrate can be removed completely ($C^* = 0$) may also lead to overly optimistic estimates of total removal, and it has also been suggested that the k - C^* model is too simple to capture real removal potential (Kadlec and Wallace 2008). Furthermore, a wetland needs to be customized for a specific site (Tomer, James, and Isenhardt 2003), and it may be incorrect to assume that a wetland of a given size can be located anywhere. Lastly, applying this model to site wetland locations in a heavily tile-drained agricultural watershed may be easier said than done. When the exact locations of tile drains are not known, it can be difficult to estimate the size of a tile-drained area accurately (Crumpton et al. 2005); therefore it can be difficult to estimate accurately discharge as a function of drainage area because the size of the tile-drained area is unknown.

Irrespective of the limitations and necessary assumptions underlying the model to site wetland locations on a watershed scale and estimate nitrate removal as a function of drainage area, the model provides a useful method to improve the rules of thumb for constructed wetland siting. Furthermore, the model can easily be adjusted to different settings with a different set of assumptions. It may even be possible to adapt the model to site constructed wetlands for removal of other pollutants such as suspended solids and phosphorus.

Conclusion and policy implications

In this thesis I utilized two well-established basic relationships that describe 1) wetlands' ability to remove nitrate and 2) discharge at a given point in a watershed. These two relationships were combined into a theoretical model of nitrogen removal as a function of location in a watershed. Afterwards the model was analyzed from first principles to enhance the understanding of wetlands' nitrate removal potential as a function of their location on a

watershed scale. In particular, four results from this thesis may lead to better siting of wetlands on a watershed scale in the future: First, if the nitrate concentration increases downstream or is constant throughout a watershed, a wetland should be constructed in the bottom of a watershed. Only if the concentration decreases downstream would it be better to locate the wetland relatively farther upstream. Second, wetland-to-watershed ratios used as rules of thumb to site wetland locations should be site specific, depending on the nitrate concentration in a watershed, the temperature and the relationship between the drainage area and discharge. Third, the model developed in this thesis of the marginal change in nitrate removal with respect to a change in the size of the drainage area can be used to develop site-specific ratios to target wetland locations. In order to develop site-specific ratios, a wetland planner should determine whether the nitrate concentration is decreasing downstream. If the concentration is decreasing downstream, the model of the change in nitrate removal as a function of the drainage area can be used to approximate the optimal location on a watershed scale for the relevant set of parameters of α , k_A and the wetland's size. Fourth, wetlands' mass removal potential of nitrate can be estimated from site-specific data on the size of the drainage area, the relationship between drainage area and discharge, the nitrate concentration in the stream and the settling velocity.

In addition to the four major results summarized above, the graphical analysis of the change in removal with respect to the size of the drainage area and the nitrate removal also provide useful insights on some specific actions a wetland planner can take in different settings. For instance, wetlands in high precipitation areas should generally be located relatively farther upstream in a watershed than wetlands in drier areas, as they require a smaller drainage area to fill sufficiently to the point of removing nitrate. Given a choice between two streams in the same watershed that differ in nitrate concentrations, a wetland planner should choose the stream with

the highest concentration because the flux of nitrate flowing through the wetland will be higher and therefore the nitrate removal will also be higher, all else being equal. When nitrate concentrations are high, there will be additional benefits from pushing wetlands downstream because the removal efficiency does not drop quite as fast as it does in low concentration streams. The same is the case for wetlands in warmer regions.

Though the model that was developed in this thesis performed quite well, there is still room to improve upon the results and extend the model to additional applications. Future work should include comparative statics to analyze the effects of changes in parameters and extend the model to deal with stochastic precipitation and nitrogen runoff. Furthermore, the model could be extended to deal with local water problems related to nitrogen pollution and sources of water quality problems, e.g. phosphorus, BOD and suspended solids. A very important additional application and extension of the model would be to integrate cost measures so that targeting of wetlands for nitrogen removal could be done cost effectively. Furthermore, empirical tests of the model's conclusions would be useful to improve the model and validate the conclusions.

The main results from this thesis can have several useful applications, including but not limited to improving siting of wetlands on a watershed scale; most importantly, they can serve as a new path to developing site-specific rules of thumb that can make it easier for planners to choose among potential wetland sites.

Tables and figures

Table 1: Wetland-to-watershed ratios: Reported ratios, ratios used for prescreening and other wetland targeting recommendations.

Source	Location of study	Recommended wetland-to-watershed ratio
Wetland-to-watershed ratios reported in studies of wetlands		
Kovacac et al. (2000)	Embarras River, Illinois	Between 1:15 and 1:20
Larson et al. (2000)	Embarras River, Illinois	Between 1:25 and 1:32
Woltemade (2000)	Maryland, Illinois and Iowa	Between 1:5 and 1:180
Wetland-to-watershed ratios reported used to prescreen wetland sites		
Tomer, James, and Isenhardt (2003)	Tipton Creek, Iowa	1:200 – 1:50 and have a larger drainage area than 200 ha
U.S. Department of Agriculture and Iowa Department of Agriculture and Land Stewardship (2009)	CREP criteria, Iowa	1:200 – 1:50 and have a larger drainage area than 200 ha
David et al. (2008)	Lake Bloomington Watershed, Illinois	1:20
Minnesota Board on Water and Soil Resources (2009)	Minnesota	Ranks wetlands with a ratio of 1:5 the highest and discourages wetlands with a ratio smaller than 1:20
Tomer et al. (2011)	Big Bureau Creek, Illinois	1:200 to 1:50; discounts the ranking of wetlands with a ratio smaller than 1:50.
Unquantified siting recommendations		
Crumpton (2001)	Walnut Creek, Iowa	Can be located in the bottom of a drainage area
Royer, Tank, and David (2004)	East-central Illinois	Reservoirs and floodplain wetlands support greater N removal than headwater stream (wetlands)

Notes: The wetland-to-watershed ratios reported in the upper section of the table are ratios of constructed wetlands with nitrogen removal data in peer-reviewed studies. The ratios in the middle section were used as a prescreening tool for wetland policies and feasibility studies. The recommendations in the bottom section come from peer-reviewed studies.

Table 2: Calculated settling velocities for nitrate in subsurface wetlands.

Source	Settling velocity k_A (m/yr)	Temperature (°C)
Hey, Kenimer, and Barret (1994)	10.5	19.8
Hey, Barrett, and Biegen (1994)	18.1	21.1
U.S. Environmental Protection Agency (1993)	23.8	22.6
U.S. Environmental Protection Agency (1993)	25.8	18.7
Crumpton, Isenhardt, and Fisher (1993)	63.0 (max)	20
U.S. Environmental Protection Agency (1993)	28.2	22.3
U.S. Environmental Protection Agency (1993)	56.0	22.3
Van Oostrom and Russell (1994)	12.8	15
Van Oostrom and Cooper (1990)	10.3 (min)	15
Kadlec and Knight (1996)	15 (Average)	N/A
Kadlec and Knight (1996)	35 (Average)	Adjusted to 20 °C

Source: Adapted from Kadlec and Knight (1996)

Notes: Settling velocities (m yr^{-1}) were calculated for nitrate in subsurface wetlands and the average temperature (C) of the studies from which they were calculated. The settling velocity denoted with min indicates that it is the lowest reported value, max that it is the highest reported value and average that it is the mean of all the settling velocities reported in Kadlec and Knight (1996).

Table 3: Limits of marginal change of nitrate removal with respect to drainage area.

	As $B \rightarrow \infty$	As $B \rightarrow A$
Case 1: $c_i' > 0$	$\frac{dR}{dB} \rightarrow 0$ (non-negative)	$\frac{dR}{dB} \rightarrow \alpha c_i$
Case 2: $c_i' = 0$	$\frac{dR}{dB} \rightarrow 0$ (non-negative)	$\frac{dR}{dB} \rightarrow \alpha c_i$
Case 3: $c_i' < 0$	$\frac{dR}{dB} \rightarrow -$ very small	$\frac{dR}{dB} \rightarrow \alpha c_i$

Notes: The limits are for three situations: When nitrate concentration is increasing downstream (case 1), when nitrate concentration is constant throughout a watershed (case 2) and when nitrate concentration decreases downstream (case 3).

Table 4: Descriptive statistics: Drainage area and nitrate concentrations.

Variable	Obs	Mean	Std. Dev.	Min	Max
Drainage area (m ²)	211	1.41e+08	2.46e+08	299751	1.27e+09
NO_3^- (g/m ³)	211	12.2281	2.025667	2.44	14.71

Source: Monchak (Unpublished data, 2011) and Crumpton (Unpublished data, 2011).

Notes: Drainage area and nitrate concentrations for the 211 identified sections where wetlands can be installed in the part of Big Bureau Creek Watershed within Bureau County, IL.

Table 5: Regression results for nitrate concentration change in Big Bureau Creek Watershed.

Drainage area (ha)	N	adj. R^2	Intercept	c_i'
<5,000	126	0.05	11.40	4.73E-8
5,001-10,500	18	0.17	14.35	-2.19E-8
10,501-20,000	24	0.19	13.51	-3.08E-9
20,001-40,000	15	0.94	14.48	-7.06E-9
40,001-70,000	16	0.98	16.78	-9.15E-9
70,001-	12	0.53	12.79	-1.18 E-9
Total	211			

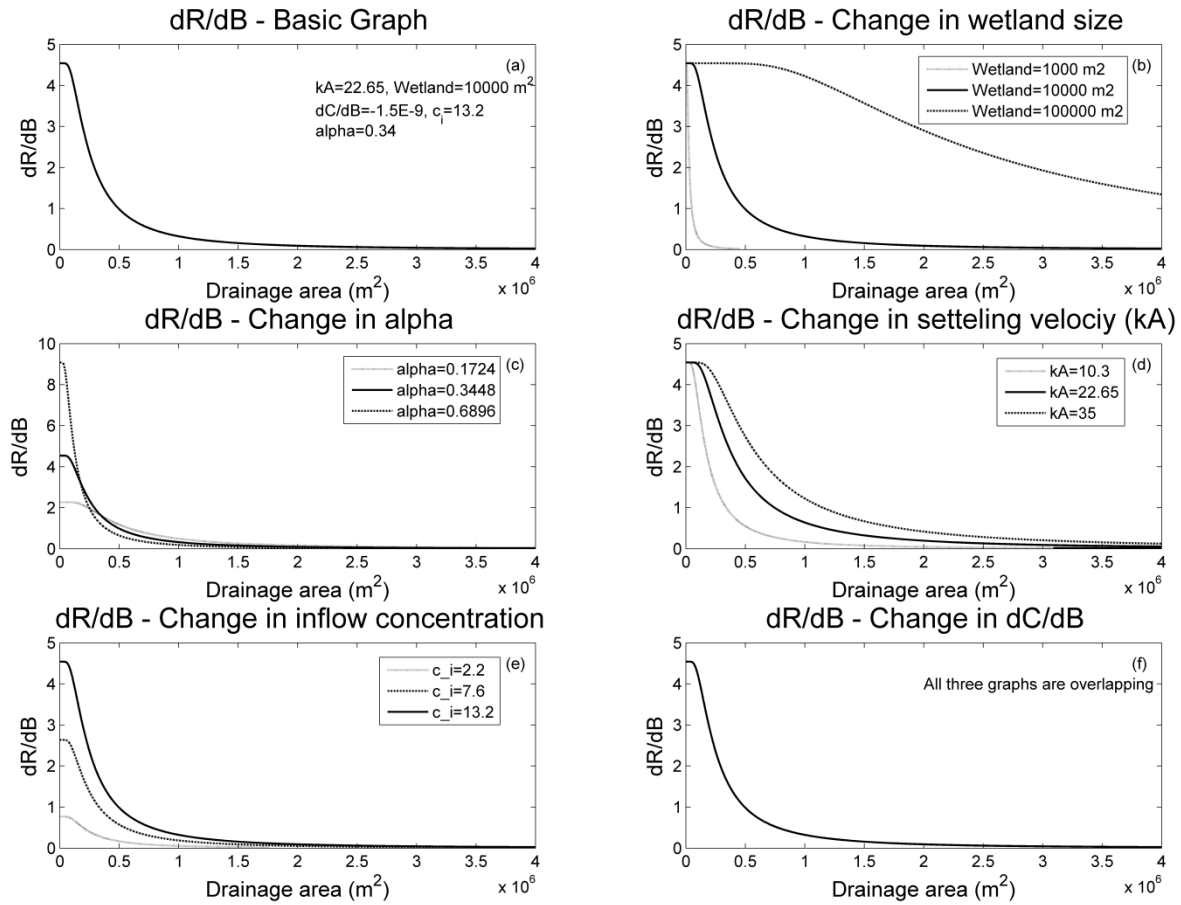
Notes: Regression results for the six clusters of nitrate concentration in Figure 9. The regression was performed on the nitrate concentrations for the 211 data points estimated by Dr. Crumpton from Iowa State University for potential wetland sites in Big Bureau Creek, IL.

Table 6: Descriptive statistics: Estimated marginal change in removal and change of nitrate removal for Big Bureau Creek Watershed.

Drainage area (ha)	N	$\frac{dR}{dB}$				Nitrate Removal			
		Mean	Min	Max	Variance	Mean	Min	Max	Variance
<5,000	126	.072	.007	1.899	.047	175.533	34.992	213.631	1642.34
5,001-10,500	18	-.003	-.003	-.003	1.94e-09	197.430	170.721	206.910	104.551
10,501-20,000	24	-.000	-.000	-.000	3.89e-11	201.955	197.64	205.972	4.389
20,001-40,000	15	-.001	-.001	-.001	3.74e-12	193.865	186.645	198.533	19.413
40,001-70,000	16	-.001	-.001	-.001	9.77e-14	193.176	185.858	197.549	17.064
70,001-	12	-.001	-.001	-.001	1.74e-14	180.405	175.137	184.631	11.547
Total	211								

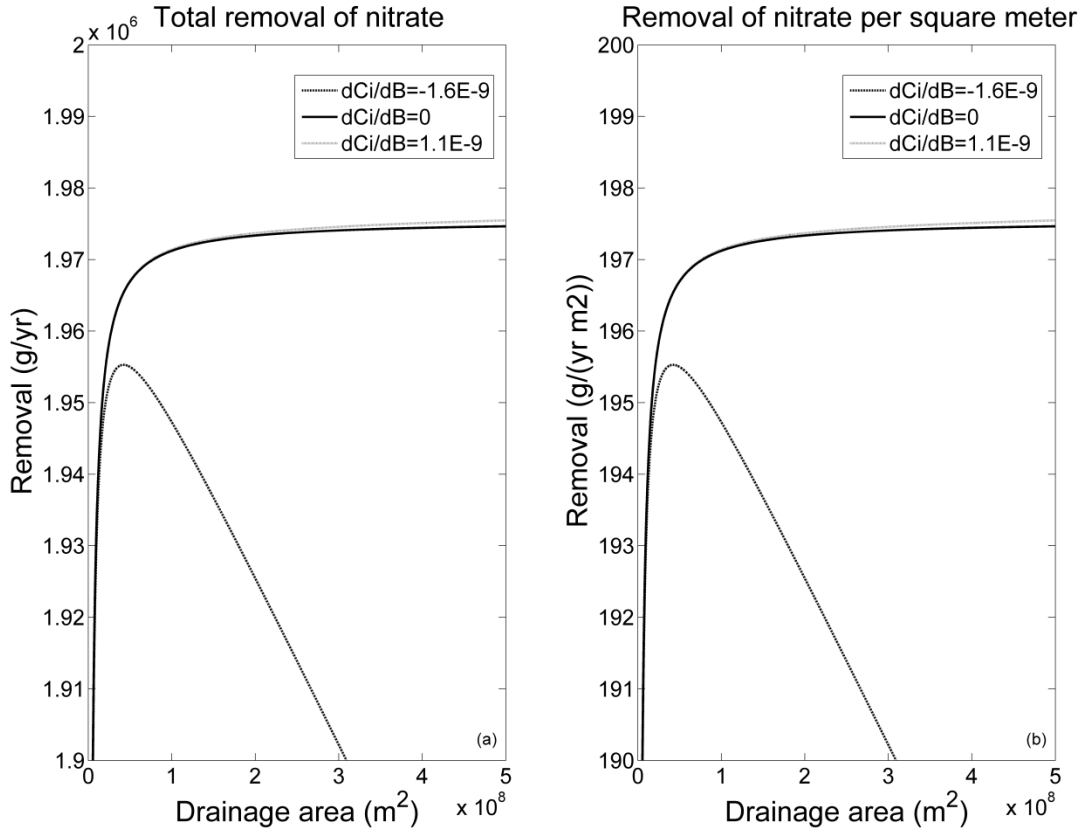
Notes: This table shows descriptive statistics on the wetlands' marginal change in removal with respect to a change in the size of the drainage area and the mass removal for sites with different drainage area sizes.

Figure 1: Graphical analysis of the marginal change in nitrate removal with respect to drainage area.



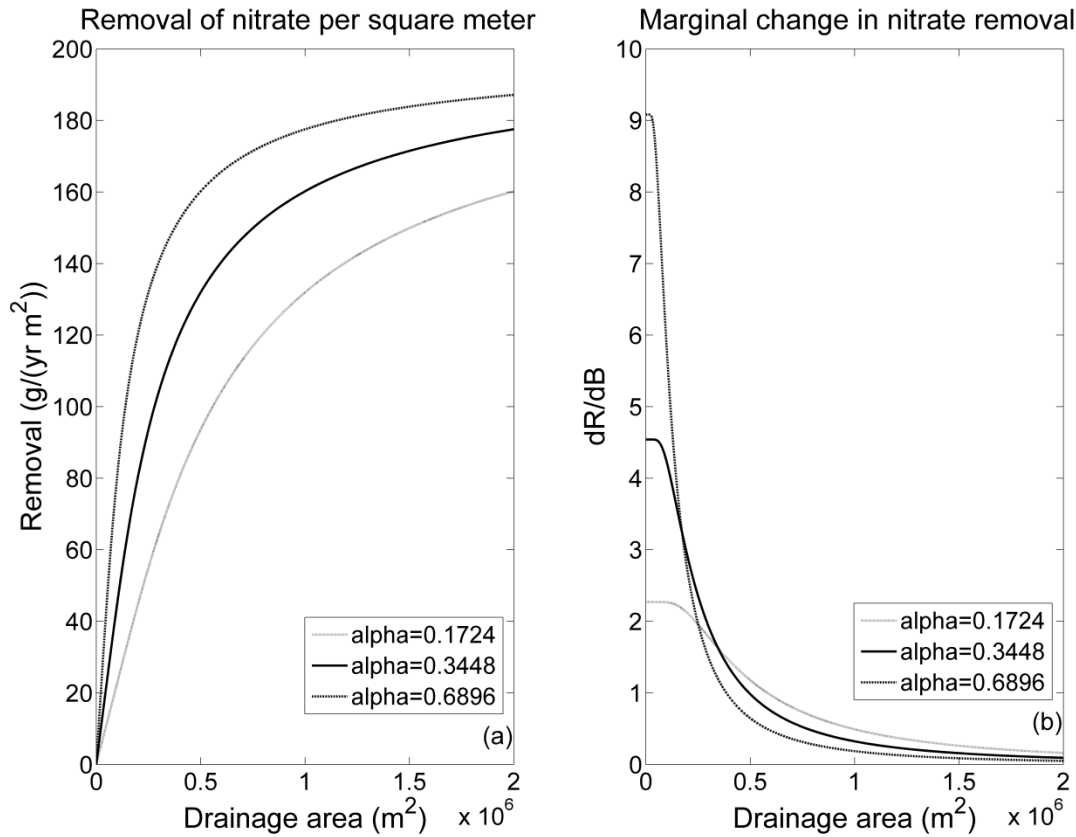
Notes: The six subplots show the curves of the marginal change in nitrate removal from wetlands with respect to the size of the drainage area (m^2). Figure 1a) shows the general curve shape for a wetland with average settling velocity ($k_A = 22.65 \text{ m yr}^{-1}$), 1 hectare in size (10,000 m^2), decrease in concentration downstream ($c'_i = -1.5E^{-9}$), high concentration for small drainage areas ($c_i=13.2 \text{ g m}^{-3}$) and $\alpha = 0.3448 \text{ m}^3 \text{ yr}^{-1}$. In Figure 1b), all parameters are the same as in (a) but for three different wetland sizes. In Figure 1c) all parameters are the same as in (a) except for three different α -values that represent low, medium and high discharge. In Figure 1d) all parameters are the same as in (a) except for three different settling velocities that represent different water and soil temperatures. In Figure 1e) all parameters are the same as in (a) except for three different influent concentrations. In Figure 1f) all parameters are the same as in (a) except for three different nitrate concentrations with respect to drainage area size: positive, constant and negative. The graphs are overlapping because they follow the same path until the graph with negative concentration change becomes negative (but very close to zero) for very large drainage areas.

Figure 2: Variation in marginal influent concentration: Change in nitrate removal and nitrate removal per square meter.



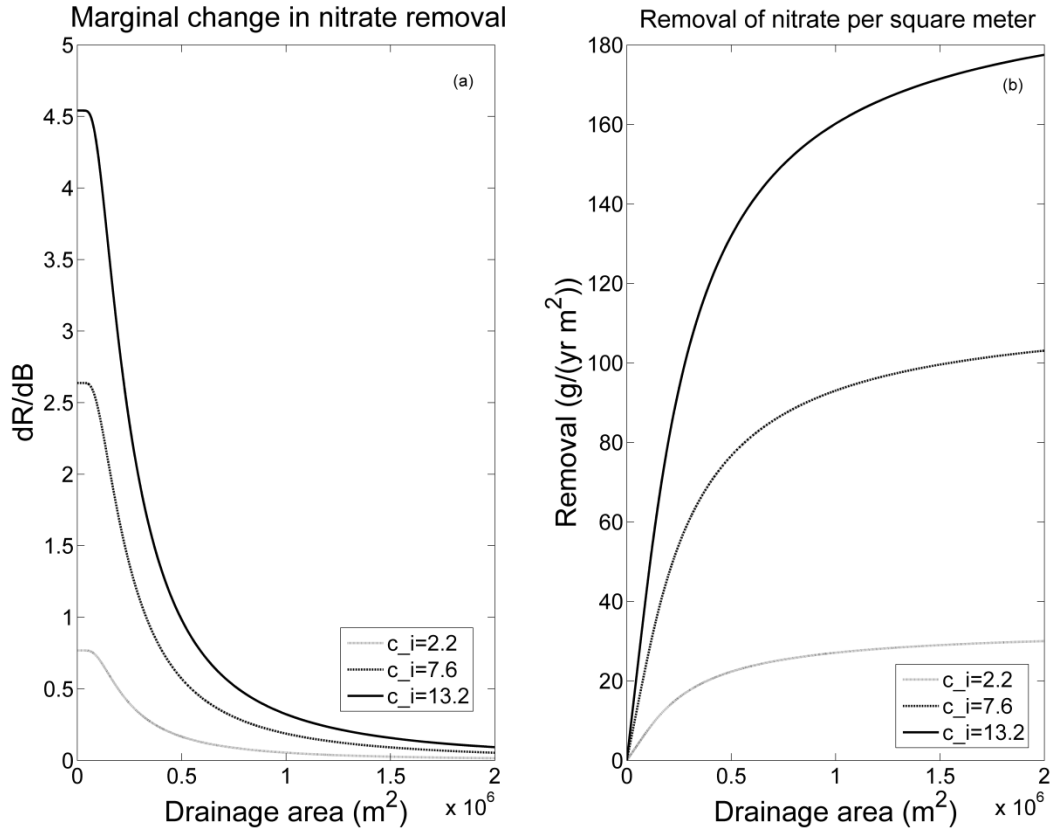
Notes: The two subplots show the curves of (a) nitrate removal per wetland of 1 hectare and (b) nitrate removal per m² calculated for a wetland of 1 hectare. The parameters that are held constant are the settling velocity ($k_A = 15.00 \text{ m yr}^{-1}$), the size of 1 hectare, high concentration for small drainage areas ($c_i = 13.2 \text{ g m}^{-3}$) and a one-to-one relationship between drainage area and discharge ($\alpha = 0.3448 \text{ m}^3 \text{ yr}^{-1}$). Three graphs are drawn for each case: increase in nitrate concentration downstream ($c'_i = 1.5E^{-9}$), constant nitrate concentration downstream ($c'_i = 0$) and decrease in nitrate concentration downstream ($c'_i = -1.5E^{-9}$).

Figure 3: Graphs of nitrate removal and the change in marginal nitrate removal: Variation in wetness.



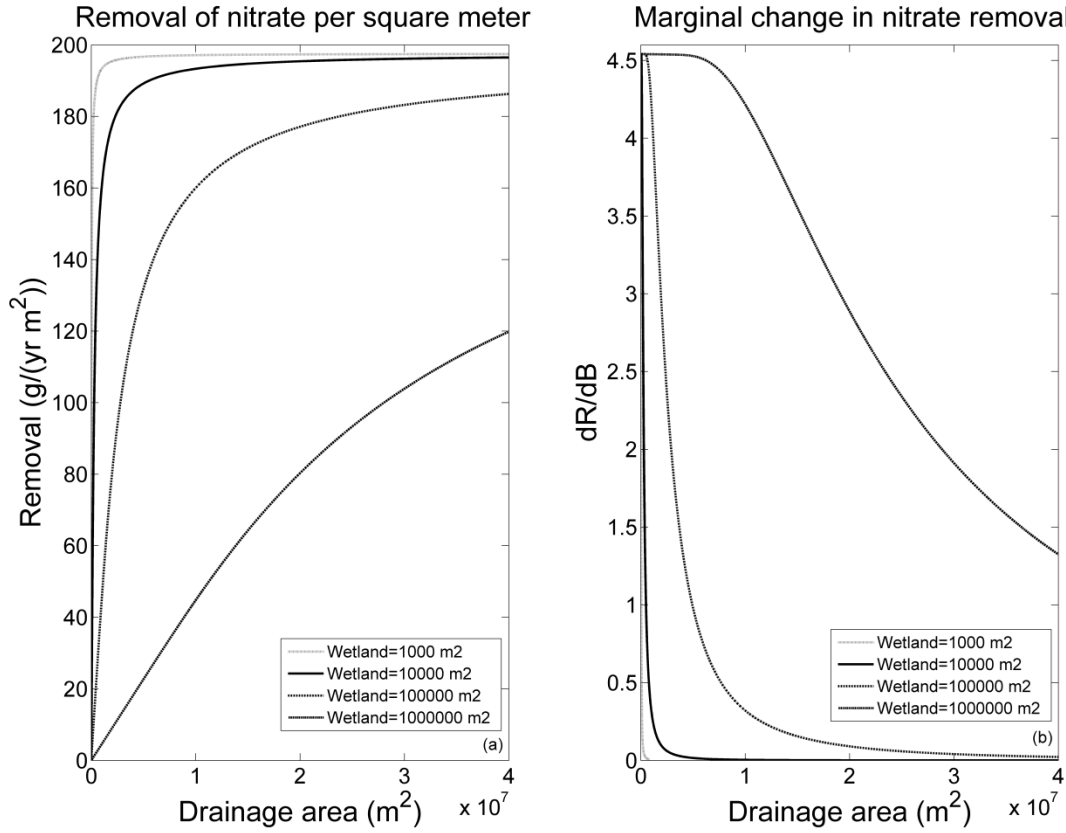
Notes: The two subplots show the curves of (a) nitrate removal per m² and (b) the marginal change in nitrate removal from wetlands with respect to the size of the drainage area (m²). The parameters that are held constant are the average settling velocity ($k_A = 15.00 \text{ m yr}^{-1}$), the size of 1 hectare, decrease in concentration downstream ($c'_i = -1.5E^{-9}$) and high concentration for small drainage areas ($c_i=13.2 \text{ g m}^{-3}$). Three levels of wetness represented by the relationship between drainage area and discharge are shown ($\alpha = \{0.1724, 0.3448, 0.6896\} \text{ m}^3 \text{ yr}^{-1}$).

Figure 4: Graphs of the change in marginal nitrate removal and nitrate removal: Variation in stream concentration.



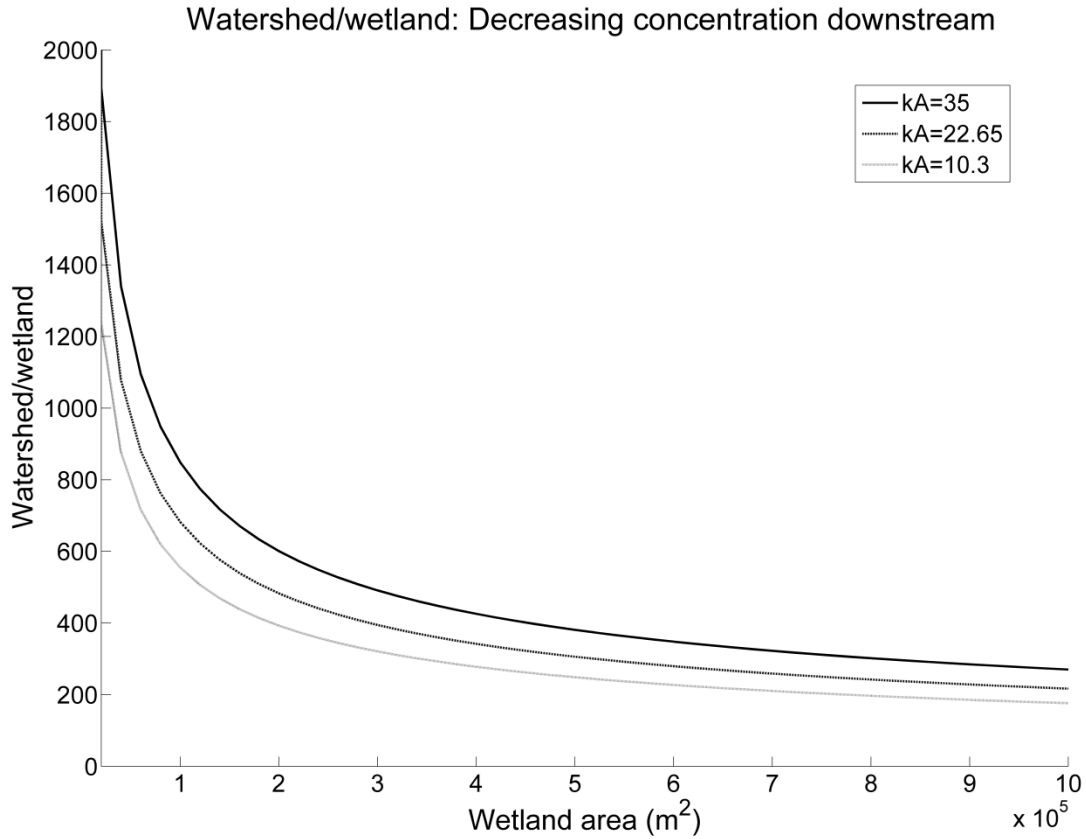
Notes: The two subplots show the curves of (a) the marginal change in nitrate removal from wetlands with respect to the size of the drainage area (m^2) and (b) nitrate removal per m^2 . The parameters that are held constant are the average settling velocity ($k_A = 15.00 \text{ m yr}^{-1}$), the size of 1 hectare, decrease in concentration downstream ($c'_i = -1.5E^{-9}$) and the relationship between drainage area and discharge ($\alpha = 0.3448$). Three levels of influent nitrate concentrations are represented ($c_i = \{2.2, 7.6, 13.2\} \text{ g m}^{-3}$).

Figure 5: Graphs of the change in marginal nitrate removal and nitrate removal: Variation in wetland size.



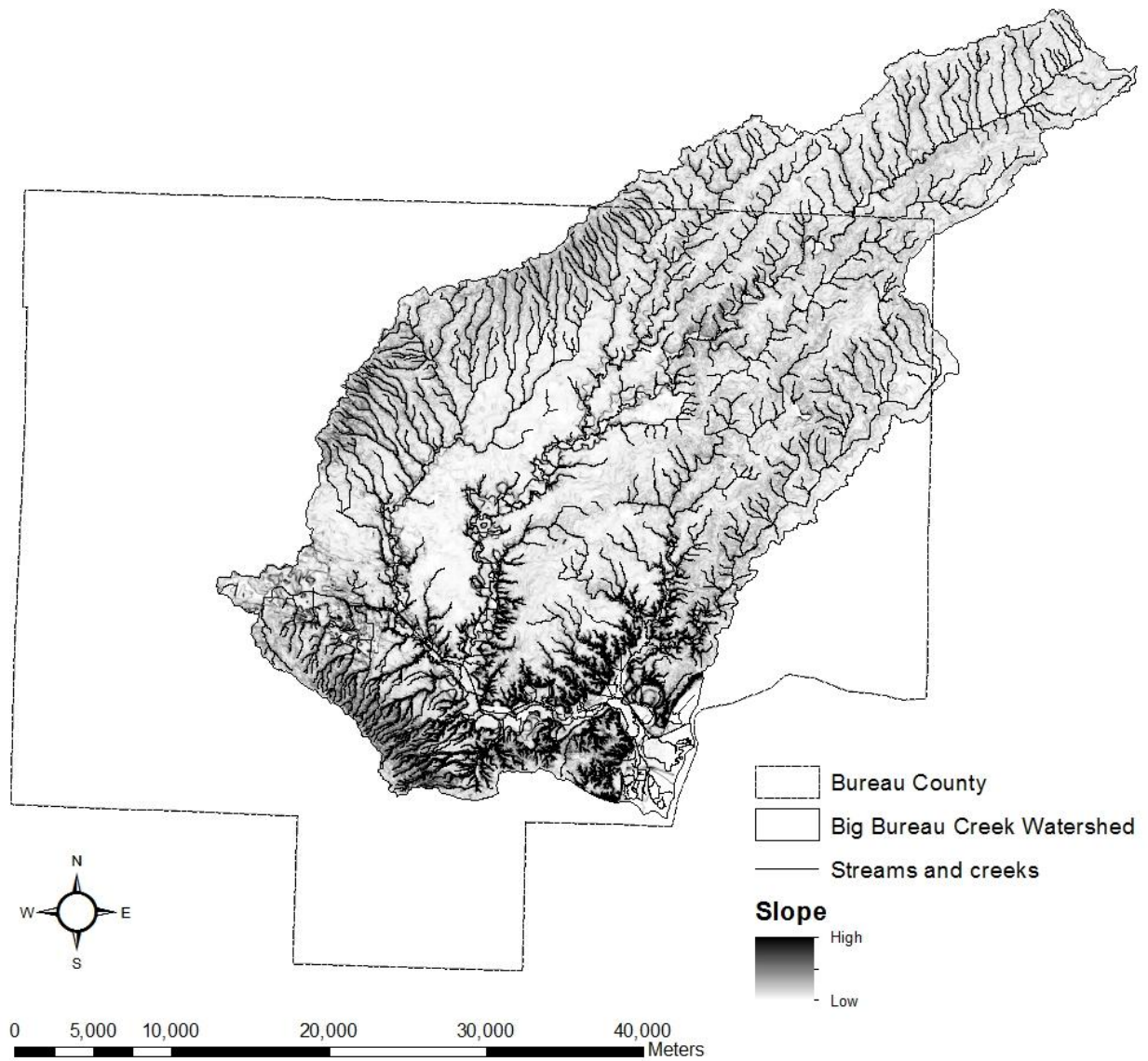
Notes: The two subplots show the curves of (a) mass nitrate removal per m^2 and (b) the marginal change in nitrate removal from wetlands with respect to the size of the drainage area (m^2). The parameters that are held constant are the settling velocity ($k_A = 15.00 \text{ m yr}^{-1}$), decrease in concentration downstream ($c'_i = -1.5E^{-9}$), high concentration for small drainage areas ($c_i = 13.2 \text{ g m}^{-3}$) and a one-to-one relationship between drainage area and discharge ($\alpha = 0.3448 \text{ m}^3 \text{ yr}^{-1}$). The sizes of the wetlands are 0.1, 1, 10 and 100 hectares.

Figure 6: Wetland-to-watershed ratio



Notes: Optimal wetland-to-watershed ratio as a function of wetland size for three levels of settling velocity ($k_A = 15.00 \text{ m yr}^{-1}$). The graph was simulated for a high level of influent concentration ($c_i=13.2 \text{ g m}^{-3}$) and the general relationship between drainage area and discharge ($\alpha = 0.3448 \text{ m}^3 \text{ yr}^{-1}$). The graph should be read as the size of the optimal drainage area divided by a wetland of a given size in a watershed where the nitrate concentration decreases downstream ($c'_i = -1.5E^{-9}$).

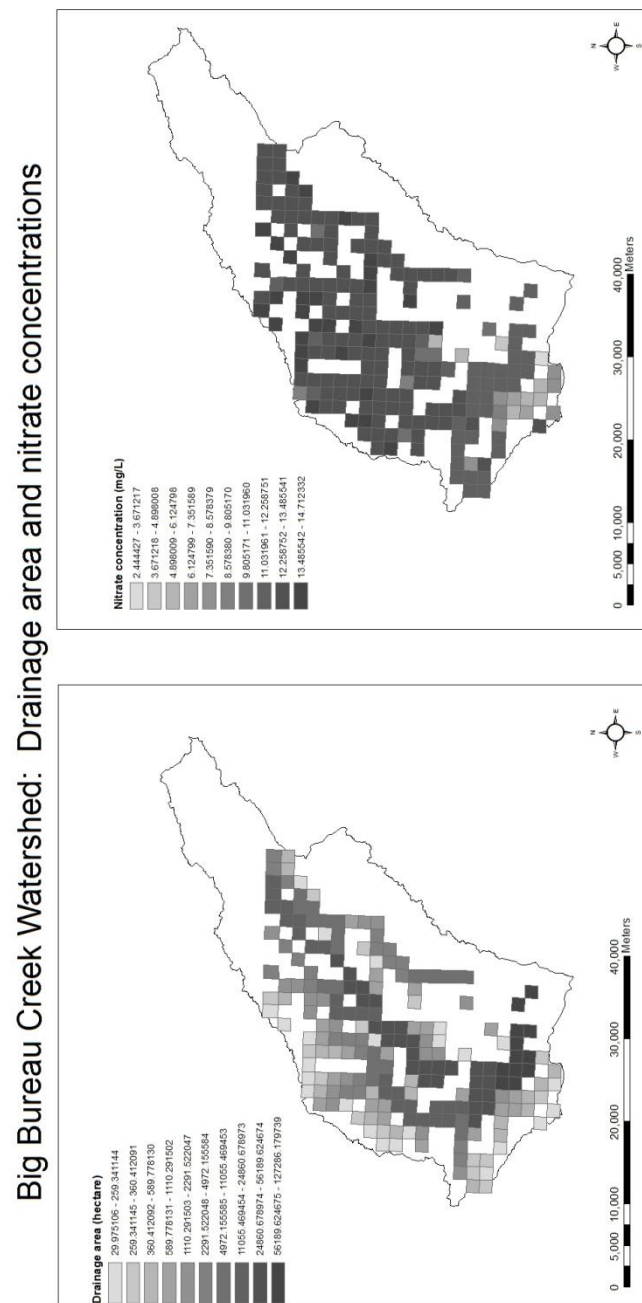
Figure 7: Study area: Big Bureau Creek Watershed and Bureau County, IL.



Source: National Atlas (2010)

Notes: Overview map of study area, the part of Big Bureau Creek Watershed within Bureau County, IL. The high slope represents 45 % or higher slopes, low slopes are 0 %.

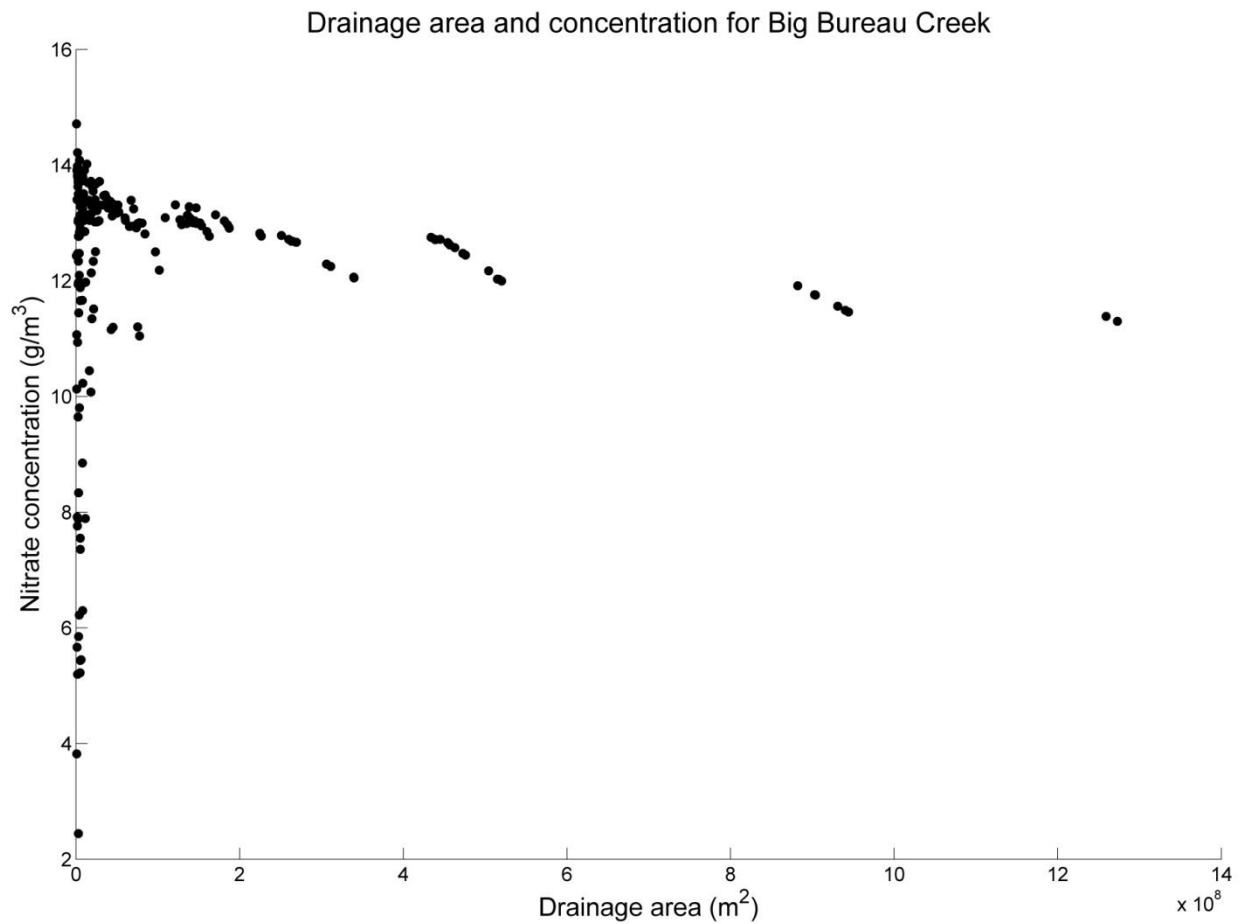
Figure 8: Spatial distribution: Nitrate concentrations and drainage area sizes in Big Bureau Creek Watershed.



Source: Monchak (Unpublished data, 2011) and Crumpton (Unpublished data, 2011).

Notes: Spatial distribution of drainage areas (hectares) and nitrate concentrations (mg/L) for the 211 suitable wetland sites in Big Bureau Creek Watershed, IL.

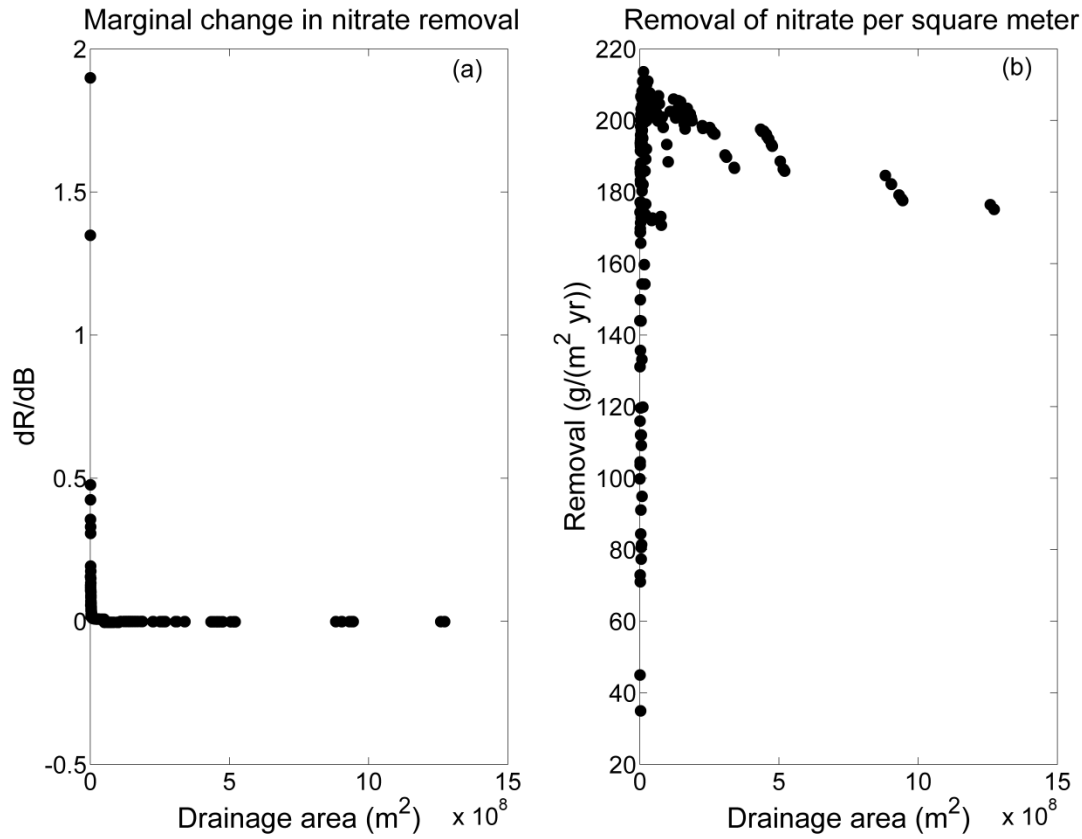
Figure 9: Scatterplot: Influent concentration for different drainage areas in Big Bureau Creek Watershed.



Source: Monchak (Unpublished data, 2011) and Crumpton (Unpublished data, 2011).

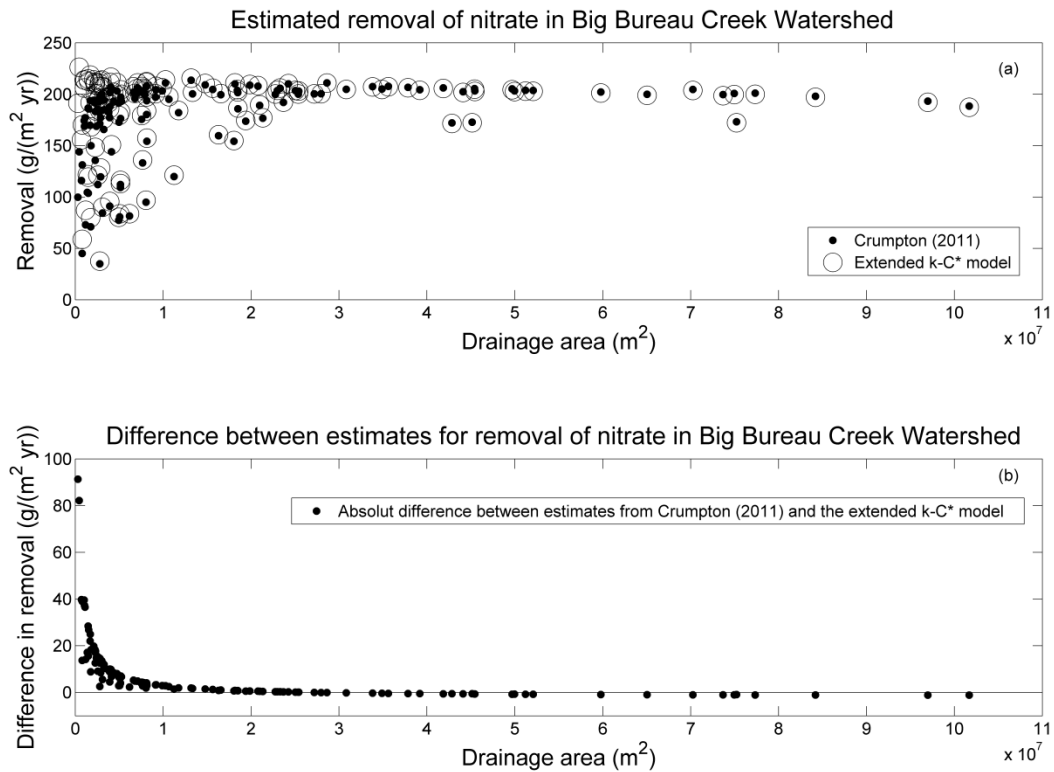
Notes: Nitrate concentration and drainage area for 211 drainage locations considered suitable for wetlands in Big Bureau Creek Watershed.

Figure 10: Graphs of the change in marginal nitrate removal and nitrate removal: Big Bureau Creek Watershed.



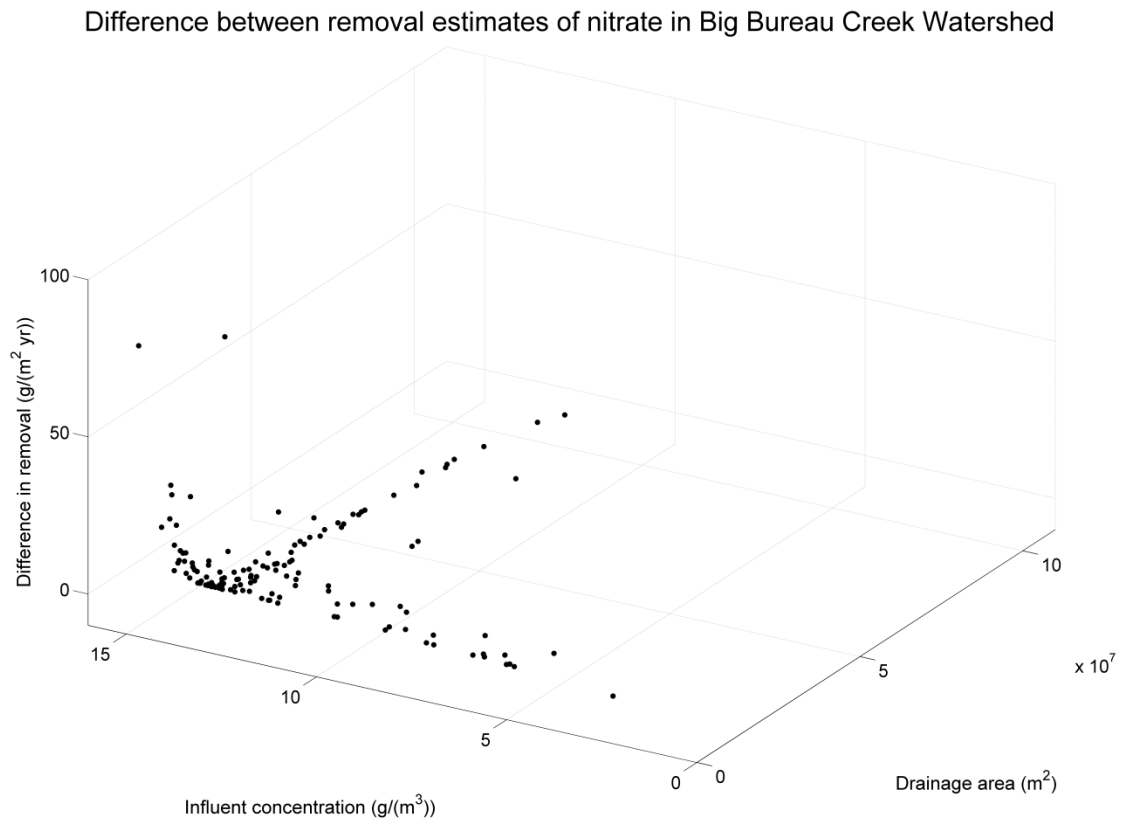
Notes: The two subplots show (a) the marginal change in nitrate removal from wetlands with respect to the size of the drainage area (m^2) and (b) nitrate removal per m^2 . The parameters that are held constant are the average settling velocity ($k_A = 15.50 \text{ m yr}^{-1}$), and the relationship between drainage area and discharge ($\alpha = 0.3448 \text{ m}^3 \text{ yr}^{-1}$).

Figure 11: Comparison of independent and author's estimates of nitrate removal for Big Bureau Creek Watershed (I).



Notes: The top figure shows the independent estimates of mass removal and the estimates from equation [8] for Big Bureau Creek Watershed. The bottom figure shows the difference between the independent estimates of mass removal and the estimates from equation [8] for Big Bureau Creek Watershed.

Figure 12: Comparison of independent and author's estimates of mass removal for Big Bureau Creek Watershed (II).



Notes: Difference between independent removal estimates and removal estimates from equation [8]. Positive differences mean that the independent estimates are higher than removal estimates from equation [8] and negative differences mean that the independent estimates are lower than the removal estimates from equation [8].

Appendix A: Matlab code

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Script of mass removal as a function of drainage area
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Written by      Adam Lentz
% Started        May 18th 2011
% Last edited    July 24th 2011
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Stylized version where one parameter is changed at a time
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% B should be 0.8 for most runs where wetland is 1000, if wetland is 40000 then B = 6

B.km2m2 = 1000^2;
B.Bkm2 = linspace(0,2,15000); % drainage area in km2, 2000 is a watershed of the size of BBC
B.m2 = B.Bkm2 * B.km2m2; % drainage area in m2

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Parameters to be changed
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% o stands for original parameter, s for small, m for medium and l for large

alpha.o = 0.3448; % Conversion between cfs and m3/yr
alpha.s = 0.01;
alpha.m = 0.3448;
alpha.l = 1.0;

kA.o =15; %22.65; % Retention rate m/yr -- kA.o should be 22.65 in most runs
kA.s =10.3;
kA.m =22.65;
kA.l =35;

A.o = 10000; % 40000; % Wetland size in m2 - original is 1000
A.s = 1000;
A.m = 10000;
A.l = 100000;

ci.zo = 13.1700268702433; % Intercept for ci
ci.zs = 2.2297298728068;
ci.zm = 7.6500268702433;
ci.zl = 13.1700268702433;

% All dc/dB are negative in this run

ci.mco = -1.59928280563678E-09; % dc/dB for the entire B 0-1270 million m2
ci.mcs = 1.10430294360972E-11;
ci.mcm = 0; %-1.59928280563678E-10;
ci.mcl = -1.59928280563678E-09;

% Change in dc/dB with constant ci.z

ci.Bo = ci.zo+ci.mco.*B.m2; % Ci as a function of B
ci.Bmcs = ci.zo+ci.mcs.*B.m2;
ci.Bmcm = ci.zo+ci.mcm.*B.m2;
ci.Bmcl = ci.zo+ci.mcl.*B.m2;

% Change in ci.z with constant dc/dB

ci.Bo = ci.zo+ci.mco.*B.m2; % Ci as a function of B
ci.Bzs = ci.zs+ci.mco.*B.m2;
ci.Bzm = ci.zl+ci.mco.*B.m2;
ci.Bzl = ci.zm+ci.mco.*B.m2;
```

```

% Other parameters
p.c = 1; % Coefficient of for power relation of discharge

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% dR/dB when various parameters are changed at a time
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Remember to set B to 4

figure(1)

% Plot 1 - Base Scenario
A1.o = (kA.o*A.o)./(alpha.o * B.m2.^p.c);
A2.o = -A1.o;
gamma.o = exp(A2.o);
dR.o = alpha.o.*ci.Bo.*(1-gamma.o.*(1+A1.o))+(1-gamma.o).*alpha.o.*B.m2.*ci.mco;

hold on
subplot(3,2,1)
plot(B.m2,dR.o,'k-','LineWidth',1.5)
xlabel('Drainage area (m^2)','FontSize',16);
ylabel('dR/dB','FontSize',16);
title('dR/dB - Basic Graph','FontSize',20);
text(2.15E6,4,'kA=22.65, Wetland=10000 m^2','FontSize',12);
text(2.15E6,3.3,'dC/dB=-1.5E-9, c_i=13.2','FontSize',12);
text(2.15E6,2.9,'alpha=0.34','FontSize',12);
text(3.75E6,4.5,'(a)','FontSize',12);
set(gca,'FontSize',12)
hold off

% Plot 2 - Scenario: Change in Wetland Area
A1.s = (kA.o*A.s)./(alpha.o * B.m2.^p.c);
A1.m = (kA.o*A.m)./(alpha.o * B.m2.^p.c);
A1.l = (kA.o*A.l)./(alpha.o * B.m2.^p.c);
A2.s = -A1.s;
A2.m = -A1.m;
A2.l = -A1.l;
gamma.s = exp(A2.s);
gamma.m = exp(A2.m);
gamma.l = exp(A2.l);
dR.s = alpha.o.*ci.Bo.*(1-gamma.s.*(1+A1.s))+(1-gamma.s).*alpha.o.*B.m2.*ci.mco;
dR.m = alpha.o.*ci.Bo.*(1-gamma.m.*(1+A1.m))+(1-gamma.m).*alpha.o.*B.m2.*ci.mco;
dR.l = alpha.o.*ci.Bo.*(1-gamma.l.*(1+A1.l))+(1-gamma.l).*alpha.o.*B.m2.*ci.mco;

hold on
subplot(3,2,2)
plot(B.m2,dR.m,'k-','LineWidth',1.5)
plot(B.m2,dR.l,'k-','LineWidth',1.5)
plot(B.m2,dR.s,'k:','LineWidth',1.5)
xlabel('Drainage area (m^2)','FontSize',16);
ylabel('dR/dB','FontSize',16);
title('dR/dB - Change in wetland size','FontSize',20);
h = legend('Wetland=1000 m2','Wetland=10000 m2','Wetland=100000 m2',3);
set(h,'Interpreter','none','FontSize',12);
text(3.75E6,4.5,'(b)','FontSize',12);
set(gca,'FontSize',12)
hold off

% Plot 3 - Scenario: Change in alpha
A1.s = (kA.o*A.o)./(alpha.s * B.m2.^p.c);
A1.m = (kA.o*A.o)./(alpha.m * B.m2.^p.c);
A1.l = (kA.o*A.o)./(alpha.l * B.m2.^p.c);
A2.s = -A1.s;
A2.m = -A1.m;
A2.l = -A1.l;
gamma.s = exp(A2.s);
gamma.m = exp(A2.m);
gamma.l = exp(A2.l);
dR.s = alpha.s.*ci.Bo.*(1-gamma.s.*(1+A1.s))+(1-gamma.s).*alpha.s.*B.m2.*ci.mco;
dR.m = alpha.m.*ci.Bo.*(1-gamma.m.*(1+A1.m))+(1-gamma.m).*alpha.m.*B.m2.*ci.mco;
dR.l = alpha.l.*ci.Bo.*(1-gamma.l.*(1+A1.l))+(1-gamma.l).*alpha.l.*B.m2.*ci.mco;

```

```

hold on
subplot(3,2,3)
plot(B.m2,dR.m,'k-','LineWidth',1.5)
plot(B.m2,dR.l,'k-','LineWidth',1.5)
plot(B.m2,dR.s,'k:','LineWidth',1.5)
xlabel('Drainage area (m^2)','FontSize',16);
ylabel('dR/dB','FontSize',16);
title('dR/dB - Change in alpha','FontSize',20);
h = legend('alpha=0.001','alpha=0.345','alpha=1',3);
set(h,'Interpreter','none','FontSize',12);
text(3.75E6,13.5,'(c)','FontSize',12);
set(gca,'FontSize',12)
hold off

% Plot 4 - Scenario: Change in settling velocity (kA)
A1.s = (kA.s*A.o)./(alpha.o * B.m2.^p.c);
A1.m = (kA.m*A.o)./(alpha.o * B.m2.^p.c);
A1.l = (kA.l*A.o)./(alpha.o * B.m2.^p.c);
A2.s = -A1.s;
A2.m = -A1.m;
A2.l = -A1.l;
gamma.s = exp(A2.s);
gamma.m = exp(A2.m);
gamma.l = exp(A2.l);
dR.s = alpha.o.*ci.Bo.*(1-gamma.s.*(1+A1.s))+(1-gamma.s).*alpha.o.*B.m2.*ci.mco;
dR.m = alpha.o.*ci.Bo.*(1-gamma.m.*(1+A1.m))+(1-gamma.m).*alpha.o.*B.m2.*ci.mco;
dR.l = alpha.o.*ci.Bo.*(1-gamma.l.*(1+A1.l))+(1-gamma.l).*alpha.o.*B.m2.*ci.mco;

hold on
subplot(3,2,4)
plot(B.m2,dR.m,'k-','LineWidth',1.5)
plot(B.m2,dR.l,'k-','LineWidth',1.5)
plot(B.m2,dR.s,'k:','LineWidth',1.5)
xlabel('Drainage area (m^2)','FontSize',16);
ylabel('dR/dB','FontSize',16);
title('dR/dB - Change in settling velocity (kA)','FontSize',20);
h = legend('kA=10.3','kA=22.65','kA=35',3);
set(h,'Interpreter','none','FontSize',12);
text(3.75E6,4.5,'(d)','FontSize',12);
set(gca,'FontSize',12)
hold off

% Plot 5 - Scenario: Change in Inflow Concentration
A1.s = (kA.o*A.o)./(alpha.o * B.m2.^p.c);
A1.m = (kA.o*A.o)./(alpha.o * B.m2.^p.c);
A1.l = (kA.o*A.o)./(alpha.o * B.m2.^p.c);
A2.s = -A1.s;
A2.m = -A1.m;
A2.l = -A1.l;
gamma.s = exp(A2.s);
gamma.m = exp(A2.m);
gamma.l = exp(A2.l);
dR.s = alpha.o.*ci.Bzs.*(1-gamma.s.*(1+A1.s))+(1-gamma.s).*alpha.o.*B.m2.*ci.mco;
dR.m = alpha.o.*ci.Bzm.*(1-gamma.m.*(1+A1.m))+(1-gamma.m).*alpha.o.*B.m2.*ci.mco;
dR.l = alpha.o.*ci.Bzl.*(1-gamma.l.*(1+A1.l))+(1-gamma.l).*alpha.o.*B.m2.*ci.mco;

hold on
subplot(3,2,5)
plot(B.m2,dR.l,'k-','LineWidth',1.5)
plot(B.m2,dR.m,'k-','LineWidth',1.5)
plot(B.m2,dR.s,'k:','LineWidth',1.5)
xlabel('Drainage area (m^2)','FontSize',16);
ylabel('dR/dB','FontSize',16);
title('dR/dB - Change in inflow concentration','FontSize',20);
h = legend('c_i=2.2','c_i=7.6','c_i=13.2',3);
set(h,'Interpreter','none','FontSize',12);
text(3.75E6,4.5,'(e)','FontSize',12);
set(gca,'FontSize',12)
hold off

```

```

% Plot 6 - Scenario: Change in dC/dB
A1.s = (kA.o*A.o)./(alpha.o * B.m2.^p.c);
A1.m = (kA.o*A.o)./(alpha.o * B.m2.^p.c);
A1.l = (kA.o*A.o)./(alpha.o * B.m2.^p.c);
A2.s = -A1.s;
A2.m = -A1.m;
A2.l = -A1.l;
gamma.s = exp(A2.s);
gamma.m = exp(A2.m);
gamma.l = exp(A2.l);
dR.s = alpha.o.*ci.Bmcs.*(1-gamma.s.*(1+A1.s))+(1-gamma.s).*alpha.o.*B.m2.*ci.mcs;
dR.m = alpha.o.*ci.Bmcm.*(1-gamma.m.*(1+A1.m))+(1-gamma.m).*alpha.o.*B.m2.*ci.mcm;
dR.l = alpha.o.*ci.Bmcl.*(1-gamma.l.*(1+A1.l))+(1-gamma.l).*alpha.o.*B.m2.*ci.mcl;

hold on
subplot(3,2,6)
plot(B.m2,dR.s,'k-', 'LineWidth',1.5)
plot(B.m2,dR.m,'k-', 'LineWidth',1.5)
plot(B.m2,dR.l,'k-', 'LineWidth',1.5)
xlabel('Drainage area (m^2)', 'FontSize',16);
ylabel('dR/dB', 'FontSize',16);
title('dR/dB - Change in dC/dB', 'FontSize',20);
text(2E6,4, 'All three graphs are overlapping', 'FontSize',12);
text(3.75E6,4.5, '(f)', 'FontSize',12);
set(gca, 'FontSize',12)
hold off

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Mass removal as a function of drainage area %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Remember to set B to 500 and kA.o to 15.
% Wetland area is original size, i.e. 10000
% This is a double plot with the next section as the second plot

mR.s=(1-gamma.o).*alpha.o.*B.m2.*ci.Bmcs;
mR.m=(1-gamma.o).*alpha.o.*B.m2.*ci.Bmcm;
mR.l=(1-gamma.o).*alpha.o.*B.m2.*ci.Bmcl;

figure(2)

hold on
subplot(1,2,1)
plot(B.m2,mR.m,'k-', 'LineWidth',1.5)
plot(B.m2,mR.s,'k-', 'LineWidth',1.5)
plot(B.m2,mR.l,'k-', 'LineWidth',1.5)
axis([0 5*10^8 1.9*10^6 2.0*10^6])
xlabel('Drainage area (m^2)', 'FontSize',18);
ylabel('Removal (g/yr)', 'FontSize',18);
title('Total mass removal of nitrate', 'FontSize',20);
text(4.65E8,1.903E6, '(a)', 'FontSize',14);
h = legend('dCi/dB=-1.6E-9', 'dCi/dB=0', 'dCi/dB=1.1E-9', 3);
set(h, 'Interpreter', 'none', 'FontSize',14);
set(gca, 'FontSize',14)
hold off

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Mass removal per square meter wetland as a function of drainage area %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

mR.s=((1-gamma.o).*alpha.o.*B.m2.*ci.Bmcs)./A.o;
mR.m=((1-gamma.o).*alpha.o.*B.m2.*ci.Bmcm)./A.o;
mR.l=((1-gamma.o).*alpha.o.*B.m2.*ci.Bmcl)./A.o;

hold on
subplot(1,2,2)
plot(B.m2,mR.m,'k-', 'LineWidth',1.5)
plot(B.m2,mR.s,'k-', 'LineWidth',1.5)
plot(B.m2,mR.l,'k-', 'LineWidth',1.5)
axis([0 5*10^8 190 200])

```

```

xlabel('Drainage area (m^2)', 'FontSize', 18);
ylabel('Removal (g/(yr m2))', 'FontSize', 18);
title('Mass removal of nitrate per square meter', 'FontSize', 20);
text(4.65E8, 190.3, '(b)', 'FontSize', 14);
h = legend('dCi/dB=-1.6E-9', 'dCi/dB=0', 'dCi/dB=1.1E-9', 3);
set(h, 'Interpreter', 'none', 'FontSize', 14);
set(gca, 'FontSize', 14);
hold off

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Plotting comparison between mass removal (m2) and dR/dB for wet. size %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Remember to set kA.o to 15 and b to 2 for original wetland sizes
% Remember to run a second set of graphs for kA.o=15, and b=40
% and wetland sizes from 10000, 100000, and 1000000 - this also requires a
% change in the legends.

A.s = 1000; %100;
A.m = 10000; %1000;
A.l = 100000; %10000;
A.xl = 1000000; %10000;

figure(3)

A1.s = (kA.o*A.s)./(alpha.o * B.m2.^p.c);
A1.m = (kA.o*A.m)./(alpha.o * B.m2.^p.c);
A1.l = (kA.o*A.l)./(alpha.o * B.m2.^p.c);
A1.xl = (kA.o*A.xl)./(alpha.o * B.m2.^p.c);
A2.s = -A1.s;
A2.m = -A1.m;
A2.l = -A1.l;
A2.xl = -A1.xl;
gamma.s = exp(A2.s);
gamma.m = exp(A2.m);
gamma.l = exp(A2.l);
gamma.xl = exp(A2.xl);
dR.s = alpha.o.*ci.Bo.*(1-gamma.s.*(1+A1.s))+(1-gamma.s).*alpha.o.*B.m2.*ci.mco;
dR.m = alpha.o.*ci.Bo.*(1-gamma.m.*(1+A1.m))+(1-gamma.m).*alpha.o.*B.m2.*ci.mco;
dR.l = alpha.o.*ci.Bo.*(1-gamma.l.*(1+A1.l))+(1-gamma.l).*alpha.o.*B.m2.*ci.mco;
dR.xl = alpha.o.*ci.Bo.*(1-gamma.xl.*(1+A1.xl))+(1-gamma.xl).*alpha.o.*B.m2.*ci.mco;

% Subplot 1 - Scenario: Change in removal

mR.s = ((1-gamma.s).*alpha.o.*B.m2.*ci.Bmcs)./A.s;
mR.m = ((1-gamma.m).*alpha.o.*B.m2.*ci.Bmcm)./A.m;
mR.l = ((1-gamma.l).*alpha.o.*B.m2.*ci.Bmcl)./A.l;
mR.xl = ((1-gamma.xl).*alpha.o.*B.m2.*ci.Bmcl)./A.xl;

hold on
subplot(1,2,1)
plot(B.m2, mR.m, 'k-', 'LineWidth', 1.5)
plot(B.m2, mR.l, 'k-', 'LineWidth', 1.5)
plot(B.m2, mR.xl, 'k--', 'LineWidth', 1.5)
plot(B.m2, mR.s, 'k:', 'LineWidth', 1.5)
% axis([0 5*10^8 190 200])
xlabel('Drainage area (m^2)', 'FontSize', 18);
ylabel('Removal (g/(yr m^2))', 'FontSize', 17);
title('Mass removal of nitrate per square meter', 'FontSize', 20);
h = legend('Wetland=1000 m2', 'Wetland=10000 m2', 'Wetland=100000 m2', 'Wetland=1000000 m2', 4);
text(3.75E7, 4.5, '(a)', 'FontSize', 14);
set(h, 'Interpreter', 'none', 'FontSize', 14);
set(gca, 'FontSize', 14);
hold off

% Subplot 2 - Scenario: Change in Wetland Area

hold on
subplot(1,2,2)
plot(B.m2, dR.m, 'k-', 'LineWidth', 1.5)
plot(B.m2, dR.l, 'k-', 'LineWidth', 1.5)

```

```

plot(B.m2,dR.xl,'k--','LineWidth',1.5)
plot(B.m2,dR.s,'k:', 'LineWidth',1.5)
axis([0 4*10^7 0 4.6])
xlabel('Drainage area (m^2)', 'FontSize',18);
ylabel('dR/dB', 'FontSize',18);
title('Marginal change in mass nitrate removal', 'FontSize',20);
h = legend('Wetland=1000 m2', 'Wetland=10000 m2', 'Wetland=100000 m2', 'Wetland=1000000 m2',4);
set(h, 'Interpreter', 'none', 'FontSize',14);
text(3.75E7,0.15, '(b)', 'FontSize',14);
set(gca, 'FontSize',14)
hold off

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Plotting comparison between mass removal (m2) and dR/dB for alpha
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Remember to set kA.o to 15 and b to 2 for original wetland sizes

alpha.s = 0.1;
alpha.m = 0.3448;
alpha.l = 1.0;

figure(4)

% Subplot 1 - Scenario: Change in Wetland Area

A1.s = (kA.o*A.o)./(alpha.s * B.m2.^p.c);
A1.m = (kA.o*A.o)./(alpha.m * B.m2.^p.c);
A1.l = (kA.o*A.o)./(alpha.l * B.m2.^p.c);
A2.s = -A1.s;
A2.m = -A1.m;
A2.l = -A1.l;
gamma.s = exp(A2.s);
gamma.m = exp(A2.m);
gamma.l = exp(A2.l);
dR.s = alpha.s.*ci.Bo.*(1-gamma.s.*(1+A1.s))+(1-gamma.s).*alpha.s.*B.m2.*ci.mco;
dR.m = alpha.m.*ci.Bo.*(1-gamma.m.*(1+A1.m))+(1-gamma.m).*alpha.m.*B.m2.*ci.mco;
dR.l = alpha.l.*ci.Bo.*(1-gamma.l.*(1+A1.l))+(1-gamma.l).*alpha.l.*B.m2.*ci.mco;

hold on
subplot(1,2,2)
plot(B.m2,dR.m,'k-', 'LineWidth',1.5)
plot(B.m2,dR.l,'k-', 'LineWidth',1.5)
plot(B.m2,dR.s,'k:', 'LineWidth',1.5)
% axis([0 5*10^8 190 200])
xlabel('Drainage area (m^2)', 'FontSize',18);
ylabel('dR/dB', 'FontSize',18);
title('Marginal change in mass nitrate removal', 'FontSize',20);
h = legend('alpha=0.1', 'alpha=0.3448', 'alpha=1',3);
set(h, 'Interpreter', 'none', 'FontSize',14);
text(1.85E6,.6, '(b)', 'FontSize',14);
set(gca, 'FontSize',14)
hold off

% Subplot 2 - Scenario: Change in removal

mR.s=((1-gamma.s).*alpha.s.*B.m2.*ci.Bmcs)./A.o;
mR.m=((1-gamma.m).*alpha.m.*B.m2.*ci.Bmcm)./A.o;
mR.l=((1-gamma.l).*alpha.l.*B.m2.*ci.Bmcl)./A.o;

hold on
subplot(1,2,1)
plot(B.m2,mR.m,'k-', 'LineWidth',1.5)
plot(B.m2,mR.l,'k-', 'LineWidth',1.5)
plot(B.m2,mR.s,'k:', 'LineWidth',1.5)
% axis([0 5*10^8 190 200])
xlabel('Drainage area (m^2)', 'FontSize',18);
ylabel('Removal (g/(yr m^2))', 'FontSize',18);
title('Mass removal of nitrate per square meter', 'FontSize',20);
h = legend('alpha=0.1', 'alpha=0.3448', 'alpha=1',3);
set(h, 'Interpreter', 'none', 'FontSize',14);

```

```

text(1.85E6,8,'(a)','FontSize',14);
set(gca,'FontSize',14)
hold off

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Plotting comparison between mass removal (m2) and dR/dB for c_i
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Plot - Scenario: Change in Inflow Concentration
% Set kA to 15 and B to 2

figure(10)

A1.s = (kA.o*A.o)./(alpha.o * B.m2.^p.c);
A1.m = (kA.o*A.o)./(alpha.o * B.m2.^p.c);
A1.l = (kA.o*A.o)./(alpha.o * B.m2.^p.c);
A2.s = -A1.s;
A2.m = -A1.m;
A2.l = -A1.l;
gamma.s = exp(A2.s);
gamma.m = exp(A2.m);
gamma.l = exp(A2.l);

dR.s = alpha.o.*ci.Bzs.*(1-gamma.s.*(1+A1.s))+(1-gamma.s).*alpha.o.*B.m2.*ci.mco;
dR.m = alpha.o.*ci.Bzm.*(1-gamma.m.*(1+A1.m))+(1-gamma.m).*alpha.o.*B.m2.*ci.mco;
dR.l = alpha.o.*ci.Bzl.*(1-gamma.l.*(1+A1.l))+(1-gamma.l).*alpha.o.*B.m2.*ci.mco;

mR.s=((1-gamma.s).*alpha.o.*B.m2.*ci.Bzs)./A.o;
mR.m=((1-gamma.m).*alpha.o.*B.m2.*ci.Bzm)./A.o;
mR.l=((1-gamma.l).*alpha.o.*B.m2.*ci.Bzl)./A.o;

hold on
subplot(1,2,1)
plot(B.m2,dR.l,'k-.','LineWidth',1.5)
plot(B.m2,dR.m,'k-','LineWidth',1.5)
plot(B.m2,dR.s,'k:','LineWidth',1.5)
xlabel('Drainage area (m^2)','FontSize',18);
ylabel('dR/dB','FontSize',18);
title('Marginal change in mass nitrate removal','FontSize',20);
h = legend('c_i=2.2','c_i=7.6','c_i=13.2',3);
set(h,'Interpreter','none','FontSize',14);
text(3.75E6,4.75,'(a)','FontSize',14);
set(gca,'FontSize',14)
hold off

hold on
subplot(1,2,2)
plot(B.m2,mR.l,'k-.','LineWidth',1.5)
plot(B.m2,mR.m,'k-','LineWidth',1.5)
plot(B.m2,mR.s,'k:','LineWidth',1.5)
xlabel('Drainage area (m^2)','FontSize',18);
ylabel('Removal (g/(yr m^2))','FontSize',18);
title('Mass removal of nitrate per square meter','FontSize',20);
h = legend('c_i=2.2','c_i=7.6','c_i=13.2',3);
set(h,'Interpreter','none','FontSize',14);
text(3.75E6,190,'(b)','FontSize',14);
set(gca,'FontSize',14)
hold off

%% Wetland to Drainage Area Ratio
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calculating wetland to drainage area ratio and plotting it
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(5)

options = optimset('TolX',1e-4,'Display','off');

% add in parameter for when "I" consider wetlands to so inefficient and
% change the cimc to positiv, zero and negative in title and subplot
% add labels

```

```

% parameters used for changeR2

kAL = 35;
kAM = 22.65;
kAS = 15;

alpha = 2;%0.3448;
p = 1;
ci = 13.07;
cimc = -1.59928280563678E-09;

Bm2=linspace(0,10000000000,10000);

% A = linspace(0,1000000,101);
% nwetlandarea = length(A);

seed = [1.5 1E20]; % guess interval

solBL = [];
ratioL = [];
solFVALL = [];
solBM = [];
ratioM = [];
solFVALM = [];
solBS = [];
ratioS = [];
solFVALS = [];
A = [];
k=1;

for A_index=1:20000:1000001

    [xL, fvalL, exitflagL] = fzero('changeR2',seed,Bm2,A_index,kAL,alpha,p,ci,cimc);
    [xM, fvalM, exitflagM] = fzero('changeR2',seed,Bm2,A_index,kAM,alpha,p,ci,cimc);
    [xS, fvalS, exitflagS] = fzero('changeR2',seed,Bm2,A_index,kAS,alpha,p,ci,cimc);
    solBL(k) = xL;
    solBM(k) = xM;
    solBS(k) = xS;
    ratioL(k) = xL/A_index;
    ratioM(k) = xM/A_index;
    ratioS(k) = xS/A_index;
    solFVALL(k)= fvalL;
    solFVALM(k)= fvalM;
    solFVALS(k)= fvalS;
    A(k)=A_index;
    k = k+1;

end

hold on
subplot(3,1,1) % change ([],[],THIS ONE)
plot(A,ratioL,'k-','LineWidth',1.5)
plot(A,ratioM,'k-','LineWidth',1.5)
plot(A,ratioS,'k:','LineWidth',1.5)
axis([ A(1,2) max(A) min(ratioS)-20 max(ratioL)+20 ])
xlabel('Wetland area (m^2)','FontSize',18);
ylabel('Watershed/wetland','FontSize',18);
title('Decreasing concentration downstream','FontSize',20);
h = legend('kA=35','kA=22.65','kA=10.3',3);
% text(3.75E6,190,'(b)','FontSize',14);
set(h,'Interpreter','none','FontSize',14);
set(gca,'FontSize',14)
hold off

%% Empirical Analysis
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Mass Removal of Nitrate in Wetlands in Bureau county
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Load drainage areas and nutrient concentrations from TWI and Prof.

```

```

% Crumpton

% -999 represents NA

N = importdata('basic_removal_5_22_999.csv','');
N.catchm2 = N.data(:,2); % Catchment of observations in BBC in square meter
N.catchha = N.data(:,1); % Catchment of observations in BBC in hectares
N.conc = N.data(:,5); % Concentration of observations in BBC in mg/L = g/m3
N.dCdBv = N.data(:,9); % change in concentration with variation for breaks
N.dCdBu = N.data(:,10); % change in concentration uniform for all observations

% Graphing data - histograms of concentration and drainage area

figure(5)
hold on
hist(N.conc,50)
h = findobj(gca,'Type','patch');
set(h,'FaceColor','k');
xlabel('Concentration (g/m^3)','FontSize',18);
ylabel('Frequency','FontSize',18);
title('Frequency distribution of concentrations','FontSize',20);
set(gca,'FontSize',14)
hold off

figure(6)
hold on
hist(N.catchm2,50)
h = findobj(gca,'Type','patch');
set(h,'FaceColor','k');
xlabel('Drainage area (g/m^2)','FontSize',18);
ylabel('Frequency','FontSize',18);
title('Frequency distribution of drainage area','FontSize',20);
set(gca,'FontSize',14)
hold off

% Graphing data: Scatterplot of drainagearea and concentration

figure(7)
hold on
plot(N.catchm2,N.conc,'k.','Markersize',20);
xlabel('Drainage area (m^2)','FontSize',18);
ylabel('Nitrate concentration (g/m^3)','FontSize',18);
title('Drainage area and concentration for Big Bureau Creek','FontSize',20);
set(gca,'FontSize',14)
hold off

% Calculating (and plotting) change in removal for wetlands in BBC, variation in dC/dB

% Remember to set kA and alpha equal to the minimizing solution with the
% difference from crumptions numbers.

kA.o = 15.5;
alpha.o = 0.3448;
A.o = 10000;
p.c=1;

A1.BBC = (kA.o*A.o)./(alpha.o*N.catchm2.^p.c);
A2.BBC = -A1.BBC;
gamma.BBC = exp(A2.BBC);

dR.BBCv = alpha.o.*N.conc.*(1-gamma.BBC.*(1+A1.BBC))+(1-gamma.BBC).*alpha.o.*N.catchm2.*N.dCdBv;

figure(8)
hold on
subplot(1,2,1)
plot(N.catchm2,dR.BBCv,'k.','Markersize',20)
xlabel('Drainage area (m^2)','FontSize',18);
ylabel('dR/dB','FontSize',18);
title('Marginal change in mass nitrate removal','FontSize',20);
set(gca,'FontSize',14)
text(13E8,1.93,'(a)','FontSize',14);

```

```

hold off

% Calculating (and plotting) mass removal potential per square meter wetland for each datapoint
in BBC

mR.BBC=((1-gamma.BBC).*alpha.o.*N.catchm2.*N.conc)./A.o;

hold on
subplot(1,2,2)
plot(N.catchm2,mR.BBC,'k.','Markersize',20)
xlabel('Drainage area (m^2)','FontSize',18);
ylabel('Removal (g/(m^2 yr))','FontSize',18);
title('Mass removal of nitrate per square meter','FontSize',20);
set(gca,'FontSize',14)
text(13E8,215,'(b)','FontSize',14);
hold off

print -r600 -dtiff mRdRBBC.tif % make sure that the style is Adam

% Plotting mass removal potential per square meter wetland for each datapoint in BBC from my K-
C*
% model and Prof Crumptions data

figure(9)

M = importdata('mass_removal_7_12.csv','');
M.catchm2 = M.data(:,2); % Catchment of observations in BBC in square meter
M.massloss_g_m2 = M.data(:,4); % Catchment of observations in BBC in hectares

hold on
plot(N.catchm2,mR.BBC,'k.')
plot(M.catchm2,M.massloss_g_m2,'ko')
axis([ 0 2E8 0 250 ])
xlabel('Drainage area (m^2)','FontSize',15);
ylabel('Removal (g/(m^2 yr))','FontSize',15);
title('Estimated mass removal of nitrate per square meter','FontSize',15);
h = legend('k-C* model','Prof. Crumpton\'s estimates',3);
set(h,'Interpreter','none');
set(gca,'FontSize',12)
hold off

%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Mass Removal of Nitrate in Wetlands in Bureau county minimizing the %
% difference between Prof. Crumpton numbers and our estimates by choosing %
% the 'right' kA and alpha %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Load drainage areas and nutrient concentrations from TWI and Prof. Crumpton
% Data matched based for existing observations where he estimated the mass
% nitrate loss.

Q = importdata('crumptoncomparion_7_16.csv','');
Q.catchha = Q.data(:,2); % Catchment of observations in BBC in hectares
Q.catchm2 = Q.data(:,3); % Catchment of observations in BBC in square meter
Q.conc = Q.data(:,4); % Concentration of observations in BBC in mg/L = g/m3
Q.percentloss = Q.data(:,5); % percent loss in nitrate that prof. Crumpton have used
Q.WCmasslosskg = Q.data(:,6); % mass loss in nitrate that prof. Crumpton calculated ((kg ha) /
yr)
Q.WCmasslossgm2 = Q.data(:,7); % mass loss in nitrate that prof. Crumpton calculated ((g m2) /
yr)
Q.dCdV = Q.data(:,8); % change in concentration with variation for breaks

options = optimset('TolX',1e-6,'Display','off');

% Initial guess of the settling velocity for Big Bureau Creek Watershed
kA.guess = 15;

% Other parameters used in function file comparision3
alpha.o = 0.3448;
A.o=10000;

```

```

p.c=1;

fminunc(@(x) comparison3(Q,A,.3448,x), [10 -1])

% kA that minimize the squared difference between the independent estimates
% and the estimates from the model in Lentz(2011) is 15.5 m yr-1

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Mass removal for kA=15.5

R2 = (1-exp(-(15.5.*A.o)./(alpha.o.*Q.catchm2))).*(alpha.o.*Q.catchm2.*Q.conc)./A.o +
(ones(size(Q.WCmasslossgm2)).*0);

% plot of both comparison and difference between two estimates.
figure(11)
hold on
subplot(2,1,1)
plot(Q.catchm2,Q.WCmasslossgm2,'ko','Markersize',16)
plot(Q.catchm2,R2,'k.','Markersize',20)
axis([ 0 11E7 0 250 ])
xlabel('Drainage area (m^2)','FontSize',18);
ylabel('Removal (g/(m^2 yr))','FontSize',18);
title('Estimated mass removal of nitrate in Big Bureau Creek Watershed','FontSize',20);
h = legend('Crumton (2011)','Extended k-C* model',2);
set(h,'Interpreter','none');
set(gca,'FontSize',14)
hold off

hold on
subplot(2,1,2)
plot(linspace(0,11E7,1000),0,'k-','Markersize',20)
plot(Q.catchm2,Q.WCmasslossgm2-R2,'k.','Markersize',20) % Difference between the two estimates.
axis([ 0 11E7 -10 100 ])
xlabel('Drainage area (m^2)','FontSize',18);
ylabel('Removal (g/(m^2 yr))','FontSize',18);
title('Difference between estimates for mass removal of nitrate in Big Bureau Creek
Watershed','FontSize',20);
h = legend('Absolut difference between estimates from Crumton (2011) and the extended k-C*
model',1);
set(h,'Interpreter','none');
set(gca,'FontSize',14)
hold off

```

```

function dR = changeR2(Bm2,A,kA,alpha,p,ci,cimc)

% This function calculates the dR/dB, i.e. the change in mass removal with
% respect to drainage area that is an approximation of the discharge.
% File written by Adam Lentz, June 10th 2011.

A1 = (kA*A)./(alpha * Bm2.^p);

A2 = -A1;

gamma = exp(A2);

ciB = ci - cimc.*Bm2;

dR = alpha.*ciB.*(1-gamma.*(1+A1))+(1-gamma).*alpha.*Bm2.*cimc - .1;

```

```

function sqd = comparison3(Q,A,alpha,x)

% This function minimizes the squared difference of Mass removal per
% squaremeter wetland estimated from the method described in:
%
% Lentz, A. 2011. "Physical criteria for wetland targeting on a watershed
% scale", Unpublished thesis, University of Illinois at Urbana-Champaign
% and

```

```

% Crumpton, W.G. Forthcomming.

% File written by Adam Lentz, July 19th 2011.
%x(1) is KA, x(2) is alpha

R = (1-exp(-(x(1).*A.o)./(alpha.*Q.catchm2)))*(alpha.*Q.catchm2.*Q.conc)./A.o + ...
(ones(size(Q.WCmasslossgm2)).*x(2));

sqd = sum((Q.WCmasslossgm2 - R).^2);

```

Appendix B: Raw data

Sec	T	R	S	C(ha)	C(m2)	Wet(ha)	HLR	NO3(mg/l)	Load (kgN/ha*yr)	Loss (%)	Loss (kgN/ha*yr)	dc_dbv
15N8E21	15	8	21	29.97511	299751.1	0.149876	56	12.43301	6962.487	0.274547	1911.531	4.73E-08
17N9E16	17	9	16	44.86426	448642.6	0.224321	56	14.71233	8238.906	0.274547	2261.968	4.73E-08
18N10E26	18	10	26	70.29835	702983.5	0.351492	56	10.12896	5672.218	0.274547	1557.291	4.73E-08
15N9E4	15	9	4	77.92789	779278.9	0.389639	56	3.822701	2140.712	0.274547	587.7264	4.73E-08
16N7E35	16	7	35	79.85419	798541.9	0.399271	56	11.06872	6198.484	0.274547	1701.776	4.73E-08
16N9E10	16	9	10	101.8043	1018043	0.509022	56	13.91497	7792.382	0.274547	2139.376	4.73E-08
17N8E19	17	8	19	104.1762	1041762	0.520881	56	13.40098	7504.55	0.274547	2060.353	4.73E-08
16N7E2	16	7	2	111.0028	1110028	0.555014	56	13.89874	7783.292	0.274547	2136.88	4.73E-08
16N9E9	16	9	9	117.4632	1174632	0.587316	56	5.665782	3172.838	0.274547	871.0935	4.73E-08
15N8E27	15	8	27	136.5316	1365316	0.682658	56	7.916765	4433.389	0.274547	1217.174	4.73E-08
18N9E2	18	9	2	146.0146	1460146	0.730073	56	13.98092	7829.314	0.274547	2149.516	4.73E-08
15N8E25	15	8	25	147.5156	1475156	0.737578	56	7.761575	4346.482	0.274547	1193.314	4.73E-08
18N9E21	18	9	21	153.456	1534560	0.76728	56	13.81392	7735.794	0.274547	2123.84	4.73E-08
18N8E24	18	8	24	169.1287	1691287	0.845643	56	12.47191	6984.269	0.274547	1917.511	4.73E-08
18N9E10	18	9	10	170.0287	1700287	0.850143	56	14.21649	7961.237	0.274547	2185.735	4.73E-08
16N9E20	16	9	20	175.3608	1753608	0.876804	56	5.196435	2910.004	0.274547	798.9331	4.73E-08
17N8E32	17	8	32	178.534	1785340	0.89267	56	10.93894	6125.806	0.274547	1681.822	4.73E-08
17N8E30	17	8	30	209.7251	2097251	1.048625	56	13.91448	7792.111	0.274547	2139.302	4.73E-08
17N10E16	17	10	16	223.8183	2238183	1.119091	56	13.76972	7711.04	0.274547	2117.044	4.73E-08
18N11E16	18	11	16	225.7017	2257017	1.128508	56	13.62856	7631.994	0.274547	2095.342	4.73E-08
17N8E17	17	8	17	227.3241	2273241	1.13662	56	13.02578	7294.435	0.274547	2002.666	4.73E-08
18N8E23	18	8	23	227.9477	2279477	1.139738	56	9.646724	5402.166	0.274547	1483.149	4.73E-08
18N9E19	18	9	19	230.7097	2307097	1.153548	56	13.70617	7675.453	0.274547	2107.273	4.73E-08
15N8E6	15	8	6	240.1919	2401919	1.200959	56	11.93898	6685.827	0.274547	1835.574	4.73E-08
17N8E3	17	8	3	249.899	2498990	1.249495	56	13.05344	7309.929	0.274547	2006.92	4.73E-08
16N7E33	16	7	33	256.5642	2565642	1.282821	56	7.8818	4413.808	0.274547	1211.798	4.73E-08
18N9E20	18	9	20	268.3612	2683612	1.341806	56	13.49544	7557.448	0.274547	2074.875	4.73E-08
17N8E20	17	8	20	270.8217	2708217	1.354109	56	12.76986	7151.124	0.274547	1963.321	4.73E-08
18N11E20	18	11	20	273.8427	2738427	1.369213	56	13.70631	7675.533	0.274547	2107.295	4.73E-08
15N9E20	15	9	20	278.7782	2787782	1.393891	56	2.444427	1368.879	0.274547	375.8218	4.73E-08
16N7E26	16	7	26	279.5301	2795301	1.397651	56	11.97194	6704.286	0.274547	1840.642	4.73E-08
17N9E36	17	9	36	279.9377	2799377	1.399688	56	13.85392	7758.194	0.274547	2129.99	4.73E-08
16N7E36	16	7	36	287.7934	2877934	1.438967	56	12.3396	6910.177	0.274547	1897.169	4.73E-08
16N7E25	16	7	25	289.5538	2895538	1.447769	56	8.334116	4667.105	0.274547	1281.34	4.73E-08
17N9E10	17	9	10	297.0344	2970344	1.485172	56	13.50509	7562.848	0.274547	2076.358	4.73E-08
17N8E9	17	8	9	301.5163	3015163	1.507581	56	13.9008	7784.45	0.274547	2137.198	4.73E-08
15N8E23	15	8	23	309.64	3096400	1.5482	56	5.851156	3276.647	0.274547	899.5941	4.73E-08
18N9E1	18	9	1	318.3747	3183747	1.591873	56	13.48332	7550.658	0.274547	2073.012	4.73E-08
16N7E34	16	7	34	324.5959	3245959	1.62298	56	11.44751	6410.606	0.274547	1760.013	4.73E-08

18N8E25	18	8	25	326.7638	3267638	1.633819	56	12.76835	7150.275	0.274547	1963.087	4.73E-08
17N10E10	17	10	10	326.7837	3267837	1.633918	56	13.4175	7513.803	0.274547	2062.893	4.73E-08
18N8E29	18	8	29	380.704	3807040	1.90352	56	12.47444	6985.687	0.274547	1917.9	4.73E-08
18N11E11	18	11	11	385.3829	3853829	1.926915	56	12.77628	7154.716	0.274547	1964.307	4.73E-08
15N8E5	15	8	5	391.4136	3914136	1.957068	56	12.09818	6774.982	0.274547	1860.052	4.73E-08
15N8E15	15	8	15	392.1404	3921404	1.960702	56	6.223173	3484.977	0.274547	956.7904	4.73E-08
18N9E12	18	9	12	393.5993	3935993	1.967996	56	13.76293	7707.241	0.274547	2116.001	4.73E-08
18N9E29	18	9	29	393.7203	3937203	1.968601	56	12.84051	7190.686	0.274547	1974.182	4.73E-08
17N8E14	17	8	14	405.9199	4059199	2.0296	56	14.08668	7888.538	0.274547	2165.775	4.73E-08
17N8E36	17	8	36	410.934	4109340	2.05467	56	9.804021	5490.252	0.274547	1507.333	4.73E-08
17N8E29	17	8	29	435.3325	4353325	2.176662	56	13.12887	7352.165	0.274547	2018.516	4.73E-08
17N8E16	17	8	16	474.6315	4746315	2.373158	56	13.73907	7693.881	0.274547	2112.333	4.73E-08
18N9E32	18	9	32	494.0119	4940119	2.47006	56	12.91397	7231.825	0.274547	1985.477	4.73E-08
15N8E24	15	8	24	494.5097	4945097	2.472548	56	5.222761	2924.746	0.274547	802.9806	4.73E-08
18N8E26	18	8	26	497.6419	4976419	2.48821	56	11.65832	6528.659	0.274547	1792.424	4.73E-08
15N8E14	15	8	14	505.7073	5057073	2.528537	56	5.438414	3045.512	0.274547	836.1365	4.73E-08
15N9E30	15	9	30	512.8622	5128622	2.564311	56	7.357375	4120.13	0.274547	1131.17	4.73E-08
15N8E4	15	8	4	513.6189	5136189	2.568095	56	7.552286	4229.28	0.274547	1161.137	4.73E-08
16N7E27	16	7	27	515.0434	5150434	2.575217	56	11.88259	6654.249	0.274547	1826.905	4.73E-08
18N11E10	18	11	10	518.0462	5180462	2.590231	56	13.28391	7438.992	0.274547	2042.354	4.73E-08
17N8E35	17	8	35	525.0472	5250472	2.625236	56	13.00605	7283.388	0.274547	1999.633	4.73E-08
15N8E10	15	8	10	617.6231	6176231	3.088116	56	5.449213	3051.559	0.274547	837.7968	4.73E-08
17N8E22	17	8	22	662.697	6626970	3.313485	56	13.47904	7548.264	0.274547	2072.354	4.73E-08
17N10E31	17	10	31	678.0953	6780953	3.390477	56	13.05795	7312.451	0.274547	2007.612	4.73E-08
17N8E15	17	8	15	700.527	7005270	3.502635	56	13.35956	7481.354	0.274547	2053.984	4.73E-08
17N10E17	17	10	17	709.074	7090740	3.54537	56	13.72751	7687.408	0.274547	2110.556	4.73E-08
16N8E29	16	8	29	755.107	7551070	3.775535	56	11.664	6531.842	0.274547	1793.298	4.73E-08
17N9E5	17	9	5	755.5886	7555886	3.777943	56	13.50155	7560.868	0.274547	2075.815	4.73E-08
15N8E3	15	8	3	766.2197	7662197	3.831098	56	8.849427	4955.679	0.274547	1360.567	4.73E-08
16N8E23	16	8	23	770.3272	7703272	3.851636	56	13.38774	7497.134	0.274547	2058.317	4.73E-08
17N9E34	17	9	34	789.0075	7890075	3.945038	56	13.32664	7462.919	0.274547	2048.923	4.73E-08
16N8E6	16	8	6	792.504	7925040	3.96252	56	13.22951	7408.524	0.274547	2033.989	4.73E-08
15N8E11	15	8	11	804.1306	8041306	4.020653	56	6.298543	3527.184	0.274547	968.3782	4.73E-08
18N8E27	18	8	27	809.3065	8093065	4.046533	56	13.75373	7702.089	0.274547	2114.586	4.73E-08
18N9E28	18	9	28	811.2571	8112571	4.056286	56	11.95522	6694.921	0.274547	1838.071	4.73E-08
18N9E27	18	9	27	811.5283	8115283	4.057641	56	13.80145	7728.814	0.274547	2121.924	4.73E-08
18N8E36	18	8	36	812.0786	8120786	4.060393	56	12.8421	7191.574	0.274547	1974.426	4.73E-08
16N9E34	16	9	34	814.6808	8146808	4.073404	56	10.23038	5729.013	0.274547	1572.884	4.73E-08
16N9E3	16	9	3	913.1408	9131408	4.565704	56	13.04013	7302.47	0.274547	2004.872	4.73E-08
17N10E1	17	10	1	920.3887	9203887	4.601943	56	13.50815	7564.565	0.274547	2076.83	4.73E-08
17N9E20	17	9	20	988.8332	9888332	4.944166	56	13.41806	7514.116	0.274547	2062.979	4.73E-08
17N10E18	17	10	18	1027.08	10270800	5.1354	56	13.91013	7789.676	0.274547	2138.633	4.73E-08
17N8E21	17	8	21	1065.711	10657113	5.328557	56	12.85138	7196.773	0.274547	1975.853	4.73E-08

15N8E2	15	8	2	1123.015	11230148	5.615074	56	7.89059	4418.731	0.274547	1213.15	4.73E-08
16N9E4	16	9	4	1175.061	11750614	5.875307	56	11.97536	6706.204	0.274547	1841.169	4.73E-08
18N9E34	18	9	34	1317.859	13178588	6.589294	56	14.01906	7850.674	0.274547	2155.38	4.73E-08
17N8E1	17	8	1	1333.407	13334068	6.667034	56	13.14196	7359.496	0.274547	2020.529	4.73E-08
18N9E23	18	9	23	1477.382	14773818	7.386909	56	13.69122	7667.083	0.274547	2104.976	4.73E-08
18N8E34	18	8	34	1563.819	15638186	7.819093	56	13.39326	7500.224	0.274547	2059.165	4.73E-08
16N9E5	16	9	5	1629.952	16299524	8.149762	56	10.44541	5849.432	0.274547	1605.945	4.73E-08
17N10E12	17	10	12	1655.844	16558441	8.279221	56	13.04581	7305.656	0.274547	2005.747	4.73E-08
16N9E8	16	9	8	1805.266	18052662	9.026331	56	10.07696	5643.095	0.274547	1549.295	4.73E-08
18N9E24	18	9	24	1815.387	18153874	9.076937	56	13.7211	7683.815	0.274547	2109.569	4.73E-08
16N8E5	16	8	5	1843.355	18433552	9.216776	56	13.29887	7447.367	0.274547	2044.653	4.73E-08
17N10E13	17	10	13	1848.835	18488347	9.244173	56	13.16033	7369.786	0.274547	2023.354	4.73E-08
18N10E7	18	10	7	1850.085	18500852	9.250426	56	12.13762	6797.065	0.274547	1866.114	4.73E-08
16N9E24	16	9	24	1938.104	19381043	9.690521	56	11.34374	6352.496	0.274547	1744.059	4.73E-08
18N10E2	18	10	2	1985.995	19859948	9.929974	56	13.62216	7628.408	0.274547	2094.358	4.73E-08
18N9E25	18	9	25	2078.514	20785140	10.39257	56	13.55266	7589.491	0.274547	2083.673	4.73E-08
18N10E18	18	10	18	2097.097	20970972	10.48549	56	12.33742	6908.955	0.274547	1896.834	4.73E-08
16N7E23	16	7	23	2132.612	21326124	10.66306	56	11.51383	6447.747	0.274547	1770.21	4.73E-08
18N8E35	18	8	35	2274.799	22747987	11.37399	56	13.0175	7289.798	0.274547	2001.393	4.73E-08
18N9E33	18	9	33	2297.866	22978658	11.48933	56	13.25801	7424.484	0.274547	2038.371	4.73E-08
17N10E14	17	10	14	2329.767	23297671	11.64884	56	13.40135	7504.756	0.274547	2060.409	4.73E-08
18N10E19	18	10	19	2367.188	23671884	11.83594	56	12.50502	7002.812	0.274547	1922.602	4.73E-08
18N10E10	18	10	10	2424.638	24246376	12.12319	56	13.67751	7659.404	0.274547	2102.867	4.73E-08
17N9E4	17	9	4	2502.904	25029038	12.51452	56	13.24578	7417.638	0.274547	2036.491	4.73E-08
17N8E2	17	8	2	2536.752	25367517	12.68376	56	13.01886	7290.564	0.274547	2001.603	4.73E-08
17N9E9	17	9	9	2542.806	25428058	12.71403	56	13.21501	7400.408	0.274547	2031.761	4.73E-08
17N8E11	17	8	11	2718.237	27182370	13.59119	56	13.03155	7297.668	0.274547	2003.554	4.73E-08
17N8E12	17	8	12	2796.58	27965801	13.9829	56	13.03977	7302.269	0.274547	2004.817	4.73E-08
18N10E16	18	10	16	2862.597	28625965	14.31298	56	13.7197	7683.03	0.274547	2109.354	4.73E-08
18N11E2	18	11	2	3082.308	30823084	15.41154	56	13.30837	7452.686	0.274547	2046.113	4.73E-08
17N10E15	17	10	15	3381.861	33818608	16.9093	56	13.47201	7544.325	0.274547	2071.273	4.73E-08
18N10E5	18	10	5	3488.156	34881555	17.44078	56	13.31254	7455.024	0.274547	2046.755	4.73E-08
17N10E22	17	10	22	3561.274	35612741	17.80637	56	13.48352	7550.77	0.274547	2073.042	4.73E-08
17N10E21	17	10	21	3784.373	37843733	18.92187	56	13.41782	7513.981	0.274547	2062.942	4.73E-08
18N11E3	18	11	3	3918.555	39185549	19.59277	56	13.25973	7425.447	0.274547	2038.635	4.73E-08
17N10E28	17	10	28	4186.149	41861492	20.93075	56	13.37315	7488.962	0.274547	2056.073	4.73E-08
16N7E24	16	7	24	4283.84	42838403	21.4192	56	11.15779	6248.365	0.274547	1715.471	4.73E-08
18N11E9	18	11	9	4410.345	44103451	22.05173	56	13.12219	7348.424	0.274547	2017.489	4.73E-08
16N8E19	16	8	19	4514.268	45142683	22.57134	56	11.19918	6271.543	0.274547	1721.834	4.73E-08
17N10E29	17	10	29	4541.099	45410990	22.70549	56	13.32598	7462.55	0.274547	2048.822	4.73E-08
18N10E20	18	10	20	4545.227	45452268	22.72613	56	13.18136	7381.559	0.274547	2026.586	4.73E-08
17N9E8	17	9	8	4968.407	49684066	24.84203	56	13.29667	7446.136	0.274547	2044.315	4.73E-08
17N9E17	17	9	17	4991.474	49914736	-999	-999	13.29334	-999	-999	-999	4.73E-08

18N11E17	18	11	17	4996.208	49962085	24.98104	-999	13.17084	-999	-999	-999	4.73E-08
17N9E18	17	9	18	5106.526	51065258	-999	-999	13.31256	-999	-999	-999	-2.19E-08
17N8E13	17	8	13	5120.568	51205684	25.60284	-999	13.20565	-999	-999	-999	-2.19E-08
18N11E18	18	11	18	5208.587	52085875	26.04294	-999	13.19278	-999	-999	-999	-2.19E-08
18N11E19	18	11	19	5978.259	59782591	29.8913	-999	13.08859	-999	-999	-999	-2.19E-08
18N10E24	18	10	24	6011.12	60111196	-999	-999	13.04479	-999	-999	-999	-2.19E-08
18N10E25	18	10	25	6503.703	65037030	32.51851	-999	12.93937	-999	-999	-999	-2.19E-08
17N9E19	17	9	19	6713.168	67131682	-999	-999	13.39382	-999	-999	-999	-2.19E-08
18N10E36	18	10	36	6832.429	68324291	-999	-999	12.94649	-999	-999	-999	-2.19E-08
17N10E32	17	10	32	7024.898	70248976	35.12449	-999	13.24524	-999	-999	-999	-2.19E-08
18N10E30	18	10	30	7367.464	73674640	36.83732	-999	12.91657	-999	-999	-999	-2.19E-08
16N10E5	16	10	5	7494.98	74949804	37.4749	-999	12.99031	-999	-999	-999	-2.19E-08
16N8E20	16	8	20	7521.285	75212850	37.60643	-999	11.20382	-999	-999	-999	-2.19E-08
18N10E35	18	10	35	7732.936	77329356	38.66468	-999	13.00476	-999	-999	-999	-2.19E-08
16N8E21	16	8	21	7754.586	77545863	-999	-999	11.04622	-999	-999	-999	-2.19E-08
18N10E34	18	10	34	8070.322	80703220	-999	-999	12.99848	-999	-999	-999	-2.19E-08
16N10E8	16	10	8	8418.837	84188373	42.09419	-999	12.81159	-999	-999	-999	-2.19E-08
16N10E17	16	10	17	9697.684	96976844	48.48842	-999	12.49955	-999	-999	-999	-2.19E-08
16N10E20	16	10	20	10168.25	1.02E+08	50.84126	-999	12.18476	-999	-999	-999	-2.19E-08
18N10E31	18	10	31	10893.98	1.09E+08	-999	-999	13.09173	-999	-999	-999	-3.08E-09
17N8E24	17	8	24	12123.77	1.21E+08	-999	-999	13.31317	-999	-999	-999	-3.08E-09
18N11E4	18	11	4	12677.18	1.27E+08	-999	-999	13.0566	-999	-999	-999	-3.08E-09
18N11E5	18	11	5	12886.69	1.29E+08	-999	-999	12.97111	-999	-999	-999	-3.08E-09
18N11E6	18	11	6	13515.85	1.35E+08	-999	-999	12.98879	-999	-999	-999	-3.08E-09
18N9E36	18	9	36	13603.51	1.36E+08	-999	-999	13.13431	-999	-999	-999	-3.08E-09
18N9E35	18	9	35	13639.32	1.36E+08	-999	-999	13.13094	-999	-999	-999	-3.08E-09
17N8E23	17	8	23	13813.9	1.38E+08	-999	-999	13.28304	-999	-999	-999	-3.08E-09
17N8E26	17	8	26	13832.11	1.38E+08	-999	-999	13.27228	-999	-999	-999	-3.08E-09
17N9E2	17	9	2	13956.56	1.4E+08	-999	-999	13.07937	-999	-999	-999	-3.08E-09
18N11E7	18	11	7	14267.19	1.43E+08	-999	-999	13.00501	-999	-999	-999	-3.08E-09
18N10E12	18	10	12	14302.32	1.43E+08	-999	-999	13.00317	-999	-999	-999	-3.08E-09
17N9E11	17	9	11	14499.93	1.45E+08	-999	-999	13.03667	-999	-999	-999	-3.08E-09
17N8E27	17	8	27	14661.32	1.47E+08	-999	-999	13.2611	-999	-999	-999	-3.08E-09
17N9E14	17	9	14	14707.89	1.47E+08	-999	-999	12.99355	-999	-999	-999	-3.08E-09
18N10E13	18	10	13	15142.45	1.51E+08	-999	-999	13.0015	-999	-999	-999	-3.08E-09
18N10E14	18	10	14	15336.09	1.53E+08	-999	-999	12.95287	-999	-999	-999	-3.08E-09
18N10E22	18	10	22	15981.89	1.6E+08	-999	-999	12.85328	-999	-999	-999	-3.08E-09
18N10E27	18	10	27	16286.53	1.63E+08	-999	-999	12.76857	-999	-999	-999	-3.08E-09
17N8E34	17	8	34	17034.07	1.7E+08	-999	-999	13.14029	-999	-999	-999	-3.08E-09
17N8E33	17	8	33	18125.55	1.81E+08	-999	-999	13.03774	-999	-999	-999	-3.08E-09
16N8E4	16	8	4	18480.37	1.85E+08	-999	-999	12.97224	-999	-999	-999	-3.08E-09
16N8E9	16	8	9	18671.99	1.87E+08	-999	-999	12.9281	-999	-999	-999	-3.08E-09
16N8E10	16	8	10	18712.91	1.87E+08	-999	-999	12.91135	-999	-999	-999	-3.08E-09

16N8E15	16	8	15	22449.25	2.24E+08	-999	-999	12.82144	-999	-999	-999	-7.06E-09
16N8E16	16	8	16	22483.2	2.25E+08	-999	-999	12.80845	-999	-999	-999	-7.06E-09
16N8E22	16	8	22	22647.91	2.26E+08	-999	-999	12.77199	-999	-999	-999	-7.06E-09
18N10E33	18	10	33	25091.85	2.51E+08	-999	-999	12.78573	-999	-999	-999	-7.06E-09
17N10E5	17	10	5	25982.8	2.6E+08	-999	-999	12.71667	-999	-999	-999	-7.06E-09
17N10E6	17	10	6	26312.54	2.63E+08	-999	-999	12.68634	-999	-999	-999	-7.06E-09
17N10E7	17	10	7	26437.18	2.64E+08	-999	-999	12.68377	-999	-999	-999	-7.06E-09
17N9E12	17	9	12	26889.62	2.69E+08	-999	-999	12.66888	-999	-999	-999	-7.06E-09
17N9E13	17	9	13	26935.31	2.69E+08	-999	-999	12.667	-999	-999	-999	-7.06E-09
16N8E28	16	8	28	30604.43	3.06E+08	-999	-999	12.29023	-999	-999	-999	-7.06E-09
16N8E27	16	8	27	31114.82	3.11E+08	-999	-999	12.2504	-999	-999	-999	-7.06E-09
16N8E26	16	8	26	31115.06	3.11E+08	-999	-999	12.2503	-999	-999	-999	-7.06E-09
16N8E34	16	8	34	31115.06	3.11E+08	-999	-999	12.2503	-999	-999	-999	-7.06E-09
16N8E35	16	8	35	33922.33	3.39E+08	-999	-999	12.06535	-999	-999	-999	-7.06E-09
16N8E36	16	8	36	33975.38	3.4E+08	-999	-999	12.04958	-999	-999	-999	-7.06E-09
17N9E15	17	9	15	43393.23	4.34E+08	-999	-999	12.75173	-999	-999	-999	-9.15E-09
17N9E21	17	9	21	43823.41	4.38E+08	-999	-999	12.72012	-999	-999	-999	-9.15E-09
17N9E22	17	9	22	43898.68	4.39E+08	-999	-999	12.71229	-999	-999	-999	-9.15E-09
17N9E27	17	9	27	44509.76	4.45E+08	-999	-999	12.71723	-999	-999	-999	-9.15E-09
17N9E28	17	9	28	45431.22	4.54E+08	-999	-999	12.66134	-999	-999	-999	-9.15E-09
17N9E33	17	9	33	45474.93	4.55E+08	-999	-999	12.65426	-999	-999	-999	-9.15E-09
17N9E32	17	9	32	45680.11	4.57E+08	-999	-999	12.61986	-999	-999	-999	-9.15E-09
17N9E31	17	9	31	46294.42	4.63E+08	-999	-999	12.5729	-999	-999	-999	-9.15E-09
16N8E1	16	8	1	47267.69	4.73E+08	-999	-999	12.4746	-999	-999	-999	-9.15E-09
16N8E12	16	8	12	47287.52	4.73E+08	-999	-999	12.4737	-999	-999	-999	-9.15E-09
16N9E6	16	9	6	47289.54	4.73E+08	-999	-999	12.47342	-999	-999	-999	-9.15E-09
16N9E7	16	9	7	47593.46	4.76E+08	-999	-999	12.446	-999	-999	-999	-9.15E-09
16N9E18	16	9	18	50430.31	5.04E+08	-999	-999	12.17261	-999	-999	-999	-9.15E-09
16N9E30	16	9	30	51502.72	5.15E+08	-999	-999	12.03063	-999	-999	-999	-9.15E-09
16N8E25	16	8	25	51693.33	5.17E+08	-999	-999	12.02608	-999	-999	-999	-9.15E-09
16N9E31	16	9	31	52025.17	5.2E+08	-999	-999	11.996	-999	-999	-999	-9.15E-09
15N8E1	15	8	1	88213.38	8.82E+08	-999	-999	11.9147	-999	-999	-999	-7.29E-09
15N8E12	15	8	12	88214.59	8.82E+08	-999	-999	11.9146	-999	-999	-999	-7.29E-09
15N9E6	15	9	6	88214.59	8.82E+08	-999	-999	11.9146	-999	-999	-999	-7.29E-09
15N9E7	15	9	7	90280.11	9.03E+08	-999	-999	11.76076	-999	-999	-999	-7.29E-09
15N9E18	15	9	18	90352.95	9.04E+08	-999	-999	11.75607	-999	-999	-999	-7.29E-09
15N9E17	15	9	17	90380.87	9.04E+08	-999	-999	11.75309	-999	-999	-999	-7.29E-09
15N9E8	15	9	8	93092.67	9.31E+08	-999	-999	11.56032	-999	-999	-999	-7.29E-09
15N9E9	15	9	9	94022.23	9.4E+08	-999	-999	11.49095	-999	-999	-999	-7.29E-09
15N9E10	15	9	10	94033.16	9.4E+08	-999	-999	11.48967	-999	-999	-999	-7.29E-09
15N9E15	15	9	15	94425.71	9.44E+08	-999	-999	11.46035	-999	-999	-999	-7.29E-09
15N9E12	15	9	12	125917.5	1.26E+09	-999	-999	11.38534	-999	-999	-999	-7.29E-09
15N10E18	15	10	18	127286.2	1.27E+09	-999	-999	11.30118	-999	-999	-999	-7.29E-09

References

- Almendinger, J.E. 1999. "A Method to Prioritize and Monitor Wetlands Restoration for Water-Quality Improvement." *Wetlands Ecology and Management* 6: 241-251.
- Babcock B.A., P.G. Lakshminarayan, J.J. Wu, and D. Zilberman. 1996. "The Economics of a Public Fund for Environmental Amenities: A Study of CRP Contracts." *American Journal of Agricultural Economics* 78: 961-971.
- Babcock, B.A., P.G. Lakshminarayan, J. Wu, and D. Zilberman. 1997. "Targeting Tools for the Purchase of Environmental Amenities." *Land Economics* 73: 325-339.
- Bernot, M.J., and W.K. Dodds. 2005. "Nitrogen Retention, Removal, and Saturation in Lotic Ecosystem." *Ecosystems* 8: 442-453.
- Bhowmik, N.G. 1984. "Hydraulic Geometry of Floodplains." *Journal of Hydrology* 68:369-401.
- Böhlke, J.K., R.C. Antweiler, J.W. Harvey, A.E. Laursen, L.K. Smith, R.L. Smith, and M.A. Voytek. 2009. "Multi-Scale Measurements and Modeling of Denitrification in Streams with Varying Flow and Nitrate Concentration in the Upper Mississippi River Basin, USA." *Biogeochemistry* 93: 117-141.
- Crumpton, W.G., T.M. Isenhardt, and S.W. Fisher. 1993. "The Fate of Non-Point Source Nitrate Loads in Freshwater Wetlands: Results from Experimental Wetlands Mesocosms." In G.A. Moshiri, ed. *Constructed Wetlands for Water Quality Improvements*. Boca Raton FL: Lewis Publishers, pp. 283-292.
- Crumpton, W.G. 2001. "Using Wetlands for Water Quality Improvement in Agricultural Watersheds: The Importance of a Watershed Scale Approach." *Water Science and Technology* 44: 559-564.

Crumpton, W.G., D.A. Kovacic, D.L. Hey, and J.A. Kostel. 2005. "Potential of Restored and Constructed Wetlands to Reduce Nutrient Export from Agricultural Watersheds in the Corn Belt." In Upper Mississippi River Sub-Basin Hypoxia Nutrient Committee. *Final Report: Gulf Hypoxia and Local Water Quality Concerns Workshop*. Ames IA: American Society of Agricultural and Biological Engineers, pp. 29-42.

Crumpton, W.G., G.A. Stenback, B.A. Miller, and M.J. Helmers. 2006. *Potential Benefits of Wetland Filters for Tile Drainage Systems: Impact on Nitrate Loads to Mississippi River Subbasins*. Washington DC: U.S. Department of Agriculture.

David, M.B., L.E. Gentry, D.A. Kovacic, and K.M. Smith. 1997. "Nitrogen Balance in and Export from an Agricultural Watershed." *Journal of Environmental Quality* 26: 1038-1048.

David, M.B., G. McIsaac, and C.A. Mitchell. 2008. *Water Quality Improvement Case Study: Assessment of the Lake Bloomington Watershed*. Springfield, IL: Illinois Environmental Protection Agency, Bureau of Water, Final Report, March.

Diebel, M.W., J.T. Maxted, D.M. Robertson, S. Han, and M.J. Vander Zanden. 2009. "Landscape Planning for Agricultural Nonpoint Source Pollution Reduction III: Assessing Phosphorus and Sediment Reduction Potential." *Environmental Management* 43: 69-83.

Doering, O.C. 2002. "Economic Linkages Driving the Potential Response to Nitrogen Over-Enrichment." *Estuaries* 25: 809-818.

Dosskey, M.G., M.J. Helmers, and D.E. Eisenhauer. 2006. "An Approach for Using Soil Surveys to Guide the Placement of Water Quality Buffers." *Journal of Soil and Water Conservation* 6: 344-354.

Dunne, T., and L.B. Leopold. 1978. *Water in Environmental Planning*. San Francisco: W. H. Freeman and Company.

Fausey, N.R., L.C. Brown, H.W. Belcher, and R.S. Kanwar. 1995. "Drainage and Water Quality in Great Lakes and Cornbelt States." *Journal of Irrigation and Drainage Engineering* 121: 283-288.

Galster, J.C. 2009. "Testing the Linear Relationship between Peak Annual River Discharge and Drainage Area using Long-Term USGS River Gauging Records." in James, L.A., S.L. Rathburn, and G.R. Whittecar, eds. *Management and Restoration of Fluvial Systems with Broad Historical Changes and Human Impacts*. Boulder CO: The Geological Society of America, pp. 159-171.

Hansen, L.T. 2009. "The Viability of Creating Wetlands for the Sale of Carbon Offsets." *Journal of Agricultural and Resource Economics* 34: 350-365.

Hansson, L.-A., C. Brönmark, P.A. Nilsson, and K. Abjörnsson. 2005. "Conflicting Demands on Wetland Ecosystem Services: Nutrient Retention, Biodiversity or Both?" *Freshwater Biology* 50: 705-714.

Hey, D.L., K.R. Barret, and C. Beigen. 1994. "The Hydrology of Four Constructed Marshes." *Ecological Engineering* 3: 319-344.

Hey, D.L., A.L. Kenimer, and R.K. Barrett. 1994. "Water Quality Improvement by Four Experimental Wetlands." *Ecological Engineering* 3: 381-398.

Illinois Department of Natural Resources. 2006. *Big Bureau Creek Watershed Inventory and Evaluation*. Final Report, December.

Kadlec, R.H., and R.L. Knight. 1996. *Treatment Wetlands*, 1st. ed. Boca Raton: CRC Press.

Kadlec, R.H., and S.D. Wallace. 2008. *Treatment Wetlands*, 2nd. ed. Boca Raton: CRC Press.

Kovacic, D.A., M.B. David, L.E. Gentry, K.M. Starks, and R.A. Cooke. 2000. "Wetlands and Aquatic Processes: Effectiveness of Constructed Wetlands in Reducing Nitrogen and Phosphorus Export from Agricultural Tile Drainage." *Journal of Environmental Quality* 29: 1262-1274.

Larson, A.C., L.E. Gentry, M.B. David, R.A. Cooke, and D.A. Kovacic. 2000. "The Role of Seepage in Constructed Wetlands Receiving Agricultural Tile Drainage." *Ecological Engineering* 15: 91-104.

Lentz, A.B. 2011. "Water Quality Trading: Credit Stacking and Ancillary Benefits." MS thesis, University of Illinois at Urbana-Champaign.

Leopold, L.B., and T. Maddock. 1953. *The Hydraulic Geometry of Stream Channels and Some Physiographic Implications*. Washington DC: U.S. Department of the Interior, United States Geological Survey Professional Paper 252.

Logan, T.J., D.J. Eckert, and D.G. Beak. 1994. "Tillage, Crop and Climatic Effects on Runoff and Tile Drainage Loss of Nitrate and Four Herbicides." *Soil and Tillage Research* 30: 74-103.

Melody, J.B. and W.K. Dodds. 2005. "Retention, Removal, and Saturation in Lotic Ecosystems." *Ecosystems* 8: 442-453.

Mitsch, W.J., and J.G. Gosselink. 2007. *Wetlands*. 4th. ed. Hoboken, NJ: John Wiley & Sons Inc.

Minnesota Board of Water and Soil Resources. 2009. *Wetlands Restoration Strategy: A Framework for Prioritizing Efforts in Minnesota. Supplement to the Minnesota Wetlands Conservation Plan 1997*. St. Paul, January 2009.

Moreno-Mateos, D., Ü. Mander, and C. Pedrocchi. 2010. "Optimal Location of Created and Restored Wetlands in Mediterranean Agricultural Catchments." *Water Resources Management* 24: 2485-2499.

National Atlas. 2010. *Streams and Waterbodies*. Accessed online September 20, 2010, <http://dds.cr.usgs.gov/pub/data/nationalatlas/hydrogm020.tar.gz>.

Newbold, S.C. 2005. "A Combined Hydrologic Simulation and Landscape Design Model to Prioritize Sites for Wetlands Restoration." *Environmental Modeling and Assessment* 10: 251-263.

Peralta, A.L., J.W. Matthews, and A.D. Kent. 2010. "Microbial Community Structure and Denitrification in a Wetland Mitigation Bank." *Applied and Environmental Microbiology* 76: 4207-4215.

Qiu, Z. 2009. "Assessing Critical Source Areas in Watersheds for Conservation Buffer Planning and Riparian Restoration." *Environmental Management* 44: 968-980.

--. 2010. "Prioritizing Agricultural Lands for Conservation Buffer Placement Using Multiple Criteria." *Journal of the American Water Resources Association* 46: 944-956.

Royer, T.V., J.L. Tank, and M.B. David. 2004. "Landscape and Watershed Processes: Transport and Fate of Nitrate in Headwater Agricultural Streams in Illinois." *Journal of Environmental Quality* 33:1296-1304.

Russell, G.D., C.P. Hawkins, and M.P. O'Neill. 1997. "The Role of GIS in Selecting Sites for Riparian Restoration Based on Hydrology and Land Use." *Restoration Ecology* 5(4S): 56-68.

Sonntag, D.H., and C.A. Cole. 2008. "Determining the Feasibility and Cost of an Ecologically-Based Design for a Mitigation Wetland in Central Pennsylvania, USA." *Landscape and Urban Planning* 87: 10-21.

Stall, J.B., and Fok, Y. 1968. "Hydraulic Geometry of Illinois Streams." *Water Resources Center Research Report No. 15*. University of Illinois, Urbana-Champaign.

Sugg, Z. 2007. "Assessing U.S. Farm Drainage: Can GIS Lead to Better Estimates of Subsurface Drainage Extent?" Unpublished, World Resources Institute.

Tomer, M.D., D.E. James, and T.M. Isenhardt. 2003. "Optimizing the Placement of Riparian Practices in a Watershed Using Terrain Analysis." *Journal of Soil and Water Conservation* 58: 198-206.

Tomer, M.D., M.G. Dosskey, M.R. Burkart, D.E. James, M.J. Helmers, and D.E. Eisenhauer. 2009. "Methods to Prioritize Placement of Riparian Buffers for Improved Water Quality." *Agroforestry Systems* 75: 17-25.

Tomer, M.D., W.G. Crumpton, R.L. Binger, J.K. Kostel, and D.E. James. 2011. "Precision Conservation in a HUC-12 Watershed: Modeling Nitrate Loads after LiDAR-Assisted Placement of Constructed Wetlands." Working paper, U.S. Department of Agriculture, Agricultural Research Service, National Laboratory for Agricultural and the Environment. Ames, IA.

Trepel, M., and L. Palmeri. 2002. "Quantifying Nitrogen Retention in Surface Flow Wetlands for Environmental Planning at the Landscape Scale." *Ecological Engineering* 19: 127-140.

U.S. Department of Commerce, Bureau of Census. 2000. *Geographic Comparison Table: Illinois – County Census 2000*. Washington DC.

U.S. Department of Agriculture. 2009. *2007 Census of Agriculture - County Profile: Bureau County Illinois*. Washington DC, October.

U.S. Department of Agriculture and Iowa Department of Agriculture and Land Stewardship. 2009. *Iowa Conservation Reserve Enhancement Program: Landowner Guide to CREP*. Des Moines, October.

U.S. Department of Agriculture. 2010. *GeoSpatial Data Gateway, National Elevation Dataset 10 Meter*. Washington, DC, September.

U.S. Environmental Protection Agency. 1993. *North American Treatment Wetland Database Electronic Database* created by R. Knight, R. Ruble, R. Kadlec, and S. Reed, version I.

Washington DC.

Van Oostrom, A.J., and R.N. Cooper. 1990. "Meat Processing Effluent Treatment in Surface-Flow and Gravel-Bed Constructed Wastewater Wetlands." In P.F. Cooper, and B.C. Findlater, eds. *Constructed Wetlands in Water Pollution Control*. Oxford UK: Pergamon Press pp. 321-332.

Van Oostrom, A.J, and J.M. Russell. 1994. "Denitrification in Constructed Wastewater Wetlands Receiving High Concentrations of Nitrate." *Water Science and Technology* 29(4): 7-14.

Wollheim, W.M, C.J. Vörösmarty, B.J. Peterson, S.P. Seitzinger, and C.S. Hopkins. 2006. "Relationship between River Size and Nutrient Removal." *Geophysical Research Letters* 33(L06410): 1-4.

Woltemade, C.J. 2000. "Ability of Restored Wetlands to Reduce Nitrogen and Phosphorus Concentrations in Agricultural Drainage Water." *Journal of Soil and Water Conservation* 55: 303-309.

Woodward, T. R. and Y.-S. Wui. 2001. "The Economic Value of Wetland Services: A Meta-Analysis." *Ecological Economics* 37: 257-270.

Xue, Y., D.A. Kovacic, M.B. David, L.E. Gentry, R.L. Mulvaney, and C.W. Lindau. 1999. "In Situ Measurements of Denitrification in Constructed Wetlands." *Journal of Environmental Quality* 28: 263-269.

Zedler, J.B. 2003. "Wetlands at your Service: Reducing Impacts of Agriculture at the Watershed Scale." *Frontiers in the Ecology and the Environment* 1(2): 65-72.