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UNDERSTANDING NONPOINT SOURCE POLLUTION IN THE CANNON RIVER WATERSHED THROUGH METHODOLOGICAL COMPLEMENTING

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Senior Comprehensive Exercise

Advised by Michael Kowaleski and Aaron Swoboda
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ABSTRACT

As one of a multitude of interconnected environmental issues, nonpoint source pollution in the Cannon River Watershed is a problem that has far-reaching negative consequences. It therefore requires effective solutions to be formulated and implemented in as timely a fashion as possible. Because of this, we engage in methodological complementing -- the process of investigating a phenomenon through conclusive and expressive processes, and dovetailing the insights of each process to discern deeper perspectives about the phenomenon and the working relationships of diverse collaborators.

We examine nonpoint source pollution in the Cannon River Watershed through the conclusive approach of nutrient emission heterogeneity modeling (Part I) and the expressive approach of writing poetry to articulate the modeling's limitation of quantification (Part II). Part I is a foundational step to assess the geographic variability of agricultural nonpoint source pollution and its relevance to strategic nutrient mitigation systems such as Water Quality Trading Markets -- a practical policy approach that seeks to ensure the continued availability of quality water. Part II expresses water's power of physical and metaphysical interconnection between landscapes, human and nonhuman communities, and environmental issues. We respect and maintain the disciplinary boundaries of each approach, but reconceptualize these boundaries as porous. Because the conclusive and expressive approaches are so different from each other, they each capture a part of the problem that the other approach cannot perceive, and each approach compensates for the major limitations of the other. Both approaches further overlap at specific points of connection (Part III). Through this, we show how methodological complementing can provide a more comprehensive understanding of an overarching problem, enabling future practical and policy solutions to be more congruent with the multifaceted nature of the issues at hand.

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STATEMENT OF RESEARCH PROBLEM

During the latter half of the twentieth century, intensified use of nitrogen (N) and phosphorus (P) fertilizers in agriculture has resulted in an unintentional increase of N and P inputs to the Mississippi River Basin (MRB) watersheds. These fertilizer inputs are necessary for continued large-scale conventional agricultural production, but have resulted in nutrient pollution, including nonpoint source pollution. Agricultural nonpoint source pollution from N and P, which results from land runoff, precipitation, atmospheric deposition, drainage, seepage, or hydrologic modification, is the driving force of nutrient pollution and its negative environmental externalities, including unbalanced aquatic ecosystem dynamics and reduced water quality (Galloway, 2003). Nutrient pollution in water has been difficult to monitor and manage due to the wide variety of land use systems that emit nutrient pollutants (Hall, 1994; Roberts et al., 2008). Unlike point source pollution -- which is discharged from a spatially specific point from conventional industrial sources -- nonpoint source pollution has no easy technological fix, and therefore requires a more systematic approach in order to be effectively addressed. On the practical level, a number of policies, incentives, and taxes have been designed to encourage a systematic reduction of nonpoint source nutrient pollution. Among these, Water Quality Trading Markets (WQTMs) have the potential to be one of the most cost-effective approaches (Roberts et al., 2008), especially when nutrient emissions are not equally distributed. Management strategies for curbing agricultural nonpoint source pollution can be more cost efficient and effective if they consider spatial hydrological models that can predict critical sources of nutrient emissions and empirically examine the spatial heterogeneity of land use and nutrient pollution. By locating and targeting specific areas within a watershed that have high nutrient emissions, available federal and state cost-sharing funds can be used more efficiently to alleviate pollution and improve water quality (Young et al., 1989).

Still, nonpoint source pollution is an issue that spills over the boundaries of a single disciplinary perspective. Natural sciences help to illuminate the biophysical properties that govern nutrient movement, economic realities drive patterns in land use, and cultural understandings of socio-ecological systems and valuing the land give rise, in part, to our economic systems. The study of these dimensions produces *conclusions* that are contained within the formalities of the scientific research process, such as research question, inputs, limitations, and assumptions. Creative processes, such as poetry, provide *expressions* of themes, experiences, and understandings derived from the phenomena studied by the natural and social sciences. Both conclusive and expressive approaches to knowledge provide insights that the other approach cannot.

Because of this, in order to more comprehensively understand the overarching problem of nonpoint source pollution in the Cannon River Watershed, our project engages in "methodological complementing." This is the process of analyzing the same phenomenon from both conclusive and expressive processes of inquiry and dovetailing the insights of each process in order to discern deeper perspectives about the phenomenon and the working relationships of diverse collaborators. We address the following research questions respectively in parts I, II, and III of our paper:

I. How does the intensity of nitrate output vary across different parts of an agriculturally dominated landscape?

II. What are the limitations of our nutrient emission heterogeneity modeling and how can poetry articulate these limitations?

III. How can the insights from Part I's conclusion and Part II's expression dovetail

to yield deeper insight about nonpoint source pollution in the Cannon River Watershed?

This project assumes that both modeling and poetry are legitimate ways of knowing, and that neither has to justify itself to the other or conform to the language and methodologies that are unique and necessary to the integrity of each approach. In the context of our project, neither the modeling discourse nor the poetry discourse is dominant, but value is placed on having multiple perspectives and ways of knowing in active scholarly communication with each other. This enables us to delve into what each approach has to offer, and examine how each can compensate for the limitations of the other.

Though Part I's conclusive model and Part II's expressive collection of poems provide two seemingly disparate ways of understanding nonpoint source pollution in the Cannon River Watershed, our approaches actually complement each other on two levels. First, each provides insights that the other cannot capture: modeling helps to provide a detailed quantitative understanding of nonpoint source pollution emission sources and how they vary throughout the watershed. Poetry helps to elucidate how water flows through and interconnects the microcosm of the Cannon River Watershed with the macrocosm of the entire earth in an ongoing physical and metaphysical process. Second, each approach compensates for the major limitations of the other: modeling provides an objective mode of inquiry that compensates for the poetry's subjectivity, and the poetry helps to elucidate water's roles and values in the human experience that cannot be captured by the abstraction of a very physical landscape into quantified units.

Ultimately, this project is an inquiry into the challenges and insights resulting from a concurrent application of conclusive and expressive methods of landscape and watershed analysis. We choose to focus on agricultural nonpoint source pollution in the Cannon River Watershed in Minnesota because of the severity of nonpoint source pollution, and the concentration of impaired water bodies in the Cannon River Watershed. The explicit collaboration between conclusive and expressive approaches to understand this issue is innovative in that it has never before been applied to address nonpoint source pollution. Two seemingly disparate lines of inquiry actually can yield complementary and thereby more comprehensive ways of understanding nonpoint source pollution in the Cannon River Watershed. Concurrently pursuing conclusive and expressive modes of inquiry puts the outcomes explicitly in dialogue with each other. In future projects, when it comes time to design practical and policy solutions to address nonpoint source pollution, having two perspectives actively in play will provide a foundational grounding for an interdisciplinary approach to complex problems that require both creativity and technical expertise.

PART I: IDENTIFYING AND EVALUATING CRITICAL SOURCE AREAS USING SOIL AND WATER ASSESSMENT TOOL

Premise and Gap in the Literature

Since the advent of the Haber-Bosch process of synthesizing nitrogen fertilizer, the MRB has been increasingly compromised by nonpoint source pollution, especially in the form of nitrate nutrient pollution. Water pollution can be categorized as point and nonpoint source. Point sources are readily identifiable, can be monitored, and are subject to regulation and enforcement of the National Pollutant Discharge Elimination System (NPDES). As a result, academics and policy makers alike have targeted point sources with the assumption that they are the largest sources of nutrient pollution. However, agricultural nonpoint source pollution, which does not originate from a specific source, is the driving force of nutrient pollution and its negative environmental effects, contributing 90% of annual N loads to the MRB. The environmental impact of fertilizer application and management practices on behalf of agricultural nonpoint source pollution are complicated by biophysical and climate factors. Precipitation, surface runoff, atmospheric deposition, drainage, seepage, soil, geology, vegetation, and hydrological properties all factor into relative environmental impact of agricultural nonpoint source pollution (Roberts et al., 2008).

Advances in hydrological and ecological modeling have made it possible to simulate the relative environmental impact of agricultural nonpoint sources as mediated by topography, soil properties, land use/cover type, weather/climate data, and land management practices. Soil and Water Assessment Tool (SWAT) is a versatile hydrologic model that simulates the flow and accumulation of N, P, and sediment adequately over similar models such as the Generalized Watershed Loading Function (Niraula et al., 2013). SWAT divides a study area composed of one or more HUC12s into subbasins and Hydrological Response Units (HRUs), which are categorized units that share similar land use, topography, and soil properties.

One of the many applications of the SWAT model is the identification of Critical Source Areas (CSAs). CSAs are subbasins with the highest unit-area nutrient emissions that contribute to 20% of the cumulative nutrient emissions in a study area (Niraula, 2013). CSA analysis can bypass some of the limitations of field studies and help in prioritizing and targeting subbasins for cost-effective policy implementation (Niraula et al., 2013). Niraula et al. (2013) ranked subbasins by their N, P, and sediment yield using a combined index and defined CSAs as the highest emitting subbasins that contribute 20% of the total nutrient and sediment yields in the study area. Niraula et al.'s study was conducted in a forest-dominated watershed with significant urban cover. Critical sources in this study were found to contribute to 14% of total nitrate loadings. Niraula et al. (2013) posited that further research should identify CSAs in watersheds that are covered predominantly by agricultural operations where land management practices are similar throughout the area. Our study addresses this gap by modeling nutrient emission heterogeneity to define CSAs in a portion of the Cannon River Watershed in an area that is primarily characterized by agricultural land cover. Applying these methods to our study area will help determine whether using SWAT to produce CSAs is a useful exercise in predominantly large-scale agricultural landscapes. For the purpose of managing agricultural nonpoint source pollution, it would be useful to know how critical are CSAs and how unequal are nutrient loads from agricultural operations with similar land management practices. This knowledge is foundational to the spatial feasibility of instituting WQTMs, which is one promising strategy for curbing nutrient emissions on a watershed scale (Roberts, 2008).

While Niraula et al.'s CSA analysis using SWAT is useful for identifying these hot spot sources, the study did not quantify the magnitude of nutrient load inequality and did not consider how the distance from a CSA and an impaired water body, as well as the length and area of the impaired water body, factor into the relative importance of prioritizing CSAs over non-CSAs. These factors are important in considering practical solutions to nutrient pollution. Roberts et al.'s (2008) spatial feasibility analysis of water quality trading devised a method of weighting the relative contribution of subbasin units by factoring nutrient load, distance from impairment, and the impairment area. Roberts et al. initially used this method to compare the relative impact of point source and nonpoint source areas.

Our study will adopt Roberts et al.'s spatial assessment method to compare the relative contributions of critical and noncritical sources of agricultural nonpoint source pollution. In addition to showing how 'critical' the critical source areas are, this analysis provides knowledge of the location and nutrient loads of large pollution sources, which enables policy makers seeking to reduce nutrient emissions to design more effective policies such as WQTMs (Niraula et al., 2013). WQTMs originate from the concept that industrial facilities and landowners face different compliance costs for reducing nutrient emissions depending on their size, scale, age, and efficiency. Therefore, it is more cost effective for some facilities to reduce emissions than others. In a nutrient trading market, credits for emitting beyond water quality standards are sold from low emission sources to high emission sources. In most hypothetical nutrient trading scenarios involving both nonpoint source and point sources, it is predicted that nonpoint sources would likely be sellers of credits to point source emitters (Greenhalgh et al., 2001; Roberts et al., 2008). Nutrient trading markets may very well incentivize farmers to adopt best management practices on their own (Greenhalgh, 2001). Our analysis quantifies the relative contributions of CSAs and non-CSAs, providing foundational material to see if WQTMs are feasible in the Cannon River Watershed.

In summary, our overarching research question is:

I. Does the intensity of nitrate output vary across different parts of an agriculturally dominated landscape?

We operationalize this question by breaking it into three question components:

A. Are nitrate emissions from agricultural nonpoint source spatially unequal when agricultural operations are assumed to be homogenous?

B. How many CSAs contribute to 20% of the total modeled nitrate emissions in an agricultural landscape and how large are these areas?

C. What is the relative impact of the CSA subbasin minority and the non-CSA majority to nitrate pollution?

Review of Related Literature

Nitrogen and Phosphorus Problems in Southeastern Minnesota and the Mississippi River Basin

The intensive and large-scale application of fertilizers on southeastern Minnesota farms contributes excess loads of N and P that cannot be fully absorbed and retained in ecological and hydrological systems. Excess nutrients are leached to groundwater, streams, rivers, estuaries, and lakes, causing eutrophication and toxic pollution in water bodies throughout the MRB, both near the Mississippi delta and within the Upper Minnesota River Basin (Heiskary, 2003). N and P enrichment of water bodies upsets the balance of nutrients in ecosystems that evolved with limited amounts of nutrients, disrupting biotic community structure and competition. The consequences of anthropogenic disturbance in the form of nutrient pollution include toxic algal blooms, diminished and deformed fish populations, non-potable and unsafe water for human use, high water treatment costs, and the phenomena known as the "Dead Zone" off the Gulf of Mexico (U.S. Environmental Protection Agency, A.E.I.L., 2012).

Heiskary (2003) observed that between the years of 1980 and 1996, the Minnesota River Basin held a mean nitrate concentration of 4.19 mg/L, the third highest nitrate concentration of all 7 river basins connected to the Mississippi river. Minnesota's numeric standard threshold for nitrate and P concentrations at sample sites is 0.1mg/L. 96% of samples collected from 1994 to 2008 were above the threshold concentration standard. It is therefore imperative to manage and mitigate nutrient loading within these watersheds.

Biophysical Processes Related to Nitrogen and Phosphorus

Nitrogen is at once the most abundant element in the earth's atmosphere, as well as the most limiting resource to biological organisms in natural environments. Limiting resources constrain the growth, function, and development of organisms and natural systems. Reactive N is an essential and often limiting component of enzymes involved in photosynthesis and most proteins. The large energy demands of N_2 fixation have reserved N_2 fixation to a select niche of species and has caused the majority of species and ecosystems to evolve in N limited settings (Vitousek et al, 1997). Nitrogen is constantly being transformed from atmospheric, to inorganic and organic compounds, including NH_4, NO_4, rN, NO, NO_x, N_2O, N_2. Each of these N compounds has unique properties. Of particular interest in this study are nitrates (NO_3) since they represent the majority of nutrients emissions in our study area. Nitrates have a negative charge and are highly mobile in negatively charged soil.

Humans have dramatically increased the amount of reactive N in ecosystems by planting N-fixing legumes such as soybeans, combusting fossil fuels, and applying ammonia fertilizers derived from the Haber-Bosch process of fixing atmospheric N using fossil fuels (Galloway et al., 2003). From 1860 to 2000, the output of global reactive N has increased by 142 teragrams (TgN) per year -- 18 TgN from the cultivation of legumes, 24 TgN from fossil fuel combustion, and 100 TgN from fertilizer production (Galloway, 2003). The total flux of annual N that flows into the Gulf of Mexico from the Mississippi river is approximately 1.5 million metric tons, 1 million of which are nitrates (Compton, 2011).

P is similar to N in that it is a crucial but limiting ingredient for many life forms and ecosystems. P is involved in building genetic material (DNA and RNA), facilitating energy transfer (ATP), and serving as a structural support for cellular membranes (phospholipids). In contrast to N, P is derived from weathered rocks and cycles and is rarely cycled into the atmosphere like N and carbon. Many ecosystems are P-limited due to the inaccessibility of undissolved phosphate and occlusion of P by iron, aluminum, and calcium in acidic and alkaline soils (Ruttenberg, 2003). P is extensively mined around the world from apatite ores to create P fertilizer to support agricultural systems (Pierrou, 1976).

The negative environmental effects of fertilization and nutrient deposition are of such a high magnitude because most natural systems evolved to be limited in both N and P. The massive inputs of reactive N and P into global systems have provided important benefits to society by sustaining a large part of the human population. However, reactive N and P inputs from humans, particularly since the latter half of the twentieth century, have had serious ramifications on nutrient cycling, biodiversity, ecosystem functions, and ecosystem services provided for humans (Vitousek, 1997; Galloway, 2003).

Excess N and P that is not absorbed by organisms is leached to groundwater, denitrified, or carried to aquatic systems via hydrologic pathways. N saturated soils become acidified, which decreases forest productivity. In aquatic systems, excess P and N -- in the form of ammonium or nitrates -- cause a surplus of algae that over consume oxygen and decimate fish and other organism populations in hypoxic and anoxic conditions. Algal blooms can make water highly toxic as well, reducing recreation opportunities, threatening human health, and increasing water sanitation costs (Galloway, 2003; Vitousek, 1997; Compton, 2011).

Key Landscape and Land Management Factors Affecting Nutrient Mobilization and Difficulty in Monitoring Nonpoint Source Pollution

The extent of N and P losses from soil is greatly determined by rainfall and land management practices, especially fertilizer and manure application (Niraula et al., 2013). Infiltration of surface water to the soil and leaching of water into aquifers affect whether nutrients are incorporated into surface or groundwater. The percentage of N loads from initial fertilizer application that are transported by subsurface and surface runoff to water bodies ranges from 10% to 40% for loam and clay soils, and 25% to 80% for sandy soils (Howarth et al., 1996). Soils in southeastern Minnesota are typically a loess soil, which are twenty percent or less clay and an equal balance of sand and silt. Loess soils are highly susceptible to erosion and sediment loss, which transports sediment bound nutrients to water bodies (Alberts, 1978). Fluxes in these percentages are influenced by fertilizer application rate, season, the chemical state and mobility of nitrogen, method of nutrient application, rainfall, and vegetative cover.

Factors controlling the transport of nutrients to a water body -- including slope, drainage, soil, and crop management practice -- determine the sensitivity of surface waters to nutrient inputs just as much as the aforementioned nutrient characteristics of the soil source (Kamprath et al., 2000). The area affected by an agricultural pollution source depends on the coincidence of the source (soil, crop, and management) and transport (runoff, erosion, channel processes) (Heathwaite et al., 2005). Nutrient biochemical reactivity and mobility determine the spatial extent of this contributing area and the degree of environmental risk. Furthermore, the content and pathways of nutrient washout from soil is complicated by changes in land use practice, population densities, agricultural practices, and urban development (Carpenter et all, 1998, Harris, 2001).

The frequencies of erosion and runoff events are affected by rainfall events. Rainfall events transport more P than rill or gully erosion alone, mobilizing nutrient enriched topsoil, manure, and plant residues. Gully erosion transports nutrient poor subsoil (Gillingham and Thorrold, 2000).

Chronic pollution occurs through quick moving surface runoff and slow subsurface flow, which are more difficult to control. Areas with deep soil and permeable bedrock result in less lateral flow and more percolation to groundwater. Artificial land drainage speeds water transit from land to stream. Pollution flow can be hastened by land management practices that damage the soil surface through deeper compaction and soil degradation and soil capping (Heathwaite, Quinn and Hewett, 2005). Best management practices can improve agricultural productivity and reduce soil degradation and nutrient emissions. For instance, applying fertilizers at different times, such as the spring, may increase crop nutrient use efficiency. Other best management practices -- including growing more nutrient efficient crops, growing cover crops, reducing tillage, and using precision fertilizer application technologies -- can all reduce leaching, N volatilization, and erosional loss of nutrients (Tilman et al, 2002).

In the case of N pollution, point sources only contribute 10% of annual N loads, whereas 90% of N is leached from nonpoint sources (Greenhalgh et al, 2001). The amount of P in fertilizers applied in the US is much less than that of N. Nevertheless, P pollution is still exacerbated by agricultural activities via erosion, sedimentation, and increased leaching associated with degraded soil (Westra, 2002). 72% - 82% percent of eutrophic lakes would require control of nonpoint nutrient inputs to meet water quality standards, even if point inputs were reduced to zero (Carpenter, 1998). Agricultural land use plays the largest role in nonpoint source emissions, and therefore is the topic that our study aspires to address (Turner and Rablais, 1994).

Current regulation and monitoring of nonpoint source pollution from the agricultural sector is difficult because of both the large spatial scale of agricultural production in the United States, and the hydrological and ecological complexity of nutrient cycling (Roberts et al., 2008; Galloway, 2003). From a hydrological perspective, it is difficult to associate observed N and P loads with particular polluters because of the lag time between fertilizer application and nutrient mobilization. The lag times of nutrient movement in natural systems also complicates the task of tracking pollutants at any given time (Galloway, 2003; Vitousek, 1997).

Watershed Management Measures for Controlling Nonpoint Source Pollution: Practical Approaches for Managing Critical Source Areas

N and P nonpoint source pollution of surface waters can be reduced by controlling nutrient flows and runoff from agricultural systems and process, by setting limits on industrial and agricultural output, and by reducing N emissions from fossil fuel burning (Carpenter, 2010). Strategic planning of filter strips, wetland restoration, Conservation Reserve Program and other vegetation-based buffers depends on an understanding of critical source areas and nutrient hotspots within a watershed. Eutrophication, ground water contamination, ecosystem degradation can be reversed by decreasing N and P loads to aquatic systems, but recovery rates are highly variable. Since vegetation has a physiological demand for N and P, the strategic placement of vegetated filter strips and riparian buffers has the potential to put excess nutrient runoff to productive use.

Filter strip construction and riparian vegetation buffers along waterways are popular best management practices in managing CSAs because they are low impact and easy to implement. Filter strips are permanent vegetation zones and have been extensively demonstrated as a tool for reducing nonpoint source pollution (Chen 2014, Volke, 2009). Lee et al. (2010) reported a 5% reduction in total nutrient load after building a 20m wide filter strip along the Gyeongancheon watershed of South Korea. Filter strips of a width between 5-10 meters have been shown to be most effective (Leet et al., 2010). Chen et al. (2014) studied the relative efficacy of several management plans for installing filter strips based on watershed simulation models and CSA identification. These management plans were chosen because they have been shown to reduce water pollution while avoiding huge impacts on agricultural activities and food security. Methods for strategically installing buffer strips using watershed simulation models include the following:

(1) Rank the subbasins by nutrient contribution coefficient and choose the top several subbasins to build a filter strip.

(2) Rank the subbasins by improvement coefficient based on the estimated impact of installing buffers and choose the top several subbasins to build a filter strip.

(3) Choose the subbasins based on the optimal solution for linear programming. The management results should minimize the total length of the filter strip in order to improve economic cost efficiency.

(4) Choose to build a filter strip in the CSAs making the width of the filter strip large enough to satisfy nutrient mitigation requirement requirements.

Our study inquires whether a SWAT based framework for identifying CSAs and analyzing nutrient emission inequality can contribute to cost-effective nutrient mitigation programs discussed in the next section.

Policy Options for Addressing Nonpoint Source Pollution

There are various policy options for addressing nonpoint source pollution, all of which can benefit from monitoring and understanding the cycling and movement of N and P. These include command and control regulation, nitrogen fertilizer taxes, conservation tillage subsidies, the Conservation Reserve Program, (carbon) trading, and Water Quality Trading Markets (WQTMs). Each has achieved certain degree of success, but all can be enhanced by a working knowledge of the spatial distribution of nutrient emission. With a combination of these policy options, the Mississippi River Taskforce has set a goal of reducing nutrient loads by 20 to 30% of levels in the year of 2000.

Command and control regulation is an approach to address nonpoint source pollution that sets legal limits on pollution emissions and relies on extensive monitoring to enforce quotas. Command and control regulation of agricultural nonpoint sources would require standardized monitoring that directly quantifies the nutrient contribution of individual tracts of agricultural land. The cost and difficulty of achieving this level of detail in monitoring is nearly impossible. Because of this complexity, policy makers have suggested a suite of options alternative to command and control regulation that approach nutrient pollution reduction more systematically.

N fertilizer taxes could reduce nutrient losses by incentivizing farmers to apply less fertilizer. Much of the N loss from land to water in the Mississippi River Basin derives from fertilizer (Greenhalgh, 2001). Farmers typically apply excessive ammonia fertilizer as a form of crop insurance in the fall after harvest, which over the course of the winter, is converted into leach-prone nitrates (Compton, 2011). N fertilizer taxes could encourage farmers to adopt best management practices that reduce fertilizer demands. They could put increasing economic pressure on farmers to reduce fixed costs in other ways, such as by expanding their agricultural operations, growing genetically modified seed, and hiring undocumented workers. While this policy hopes that farmers would adapt to fertilizer taxes by decreasing their fertilizer demand, there is no guarantee against the possibility that farmers will continue emitting high amounts of nutrient pollution at the expense of reducing their fixed costs in other ways (Greenhalgh, 2001).

Another policy option that is currently being implemented is the Conservation Reserve Program (CRP). The CRP was instituted in the 1986 Farm Bill to convert marginal, erodible land into grasslands and forests. The benefits of CRP land include reduced soil erosion, improved water quality, carbon sequestration, and nutrient retention (Feather et al, 1999). As a federally funded program, the CRP budget is continually fluctuating and is vulnerable to budget cuts, given its marginal political interest. Even if many farmers desired to convert some of their land to CRP, the application process is complicated and the likelihood of being accepted is slim given restricted budgets. The use of hydrological modeling and CSA identification could help federal offices establish CRP land in strategic areas that mitigate nutrient runoff more effectively.

Finally, WQTMs give market participants flexibility in achieving their designated reduction goals by enabling credit trading. Sources that can meet their reduction goals at a lower cost can sell their extra credits to sources that require more credits due to their high costs of reductions. Since water pollution control costs vary considerably from source to source, water pollution control can benefit from this cap-and-trade approach (Jensen, 1989). Under constant pressure to reduce discharges, each source will likely seek the most innovative and the low-cost way to meet their reduction goals; in the end this policy could result in a cost-effective outcome. In addition, WQTMs provide flexibility in how regulations are met and potentially lower regulatory compliance and abatement costs (Selman et al., 2009). The National Cost to Implement Total Maximum Daily Loads (TMDLs) Draft Report estimates that flexible approaches to improving water quality could save $900 million dollars annually compared to the least flexible approach. Furthermore, benefits such as restored wildlife habitat, wetland creation, stream bank stabilization and carbon sequestration also result from this policy (MPCA, 2008). Roberts et al. (2008) stress the importance of spatial variability in nutrient contribution and geographic dispersion of nutrient emission hotpots as critical elements of a feasible WQTM. Therefore, our study focuses on identifying CSAs and assessing nutrient emission inequality to partially address whether WQTMs may be relevant to mitigating agricultural nonpoint source pollution in areas such as the Cannon River Watershed.

Methods

Refer to Figure 1 for a flow chart of our Part I concepts and methods.

Study Area

Our study area is a portion of the Cannon River Watershed (Figure 2) that contains a high concentration of impaired water bodies as determined by the Environmental Protection Agency (EPA, 2014). 25 impaired lakes are located within a 55,290 hectare area that consists of 6 HUC12 watersheds. HUCs are hydrologic units that are often used to specify spatial scale. HUC8s are the most coarse (the entire Cannon River Watershed is one HUC8). HUC12s are the finest resolution watersheds that are made available by most online hydrologic databases. Our study area overlaps Rice, Le Sueur, Waseca, and Steele counties. The study area is predominantly covered by agricultural land row crops (28,541 hectares, or 51.8% of the total study area) (Figure 3). Water bodies account for 8.6 percent of the study area or 4,758.6 hectares. All 6 HUC12s that compose the study area drain into the southern point of Wells Lake. This area was covered by thick glacial deposits which date back 14 thousand years. Karst features are not present in the area (Savina, 2014), and water quality is well defined by surface and shallow subsurface characteristics. The area is characterized by very short and intense growth period in the summer from May to September and a long, cold winter. Roberts et al. (2008) and other SWAT studies have successfully analyzed larger study areas and have cross-examined multiple watersheds (Debele, Srinivasan and Parlange, 2006; Roberts et al., 2008). However, due to the limitations of time and expertise, our study only sought to examine a smaller set of HUC12 boundaries.

Our model relies on a standardized agricultural management schedule that generalizes agricultural operations throughout the study area. We used an interview script created by the Minnesota Pollution Control Agency for the purpose of obtaining necessary SWAT input data from the National Resource Conservation Service (NRCS) county offices (Watkins, 2014). The interview format is designed to obtain SWAT relevant information on crop rotations, tile drainage, fertilizer application, manure management, and tillage practices. Justin Watkins from the MPCA provided us with SWAT advice and referred us to interview Thomas Coffman from the Rice County NRCS Soil and Water Conservation District. After interviewing Thomas Coffman, we also asked Karl Hakanson from the Cannon River Watershed Partnership the same questions in order to have another perspective on general agronomic practices. The information gleaned from our interviews and correspondence allowed us to construct the agricultural management calendar (Appendix A), which was extended to all HRUs with agricultural land use in the study area.

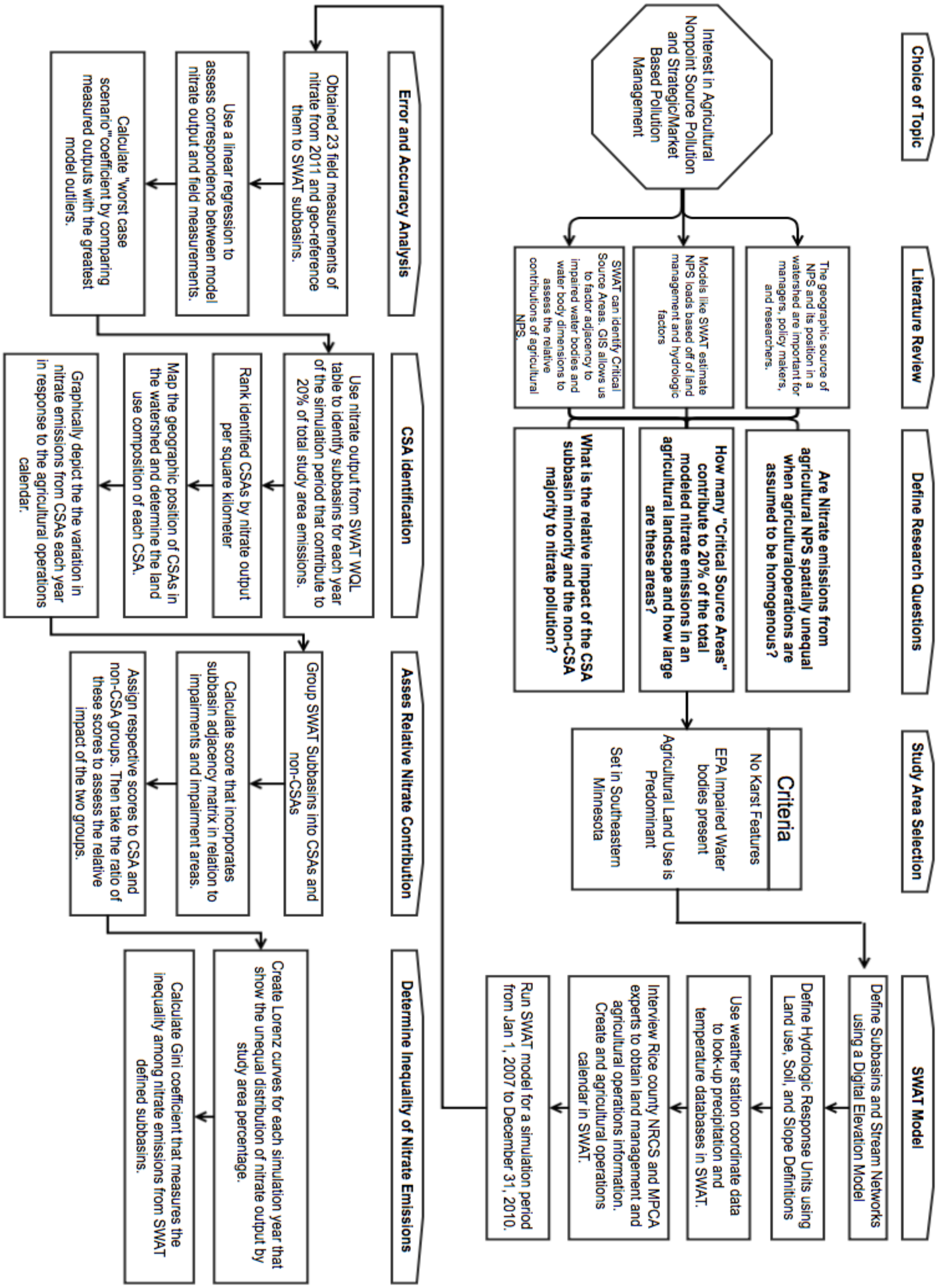

Figure 1. Flow chart of Part I study concept and method.

According to the Minnesota Pollution Control Agency and the NRCS office in Rice County, the vast majority of agriculturalists follow a corn-soybean intercrop rotation with two years of corn cultivation and one year of soybean cultivation, although there is a small presence of livestock and non conventional organic farming in the region (Coffman, 2013). The University of Minnesota recommends an annual application of 120 pounds of anhydrous ammonium fertilizer per acre for these conventional corn-corn-soy rotations, but the MPCA reports that the common practice is to apply 180 pounds per acres and 20 pounds of phosphorus and potassium (Randall and Schmitt, 1993).

Study Area Land Use / Land Cover

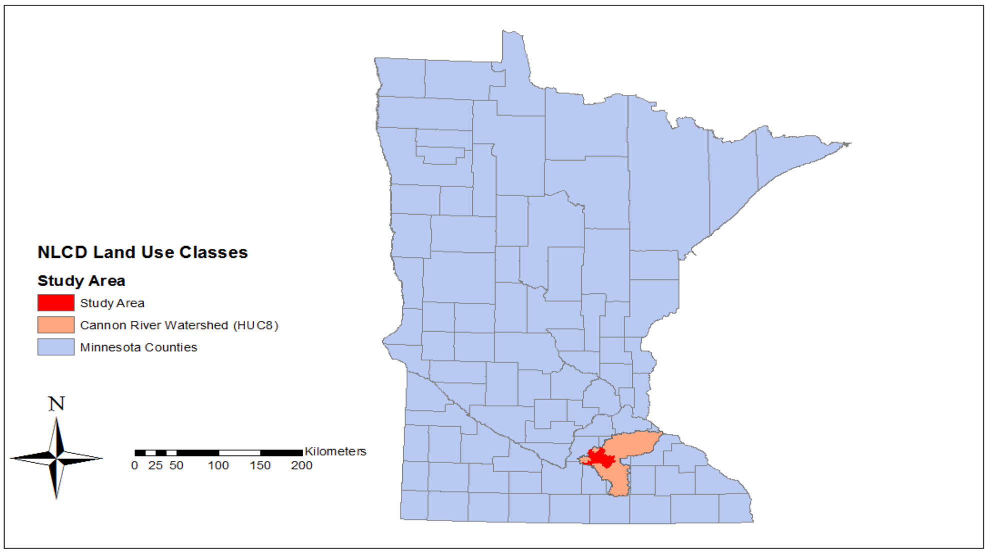

Figure 2. Nested location of the study area within the Cannon River Watershed and Minnesota. Our study area contains portions of Rice, Le Sueur, Waseca, and Steele counties.

Study Area Land Use / Land Cover

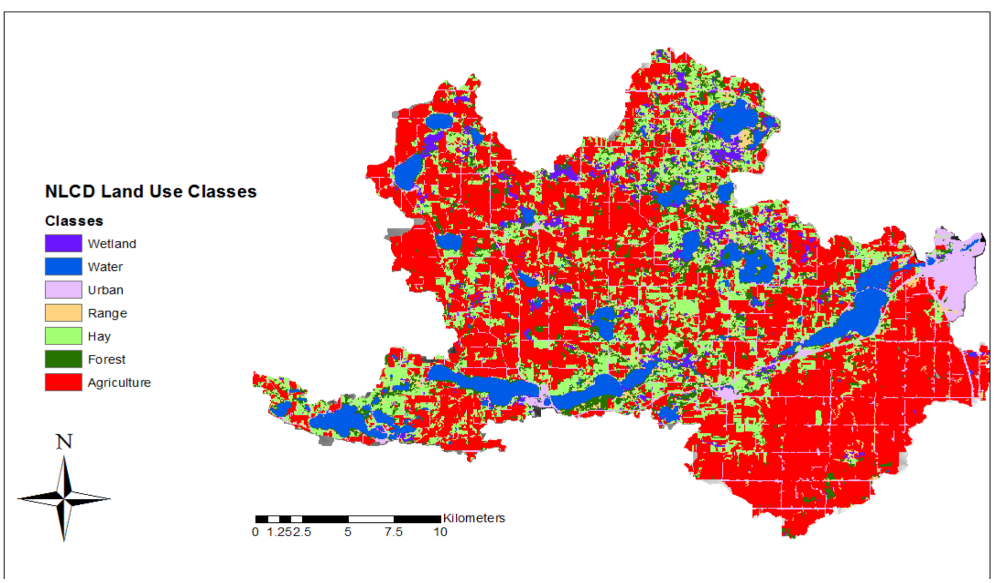

Figure 3. Land use / land cover in the study area. Agriculture accounts for 51.8% of the entire study area. The Cannon River runs through the area and there are multiple impaired lakes.

SWAT Model

SWAT is designed to model and predict the impact of land management practice on water, sediment, and agricultural chemical yields in large complex watershed over time (Neitsch et al., 2005**)**. Inputs include topography, soil type, land use/cover, weather, and land management practice data. SWAT divides HUC12 watershed into smaller subbasins and reaches. Subbasins are further divided into HRUs based on commonalities in topography, land use, and soil (Neitsch et al., 2005).

SWAT uses 5 pools of nitrogen (NH_4+, $N0_3$-, Organic, Stable, and Active) and 6 pools of phosphorus (inorganic: solution, active, stable; organic: fresh, stable, active) in its model of the N and P cycles (Neitsch et al., 2005). This model addresses mineralization, decomposition, and immobilization in both nitrogen and phosphorus cycles. Daily organic N and P runoff are calculated based on concentration of each element in the topsoil layer, the sediment yield, and an enrichment ratio. Nitrate concentration in mobile water is multiplied with mobile water volume to estimate total nitrate lost from the soil layer.

Model Inputs

ArcSWAT 10.1 was used as an interface for running SWAT. Inputs included a Digital Elevation Model (DEM), SSURGO soil data, NLCD 2006 land use/cover data, and climate data from NOAA. We chose a 10-m resolution DEM as recommended in the literature (Niraula et al., 2013). Climate data on a daily basis was obtained for the timespan from January of 2007 to December of 2010 from four weather stations near Faribault and Mankato, Minnesota. Since our study is mostly concerned with agricultural nonpoint source pollution and did not have the time or information to make more detailed calibrations, surface runoff, flow, erosion and sediment yield, and sediment transport capacity factors were left to the model defaults. As previously explained, advice from representatives of the NRCS Soil and Water Conservation District and the Cannon River Watershed Partnership was used to create an agricultural management calendar.

Please refer to Part III for a discussion of the rationale of the model and the limitations of this framework for conceptualizing the hydrologic landscape.

Model Calibration and Accuracy Test

It is necessary to perform model calibration in order to obtain realistic outputs from SWAT. For the purpose of our study, we focus our efforts on obtaining accurate nitrate outputs for each subbasin. Suggested by Arnold et al. (2012), we calibrated the model using a two-step approach:

1. We used expert judgments (Coffman, 2014) to adjust input parameters. For this study, management operations such as fertilization and tillage are our main targeting parameters.

2. We compared model predictions with 23 field-measured data points of nitrate output that fall within our study area and further adjusted input parameters (Arnold et al., 2012). These field measurements (Figure 4) were collected in July 2011 (Haileab, 2011). 74 soil samples were processed by a WQ-CL sensor and NExSens software. The sensor measures water quality parameters including temperature, dissolved oxygen, pH, ORP, N03, NH4, and CL in parts per million (Misra, Poaster, Weiss, 2010). Since these data were collected in July 2011, they act only as a prediction of our modeled years (2007-2010).

3. To assess the accuracy of the modeled nitrate outputs, we performed a correlation test between modeled nitrate outputs and their corresponding field measurements.

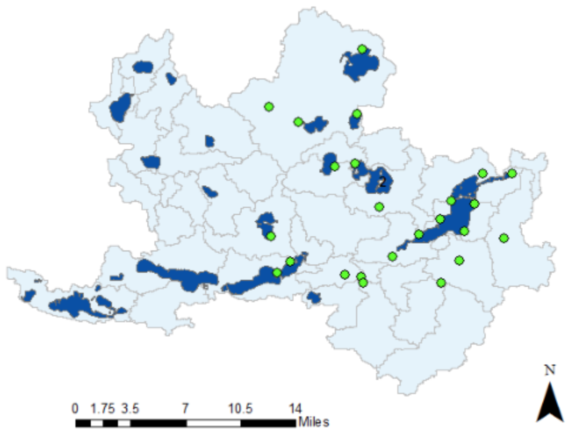

Figure 4. Field measurement observation points in the Cannon River Watershed. Field measurements were collected in 2011 by Carleton College geology students. These field measurements have not been published or peer reviewed.

Identification and Evaluation of Critical Source Areas (CSAs)

In this project, we employed Niraula et al.'s (2013) approach to identify CSAs. After generating modeled nitrate outputs, we ranked the 43 subbasins in our study area by their total nitrate yield per unit area (kg/km^2) for each of the simulated four years 2007-2010. Our study only identified CSAs with respect to nitrates because of the critical and highly mobile nature of nitrates and their impact on eutrophication. Then we identified CSAs for each year as the highest unit-area nitrate emitting subbasins that contributed to 20% of the total nitrate output for each year. CSAs for the overall four-year period were selected based on a ranking of total nitrate emission per unit area (kg/km^2) averaged over the four years.

Lorenz Curves were created for each of the four years and the overall period to display the inequality of distributions in nitrate output among subbasins. For each of these time periods, after ranking subbasins by their total nitrate yield per unit area (kg/km^2), cumulative distribution of nitrate output was plotted against cumulative area of the subbasins. Gini Coefficients were then calculated for each of these curves to measure the degree of inequality in nitrate emissions among subbasins.

Spatial Assessment of Relative Nonpoint Source Contributions to Nitrate Pollution

In order to explore the potential for targeting nonpoint source pollution in our watershed using a WQTM, a spatial assessment of relative nonpoint source contributions to nitrate pollution was adapted from Roberts et al. (2008). Roberts et al.'s method was integrated with CSA identification using SWAT in order to provide a more comprehensive and robust understanding of targeted management of nonpoint sources.

First, water bodies in our study area impaired with nitrates were identified from the set of impaired Minnesota streams, lakes, and rivers (EPA, 2014). Based on Roberts et al.'s (2008) method, we first eliminated impairments that were not downstream of one or more sources because in a WQTM scheme, there would be no potential buyers of offsets for these impairments. The remaining impaired water bodies are the "Tradable Nitrogen Impairments" (Roberts et al., 2008). This concept is important when considering the potential for a WQTM since the geographical relationships between pollution sources and receptors are essential factors of trade.

Second, subbasins that neither contained nor were upstream of a Tradable Nitrogen Impairment were eliminated since they did not contribute to this tradable impairment. This left the nonpoint source located within the remaining subbasins to be the subjects of our study.

The following information was then gathered for the study area:

1. The aggregate length or area of Tradable Nitrogen Impairments. This is a measure of the expected "benefits" from reducing these impairments associated with a potential trading program (Roberts et al., 2008). The aggregate length of Tradable Nitrogen Impairments is calculated by summing the length of impaired streams and rivers and the area of the impaired lakes.

2. Estimated nitrate emissions (kg) from each subbasin. These were calculated based on model outputs. This is a measurement of the likelihood of a subbasin being the target of a management program or policy.

Based on these information, and taking into account the adjacency relationships of the subbasins, a pair of scores representing the relative pollutant contributions to the water bodies from the CSAs and non-CSAs within the study area were calculated as

(1) CSA Score:

$$S_c = \sum_{i=1}^{m}(C_i \sum_{j=1}^{m}(\frac{1}{x_{ij}}M_j))$$

(2) Non-CSA Score:

$$S_n = \sum_{i=1}^{n}(N_i \sum_{j=1}^{n}(\frac{1}{x_{ij}}M_j))$$

where C_i is the total estimated nitrate emission from the ith CSA; N_i is the total estimated nitrate emission from the ith Non-CSA; M_j is the aggregate length of the Tradable Nitrogen Impairments in the jth CSA/Non-CSA; x_{ij} is the distance (in number of subbasins) between the ith and jth subbasins, such that, if $i=j$ then $x_{ij}=1$, if i and j are contiguous then $x_{ij}=2$, and so on; m is the number of CSAs, and n is the number of Non-CSAs.

Our method is similar to that of Roberts et al. (2008), but is distinct in three primary ways:

1. The unit of analysis in this adapted method is the SWAT generated subbasin, rather than HUC12.

2. Point source nitrate emission is replaced in our method with CSA nitrate emissions.

3. NPDES permitted nitrate discharge is replaced in our method with the estimated total nitrate emissions based on modeled outputs.

Policy makers can use these scores to assess the feasibility of implementing an effective WQTM in the Cannon River Watershed. These scores indicate the relative contributions of different pollution sources to impairments accounting for their spatial relationships. Whether a particular source is capable of participating in such a trading program depends upon not only its nutrient load, but also the spatial relationship of that source to both impairments and other sources (Roberts et al., 2008).

Results

Results will be presented in this section in the following order:

- Accuracy Test of Calibrated Modeled Nitrate Output
- Identification of Critical Source Areas (CSAs)
- Lorenz Curves of Inequality and Gini Coefficients

● Spatial Analysis of Relative Contribution of CSAs and Non-CSAs

Accuracy Test of Calibrated Modeled Nitrate Output

Observed nitrate concentrations were compared against modeled nitrate emissions in the corresponding subbasins for each of the four modeled years. Correlation coefficients are listed in Appendix B. These coefficients represent the worst-case scenarios in which observed data is correlated with the maximum and minimum modeled outputs in the month of July of each modeled years. Since our field data source did not delineate dates more specific than the month of July, we also paired each observation with its closest modeled nitrate outputs in July 2009 and obtained a correlation coefficient of 0.98.

Identification of Critical Source Areas

The four-year simulation period from 2007-2010 identified 8 CSAs (Figure 5), which covered 2.84% of the study area (Table 1) and contributed to 20% of the total nitrate emissions in the study area. Table 3 shows the land use compositions of these CSAs. The 8 CSAs were consistent throughout each study area, but their nitrate emissions per square kilometer rankings were varied. The percentage of total nitrate emissions produced by CSAs in the study area for each year ranged from 17.67% to 19.44% (Table 2).

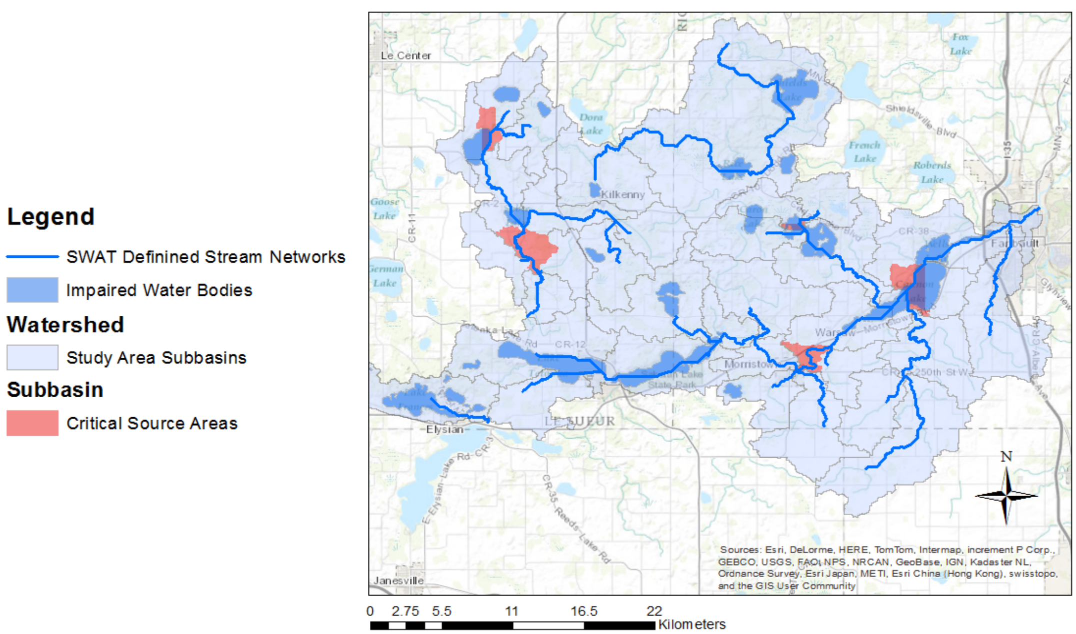

Figure 5. CSAs identified from 2007 to 2010. All were proximate to impaired water bodies.

Table 1. CSA area statistics.

CSA	Area (Km^2)	Percent of Study Area
4	2.16	0.39
12	0.47	0.08
15	2.45	0.44
21	1.87	0.34
22	3.71	0.67
24	2.75	0.50
32	2.32	0.42
35	0.03	0.01
CSA Total	15.75	2.85

Table 2. CSA nitrate emissions by percentage contribution to total study area emissions.

CSA ID	2007 CSA Emission Percentage of Total Area	2008 CSA Emission Percentage of Total Area	2009 CSA Emission Percentage of Total Area	2010 CSA Emission Percentage of Total Area	4 Year CSA Emission Percentage of Total Area
4	1.77	2.03	2.28	2.22	2.02
12	1.94	2.95	1.97	2.78	2.39
15	2.03	2.15	2.59	2.14	2.18
21	2.14	2.20	2.59	2.15	2.23
22	2.52	2.39	2.11	2.29	2.37
24	2.48	2.53	2.21	2.43	2.44
32	2.67	2.56	2.33	2.48	2.54
35	2.83	2.26	2.46	2.21	2.48
CSA Total	18.38	19.06	18.54	18.69	18.64

Table 3. Land use statistics of CSAs. Most CSAs have large portions of agricultural land cover.

CSA ID	Water	Residential	Forest	Range	Hay	Agriculture	Wetlands
4	22.81%	3.21%	9.83%	1.09%	10.79%	42.99%	9.29%
12	68.60%	2.24%	16.29%	3.89%	1.14%	0.00%	7.85%
15	0.00%	6.16%	3.95%	1.12%	27.91%	60.80%	0.18%
21	0.00%	1.05%	5.81%	0.72%	52.22%	35.84%	4.06%
22	51.20%	5.71%	5.67%	1.12%	11.70%	21.77%	2.44%
24	34.45%	7.93%	6.89%	2.56%	17.19%	26.87%	1.92%
32	0.00%	9.11%	15.06%	4.96%	43.05%	22.45%	5.00%
35	0.00%	88.99%	11.02%	0.00%	0.00%	0.00%	0.00%
CSA Average Land Cover	22.13%	15.55%	9.32%	1.93%	20.50%	26.34%	3.84%

Lorenz Curves of Inequality and Gini Coefficients

Figures 6-7 below show the Lorenz Curves compared with Equality curve for years 2007-2010 and the overall four-year period. All Lorenz Curves show an unequal distribution of nitrate emissions among subbasins.

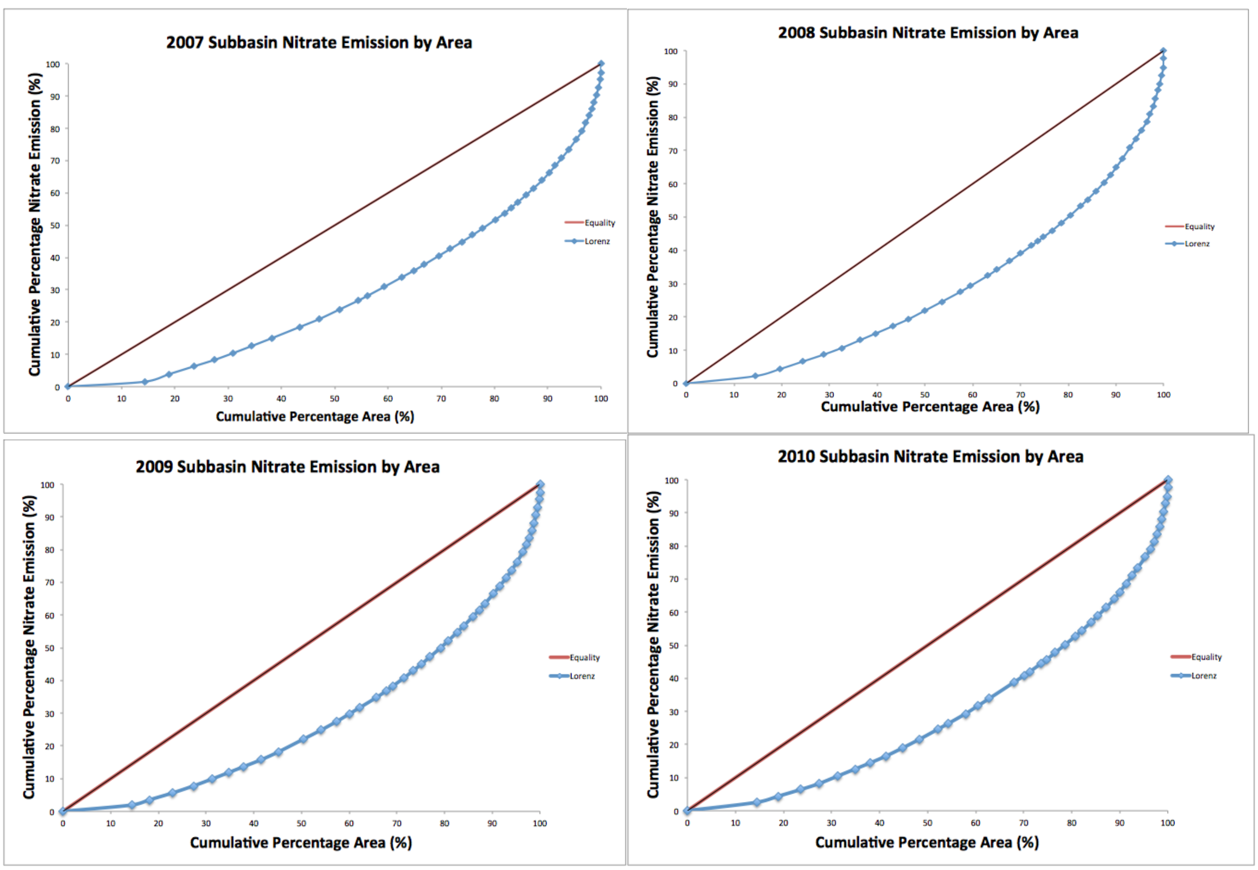

Figure 6. Lorenz Curves of Inequality vs. Equality Curves for years 2007-2010. Subbasins are ranked by unit-area nitrate emission from lowest to highest. Their cumulative percentage area is plotted on the x-axis, and their cumulative percentage nitrate emission is plotted on the y-axis.

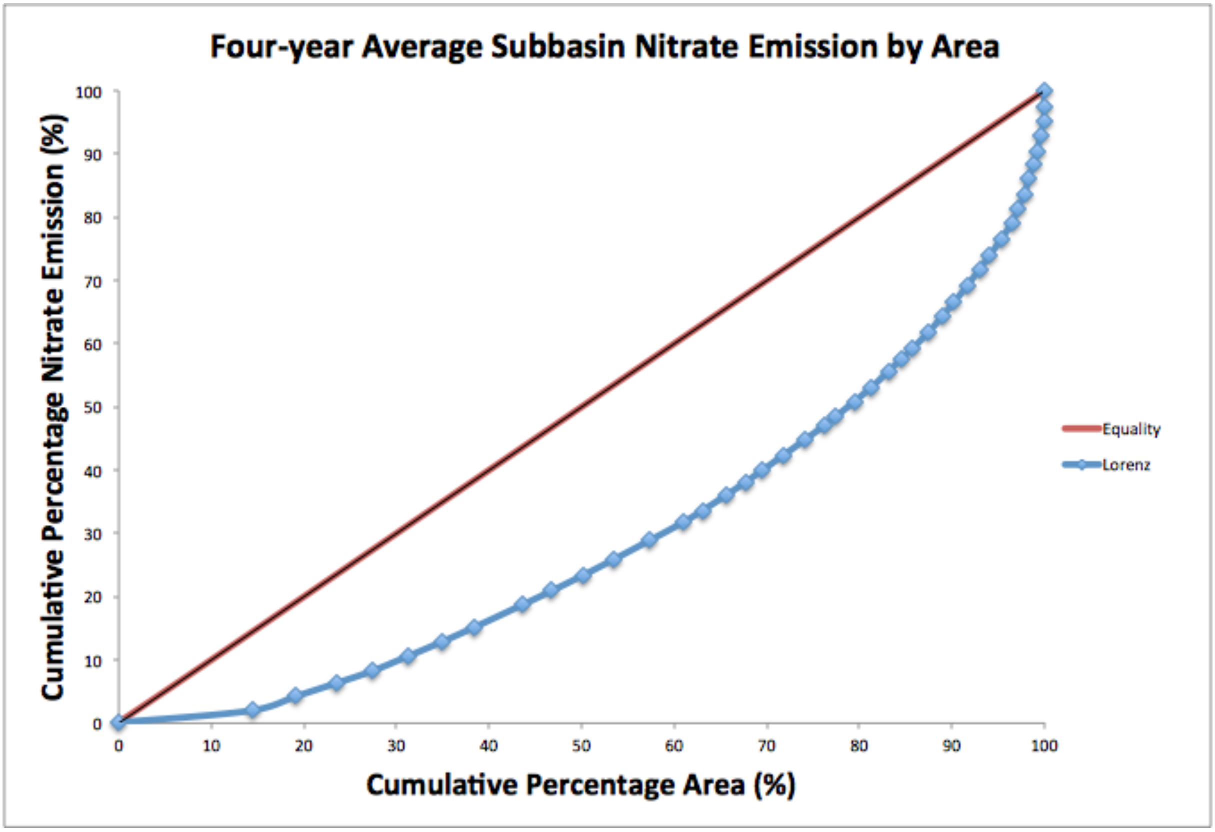

Figure 7. Lorenz Curves of Inequality vs. Equality Curves for the total simulation period. Subbasins are ranked by unit-area nitrate emission from lowest to highest. Their cumulative percentage area is plotted on the x-axis, and their cumulative percentage nitrate emission is plotted on the y-axis.

Gini Coefficients for each of these periods are listed in the Table 4. For each of these four time periods, there was a considerable degree of inequality (>0.4) in the distribution of nitrate output among the subbasins (Table 4).

Table 4. Gini Coefficients measuring the inequality of distribution of nitrate emissions among subbasins for years 2007-2010 and the overall four-year simulation period.

Year	2007	2008	2009	2010	Four-Year Average
Gini Coefficient	0.415	0.434	0.430	0.416	0.416

Spatial Analysis of Relative Contribution of CSAs and Non-CSAs

Non-CSA scores, CSA scores and their ratios for each of the four years 2007-2010 and the overall period are shown in Table 5 below.

Table 5. CSA, non-CSA scores and their ratios measuring the their relative nitrate contributions to the study area for years 2007-2010 and the overall four-year period average.

	Non-CSA Score	CSA Score	CSA : Non-CSA Ratio
Four-year average	512,124.61	31,785.59	0.06
2007	689,759.54	61,909.09	0.09
2008	516,869.16	23,472.46	0.05
2009	376,958.24	7,870.29	0.02
2010	433,455.02	48,680.64	0.11

Discussion

Evaluation of CSAs

For each year of the simulation, 8 out of 43 subbasins were found to contribute 20% of the total nitrate output in the whole study area. This suggests spatial concentration in intense nitrate emissions. The Lorenz Curves of Inequality show that in each of the time periods, about 30% of the total watershed area contributed to more than 60% of total nitrate output. The Gini Coefficients for each of these time periods indicate a high degree of inequality in the distribution of nitrate emissions among subbasins.

Key Findings and Implications for Nonpoint Source Pollution Management

When taking into consideration the distances between the subbasins to the impaired water bodies as well as the length of the impairments, the spatial assessment calculated low scores for the identified CSAs. This suggests the following:

1. CSAs do not have the potential to become “buyers” in a WQTM scenario in our study area. In an ideal market, the few “buyers” (CSAs, in this case) would contribute almost equally to the nutrient load as the many “sellers” (non-CSAs, in this case). The fact that the ratio of the CSA and Non-CSA scores is lower than 0.2 (Table 5) suggests that their relative contributions to nutrient load are not comparable, and that WQTM development is highly unlikely within this study area (Roberts et al., 2008).

2. However, these results suggest a potential for targeting nonpoint source areas with high outputs within this watershed. In particular, management should be targeted at small areas that contributed large amounts of total nitrate in order to obtain high marginal benefits. This could theoretically contribute to the implementation of a more cost-effective nonpoint source management approach.

Furthermore, we were surprised by the land cover statistics in Table 3. We expected agricultural land cover to be much more extensive in all of the CSAs. Several CSAs had no agricultural land cover and were covered extensively by water. This may suggest that identified CSAs are actually sinks, rather than sources of high nutrient emissions. Figure 5 shows that all identified CSAs happened to be located next to or contained impaired water bodies. Future work could more thoroughly track the nutrient movement between SWAT defined subbasins to differentiate critical source areas from critical sinks. This is an important element of uncertainty and we are hesitant to make recommendations for nutrient mitigation strategies based on our CSA analysis.

***Limitations**: Sources of Error in SWAT Modeling*

Even with appropriate calibration of the model input parameters, the inherent structural uncertainty of the model cannot be fully overcome (Schoups et al, 2005). We identify the following possible sources of error that causes biases in our outputs:

Inaccurate nitrate measurements during field data collection are a potential source of error because they were obtained by high school students that participated in a Carleton summer science program. We cannot account for any human or systematic error in that process. Ideally, we would use field measurements taken between 2007 and 2010 at multiple times in the year. Since these data were not available to us, we used 2011 measurements to compare to all model outputs 2007 to 2010 for the month of July. Additionally, this is problematic because we do not know if farmers were growing corn or soybeans that year. This is important because our agricultural operation schedule assumes very different fertilizer application standards depending on which crop is grown.

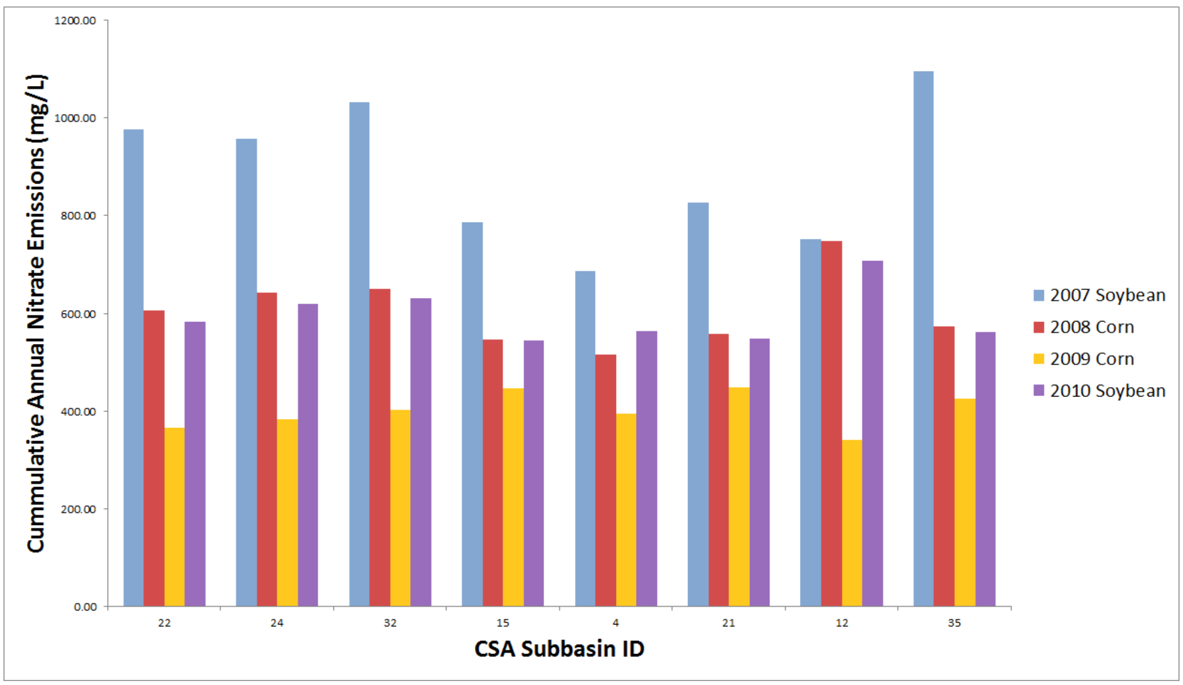

Figure 8. CSA cumulative contributions of nitrates by year and crop rotation sequence. Nitrate loads were highest in 2007, and lowest in 2009.

Additionally, it is likely that farmers are not on a uniform schedule: in the same year some farmers may grow corn and other may grow soy. Using a uniform agricultural schedule that has all farmers growing the same crop at the same time may very well over-saturate the landscape with nutrients one year and under-estimate nutrient loads on other years. The synergistic effects of a heterogeneous patchwork of corn and soybean operations are not well understood, and may produce outcomes that are drastically different than our model. This problem could be addressed to an extent by specifying land use classes in more detail and assigning multiple agricultural management schedules to more HRU class groups. Figure 8 suggests that the difference in agricultural management parameters between corn and soybean rotations had a large impact on nitrate loads for CSAs. 2007 was specified as a corn rotation year and had notably high nitrate outputs for all CSAs, whereas 2009 CSAs had much lower nitrate loads across all CSAs. This emphasizes the importance of agricultural management parameters for nutrient pollution analysis and necessitates a full sensitivity analysis of the impact of agricultural parameters on SWAT outputs, which this study did not have time to do.

Our agricultural management calibration only extended to HRUs that were classified as agricultural land cover by the NLCD 2006 dataset. As seen in Table 3, our study area also has a large extent of land cover that is classified as "Hay". The NLCD 2006 dataset defines Hay as "areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation. (MRLC, 2006)." Nitrogen fixing legumes, manure deposition, and erosion due to high stocking rates of cattle are very significant sources of nutrient emissions that were not considered in our calibration. Therefore, our model likely underestimates nutrient loads from many HRUs and subbasins.

In the process of delineating the watershed in SWAT, the software allows the user to select outlets to construct the subbasin units. The number of outlets specified by the user will affect the size, shape, and number of subbasins defined by SWAT, which changes the definition and distribution of HRUs. We selected 21 outlets that covered the full expanse of our study area because we were interested in the effects of agricultural nonpoint source pollution in the whole study area. Outlet definition delineates the shape and configuration of subbasins, which fundamentally reorganizes the HRUs and nutrient load estimates.

Data sources are a potential source of error. We used 2006 NLCD data in a simulation period that spanned from 2007 to 2010. SWAT can use USGS SSURGO or STATSGO soil data, which may affect model output. Our model used SSURGO, which is in a vector file format. We did not investigate whether SSURGO or STATSGO produce significantly HRU classes.

SWAT connects weather station coordinates specified by the user to connect to a database of precipitation and temperature measurements taken on a daily bases. Four precipitation and temperature gauges were located near our study area, all of which were on the periphery of the study area. Because of this, a lack of precipitation and temperature information in the center of our study area is a likely source of error. Measurements from stream flow gauges were not used to calibrate flow rates, which is almost as important as land use and management for determining nitrate mobilization.

In our agricultural management operations calendar, we divided annual ammonium fertilizer application of 180lbs for corn rotation years into two application periods: first, 6 weeks after corn is planted in May, and second, in the fall after harvest. Fertilizer application in the fall is not ideal, but our conversations with the NRCS and MPCA indicate that farmers are likely to fertilize in the fall because of the difficulty of driving fertilizer vehicles in the spring. SWAT does not permit us to specify the technique by which fertilizer is applied to the land. For instance, fertilizer can be broadcasted, injected, placed on the ground surface, or distributed in pellets (Haynes et al., 1985). These different fertilizer application schedules and methods may have unexamined effects on agricultural nonpoint source pollution heterogeneity.

Our agricultural management calendar does not consider the technological resources that farmers may have at their disposal for precision agriculture. The Cannon Valley Co-op has acquired new technology that uses a model similar to SWAT to reduce fertilizer application to land that might already have received runoff nutrients from uphill (Vrtis, 2014). Due to time constraints, our study did not explore these different management options available to farmers. Accounting for such advents in agricultural management in our study area might completely invalidate our agricultural management schedule, which assumes fertilizer over-application, moldboard plowing, and a uniform rotation that does not include fallowing time. As members of the Northfield community, we are aware of growing trends in small-scale organic agriculture in the area, which typically use management schedules different from our schedule. This is a potential source of error, because SWAT oversimplifies farmers' land management practices.

Overall Limitations

Throughout the process of constructing and executing our model, it was clear that the unfolding of both natural processes and land management practices over time causes significant discrepancies in nutrient outputs from year to year. Surface runoff is the mechanism by which nutrients are transported across the watershed and is highly variable and dynamic in an evolving and changing climate. Large tracts of CRP land and wetlands have been converted to corn-soybean rotation systems since corn prices began to rise in 2009 (Coffman, 2008). Our modeling period addresses the beginning of this time period but relies on 2006 land cover data, which does not capture these recent economic and land use dynamics. Although our precipitation input data is temporally relevant to the modeling period, we did not adjust and calibrate surface water flow rates with supplementary field data. The short time span of the modeling period and the temporally dynamic nature of climate and agricultural economics raises great concern about the validity of applying the results of this model to other time periods. For example, even though subbasin 22 was designated as a CSA each year of the modeling period, it is dangerous to assume that this area is characterized by fundamentally poor agricultural management practices and perpetual excessive fertilizer application without further fieldwork supplemented by long term modeling.

The methods by which this study investigated the spatial inequality of nitrate emissions raise fundamental questions about the ways in which environmental scientists conceptualize land. The process of building and applying a model involves a sequence of categorizations and spatial delineations based on mathematical abstraction. The notion of a watershed as a biophysically bound network of moving water is perhaps the most important category imposed upon the landscape in the case of this model. Unless viewed from above, watersheds are elusive to the eye and are structurally independent of human land use classes and political jurisdictions. For example, our study area overlapped four counties and contained a full range of land use classifications including forest, agricultural, and developed areas. The intention of this study is to aid in the strategic management of agricultural nonpoint source pollution, but is based on hydrological classifications. The smallest level of analysis in this study -- the HRU -- does not fit neatly within the spatial arrangement of agricultural operations. This makes it difficult to translate the idea of hydrological critical source areas to regional managers and policy makers who deal primarily with agricultural operations that are managed within the framework of county jurisdictions.

Our spatial assessment of the relative nitrate emissions of the CSAs and non-CSAs was a method modified from Roberts et al. (2008) to fit the scale of our study area. In addition, the scores we calculated did not account for nitrogen dissipate during in-stream transport (Hung and Shaw, 2005). Therefore, our conclusions should not be interpreted with the same standards that Roberts et al. used. In particular, when determining whether the ratio of the scores indicate the possibility of setting up a nutrient trading market, we may need to use different thresholds.

Nevertheless, our modified methodology provides insights into new approaches for formulating nonpoint source nutrient trading scenarios. This is an important practical step in working towards ensuring quality water availability in the Cannon River Watershed.

PART II: POETRY EXPLORATION OF MODELING LIMITATIONS

Review of Related Literature

Premise

It is obvious that quality water's continued availability is valuable because it is necessary for the existence of human and nonhuman communities. Nutrient emission heterogeneity modeling is a practical approach to provide a foundation for policy initiatives, such as Water Quality Trading Markets, that help humans secure the availability of quality water. Our quantitative modeling partitions the study area and variables into units with discrete values. These values are necessary to execute the model. However, the model can only make valid claims within its specified boundaries, since quantification provides a common yet singular way of knowing what the quantified entity "is" on the basis of its unit value (Castree, 2003; Radin, 1996). This greatly oversimplifies the issue of water quality availability. Since water literally connects all physical beings and flows across space, time, and cultures, water and the spatial extent of the human impact on water quality cannot be contained within the boundaries of a specific study area or units. (Castree, 2003; Chan et al., 2012; "Criticisms of Economic Analysis"; Gomez-Baggethun and Ruiz-Perez, 2011; Neimanis, 2009; Radin, 1996). We argue here that writing poetry is an effective method to explore this limitation of our nutrient emission heterogeneity modeling that seeks to address nonpoint source pollution.

Using Poetry to Articulate Limitations of Nutrient Emission Heterogeneity Modeling

Our nutrient emission heterogeneity model understands selected factors of our study area's landscape -- land use, soil, topology, and weather -- as units with discrete values that combine in a directly calculable manner to impact water quality. Specifically, our study uses the unit of milligrams per liter per square kilometer of nitrate pollution to quantify water quality. This quantification is necessary to conduct the model, but hinders understandings of water's other values. Water is a natural entity that only becomes quantified when it is fit into the framework of a model (Castree, 2003). However, quantification only captures some of water's values. It is impossible to fully frame quality water -- a concept with diffuse, overlapping, and interactive borders -- as a concept with well-defined limits (Anderson, 1993). A unit value imposed upon water impoverishes our understandings of quality water, because a unit value cannot adequately quantify the subjective, aesthetic, physical, cultural, and spiritual significances of water that have been embedded within human societal contexts throughout human history. These values go beyond and therefore cannot be captured by a unit value (Anderson, 1993; "Criticisms of Economic Analysis"; Day, 1996; Gomez-Baggethun and Ruiz-Perez, 2011; Ioris, 2012; Neimanis, 2009; Radin, 1996; Roberts, 2008).

"Words and the world" are intimately linked in humans' understandings of ecosystem services, including quality water: the written forms and rhetoric applied to a given ecosystem service shape the concepts and categories that humans use to describe, articulate, and thereby understand that service (Keys, 1998; Radin, 1996). Because of this, and since the integrity of many ecosystem services is becoming increasingly compromised, it is important to choose a writing style that most effectively describes the concepts relevant to the ecosystem service in question. Different genres of writing are more dexterous at navigating the subtleties of some concepts than others. For example, in a science education context, writing poetry can yield deeper understandings of scientific concepts when combined with scientific writing (Keys, 1998). This reflects a need to use communication styles that are best suited for the kinds of insights gleaned from the concepts at hand.

Poetry is a writing style that can make explicit the subjective, dynamic, and nonlinear processes of valuing water. Poetry can therefore effectively articulate our model's limitations by expressing non-quantifiable values of water. The poetic process reconfigures the ways in which language is used so that it synthesizes, rather than is bound by the rigidities of academic prose (Welsch, 2009). In doing so, poetry can articulate subtleties overlooked by academic prose, and integrate them across multiple spatial and temporal scales (Buell, 2005; Stables, 2010; Zapf, 2006). Through this less systematic but equally nuanced process, the boundaries of concepts can be shrunk, stretched, morphed, blended, interwoven, and erased. New ways of describing and connecting phenomena can give rise to new concepts and/or new ways of thinking about established concepts concerning the ways in which humans value water (Stables, 2010; Zapf, 2006).

Poetry, among other art forms, is a way to both learn about and articulate non-quantifiable values of quality water. Humans form their own values of an ecosystem service -- in this case, quality water -- by interacting with the ecosystem service in a number of different contexts at different points throughout a lifetime (Chan et al., 2012; Welsch, 2009). For example, as articulated in the poetry collection's preface, humans can interact with quality water by obtaining water (from a faucet, from a well, from a stream, from a many-mile journey), drinking water, excreting water, swimming, fishing, and boating in water, studying water academically, changing subsistence practices to coincide with the seasonal availability of water, participating in cultural rituals and traditions concerning water, and creating art about water. Individuals are more mindful in some of these interactions than in others, and all of these interactions differ from human to human, community to community, and culture to culture. Though these interactions are subjective and not necessarily straightforward on an individual level, they are still inseparable from larger local and global systems (Chan et al., 2012). Humans form values about an ecosystem service from knowledge acquired through a combination of these interactions. These values can be quantitative -- for example, placing a unit value on water -- and qualitative -- for example, embodying cultural values of water (Halsall et al., 2009; Raskin, 2009). The process of writing poetry provides a way to interact with and thereby learn about qualitative ways to understand water. Poetry itself can articulate experiences of quality water that become synthesized through this interactive learning. In doing so, poetry can express the multiple, overlapping, and conflicting meanings and values of water more effectively than most other written forms.

Because every human is dependent upon quality water to live and must therefore interact with water in some manner, there are as many individual relationships with water as there are humans on the earth. Though individuals' understandings of quality water cannot be systematically incorporated into an empirical model even within a specific watershed, every human's own way of conceptualizing water is still equally valid. Poetry writing, among other creative processes, provides a way to explicitly express this reality of humans' multiple perspectives of water (Chan et al., 2012).

Practical Implications

Using poetry to examine water quality, in interdisciplinary conjunction with nutrient emission heterogeneity modeling, offers a practical approach to address nonpoint source pollution. It is imperative to articulate the non-obvious emotional and tangible implications of environmental issues, and to challenge preconceived assumptions that may be hindering understandings of these issues (Davey, 2009). If humans have no language with which to describe environmental problems, and no practical and emotional reasons to confront them, it is unlikely that innovative means to address these problems will be pursued (Zapf, 2006). Nonpoint source pollution is a far-reaching issue that has motivated a variety of scholarly, policy, and practical responses that quantify water. Exploring alternative re-imaginings of water valuation within and outside of our model will yield more comprehensive understandings of humans' ways of valuing water in the context of nonpoint source pollution.

Poetry provides a way in which environmental issues, in this case nonpoint source pollution, can be conceptualized through a creative *process* that alternates with and complements conventional academic procedures (Zapf, 2006). On the individual level, writing poetry deliberately focuses the mind to think about relevant issues through a creative cognitive lens. Resulting insights layer upon and interact with each other in a process that is conducive to increasingly complex syntheses of ideas and perceptions. When individuals -- who themselves have engaged in such processes -- think creatively together, more diverse and nuanced visions of practical approaches are likelier to emerge (Zapf, 2006). Individual immersion in creative processes gives individuals more to bring to the table when it comes time to design practical solutions to address environmental issues.

Similarly, the *outcome* of such a creative process -- in this case, a collection of poems -- is a physical entity whose actual presence can spark discussion between individuals concerning the present themes and other artistic expressions. In order to design and implement practical approaches to environmental issues, individuals ideally converge to examine, discuss, and formulate solutions appropriate to the problems at hand. Generating solutions is directly informed by collaborators' understandings of the issues at stake. The physical presence of the outcome of a creative process in such collaborative settings provides a shared art form that suggests alternative interpretations of common issues (Bishop, 2009) -- in this case, valuing water in the context of nonpoint source pollution. Such a creative outcome is intentionally open to multiple interpretations due to the diverse perspectives of collaborators, even if collaborators themselves did not directly engage in creative processes. The incorporation of a tangible creative outcome into the process of practical solution formulation can complicate the exchanges at hand, integrate emotional and cultural interpretations into the empirical realm, and make non-obvious connections explicit (Bishop, 2009).

Quantitative analysis of nutrient emission heterogeneity uses concepts that have been given certain labels with boundaries of value. We will attempt to explore, challenge, and unpack these boundaries in order to draw attention to values of quality water that cannot be quantified and therefore cannot be captured in our modeling alone. Poetry can articulate how these values relate with each other, serving as a point at which many interpretations of water quality value can converge, and from which further discussions and practical solutions can emerge. Effective responses to environmental problems require as much communication as possible from and between multiple perspectives, and poetry has been a predominant form of communication across cultures for much of human history (Cronyn, 2006; Primavesi, 2000; Zapf, 2006). Poetry writing in this case is not a stand-alone methodological approach, but an important component of the process of devising successful practical policy initiatives to address nonpoint source pollution in the Cannon River Watershed.

Methods

In order to explore the limitations of our nutrient emission heterogeneity analysis, a collection of poems was written that is thematically integrated with the rest of the project. The creative process of writing poems is inherently nonlinear and non-systematic, but is extremely nuanced and time intensive. The composition process was informed by William Least Heat-Moon's concept of a "deep map" (Heat-Moon, 1991), in which a spatially specific area is integrated with interconnected layers of the phenomena in question on multiple temporal scales to which the area has played host. In this case, the "deep map" was based on the Cannon River Watershed, the study area of the nutrient emission heterogeneity modeling. Considerable time was spent in open-ended exploration of the Cannon River Watershed. This provided an experiential framework, during which intense observation, contemplation of, and interaction with the study area occurred, and was later synthesized through poetry. Poetic and empirical content was integrated through meetings between all group members. All group members regularly discussed the content, implications, interconnections, and limitations of the work that was being executed at a given time on both the modeling and poetry components of the project.

Results

Please refer to poetry collection.

Discussion

The process of creating poetry and the final poetry collection have enriched our understanding of nonpoint source pollution in the Cannon River Watershed by complementing Part I's conclusion. Water and everything through which it flows cannot naturally be contained by the rigid boundaries of unit quantification. The poetry articulates this limitation of modeling by expressing water as it flows across its three states of vapor, ice, and water, and across time, space, organisms, and cultures. In this way, the poetry evokes major themes that the modeling does not capture. Among the most important of these themes are 1) water's physicality, 2) the very real and significant presence of communities in a landscape, 3) linear and cyclical understandings of a landscape, 4) spiritual connections to water, and 5) practical implications of environmental issues, including quality water availability. These five major themes intertwine with each other across many of the poems and interweave other artistic elements not discussed here (please refer to the poetry collection's artist statement). Like all disciplines, poetry has limitations: most notably in this project, poetry's nonsystematic, subjective nature precludes explicit integration into an empirical model. However, overall, the poetry here provides an expression of how water's fundamental property of interconnection renders the microcosm of the Cannon River Watershed -- including its human and nonhuman inhabitants and environmental challenges such as nonpoint source pollution -- inseparable from the macrocosm of the entire earth.

1) Water's Physicality

Though the reality of water's physical nature may seem readily obvious, it is crucial to realize that given the severity of environmental problems, including nonpoint source pollution in the Cannon River Watershed, deep physical awareness of water as an agent of interconnection can help to put into perspective the importance of undertaking research endeavors -- such as empirical modeling of nutrient emission heterogeneity -- to better ensure quality water availability, especially when research must categorize, quantify, and thereby abstract water's true physicality. As articulated in the poetry collection's preface, our present abject state of decreased quality water availability has coevolved with social-political-economic conditions that have increasingly imposed human control over water; controlling water has encouraged a dulling of humans' visceral, sensory awareness of water's depths. However, we humans are fundamentally physical creatures. As a result, the ways in which we perceive phenomena influence our behavior. Because of this, we tend to attain a heightened awareness of our environment only when it palpably enters the realm of our physical consciousness, and societal level responses to environmental problems often emerge only when such problems reach the visceral consciousness of those affected, and those empathizing with the affected. Before an accident or disaster forces us to become physically aware of water in a negative way, each of us can harness the immense intelligence of our mindbody to perceive and thereby know water in the larger context of its cycles by experiencing the water that flows through us. Such visceral mindfulness of water -- in its current spectrum of health and pollution, across its molecular states of vapor, ice, and water, and through its seasonal manifestations -- enables us to physically and metaphysically fathom how water literally enables our existence, our consciousness, and our interconnectedness with the world around us.

Poetry is one of many creative mediums that can reflect humans' physical experiences of water, and the poem "prairie moon(s)" provides an expression of how water is experienced through a human body in a single location across the span of an entire year. In this poem, water flows through a human body to manifest as dance -- a profound subjective integration of the physical and metaphysical -- in the same location of a prairie in the Cannon River Watershed. Even a particular body in a particular prairie is inseparable from the forces of water's flows across time. As the full moon occupies a particular place in space and time (indicated parenthetically) by passing over the prairie each month, water reveals itself through snow, frosted breath vapor, snowmelt, rain, steam, thunderstorms, mist, creeks, and ice crystals. Water forces humans and nonhumans to survive a brutal winter and a late-summer drought, and brings forth worms for birds, conditions for humans to cultivate and harvest crops, animals to fatten and be hunted, barren trees to turn green and then red, and then to repeat these cycles again, even as humans and nonhumans each continue to progress through successive life stages. Water's specific manifestations are always subject to such forces as wind, the physical presence of flora, fauna, rocks and other inorganic objects, temperature, and evapotranspiration. In these ways, it is impossible to physically separate individual bodies and landscapes from each other and from the entire global water cycle, because water is constantly flowing through everything, blurring spatial-temporal boundaries.

2) The Presence of Communities in a Watershed

A second theme is the significance of different communities interacting and coexisting in a particular watershed. The poem "evening eddy" expresses this by expressing the richness of human interactions in a community setting in the Cannon River Watershed, in which water is a critical facilitator of community processes. In this poem, the implied community gathering place -- a place in space, and the evening -- a place in time -- provide a respite for community members from the flows of everyday life, as they engage together in a swirl of conversation, nourishment, and nonverbal expressions of creativity. Water from the watershed boils over bean pots, steams from plates and cups of tea into the swirl of conversation and music, and thereby lubricates exchanges of some of the deepest elements of shared human existence -- community, art, beauty, resilience, interrelation, gratitude, and creative expression. This is one of the many diverse community settings in which conclusions are formed and ideas are expressed, and cultural understandings of people's individual and communal places in space and time can grow.

Ultimately, all of these interactions are highly place-specific in that they are embedded within the landscape of the Cannon River Watershed, and all community members have very real and legitimate subjective ways of interacting with and among each other and with the land. Explicit evocation of communities' presence within the Cannon River Watershed makes visible the stories of the many communities that experience and influence the land and water of the Cannon River Watershed.

3) Linear and Cyclical Understandings of a Watershed

The poetry evokes a discrepancy between "linear" and "cyclical" modes of thinking and knowing a landscape. Linear thinking is characterized by understanding the human passage through time as unidirectional, in which the accumulation of products and/or profit is a critical marker of progress and success. Cyclical thinking attempts to conceptualize the human passage through time as concordant with natural cycles and processes -- seasonal progression, water cycles, cycles of birth and death, and the like. When applied to land use, linear thinking tends to be much too narrow to encompass the cyclical reality of earth's natural rhythms. Applying linear thinking to a cyclical landscape -- in this case, imposing fossil fuel and technology-based conventional agriculture on the lands of the Cannon River Watershed -- has significantly contributed to severe negative environmental consequences, including the nonpoint source pollution that has generated this Comps project.

The ways in which a landscape is perceived -- as linear, cyclical, or some combination thereof -- influence humans' relationships with and the resulting impacts on a landscape. Poetry is one of the processes that can help illustrate patterns of perception and suggest alternative approaches to perception. The poem "the guys" explicitly evokes how continued literal linear movement in a car through the Cannon River Watershed -- a cyclical landscape -- precludes human perception and the experience of cyclical phenomena. The lone oak, the gliding eagle, and the confined buffalo embody the remnants of the oak savanna and prairie landscapes that once held fast to the lands of the Cannon River Watershed in a cyclical existence concordant with the capacities of the land. Though the experienced landscape is now dominated by conventional agriculture -- a manifestation of a linear system founded on seeking profit using fossil fuel based technology and industries -- water and nutrient cycles still govern the health of the land. Because the cyclical reality of global cycles and interconnectedness is not readily experienced or perceived through rapid unidirectional movement, linear agricultural practices may be more likely to persist in a positive feedback loop: when a landscape is regarded as linear, linear agricultural practices are more likely to be continued, which in turn exacerbate the associated environmental problems that dull the perceptible cyclical characteristics of the landscape. Though this system of linear thinking may appear to be dominant and infallible, its effluent becomes incorporated into the Cannon River Watershed, whose water enters the global water cycle and affects the physical and cultural health of present and future communities. Again, water is an agent of interconnection that connects lands and species across space and time, and prevents even the most linear modes of thinking from existing independently from the cyclical reality of the earth.

The poetry elaborates on the cyclical characteristics of the Cannon River Watershed by conveying the embeddedness (Primavesi 2000) of the microcosm of the Cannon River Watershed within the macrocosm of the entire earth. This is illustrated in the poem "bubbles." In this poem, the place in space is ambiguously set in the "far north" -- which encompasses the Cannon River Watershed and similar landscapes -- and the place in time is "january" when temperatures are far above average. This is a manifestation of climate change, which in itself can be viewed as an outcome of linear industrial profit and power-centered ways of understanding (or not understanding) the earth. A mother and her young daughter engage in the shared act of exploring how literal bubbles form, exist, and disappear. This can express how all humans, in a sense, are children in that we can never individually have the omniscience requisite to understand environmental issues such as nonpoint source pollution in their full complexity. The actual bubbles can be interpreted as individual beings' realms of perception, thought, imagination, creation, and existence, and their resulting interactions with and among each other; the sun, moon, and stars, and the rhythms derived from their cyclical relationships to earth as perceived on a human lifespan time scale; and most profoundly, the sphere of the earth and all of its cycles that enable life in the first place. All of these bubbles are of different sizes and float across space and time at different rates, and interact as they flow through and among each other. Ultimately, this poem can be interpreted as expressing the idea that even though it is impossible for humans to comprehensively understand environmental issues, if we disregard the dynamic cyclical nature and interrelationships of these bubbles, we detrimentally disassociate ourselves from the cycles that are essential for healthy human existence. It is therefore critical to perceive and thereby deepen understandings of experienced microcosms -- in this case, the Cannon River Watershed -- as they are embedded within and interrelate with the macrocosm of the (literal) sphere of the entire earth.

The poetry also helps to convey the cyclical nature of the Cannon River Watershed by illustrating water's continual flux across its global cycles and through its three states of vapor, ice, and liquid water. The poem "frigid days" interrelates both of these sub-themes through a human's physical experience of a harsh winter in the Cannon River Watershed. In "frigid days," water is omnipresent: as ice, as snow, as vapor apparent through frosty breath, and as snowflakes melting to liquid water, which enters the human bloodstream. Water blurs the boundaries of body and land as it travels through the human circulatory system, which is arranged by convergence of flowing channels to higher levels of integration -- the same pattern that characterizes watersheds. In this sense, human anatomy and physiology mirror the global water cycle as water moves through the channels of a watershed -- streams/capillaries, to rivers/arteries and veins -- to oceans in the form of respiration and back again through continual cyclical movement across the entire cyclical earth. All of this attempts to direct readers' attention to and thereby magnify perceptions of water's property of interconnecting microcosms -- the Cannon River Watershed and all beings and communities embedded therein -- within the global macrocosm through water's movement through its states and cycles.

4) Spiritual Connections to Water

A fourth theme that emerges from the poetry is spirituality related to water. In addition to enabling the physical lives of every single human and other being that has existed, currently exists, or will ever exist on the earth, water has been an integral component of religious and spiritual expressions throughout virtually all of human history. The poem "to gaia" is an intensely emotional poem that suggests a miniscule component of water's vast power in flowing through the mysterious depths of humans' metaphysical consciousness. In this poem, "gaia" is expressed as a being more omniscient and thereby more powerful than human individuals and communities, especially since gaia as the life giver has the power to drive water cycles through microcosms of bodies and watersheds, and across the earth macrocosm. Profound gratitude is expressed to gaia for pulling water through bodies, air, mountains, seas, and clouds so that water connects families and generations so they can work together for resilience in difficult times, and survive and thrive together. Such spiritual experiences involving water, which of course are immensely diverse, have enormous value to the humans and communities that experience them. All beings share exactly the same physical water, and renderings of water as ineffable, sacred, and the like cannot be contained with boundaries of microcosm or scholarly discipline.

5) Practical Implications of Environmental Issues

Finally, the poetry addresses the practical implications of environmental issues -- all of which are interconnected -- and how human individuals and communities can be resilient in the face of these unprecedented challenges, including but not limited to nonpoint source pollution. The three poems that most explicitly address this theme -- "Flood Warning," "reinventing the wheel," and "weaving ropes by the river" -- follow the conceptual and emotional pause evoked by the blank page after the emotional and spiritual evocations of "to gaia." This expresses the stark disconnection between deep human connections to land and water, and the domination of linear thinking that has helped give rise to the present enormity of environmental challenges.

"Flood Warning" in particular attempts to convey the hidden disconnection institutionalized into what have become many humans' everyday choices -- driving cars, going to supermarkets, consuming television and all ideas and marketing contained therein -- from environmental impacts manifesting as "Flood Warnings." Literally and metaphorically, flood warnings in this poem are driven by climate change. In the context of this project's investigation of nonpoint source pollution, it is implied that exacerbation of nonpoint source pollution is implicated in this increased frequency of flood warnings. Floods, of course, can impact human infrastructure and livelihoods in a negative way. Less obviously, floods can magnify nonpoint source pollution especially in agriculturally dominated landscapes such as the Cannon River Watershed. Both amplified flood frequency and intensity increase the amount of quick-moving surface and slow-moving subsurface runoff that transports nitrates and other nutrients as nonpoint source pollution into waterways. Yet even as the manifestations of climate change can magnify nonpoint source pollution in a given watershed, maintaining such practices as conventional agriculture can continue both to deposit nutrients and to magnify flood events that in turn exacerbate nonpoint source pollution in a positive feedback loop that can be both expressed through poetry and empirically modeled with increasing levels of accuracy. In "Flood Warning," poetry again expresses water's property of interconnection, in this case of environmental issues with each other and with human livelihoods.

In response to this, both the poems "reinventing the wheel" and "weaving ropes by the river" are expressions of how humans can be mindful (a proactive measure) about their place in their larger nonhuman environments, and how humans can be resilient (a reactive measure) to environmental challenges. The former is a call for humans to be deeply aware of the governing power of cycles and how all parts of a cycle are integral to the integrity and healthy functioning of the whole. In the context of this project, this applies most pertinently to water as it interconnects microcosms in macrocosms, and exists across its cycles and states. The latter is a call for humans to maximize individual and collective intelligence and creativity to be resilient to environmental and other problems, especially as these problems reach high levels of severity. Ultimately, these cycles are not only essential for continued existence, but they can also be experienced as profoundly beautiful. These last two poems address the question not of *what* the actual content is of empirical research inquiries into environmental issues, but *why* it is important to engage in such investigations.

Fundamentally, poetry is an *expression* and not a conclusion. It is therefore unproductive in this context to overinterpret or analytically scrutinize the content of every poem for possible conclusions. Still, poetry's expressive nature poses a number of limitations that make it difficult to use poetry in and of itself to directly address environmental issues, especially in a society that privileges the legitimacy of quantitative, scientific, reductionist, and allegedly objective ways of knowing. Poetry flows from the layering and synthesis of a particular subjective experience and of course it cannot objectively generalize about a larger phenomenon. Further, genuine engagement in the creative process is nonsystematic, and outcomes of the creative process are inherently unpredictable since creativity loses much of its authenticity when confined to predetermined specifics. However, the purpose of poetry -- among other expressive endeavors -- is for every reader to experience the poetry differently, because the poetry will resonate distinctly with the richly diverse experiences, perspectives, and ways of knowing that make every human being unique. The variety of interpretations of poetry can provide material to deepen and complicate readers' discussions with each other, ideally encouraging more nuanced and creative understandings. Poetry's practical significance is thus derived from how it relates with and is embedded within the network of its audience, other disciplinary lines of inquiry, and current social, political, economic, and environmental realities.

PART III: INTEGRATIVE DISCUSSION: CONCLUSIVELY AND EXPRESSIVELY UNDERSTANDING NONPOINT SOURCE POLLUTION IN THE CANNON RIVER WATERSHED THROUGH METHODOLOGICAL COMPLEMENTING

In this project, we engage in methodological complementing to understand nonpoint source pollution in the Cannon River Watershed both through the *process* of executing this project, and through the *results* of our conclusive nutrient emission heterogeneity modeling and our expressive poetry. The results of each approach are dovetailed on two levels of complementarity and overlap at seven specific points of connection. We respect and maintain the disciplinary boundaries of each approach, but reconceptualize these boundaries as porous. This gives each approach the freedom to investigate the issue in the depth that is enabled by disciplinary conventions, and provides a breadth of perspectives when information is exchanged across disciplinary boundaries within a larger evolving system of human knowledge. Together, both conclusive and expressive modes of inquiry provide complementary and thereby more comprehensive ways of understanding the overarching issue.

Methodological Complementing Through the Research *Process*

We used methodological complementing as a process of group collaboration. This enabled us to explicitly engage our diverse strengths and interests to explore nonpoint source pollution in the Cannon River Watershed in greater breadth and depth. We had to trust each other to fulfill our respective responsibilities of the project to the best of our abilities in a timely manner. Likewise, we had to constantly and deliberately work to communicate the progress and insights of our respective portions of the project, and do so in a way in which our assumptions about each other and our respective methodologies were addressed, and the ideas we sought to communicate actually were communicated. This process led to discussions that examined the assumptions, limitations, and contributions of each approach separately, and then explored how they connected and complemented each other.

From the modeling side, the processes of executing this Comps became less a discussion specifically about agricultural nonpoint source pollution, and more a discussion about how scientists and artists can experience varying degrees of success in communication, and how each approach can be relevant and useful to the other. The process of designing and implementing the model made clear the vast expanse of variables and factors that influence hydrological functions, and how even the most complex models must make assumptions that are simplistic and reductionist to some degree. In the context of modeling, boundaries are critical: it is necessary to limit the scope of what is being examined, since the only questions about which conclusions can be drawn are those questions that are contained within tight isolated bounds and thresholds. The process of nutrient heterogeneity modeling has required the isolation of key variables, which in a sense is opposite to the approach of poetry. All of this has been a humbling process because it has illustrated how difficult it is to adequately capture the intricacies of a particular aspect of reality within the quantitative constraints of a specific model. This process has helped to reveal that while modeling can be extraordinarily useful and worthwhile, it should not be regarded as an objective or definitive answer to problems, since it captures neither that which cannot be quantified, nor that which is not yet known.

From the poetry side, this research process has also been humbling. One of the most challenging aspects of writing poetry has been to navigate the issue of boundaries. As discussed in the next section, boundaries are integral to the coherence and successful execution of a model, but hinder the creative freedom that poetry requires. This has been challenging in formulating specific insights gleaned from the poetry about nonpoint source pollution in the Cannon River Watershed. When trying to express a reality through creative artistic processes, it can be overwhelming to consider how many different and diverse understandings of reality there are, and how it is virtually impossible to systematically and creatively account for all of them, especially since poetry stems from merely one reality and subjective engagement in the creative process. Like modeling, poetry is limited in the scope of its applicability and accounts for merely a small fraction of what humans understand about their existence.

During the process of attempting to actually complement our methodologies, we engaged in regular explicit discussions, deliberately addressing how our parts of the project fit and did not fit together. We brainstormed and discussed concepts and points of connection, and explored how the methodologies related with each other through these points of connection, how each disciplinary approach conceptualized these points differently, and what we assumed could best be captured by each approach. Often, it was only after a long discussion that we realized that each side was attempting to convey the same concept, but was just doing so with different words. This of course parallels how our two different approaches to understanding nonpoint source pollution in the Cannon River Watershed both speak to the same overarching concept, but in different ways. These conversions were premised on the primary assumption of our Comps that both modeling and poetry provide legitimate perspectives, neither of which has to justify itself to the other, and that value exists in having multiple perspectives in dialogue with each other. Operating under this assumption better enabled us to trust each other, validate each other's points of view, and focus on what each perspective has to offer. In doing so, we were better able to capitalize on each other's unique interests and strengths.

Methodological Complementing Through Conclusive and Expressive *Outcomes*

Our conclusive nutrient emission heterogeneity modeling and expressive poetry writing are complementary on two levels: each provides insights the other cannot capture, and each compensates for the limitations of the other. Our modeling provides a detailed quantitative analysis of nutrient emission heterogeneity in the Cannon River Watershed, which is an important foundational step in determining whether or not practical policy options such as Water Quality Trading Markets would be feasible to better ensure quality water availability in this watershed, given the severity of water body impairment. The modeling is limited because it reduces the values of water and landscape variables to quantified units, which overlooks all other values of water that have a legitimate and significant role in mediating human and nonhuman parts of a watershed. The poetry expresses water's property of interconnection of these values. However, the poetry stems only from one subjective experience, and there are as many subjectivities as there are beings on the earth. Modeling compensates for this limitation because it does have the capacity to objectively generalize within its constraints and assumptions.

These two levels of complementarity apply to the notion that each mode of inquiry captures a separate part of the larger picture of nonpoint source pollution in the Cannon River Watershed. Both approaches also overlap at seven specific points of connection: 1) water, 2) nutrient pollution, 3) space, 4) time, 5) cause and effect, 6) epistemology and legitimacy, and 7) the outcome of each process of inquiry about nonpoint source pollution in the same watershed. We discuss these below.

1) Water

Both the modeling and the poetry address the same water, but through different approaches. Modeling assesses how water flows through and thereby interconnects specific categories of processes that humans have observed, studied, and labeled. Empirical modeling of hydrological systems is based on the fundamental idea of a watershed as a naturally bound spatial hydrological network: all points within a hydrological network matriculate into outlets, which feed into other hydrological networks. SWAT is built on a mathematical model of the hydrologic cycle that occurs within and throughout each watershed subbasin that it delineates. The SWAT model is actually an amalgamation of sub-models that break down the hydrologic cycle into manageable components. To operate, SWAT makes explicit categorizations and separations of specific landscape variables from each other within the context of the specific microcosm of the Cannon River Watershed (Neitsch, Arnold, & Kiniry, 2005).

The poetry does not systematically employ these categorizations, but evokes experiences of water that likewise interconnect emotional, metaphysical, and other non-quantifiable realms. The poetry understands hydrological networks as components of larger global water cycles that span the macrocosm of the earth, but that are also mirrored in human anatomy and physiology, and relationships within and between human and nonhuman communities (please refer to poetry collection and discussion). Throughout the poetry, water is explicitly expressed as an agent of interconnection that spans cultures, spirits, and lands across spatial-temporal boundaries. This captures values of water that spill over empirical objectivity into the realm of the experiential, emotional, spiritual, relational, and metaphysical.

That both approaches address the same water may seem to be too obvious a point to even warrant discussion. However, this fundamental fact explicitly illustrates how neither perspective can capture the whole reality of water's existence. Regardless of how humans categorize and/or experience water, it will still flow across our classifications in accordance with its natural propensities. Since we all depend on the same water to exist, and water is literally a physical medium that flows across, interconnects, and thereby has the potential to bridge different ways of knowing, it is in our best interest to communicate these ways of knowing water as much as possible to gain as comprehensive a perspective of water as possible -- in this case, in order to define more effective ways to address nonpoint source pollution.

2) Nutrient Pollution

Agricultural nonpoint source pollution is the fundamental driver of the nutrient emissions that are the central motivator of this project. Nutrient emissions are directly addressed by the modeling in a detailed spatial manner, but can only be inferred from the poetry. SWAT allows the user to gain a birds-eye view of the study area and simulate the relative impact of agricultural nonpoint source pollution by location within the hydrological landscape. SWAT modeling thus captures the spatially driven nutrient emission heterogeneity that is not immediately perceivable from a single subjective human perspective. A subjective human perspective can, however, experience and express the tangible ramifications of nonpoint source pollution, as they manifest in microcosms and interact with other environmental challenges such as climate change and impacts individual and communal livelihoods, health, and the surrounding environment. Nutrient pollution is thus a key point of connection between the empirical modeling and the poetry: SWAT enables the systematic perception of nutrient flow patterns that delineates a specific way to pragmatically address nonpoint source pollution, and poetry can express subjective experiences of nutrient pollution both separately from and including the spatial insights of SWAT.

3) Space

The model and the poetry both center on the same spatial area: the Cannon River Watershed. SWAT model operations define space using elevation, soil type, and land cover. Subbasin spaces are bound networks of association, and HRU spaces are categories produced by overlaying soil, land use, and slope classes. To function, the model must digitize the landscape and define space by the smallest common denominators. The boundaries of space that SWAT uses cannot be validated by aerial photography, nor are they reflected by a personal visit to the study area. The poetry compensates for SWAT's abstraction of the landscape in that much of the material for the poetry was gleaned from personal visits to the study area. Modeling and poetry provide two different ways of understanding the same space, and through this, convey intricacies of both nutrient emission heterogeneity and subjective experience. Neither of these understandings of the landscape could be captured by the other method.

4) Time

Modeling and poetry both provide alternative conceptualizations of this same study area across different scales and ways of measuring time. Time steps in the SWAT model permit hydrological and agricultural processes to unfold. Time steps are linear and uniform, and occur at different scales depending on the variable. For example, precipitation and temperature are hourly, but agricultural management practices are daily. SWAT model output also is specified at varying temporal scales, whether on a monthly or daily scale. SWAT operations are therefore temporally hierarchical and rigid. In addition, the model does not specifically address what occurs on the land during the winter months, which the poetry explicitly captures. Furthermore, the poetry is unbounded by rigid measurements of time, has the dexterity to navigate from seconds to centuries, and between the perspectives of human and nonhuman individuals and communities. Our conclusive and expressive approaches each provide a conceptualization of time that the other mode of inquiry cannot capture.

5) Cause and Effect

Both our conclusive and our expressive approaches assume different agents of cause and effect in the process of addressing the same problem in the same spatial and temporal context. In the case of modeling, user-specified model inputs and schedules are the agents of change. Model inputs and the logical structure of the model have full control over model outputs and results. Although SWAT addresses land cover and agricultural management, SWAT does not consider the agency of biota. For instance, SWAT and other hydrological models use weak ecosystem and growth models. SWAT has the capacity to differentiate between annual and perennial vegetation cover, but presumes the growth rate of all plants within these two categories to be the same. SWAT does not account for herbivores, which have a large impact on plant growth, biodiversity, and nutrient absorption by vegetation. Most importantly, SWAT assumes but does not explicitly state that humans are the drivers behind the fertilizer applications that cause nutrient pollution. Overall, SWAT does not directly give agency of causation to biota, including humans, who in reality interact with and exert varying degrees of influence over the study area's land use.

The poetry does not express definitive agents of causation as user-specified quantifiable variables. Rather, the poetry expresses the ability of many participants in a landscape -- weather, topography, vehicles, humans, animals, and spirits, for example -- to interact with each other in non-quantifiable physical, emotional, and even metaphysical manners across space and time. The ultimate agent throughout all of these is water. Water is explicitly expressed as the cause of interconnection of everything through which it flows, providing a matrix in which all other participants in a landscape and a watershed can interact with each other in a complex nonlinear manner.

These two different understandings of how causation manifests in the landscape of the Cannon River Watershed illustrate how giving conceptual agency to different participants in a landscape render completely different understandings of who and what participates and does not participate in the landscape, and who and what has and does not have power and agency, and ultimately, how agents -- who exert varying degrees of power -- interrelate. This can have important practical manifestations in terms of how land and its encompassed agents are perceived and treated (please refer to Part II's discussion of linear and cyclical modes of understanding landscapes, p. 31).

6) Epistemology and Legitimacy

Scientific applications of empirical modeling are often readily accepted as legitimate and objective. Empirical modeling is designed to produce quantified outputs for the purpose of making conclusions and validating theories. The logical rigor of empirical modeling is beneficial because it allows researchers to test assumptions and build off of previous work and knowledge. However, empirical modeling creates levels of abstraction that simplify and reduce landscapes to variables and coefficients. Because of its concurrent use of objectivity and abstraction, logical rigor can be easily confused with realism. It is ironic that empirical modeling is considered an unquestionably objective way of studying a landscape when its understanding of landscape factors is based on mathematical abstraction, not concrete personal experience. Poetry and the arts are often dismissed in scientific fields of study for being ethereal, abstract, and nonobjective. However in the case this project, poetry makes a more deliberate attempt to grapple with the tactile and visceral connection between people, communities, and the hydrologic landscape.

Empirical modeling uses quantification to create meaning, show relationships, and assess outcomes. Our study uses milligrams per liter per square kilometer of nitrate pollution to identify, compare, and rank critical subbasin sources of agricultural nonpoint source pollution. Poetry interweaves words, space, and grammar to arrange concepts, evoke metaphor, and express meaning. Formal artistic decisions illustrate critical concepts and mirror the relationship that the artist has with the concept at hand -- in this case, water.

Boundaries are an essential feature of modeling, because they empower modelers to differentiate and compare spatial units within the study area. For the poet however, boundaries are constraining because they stifle the growth of new ways of understanding. The poet interested in contemplating the natural world understands boundaries as porous and dynamic.

In this project, the modelers engaged with the study area and topic by managing spatial datasets, specifying inputs, sorting and processing model output, and considering the theoretical implications of the hydrologic cycle, the phosphorus and nitrogen cycles, and agronomic practices. In order to communicate with other researchers involved in the field, the modeler/scientist uses the vocabulary of data sources, coefficients, equations, relationships, assumptions, limitations, scope, and future research suggestions to contextualize their work. Poetry communicates with readers by heightening perception, revealing new ways of understanding, and synthesizing experiences in a creative space that flows through emotional and spiritual realms of collective consciousness. Poetry is an ancient art that has often been intimately intertwined with song, dance, music, community, land, and spirituality, and has thus been highly valued throughout human existence. By conceptualizing poetry, modeling, and other disciplinary approaches as rigidly discrete, we are severing the ties between different ways of knowing that are critical for human livelihoods and connection with the land, including all of its human and nonhuman inhabitants of past, current, and future generations.

7) Outcome

Outcomes from the two approaches also differ significantly but provide complementary modes of understanding nonpoint source pollution in the Cannon River Watershed intended for the same audience. The outcome of our empirical model and methodology is a set of figures and coefficients that illustrate the spatial inequality and distribution of agricultural nonpoint source pollution; the Gini Coefficient is a number that represents an abstract concept that cannot be perceived or validated personally. This outcome is neatly defined so that is can be compared and related to the research of others, and provides the *conclusion* that within the constraints of the model, nutrient emissions are not heterogeneous enough to justify the efficient implementation of Water Quality Trading Markets in the Cannon River Watershed. This conclusion, stemming from the objectivity of the model within its constraints, is generally more likely to be received by peers who are engaging with similar topics and lines of inquiry, rather than the general public. The objective of a conclusion is to have all audience members receive the same message so that further research can build off of the conclusion.

The outcome of engagement in the creative process is a collection of poetry stemming from a single subjectivity, which in this case is an artistic *expression* of water's property of interconnection. The intended audience is a wider public readership, and the entire purpose of expressive endeavors is for all readers to experience the poetry differently in accordance with their diverse experiences and perspectives. Still, though the poetry will inevitably resonate differently for every person, the actual poetry collection enables readers to discuss deeper understandings of the poetry that have the potential to span and integrate individual and collective intellectual, spiritual, and emotional ways of knowing.

Through methodological complementing, we present the outcomes of both our conclusive and expressive modes of inquiry together in such a manner that they can be juxtaposed. In this way, the same audience is intended to receive both, and can further explore and discuss for themselves how the two might be in dialogue with each other. If pursued to the point of designing practical solutions to address quality water availability in the Cannon River Watershed, having two perspectives actively in play can provide a more comprehensive understanding, ideally increasing the likelihood that resulting approaches will be more congruent with the overarching issue.

CONCLUSION

Water is the definitive physical matrix through which all life forms on earth are connected. Within the Mississippi River Basin and its subbasins, including the Cannon River Watershed, human and nonhuman inhabitants share water's physical channels. However, nonpoint source pollution has increasingly threatened the continued availability of quality water within southeastern Minnesota and the Mississippi River Basin.

This project approaches the overarching problem of nonpoint source pollution in the Cannon River Watershed through methodological complementing -- the process of investigating a phenomenon through conclusive and expressive processes, and dovetailing the insights of each process to discern deeper perspectives about the phenomenon and the working relationships of diverse collaborators. In our project, we complement empirical modeling of nutrient emission heterogeneity with poetry's rendering of water's property of interconnection. This gives rise to a conclusion from the model (Part I) and an expression from the poetry (Part II). The model concludes that within its constraints, though the spatial distribution of nonpoint source pollution within the study area is heterogeneous, the discrepancy between critical and noncritical source areas is not large enough to warrant the efficient and thereby effective implementation of Water Quality Trading Markets (WQTMs) in the Cannon River Watershed. The poetry explores the model's limitation of quantifying landscape variables. The poetry evokes water's property of interconnection across the microcosm of the Cannon River Watershed, within the macrocosm of the entire earth, across themes including water's physicality, the very real and significant presence of communities in a landscape, linear and cyclical understandings of a landscape, spiritual connections to water, and practical implications of environmental issues, including quality water availability.

Though conclusive modeling and expressive poetry writing may initially be perceived as completely disparate and even mutually exclusive modes of inquiry, both the *process* and the *outcomes* of methodological complementing strengthen the connections between both approaches (Part III). During its process, methodological complementing empowers collaborators to harness their individual strengths and interests. This makes it possible to cover more territory more effectively, since people tend to become more efficient at conducting inquiries about which they are actively curious. Greater depth can be attained through collaborators' individual investigations, and greater breadth can be attained when collaborators dovetail the outcomes. In the case of our project, these outcomes are complementary on two levels: each captures a part of the overarching issue of nonpoint source pollution that the other cannot perceive, and each compensates for the major limitations of the other. Modeling compensates for poetry's limitation of non-generalizable creative subjectivity, and provides an important first step in determining whether or not WQTMs are a viable option to pragmatically address nonpoint source pollution in the Cannon River Watershed. Poetry compensates for modeling's limitation of partitioning a dynamic physical watershed into discrete units, by articulating water's power of physical and metaphysical interconnection of microcosms in macrocosms. Modeling's conclusion and poetry's expressions further overlap within seven specific points of connection: water, nutrient pollution, space, time, cause and effect, epistemology and legitimacy, and the outcome of each process of inquiry. Together they reveal a much more comprehensive perspective about water as affected by nonpoint source pollution in the Cannon River Watershed than either approach could capture alone.

It is impossible to omnisciently understand the many dynamics of nonpoint source pollution, but explicitly juxtaposing a conclusive and an expressive mode of inquiry through methodological complementing enables the two approaches, as well as the people behind those approaches, to be actively in dialogue with each other. Methodological complementing has not been utilized to address environmental and other problems, but has the potential to become a powerful approach to address complex systemic issues. As such, we hope that it will be further applied and refined in other research, policy, and practical contexts. Through its process, methodological complementing enables diverse collaborators to concurrently engage their own strengths and interests in a complementary fashion. Through its outcomes, methodological complementing dovetails the different perspectives of collaborators. By increasing understanding in this manner, methodological complementing provides a foundation to develop practical and policy approaches that are more congruent with the intricacies of the overarching issue, and are therefore more likely to be effective. In this way, methodological complementing can contribute to the healthy coexistence of human and nonhuman individuals and communities, even in the face of unprecedented environmental challenges.

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Appendix A: Agricultural Calendar

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007 & 2010					15th: Plant/begin growing Soybeans 16th: Fertilizer Application (Elemental Phosphorus 9.07 kg)		8th: Harvest	1st: Tillage (Moldboard Plow Reg 406b)	15th: Fertilizer Application (Urea 59.967 kg)			
2008					15th: Plant/begin growing Corn 16th: Fertilizer Application (Elemental Phosphorus 9.07 kg)	30th: Fertilizer Application (Urea 22.67 kg)			15th: Harvest	1st: Tillage (Moldboard Plow Reg 4-6b)		
2009					15th: Plant/begin growing Corn 16th: Fertilizer Application (Elemental Phosphorus 9.07 kg)	30th: Fertilizer Application (Urea 81.65 kg)			15th: Harvest	1st: Tillage (Moldboard Plow Reg 4-6b)		

2007 Year 1:

May 15th Plant/begin growing Soybeans

May 16th Apply Fertilizer (Elemental Phosphorus 9.07 KG)

July 8th Harvest operation

August 1st Tillage operation (Moldboard Plow Reg 4-6b)

September 15th Fertilizer Application (Urea 59.967 KG)

2008 Year 2:

May 15th Plant/begin growing Corn

May 16th Fertilizer Application (Elemental Phosphorus 9.071 KG)

June 30th Fertilizer Application (Urea 22.67 KG)

September 15th Harvest Operation

October 1st Tillage (Moldboard Plow Reg 4-6b)

2009 Year 3:

May 15th Plant/begin growing Corn

May 16th Apply Fertilizer (Elemental Phosphorus 9.07 KG)

June 30th Apply Fertilizer (Urea 81.65 KG)

September 15th Harvest operation

October 1st Tillage Operation (Moldboard Plow Reg 4-6b)

2010 Year 4:

May 15th Plant/begin growing Soybean

May 16th Fertilizer application (Elemental Phosphorous 9.07 KG

July 8th Harvest Operation

August 1st Tillage Operation (Moldboard Plow Reg 4-6b)

September 15th Fertilizer Application (Urea 59.967 KG)

APPENDIX B: MODEL ACCURACY: CORRELATION COEFFICIENTS BETWEEN MODELED AND MEASURED NITRATE EMISSIONS

	2007	2008	2009	2010
Observed vs. Maximum Modeled Output	0.61	-0.18	0.11	-0.23
Observed vs. Minimum Modeled Output	0.65	-0.33	-0.29	-0.38

APPENDIX C: ABBREVIATIONS AND DEFINITIONS

Conservation Reserve Program (CRP)	The Conservation Reserve Program (CRP) is a land conservation program administered by the Farm Service Agency (FSA). In exchange for a yearly rental payment, farmers enrolled in the program agree to remove environmentally sensitive land from agricultural production and plant species that will improve environmental health and quality. Contracts for land enrolled in CRP are 10-15 years in length. The long-term goal of the program is to re-establish valuable land cover to help improve water quality, prevent soil erosion, and reduce loss of wildlife habitat.
Critical Source Areas (CSAs)	The highest emitting subbasins that contributed to 20% of the total annual nitrate output.
Hydrologic Unit Code (HUC)	The United States Geological Survey created a hierarchical system of hydrologic units originally called regions, sub-regions, accounting units, and cataloging units. Each unit was assigned a unique Hydrologic Unit Code (HUC).
Mississippi River Basin (MRB)	The world's fourth largest drainage basin that covers over 3,220,000 km^2, including 32 U.S. states and two Canadian provinces (Wikipedia).
National Pollutant Discharge Elimination System (NPDES)	As authorized by the Clean Water Act, the National Pollutant Discharge Elimination System (NPDES) Permit Program controls water pollution by regulating point sources that discharge pollutants into waters of the United States.
Hydrological Response Unit (HRU)	SWAT categorized subbasin units that share similar land use, topography, and soil properties.
Nonpoint Source Pollution (NPS)	Refers to both water and air pollution from diffuse sources. Nonpoint source water pollution affects a water body from sources such as polluted runoff from agricultural areas draining into a river, or wind-borne debris blowing out to sea.
Point Source Pollution (PS)	A point source of pollution is a single identifiable source of air, water, thermal, noise or light pollution. A point source has negligible extent, distinguishing it from other pollution source geometries
Soil and Water Assessment Tool (SWAT)	A hydrologic model that has modeled the flow and accumulation of N, P, and sediment adequately over similar models such as the Generalized Watershed Loading Function.

APPENDIX D: DATA REPORT

Source: USGS National Hydrography Dataset Geodatabase
Information: Location and Flow of Rivers and Streams

Source: National Land Cover Dataset from Multi-resolution Land Characteristics Consortium
Information: Land Use Land Cover Data

Source: USDA NRCS Geospatial Data Gateway
Information: HUC12 Watershed and Sub-watershed Boundaries Shapefile

Source: University of Minnesota
Information: Karst Feature Database from University of Minnesota

Source: EPA Watershed Assessment, Tracking, and Results Website
Information: Land Shapefile of Impaired Water Bodies

Source: Minnesota Pollution Control Agency
Information: Water Quality Impairments in Rivers and Streams

Source: Bereket Haileab, Professor of Geology, Carleton College. Unpublished Data.
Information: Field Measurements of Surface Nitrate Runoff

Model: Soil and Water Assessment Tool (SWAT)
Developer: USDA-ARS
Utility: Predicts the effects of management decisions on water, sediment, nutrient, and pesticide yields on large, ungauged river basins.

water

by Liz Wilson
in conjunction with Anthony Abercrombie and Cody Wang
2014 Environmental Studies Senior Comprehensive Exercise

contents

Swift being, green beings, all beings -- all persons;
the two-legged beings
shine in smooth skin and their furred spots

Drinking clear water together
together turning and dancing
speaking new words,
the first time, for

Air, fire, water, and
Earth is our dancing place now.

Gary Snyder, from “All the Spirit Powers Went to Their Dancing Place” in *Regarding Wave* (1970)

preface

Water is the physical lifeblood of all life forms on earth. In order to survive, we human animals -- alongside our fellow life forms, within ecosystems and earth systems -- interact with water across hours, days, months, seasons, years, centuries, eons. We can do this, for example, by procuring water (from a faucet, from a well, from a stream, from an obscure water source reached by a long journey), drinking water, excreting water, swimming, fishing, and boating in water, studying water academically, changing subsistence practices to coincide with seasonal availability of water, participating in cultural rituals and traditions concerning water, and creating art about water. Individuals are more mindful in some of these interactions than in others, and all of these interactions differ from person to person, community to community, and culture to culture.

Our present state of decreased freshwater availability has coevolved with social-political-economic conditions that have increasingly imposed human control over water. Potable water is readily accessible to some of the world's population via a mere turn of a knob; water fills washing machines and bathtubs; water cools nuclear reactors, transports fertilizer, runoff, and chemicals; water is wasted in great quantities while drought parches other areas of the world. Societal processes facilitating control over water in some parts of the world have reduced water to a singular meaning -- a commodity, a burden, and/or an object to be controlled. Such reduction overlooks water's innumerable other meanings and "de-physicalizes" its existence across its three states of vapor, ice, and liquid. It ignores the continual flux of water through cycles that span the spatial scale of the entire earth, its metaphorical omnipresence across human cultures and spiritualities, and the immense power derived from these properties that enables life in the first place. Controlling water has encouraged a dulling of humans' visceral, sensory awareness of water's depths.

However, we humans are fundamentally physical creatures since we experience the world through our "mindbodies" -- our layers of being that emerge from the integration of our physical and cognitive realms. As a result, the ways in which we perceive phenomena influence our behavior. Because of this, we tend to attain a heightened awareness of our environment only when it palpably enters the realm of our physical consciousness. Likewise, societal level responses to environmental problems often emerge only when such problems reach the visceral consciousness of those affected, and those empathizing with the affected. We see this with reactive measures to toxic chemical spills that leave thousands of people in a watershed without safe tap water, with natural disasters such as hurricanes, typhoons, earthquakes, and the nuclear contamination of water.

Before an accident or disaster forces us to become physically aware of water in a negative way, each of us can harness the immense intelligence of our mindbody to perceive and thereby know water in the larger context of its cycles by experiencing the water that flows through us. Such visceral mindfulness of water -- in its current spectrum of health and pollution, across its molecular states of vapor, ice, and water, through its seasonal manifestations -- enables us to physically and metaphysically fathom how water literally enables our existence, our consciousness, and our interconnectedness with the world around us.

Poetry is one of many creative mediums that can reflect humans' experiences of water. The poems here explore water across its three states of vapor, ice, and water. Though the poems emerge from my own experience, they stand as a call for every person to harness her or his own uniquely rich creativities to explore the depths and interconnections of fluid mindbody existence.

artist's statement

This is my first formal poetry undertaking, and I wish to elaborate upon my major influences and the artistic decisions that have shaped this project. In terms of influences, I am grateful for Gary Snyder's work. His poetry resonates with me because it integrates the depths of experiential awareness in moments of intense visceral perception and knowledge with and across space, time, species, communities, lands, and spirits. To me, he captures the human experience, embedded in the earth, with penetrating insight. For these reasons, I am also grateful for the poetry of Duane Niatum and other Native American poets across generations and lands. Arne Naess, George Sessions, Bill Devall, Dolores LaChapelle, and other deep ecology proponents have influenced my understandings by interrelating poetry of the earth with prose imperatives for deeper societal-level integration with our animate, animalistic, and embedded reality.

I am still new to the process of poetic distillation, and the time constraints inherent in Carleton's institutional Comps framework do not accommodate the years of learning requisite to honing an art form. I certainly have much to experience and learn in order to wield the poetic medium more skillfully and effectively, and I appreciate readers' patience in recognizing this compilation not as a fixed product, but as a fluid process.

This poetry is limited by the nature of the English language, which conceptualizes phenomena as discrete. A concept tends to be afforded meaning because of the *substance* it contains as a separate existence -- A derives meaning from being A, B from B, and so forth. This often overlooks the *relational* nature of many phenomena (LaChapelle): a relational interaction between A and B can be characterized as AB -- an interaction that is dependent upon both A and B, but is more than the sum of its parts. Through this poetry, I attempt to evoke the relational nature of water: though labeled as a discrete entity, water courses across time and space, blurring boundaries of selves, species, lands, communities, seasons, lives, and eons, and water's literal, physical relation with other elements of life gives rise to the existence, sentience, and metaphorical channels of life.

I am finding that I am drawn to themes and poetic elements that suggest the physical process and experience of being immersed in a particular sensory mindbody place. The collection is organized according to water's three states in order of increasing molecular density -- vapor, ice, and liquid water. This attempts to evoke movement from the most abstract to the most physically intimate forms of water as experienced from a human mindbody perspective, since mindbody awareness can play a powerful role in perception of and interaction with the multifaceted values and manifestations of water. The sparse and compact language seeks to evoke deliberate experiential immersion over time in a particular phenomenon, akin to spending a day under a tree by a river -- new layers of artistic and poetic insight are illuminated in new lights through continued observation, as the sun makes its way across the sky in time for moonrise. Many of the formatting decisions -- the look of the poems on the page -- are derived from understanding words and spaces in poetry as complementary. The interrelation of words and spaces is what gives rise to meaning rather than simply words themselves, just as rhythm emerges from the coherent and creative organization of sound and silence in relation to each other. Non-adherence to conventions of capitalization seeks to allow words and concepts to flow together, as water runs according to its wild nature through mountains, forests, prairies, and fields alike. It is only when formal substantive human control -- Dams, Canals, Locks, Irrigation, Plumbing -- are imposed upon water that it alters its path, but never its propensities.

Most importantly, *this work is not ultimately about the poetry. This collection is an exercise in engagement in the creative process concurrently and in communication with a* *drastically different disciplinary approach to gain deeper perspective on a phenomenon of our collective reality* -- in our case, the pressing environmental issue of nonpoint source pollution in the Cannon River Watershed. We are labeling this concept "methodological complementing." My poetry stems merely from my own perspective and creative propensities, but there are just as many human perspectives and creativities as there are human beings, and likewise there are just as many nonhuman perspectives as there are nonhumans. In order to better understand the immense problems we humans confront today, we must first work towards the ideal of encouraging all humans to channel the full potential of their mindbodies -- through mathematics, poetry, music, visual arts, physical labor, engineering, physics, chemistry, religion, dance, economics, crafts, or whatever else. Second, we must communicate the insights gleaned from drastically different lines of inquiry with each other. In this framework, the knowledge contained within the labels of "poetry" and "quantitative modeling," for example, must be understood not solely as substantive, deriving meaning only within and because of their own boundaries. Rather, we must reframe humans' collective potential understanding as relational: disciplinary boundaries can be porous, and knowledge evolves as disciplines interpenetrate.

We hope that future interdisciplinary pursuits -- creative processes, research, and practical implementation -- will explore how drastically different lines of inquiry might relate to each other to yield deeper insight through methodological complementing. Given the urgency and severity of the challenges we face today, we cannot afford to maintain the arrogant notion that some disciplines deserve to overshadow the insights of others. Rather, we must realize that each way of knowing has something valuable to contribute to our collective knowledge, and we need all of these insights to layer upon, communicate with, and inform each other. Methodological complementing is a concept that should be applied to as many contexts as possible, in order to continue to attempt to cultivate creativity, whether alone or together. This will help us to maximize our individual and collective mindbody intelligence in as complex, rich and healthy a manner as possible.

water drop
echo
ripples
through
cave

silence
sound
of each
other

as
vapor
ice
water

drip

sculpt
body caverns

vapor

evening eddy

the evening after pete seeger died
wind howls outside, souls
flow through doors to
molecules swirling in heat

shaping dough as heart
biscuits -
“what is community?”
“what is art?”
“how to make beauty”

long cold day
roasted away in spices and bean
pots boiling over,
“suppertime!”
bell ripples through every door

steam awake,
molecules swirling through mindbodies
settling on old sofas.
“in winter, heat is more easily perceived.”
our shelter an extension of ourselves and
we depend on each other,

“what does it mean to relate?”

music spilling over cups of tea, steam
dissolving to rhythm, chords wafting

with baking bread,
“we are grateful.”

soft breath,
tongues wrap around
candle flame tossed to darkness,

“let’s make poems tonight”

(soaking in hot springs)

all flesh
but eyes, nose,

soaking in

frigid dawn

springs,
water
hot from
earth

icicles

suspend from
tree limb,
chime in
wind -

crimson

sun
shafts

through
swelling
steam

to
skin

wafting

breaths of being
waft
through sky flesh sky

incense
whorls in
candlelight

particles
vibrate translate rotate
float glide waft
energy
to
patterns

steam
drifts
from icy creek

breath
wafts through muscles
spirals
up spine
fingers hair
dancing
bodies swirl
in
souls

aurora
surges through
infinity's sinewed colors

ice

owl

owl singing in
coldest winter night

pine

song drifts
through snow

deep
cold

this soil
labored to fields

these bones
blood to breath

these species

anything
to stay alive

“the guys”

alone under sky
in a car
hurtling linearly
across spherical earth,
too fast to perceive
watersheds
cycles -

straight fields of agriculture
snowcovered in water cycle
for the time being

land yields to linear corn corn soy corn corn soy
fertilizers pesticides technology oil
progress of “the guys”
“the land is ours”

for the time being

corn corn soy to profit lines, combines, factories,
time machines, supermarkets -
fossil fuels to atmosphere -
nitrates to water -
water to watershed
streams, rivers, sea, sky, rain, snow
cells, bodies, minds, communities
future
generations
(we are the land’s)
(we are the land)

lone oak stretches to
eagle gliding through sky -
buffalo pace in pasture, fenced from wildness

bubbles

silver dusk,
far north,
january,
positive forty
fahrenheit,
little girl
and
mother
blow bubbles
to sky.

- mother

what are bubbles?

- daughter

spheres
floating through
space and time:

your eyes to see,
your brain to be,
your heart to beat,
your lungs to breathe

the sun who brings you light,
the moon who brings you night,
the stars who bring you dreams

my womb,
the earth,
who brings you life.

stars blur, shimmer through
floating bubbles

- pop -

to
warm
winter
sky

through bubbled breath:

- mother

it isn’t cold
enough for
winter
bubbles

\- pop -

- mother

what happens
when

earth

bubble

pops

while walking home

through midnight
winter falling silent on
pathways -

    water

    everywhere -

breathe -
blood
through
capillaries, arteries,
body's celled
watershed

breathe -
energy
through
nerves
to sight,
ice on eyelashes

breathe -
feet
through
snow,
time crystallized
in footprints

breathe -
deep
as sleep
dissolves breath
to dreams

frigid days

ice
sings to boot tempo,
tympanic
through
drifting silence,
frosted breath
to
starry

snowflakes

melt
on naked tongue,
quench senses
parched
by
barren

air,

see
breath
deep
cold
thought streams,
blood rivers,
oceans
of mind -
waves swell
with
heartbeats.

as ice
melts to
sea,

savor

these
frigid days.

water

web

water

    weaves
    life

as

    streams
    through
    flesh:

spider

web

swaying in
dawn

glistening
dew
drops
to

ripples

water falling

water shows gravity,
flows

through

snow,
stars sink to
skin
shivering in
frigid winter
night -

through

rain,
spilling soil
grains to
streams -

through

water
soaring over
sun-soaked cliffs,
carving mountain
flesh deep

someday to
sea

(water (music))

pulls
flesh
to move

is
everything
through which we
dance

prairie moon(s)[1]

gravity flows through muscles to
dance
(in) prairie
at full moon -
    (january)
    (wolf moon)
wind howls through hill, whips
flurried minds through prairie grass, snow
billows in cold
    (february)
    (snow moon)
silence floats through heavy
frost breaths to sky
    (march)
    (worm moon)
drips birdsong, sunlight softens
night, freeze sinks
to spring
    (april)
    (sprouting grass moon)
rains
pour through
flesh to
mud
    (may)
    (flower moon)
blooms,
showers echo
flushing color
    (june)
    (strawberry moon)
steams
sweetness, ripe
streams
sweat
    (july)
    (thunder moon)
clouds drum light,
air deep with
green

[1] Moon names are from the Old Farmer's Almanac, http://www.almanac.com/content/full-moon-names.

(august)
(green corn moon)
wind’s smoky shades cloak
grains in
haze
(september)
(harvest moon)
grasses ripple through dawn mist,
crimson wind lifts dewy hair as
sparrow sings soft to morning
harvest
(october)
(hunter’s moon)
creeks run red with
last rain
leaves
blood
of hunt
of all being
(november)
(frost moon)
crystals catch
stories in
ice
(december)
(long nights moon)
sets deep in
powdered
hush

midnight stream

stream murmurs through midnight
meadow

weaves sinews of fallen
petals, insect wings

draws
heartstrings to

music
fill
        spill
            to

dance as water

                gush
                        through stones

pine dance moonlit in
penumbra

        how do we know?
                                        know
                                                we
                                                        flow

to gaia

thank you

for water

because of water
our hearts beat blood, we breathe air

gaia

pull mountain streams to sea to clouds so
we can spin together, barefoot in rain
run inside, mud on floor
scream our joy
soak grandparents in embrace

gaia

give us water drop
threads
to tether our bodies to time

and gaia

give us drought
give us thirst
parch land until soil is
dust

let us live only when we
weave our threads
as sediments braided through
dried stream beds

gaia

as lightning leaps to thunder's drums
let us sing harmonies of sweaty dust pouring to fields
where water runs to sky
bending sunlight to rainbows

thank you

Flood Warning

A Flood Warning
has been issued by the National Weather Service
and
is in effect until midnight:

> Stay away
> from flowing water.
> Don't
> drive your car through water.
>
> It might be deeper than you think.
>
> Hopefully
> you've got friends
> uphill
> from you.
>
> You might have to climb to them to save yourself
> if water flows real wild.
> Especially if you drive your car through water.
>
> Hopefully
> the roots hold.

The more
we drive our cars through water
to the supermarket
to get cheap beef,
the more
Flood Warnings
will interrupt TV commercials.

> Hopefully
> you've got friends
> uphill
> from you
> and
>
> some damn strong roots.

reinventing the wheel

it is fine
just
as it is

when you reinvent the wheel
you also reinvent
roads
vehicles
energy
industry
politics
war
humans
land
space
time
earth

but the wheel
is just fine
as it is

it is

inhale exhale
sleep wake
listen speak
rest work

feel think
laugh cry
be
and

hot cold
light dark
still move
silent sound

summer autumn winter spring

stream mountain forest prairie desert sea

vapor ice water

the wheel
only works
when
whole

it is
just fine
as
it
is

weaving ropes by the river

together by the river in green tree shadows,
we dance ancient songs of
water slithering through land as
snake slips over moss.

we weave our ropes with the threads of our deepest creativities,
spiraling as genetic information to the center of earth.

the more threads, the stronger the rope.

of what are you woven?

when ancient songs have washed downriver
in carbon-saturated january rains,
when snakes drown and water forgets to dance through land,

let us hold fast to our ropes

and when they fray,
let us return to green tree shadows,

weave together
new threads,
stronger

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