THESIS

ASSESSING NUTRIENT MANAGEMENT SCENARIOS AT THE SYSTEM LEVEL

Submitted by

Olivia Jobin

Department of Civil and Environmental Engineering

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Master's Committee:

Advisor: Mazdak Arabi

Dana Hoag
Sybil Sharvelle

ABSTRACT

ASSESSING NUTRIENT MANAGEMENT SCENARIOS AT THE SYSTEM LEVEL

The exponential increase in urbanization and population has led to water quality degradation throughout the country. This can be linked to the increase in impervious surfaces from urban expansion, most wastewater treatment plants (WWTPs) not being equipped to handle higher nutrient inflows, and the exponential demand for food that has led to more intensive farming practices that erode and degrade the soil, further enhancing runoff. The overall goal of this study was to assess nutrient management scenarios at the system level. The objectives included: 1) determine a methodology that could be used to quantify nutrient load contributions from each sector at the watershed scale; 2): determining delivery ratios for each sector based on the ambient nutrient loads at the outlet of the watershed; 3): and assess the cost, equity, and water quality effects of conservation management practices, BMPs, wastewater treatment technologies, and water conservation practices.

Assessing the effectiveness of agricultural management practices is often jeopardized by lack of comprehensive monitoring data and computational burden at larger scales. The Soil and Water Assessment Tool (SWAT) within the eRAMS platform was used to assess the benefits of different agricultural management practices at field and watershed scale for the South Platte River Basin (SPRB), a moderately large semi-arid watershed located in northeastern Colorado. The model was calibrated using measured field observations from a study site in the watershed where the target management practices were implemented and monitored for their effectiveness. The agricultural management practices studied included fertilizer application rate and timing, tillage practices (i.e. conventional, reduced, strip, and no-tillage), and center pivot versus surface irrigation for roughly 21,000 irrigated agricultural fields (740,000 acres) in the SPRB. Center

pivot irrigation showed the highest potential for nutrient reduction while tillage practices had an intermediate effect.

Due to interim warm water instream total nitrogen (TN) and total phosphorus (TP) levels being exceeded over the period of 2002-2015, nutrient management scenarios were assessed at the system level for the Cache la Poudre (CLP) watershed in Colorado. The CLP watershed consists of 13 WWTPs, as well as irrigated agricultural fields, forested land, rangeland and urban areas making it an ideal candidate for this analysis. The scenarios created involved a combination of different practices and technologies for each sector and their associated costs to determine cost effective solutions for the issue at hand. A Gini Index coefficient was also determined in order to determine how equitable each scenario was. Models were used to determine the nutrient load contributions over the 14 year time frame with and without the implementation of the different practices and technologies tested, and were validated based on previous research and monitoring data. It was found that TN reductions needed for regulations could be achieved through the adoption of carbon addition, WWTP effluent reuse, 10% adoption of strip tillage, and a 25% adoption of bio-retention basins for a total of roughly $6,000,000. Whereas the TP reduction needed for regulations for all hydrologic conditions could not be achieved with any combination of the practices looked into, however 2 out of the 3 reductions could be achieved from the adoption of Chem-P, WWTP effluent reuse, 10% adoption of strip tillage, and 25% adoption of bio-retention basins for roughly $11,000,000. Further research would be needed to determine a scenario that could achieve a 70% TP reduction and 40% TN reduction simultaneously at the outlet, which was needed at the system level to be in compliance with regulatory standards.

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CHAPTER 1: INTRODUCTION

Over the last few decades, population has been increasing substantially, leading to a wide array of environmental problems. These include deforestation, depletion of natural resources, habitat loss, more pronounced and frequent weather events due to the effects of climate change, and water quality degradation, to name a few. Water quality impairments have led states to establish regulations that limit the amount of nutrients, specifically total phosphorus (TP) and total nitrogen (TN), that can enter nearby water bodies, and for Colorado these are the Colorado Department of Public Health and Environment (CDPHE) Regulations 31 and 85 (CDPHE, 2012a; CDPHE, 2012b). Regulation 85 pertains to point sources of pollution (e.g. WWTPs and factories) and is mandated, whereas Regulation 31 sets in-stream water quality standards to maintain ecological health. Due to Regulation 85, WWTPs usually fall burden to dealing with these impairments since nutrient contribution amounts are known; whereas the nutrients that enter streams and rivers from non-point sources are difficult to quantify due to the numerous factors that affect how nutrients are transported through the environment (i.e. soil characteristics, slope, weather, etc.). Since both point (WWTPs) and non-point sources (stormwater and irrigated agriculture) contribute to the water quality impairments being faced today, the need for a system level analysis of nutrient load contributions and potential reductions from the implementation of different practices and technologies for each sector is paramount.

1.1: Modeling Irrigated Agriculture

A watershed scale assessment on irrigated agricultural conservation practices would be impractical to do using field monitoring data alone due to time and budget constraints. There are numerous models that can be used to simulate agricultural processes and determine annual nutrient load contributions from each irrigated agricultural field within a watershed (Alarcon &

Gretchen, 2016; Vagstad et al., 2009). SWAT, a continuous-time, semi- distributed, process-based watershed model, was chosen to model the effectiveness of agricultural management practices on irrigated agricultural fields due to its extensive use within the literature (Gassman et al., 2007; Arnold et al., 2012a, SWAT Literature Database, 2016). Most distributed models have long set up and run times because of the complexities in parametrization and spatial discretization. However, SWAT uses hydrological response units (HRUs), greatly reducing the parameterization, setup, and run time, making it beneficial for an analysis of this size. SWAT was used within the Environmental Resource Assessment and Management System (eRAMS) open platform. Using SWAT under the eRAMS platform substantially reduces the computational burden by benefitting from automatic data extraction, cloud-based storage and operations and parallel computing when modeling large watersheds. Field observations were coupled with the use of models for this research to get a more representative regional assessment of the effects of different agricultural practices on a watershed scale.

1.2: Modeling Urban Stormwater

Calculating urban stormwater contributions with and without the implementation of different best management practices (BMPs) is difficult to do. An in depth analysis on how to determine these loads has been completed for the City of Fort Collins (Dell, 2017), and the methods established from this analysis were used when calculating stormwater contributions within the watershed. The methods to determine the baseline conditions were based on The Simple Method (Schueler, 1987), which uses precipitation data, a runoff volume coefficient, drainage area, pollutant concentration, and the fraction of precipitation that produces runoff to determine an annual pollutant load for the watershed using ArcGIS. This equation was then slightly modified in order to determine the annual nutrient load contribution after the implementation of different BMPs by incorporating the volume reduction (Leisenring et al. 2014) and median concentration of each nutrient (Poresky et al. 2011) for each practice.

1.3: Modeling WWTP Technologies and Water Management Practices

Regulation 85 regulates WWTPs and states that TP and TN levels need to be monitored in the effluent of WWTPs every month for large plants (effluent discharge > 1 MGD) and every other month for small plants (effluent discharge < 1 MGD) (CDPHE, 2012b). The annual median concentration cannot exceed 0.7 mg/L and 7 mg/L for TP and TN, respectively (CDPHE, 2012b). Baseline conditions were determined based on samples taken from each facility in accordance with Regulation 85 collected in 2014 and 2015. Modeling efforts for the different technologies and practices were performed on all publicly owned treatment works (POTW) with permitted capacities greater than 1 MGD using BioWin modeling based on previous work completed in the City of Boulder and other facilities within the state of Colorado (Hodgson et al., 2017a; Hodgson et al., 2017b). The water management practices of interest included source separation and WWTP effluent reuse. The WWTP treatment technologies analyzed were carbon addition, chemical phosphorus, and struvite precipitation.

1.4: Natural Background Loads

Even though a majority the nutrient loads within a watershed are due to human influences, nutrients also exist within the environment naturally, and should be accounted for when performing a system level analysis. Natural sources of TN and TP come from groundwater forest and rangeland, and atmospheric deposition. When determining in-stream loads pertaining to groundwater, well data along with the USGS Modular Finite Difference Flow Model (MODFLOW) (Niswonger et al., 2011) were used. The estimated nutrient load contributions from forest and rangeland were determined using the USGS Spatially Referenced Regression on Watershed Attributes (SPARROW) (Schwarz et al., 2006).

1.5: Ambient Water Quality

Ambient water quality data was used for determining delivery ratios. Delivery ratios, which account for the nutrient losses seen from each source to the outlet, were established for each sector using the simulated loads from each model and the observed water quality loads by minimizing the error between these values. Monitoring gauges stations have been implemented by the United States Geological Survey (USGS) and Environmental Protection Agency (EPA). The gauge station located at the outlet of the watershed was used. The measurement of nutrient data at these stations has only recently begun, therefore LOADEST, which is a load estimator model developed by the USGS that uses regression equations to fill in missing data points (Runkel et al., 2004), was used to determine the annual TN and TP in-stream loads for the years 2002-2015.

1.6: Cost and Equity

When performing a system level analysis, cost is an important factor to take into consideration. Usually the deciding factor for whether or not a practice will be implemented is cost. The net present value (NPV) was used to determine the lifetime cost (i.e. 25-year analysis) of each technology and practice analyzed, and then this value was used to determine the cost per pound of nutrient removed. Equity between the sectors is also an important factor, and was quantified in terms of a Gini index.

1.7: Objectives

The overall goal of this study was to assess nutrient management scenarios at the system level for the Cache la Poudre watershed in Colorado. The objectives included: 1) determine a methodology that could be used to quantify nutrient load contributions from each sector at the watershed scale; 2): determining delivery ratios for each sector based on the ambient nutrient loads at the outlet of the watershed; 3): assess cost, equity, and water quality effects of conservation management practices, BMPs, wastewater treatment technologies, and water conservation practices.

CHAPTER 2 : ASSESSING CONSERVATION EFFECTS OF AGRICULTURAL MANAGEMENT PRACTICES IN IRRIGATED RIVER BASINS

2.1: Introduction

Robust assessment of the effectiveness of agricultural management practices is essential in order to assure meeting target water quality goals. It is infeasible to assess the effectiveness of these practices using only monitoring campaigns specifically at larger scales (Tasdighi et al., 2017). Hence, models are used to simulate the water quality benefits of agricultural conservation practices (Motallebi et al., 2017). However, application of models for assessing the effectiveness of agricultural conservation practices is often plagued by lack of comprehensive monitoring data to corroborate the results and high computational burden at larger scales. Agriculture is the leading source of water degradation, specifically nutrient impairment in rivers and lakes (EPA, 2006). This can be linked to nitrogen and phosphorus abundance in nutrient fertilizers used on agricultural fields world-wide. Conventional agricultural practices, used by most farmers in the United States, involve a multitude of tillage operations that ultimately loosen and level the soil surface to create a suitable seedbed, yet this inadvertently increases susceptibility to wind and water erosion (Wardle et al., 2015) which enhances the amount of nutrients and sediments transported to the nearest waterbodies. In this regard, agricultural management practices can be employed to alleviate the pollution footprint of agriculture in water bodies.

Watershed models are valuable tools used by scientists and researchers around the globe for simulating different hydrologic and water quality processes. The Soil and Water Assessment Tool (SWAT) is a semi-distributed model that is commonly used for simulating hydrologic and water quality processes under different conservation practices at the watershed scale (Arabi et al., 2007; Gassman et al., 2007; Arnold et al., 2012, SWAT Literature Database, 2016). SWAT has been used extensively in research related to agricultural practices (Her et al., 2016; Bracmort et al., 2006; Cho et al., 2006). Yet it is a highly parametrized model for which the relative accuracy entails application of some calibration scheme to determine parameters that generate good results. Site specific field observations for the area of study can be used to assess the accuracy of the model outputs. Field observations alone, however, are not feasible for agriculture in a watershed scale assessment due to time and budget constraints. Field observations coupled with the use of models are a more representative way to determine a regional assessment of the effects of different agricultural practices on a watershed scale.

In order to minimize the amount of nutrient pollution entering water bodies from agricultural fields, different management practices can be adopted by farmers to help reduce the amount of nutrient yields from a field. Studies have been done to investigate these practices in several watersheds around the country (Motallebi et al., 2017; Bracmort et al., 2006; Cho et al., 2006; Saleh et al., 2015; Her et al., 2016; Stang et al., Rao et al., 2009). These studies examined practices including conservation tillage, riparian buffers, cover crops, and nutrient management. In some studies models were used to investigate the possible nutrient reductions that could be seen due to the implementation of agricultural conservation practices (Chaubey et al., 2010; Romkens et al., 1973).Other studies have used field observations (Merten et al., 2016, Williams et al., 2016). However, to our knowledge, there has not been a study which incorporates both field observations and model simulations to assess the effectiveness of conservation practices in large scale agricultural watersheds specifically in semi-arid regions.

The previous studies on effectiveness of agricultural conservation practices (Bracmort et al., 2006; Cho et al., 2006; Saleh et al., 2015; Her et al., 2016; Stang et al., Rao et al., 2009; Merten et al., 2016; Williams et al., 2016; Chaubey et al., 2010; Romkens et al., 1973) focus primarily on humid climates with higher annual precipitation resulting in higher potential for nutrient transport. Most studies in semi-arid regions are concerned with water conservancy due to the reduced precipitation in these areas (Bescansa et al., 2005; Unger et al., 1991). This, in combination with a lack of knowledge on semi-arid soils, climate, and farming systems decrease interests in conducting research on water quality benefits of agricultural conservation practices in semi-arid areas. However, these regions experience severe rainfall erosion, potentially more so than most humid climates, since the area is inherently dry increasing susceptibility of soils to wind and water erosion (Hudson, 1987). Some studies have examined nutrient reduction in agricultural fields in semi-arid regions (Thomas et al., 2006; Su et al., 2015), but these studies do not combine both field observations and model simulations.

In this study, SWAT-CP was used to model different conservation tillage practices (no-tillage, reduced tillage, strip tillage), irrigation practices (center pivot irrigation versus surface irrigation), and the adjustment of fertilizer application rates and timing for the fields located in the South Platte River Basin (SPRB) in eastern Colorado. The overall goal is to assess water quality effects of conservation management practices in irrigated semi-arid river basins.

2.2: Methods

2.2.1: Study Watershed

The South Platte River Basin (SPRB) is a sub-basin of the Platte River Basin. The majority of the SPRB is located in Colorado (79%), with the remainder in Nebraska (15%) and Wyoming (6%) (Paschke et al., 2008). The focus of the study is on the Colorado portion of the watershed, which has a total area of approximately 15.5 million acres. There are 25,400 irrigated agricultural fields in the SPRB that amount to roughly 885,000 acres, which is 5.8% of the total area. Precipitation can vary significantly across the watershed. An average annual precipitation of 30 inches and over 300 inches of snowfall is seen near the continental divide. In the plains located east of Denver, where most of the irrigated farmland is, the average annual precipitation is only between 7-15 inches (NAWQA, 2016), making it a semi-arid climate. The majority of the South Platte River Basin is rangeland and agricultural land (**Figure 2.1**). SWAT was calibrated based on actual field measurements taken at a study site in the watershed. The SPRB has a semi-arid climate with roughly 885,000 acres of irrigated agricultural fields, making it an optimal watershed to study to fill in the gaps associated with past research.

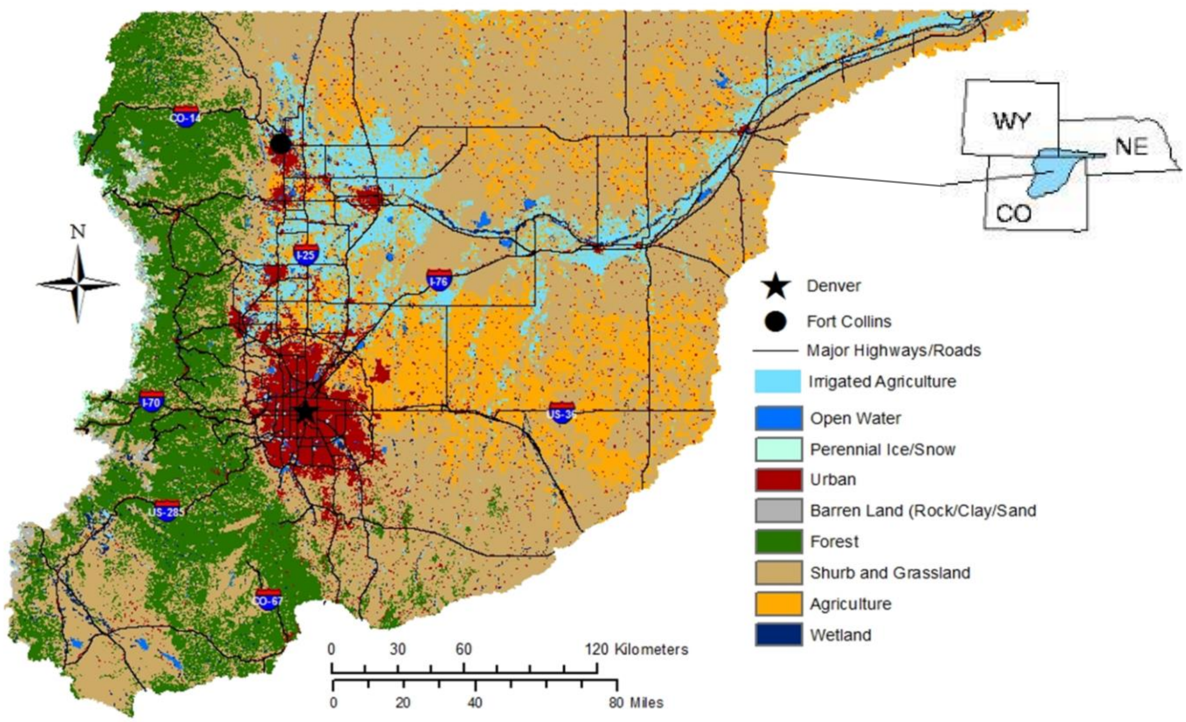

Figure 2.1: Map depicting land use within the Colorado portion of the SPRB

2.2.2: Model Description

SWAT is a continuous-time, semi-distributed, process-based watershed model which is extensively used in the literature for simulating hydrologic and water quality processes (Gassman et al., 2007; Arnold et al., 2012a, SWAT Literature Database, 2016). It has sophisticated routines for agricultural management practices pertaining to fertilizer, manure, tillage, and crop growth.

Watershed hydrology is simulated for both the land phase and the in-stream (or routing) phase. Climate data drives the hydrologic cycle and provides moisture and energy inputs. Hydrologic processes simulated by SWAT include canopy storage, surface runoff, infiltration, evapotranspiration, lateral flow, tile drainage, redistribution of water within the soil profile, consumptive use through pumping, return flow, and recharge by seepage from surface water bodies, ponds, and tributary channels (Arnold et al., 2012a). The model is widely used in literature to evaluate water quality benefits of agricultural conservation management practices (Motallebi et al., 2017; SWAT literature database 2016) which makes it an ideal candidate for this study. Most distributed models have long set up and run times because of the complexities in parametrization and spatial discretization. However, SWAT uses hydrological response units (HRU), greatly reducing the parameterization, setup, and run time. Defining HRUs during the pre-processing of land use and soil data before developing the model can be done to make HRUs represent specific fields (agriculture, etc.), reflecting actual management practices and field specific outputs for examination of conservation practices.

The Environmental Resource Assessment and Management System (eRAMS) is an open platform supporting development of geospatially-enabled web applications for sustainable management of land, water, and energy resources. The system includes a graphical user interface providing user access to modeling services and GIS-enabled tools for various purposes. eRAMS facilitates access to public data via web services from a single point of access, hence enabling developers to add these data to their tools on eRAMS or other systems. These data include, but are not limited to: climate data from NOAA, National Climatic Data Center (NCDC), and USDA Snow Telemetry (SNOTEL); U.S. Census Demographic Profile and Economic data; National Agricultural Statistic Service (NASS) Land Use; USGS National Land Cover Dataset (NLCD);

USGS National Water Information System (NWIS) real-time for the Nation; EPA STORET/WQX and WATERS, USGS Hydrography, Transportation, and Government Boundaries. The SWAT-CP interface in eRAMS allows a SWAT model to be developed for agricultural fields with a single-HRU setup. Using the SWAT-CP under the eRAMS platform substantially reduces the computational burden by benefitting from automatic data extraction, cloud-based storage and operations and parallel computing when modeling large watersheds.

2.2.3: Field Observations

A study field was used to gather average annual nutrient loads for different tillage practices that could then be used to compare against model results. The Kerbel study site was a 14 acre field located in eastern Colorado. Kerbel has similar soil characteristics to other fields within the SPRB and therefore seemed appropriate to use for calibration purposes. The field has been monitored for nutrients, sediment, and surface runoff during precipitation and irrigation events for 2013 to 2015. In 2015, corn was grown and the different parts of the field were subjected to different tillage practices including: conventional tillage, reduced tillage, and strip tillage. Surface (flood) irrigation was used to irrigate the crops and the nutrient data during the irrigation events were gathered at the edge of the field using a Teledyne ISCO 6712 Portable Sampler (PS) that was equipped with a 730 Bubbler Flow Module. For storm events, grab samplings or the PS system were used to measure nutrient data flow and were flow weighted. Under conventional tillage, all of the fertilizer was applied at once (160 lbs/ac of N, 60 lbs/ac of P). Reduced and strip tillage had two fertilizer applications amounting to 90 lbs/ac of N and 30 lbs/ac of P after the initial tillage operations and then a second application of nitrogen was applied after planting at a rate of 70 lbs/ac.

2.2.4: Model Calibration

SWAT-CP was calibrated to the Kerbel field observations in an attempt to get the results in an acceptable range. Values for curve number (CN), denitrification exponential rate coefficient (CDN), overland manning number (OV_N), nitrogen (nitrate) percolation coefficient (NPERCO), phosphorus percolation coefficient (PPERCO), phosphorus soil partitioning coefficient (PHOSKD), and phosphorus uptake distribution parameter (P_UPDIS) were changed based on the literature (SWAT Literature Database, 2016, Arnold et al., 2012b), and a previous sensitivity analysis (Ahmadi et al., 2014; Arabi et al., 2007). The model was calibrated using the monitoring data from Kerbel field during 2013 to2015. After calibration, the model was run for the period of 2002 to 2017 and the outputs from the model conformed to field observations very well (**Figure 2.2**). The values chosen for each tillage practice based on manual calibration can be seen in **Table 2.1**. No-tillage practice was not tested on Kerbel, so these values were chosen based on typical values used in the literature (Arnold et al., 2012b).

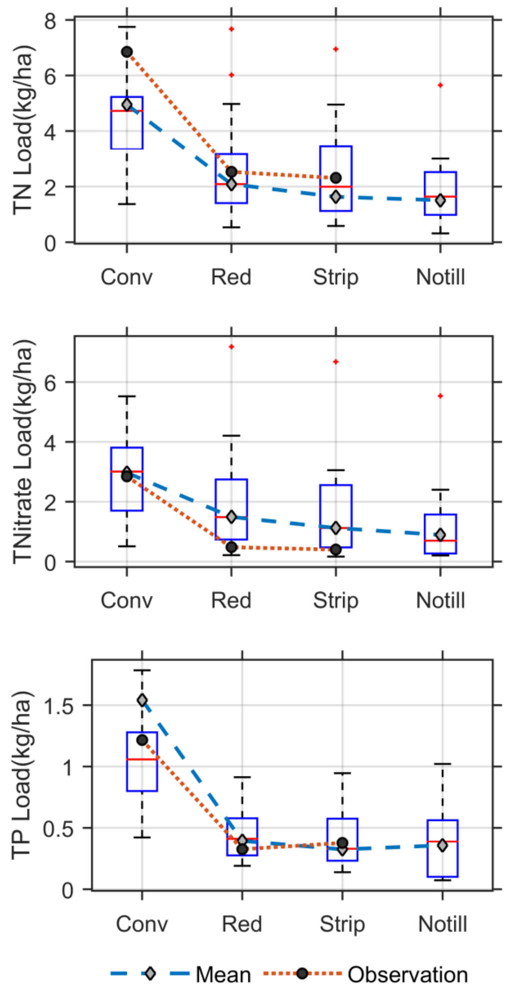

Figure 2.2: SWAT-CP output of average annual loads over a 16 year period (2002-2017) for total nitrate, total phosphorus, and total nitrogen with average annual field observation values

Table 2.1: Parameters used in SWAT-CP based on manual calibration for the (SPRB)

Parameters	SWAT Parameter Name	Default	Range Lower	Range Upper	Calibrated Values Conventional Tillage	Reduced Tillage	Strip Tillage	No Tillage
Curve number	CN	80	65	80	82	72	67	60
Overland manning's number	OV_N	0.15	0.1	0.4	0.1	0.2	0.25	0.4
Denitrification Exponential Rate Coefficient	CDN	1.4	0	3	1.2	1.5	1.8	2.0
Nitrogen percolation coefficient	NPERCO	0.2	0.01	1.0	0.1	0.25	0.3	0.33
Phosphorus percolation coefficient	PPERCO	10	10.0	17.5	10	12	15	17
Phosphorus soil partitioning coefficient	P_UPDIS	175	100	300	175	175	300	300
Phosphorus uptake distribution parameter	PHOSKD	20	20	40	20	20	20	40

2.2.4: Scenario Analysis

For this study, scenarios were developed for each field based on dominant crop, data availability, and general interest. Using NASS land use data from 2008 to 2015 coupled with the development of the land-use and agricultural management practice web-service (LAMPS)(Kipka et al., 2016), the dominant land use and top three most frequent crop types for each irrigated field were identified. Using this information along with an algorithm, crop rotations were determined which were ultimately used to develop different scenarios. The dominant crop rotations in the

South Platte River Basin, which were selected for this study, include continuous corn, grass pasture, silage corn/winter wheat, alfalfa/corn, and silage corn/winter wheat/sugar beets (**Table 2.2**). Since not all of the irrigated agricultural fields follow these crop rotations, assumptions were made in order to include a majority of the fields within the watershed in scenarios. All two year rotations with at least one year of alfalfa were modeled using the alfalfa/corn scenario. Corn plus any other two crops were modeled using the silage corn/winter wheat/sugar beets scenario. Corn plus any other single crop were modeled using the silage corn/winter wheat scenario. Any rotations with grass hay, other hay, other hay/non-alfalfa that did not fall into the above categories were modeled using the grass pasture scenario. Corn alone was modeled using the continuous corn scenario. The rest of the rotations that did not fall under these categories were not modeled in this study.

Table 2.2: Area and number of fields for each dominant crop rotation within the SPRB

Dominant Crop Rotation	Area (acres)	Number of Fields
Continuous Corn	230,614	4723
Silage Corn/Winter Wheat	85,291	2461
Grass Pasture-One harvest	2,785	46
Grass Pasture-Three harvests	138,564	5083
Alfalfa/ Corn	257,343	7866
Silage Corn/Winter Wheat/Sugar beets	35,030	1060
None	134,969	4,145
Total	**884,598**	**25,384**

The combination of different scenarios involved timing and rate of fertilizer application, different tillage practices (i.e. conventional, reduced, strip, and no-till), as well as surface versus center-pivot irrigation. The intention was to compare the effects of different tillage, fertilizer, and irrigation operations on nutrient yields from fields. The baseline scenario (conventional tillage with surface irrigation) was assumed the most common practice currently employed for different types of cropping systems within the watershed. SWAT-CP was used to simulate each scenario for each crop rotation and run for all fields for a 16 year time period (i.e. 2002-2017). The selected outputs include average annual load, average minimum, average maximum, and average median value for total nitrate, total nitrogen (TN), and total phosphorus (TP) (lbs/acre).

2.2.5: Description of Scenarios

For each crop rotation, experts in the field determined a representative schedule for each scenario that included dates for tillage operations, fertilizer applications, planting, and harvesting. Fertilizer amounts and typical irrigation volume were also assumed for each crop rotation. Exact dates, scenario code, and the order of operation that was inputted into SWAT-CP for each scenario can be found in Appendix A.

Continuous Corn. Conventional tillage for continuous corn began in the middle of March. The conventional tillage practice involved 4 operations which were done during the first two weeks including rip (DEEP RIPPER-SUBSOILER (only performed every other year), disk (OFFSET DIS/HEAVDUTY GE19FT), plow (MOLDBOARD PLOW REG GE10B), and mulch (CULTI-MULCH ROLLER GE18FT). Two weeks after completing initial tillage, fertilizer was added to the fields and the soil is tilled (BEDDER (DISK) and CULTI-PACKER PULVERIZER). The amount of added fertilizer was 160 lbs/ac of elemental nitrogen and 60 lbs/ac of elemental phosphorus. Corn was then planted two weeks after the fertilizer had been applied. About two months after planting, the soil was cultivated (FURROW-OUT CULTIVATOR) and finally the corn was harvested on November 1st. The bedder (disk) operation was not employed in center pivot irrigation scenarios.

In the reduced tillage scenario, the tillage operation was initiated around the end of March each year. Instead of four different tillage operations as with conventional tillage, only two tillage operations were performed in reduced tillage: vertical till (SINGLE DISK) and strip till (STRIP TILLING). Fertilizer was applied in two separate applications. The first application was on the same day the soil is strip tilled, two weeks into April. Elemental nitrogen and phosphorus were added to the fields at rates of 90 lbs/ac and 30 lbs/ac, respectively. Similar to conventional tillage, the corn was planted two weeks after the first fertilizer application. Two months after planting, the soil was cultivated (FURROW-OUT CULTIVATOR) and second round of fertilizer (70/lbs of elemental nitrogen) was applied. The crop was then harvested on November 1st.

The operations in the strip tillage scenario were the same as reduced tillage except there was no vertical till (SINGLE DISK) operation. The no-tillage scenario adds the fertilizer directly to the field with no initial tillage while fertilizer application rates and dates are the same as reduced and strip tillage.

Alfalfa /Corn. The order of this crop rotation involves four consecutive years of alfalfa followed by two consecutive years of corn. The process for the conventional tillage scenario began with tilling the soil in the beginning of August. The operations included rip (DEEP RIPPER-SUBSOILER), disk (OFFSET DIS/HEAVDUTY GE19FT), plow (MOLDBOARD PLOW REG GE10B), and mulch (CULTI-MULCH ROLLER GE18FT). Fertilizer was added a few days after the soil had been tilled, with 125 lbs/ac and 26 lbs/ac of elemental nitrogen and elemental phosphorus being added, respectively. Five days after fertilizer application, alfalfa was planted. The first harvest of alfalfa occurs on the first day of June. Three more harvests occur during that year in July, August, and September. The next year, fertilizer was applied in the middle of April, but at a reduced amount of 10 lbs/ac and 50 lbs/ac of elemental nitrogen and elemental phosphorus, respectively. The process repeats, harvesting and applying fertilizer, for the next three years. The corn operations start in the fifth year. The corn is grown using the same management operations as continuous corn's conventional tillage, excluding the tillage operation (DEEP RIPPER SUB-SOILER) for the second year of the silage corn rotation, and are performed for two years before reverting back to alfalfa.

Grass Pasture. The harvesting of grass pasture varies based on location in the South Platte River Basin. Mountainous watersheds typically only harvest once per year, while the Front Range and plains fields are harvested three times a year. To reflect this management difference, grass pasture fields in the hydrologic unit codes (HUCs) 10190001 (South Platte Headwaters), 10190002 (Upper South Platte), and 10180010 (North Platte Headwaters) were modeled with a once per year harvest and the others were modeled with a three times per year harvest. The once per year harvest took place in the first day of August, while the three times per year harvest took place in the middle of May, the first day of August, and the first day of September. During the first year of planting, however, grass pasture was only harvested in August, and the following year it would be harvested on all three dates.

Typically, in pastures, there is no tillage operation; only fertilizer is applied. Accordingly, fertilizer was applied in the middle of April at a rate of 50 lbs/ac of elemental nitrogen and 40 lbs/ac of elemental phosphorus. An additional 50 lbs/ac of elemental nitrogen was added at the end of June. Under the no fertilizer scenario for grass pasture fields, nothing was applied. Only planting and harvest operations occurred.

Silage Corn /Winter Wheat. Silage corn and winter wheat follow a two-year rotation. Silage corn was planted and harvested with the same operations and dates as detailed for continuous corn. The corn was harvested on September 14th, and two days later the soil was tilled in preparation for the planting of winter wheat. The conventional tillage operations proceed over a 5-day period, including disk (OFFSET DIS/HEAVYDUTY GE19FT), plow (MOLDBOARD PLOW REG GE10B), and mulching (CULTI-PACKER PULVERIZER). Five days after these tillage operations have been completed, fertilizer was applied to the fields at a rate of 90 lbs/ac of elemental nitrogen and 30 lbs/ac of elemental phosphorus. On the same day as fertilizer application, another tillage operation was done (BEDDER (DISK)). Three days later, the last tillage operation was completed (CULTI-PACKER PULVERIZER). The winter wheat was planted on the last day of September and harvested in July. The bedder (disk) operation was not completed when using center pivot irrigation.

The reduced tillage silage corn was planted and harvested with the same operations and dates as detailed for continuous corn's reduced tillage. The winter wheat reduced tillage operations began a day after the silage corn is harvested. Two tillage operations were used before the first fertilizer application including vertical (SINGLE DISK) and strip tillage. The first fertilizer application occurs roughly two weeks after the soil was tilled, on September 30th, at a rate of 50 lbs/ac of elemental nitrogen and 30 lbs/ac of elemental phosphorus. The same day as fertilization, the winter wheat was planted. The first day of April an additional 40 lbs/ac of elemental nitrogen was applied. At the end of June, the soil was tilled once again (FURROW-OUT CULTIVATOR) and finally one week into July the winter wheat was harvested. These same operations and fertilizer applications are used for strip tillage without the vertical till (SINGLE DISK) step. Under the no-tillage scenario, there are no tillage operations and only fertilizer is applied to the field, at the same rates as reduced and strip tillage.

Silage Corn/Winter Wheat/Sugar beets. This three-year crop rotation included doing one year of silage corn followed by one year of winter wheat and finally one year of sugar beets. The same operations and fertilizer application rates were done for corn with conventional, reduced, strip, and no tillage as previously described. The winter wheat rotation with conventional tillage did not include the initial tillage operation (i.e. DEEP- RIPPER SUSOILER), but the rest of the operations remained the same for all scenarios. The sugar beet operation began after the corn and winter wheat rotations in March with four tillage operations including rip (DEEP RIPPER-SUBSOILER), disk (OFFSET DIS/HEAVDUTY GE19FT), plow (MOLDBOARD PLOW REG GE10B), and mulch (CULTI-MULCH ROLLER GE18FT). Almost two weeks after these tillage operations, fertilizer was applied, at a rate of 75 lbs/ac of elemental phosphorus and 120 lbs/ac of elemental nitrogen. That same day, two more tillage operations were performed, a bed (BEDDER (DISK)) and cultipack (CULTI-PACKER PULVERIZER). Approximately a week later, the sugar beets were planted and at the end of June the soil was cultivated (FURROW-OUT CULTIVATOR). The sugar beets were harvested on the first day of October. The bedder (disk) operation was not performed when using center pivot irrigation.

The reduced tillage scenario for corn and winter wheat are the same as previously described. For the sugar beets, a vertical tillage (SINGLE DISK) and strip tillage operation was performed at the end of March/beginning of April before planting. The same day that strip tillage was performed, fertilizer was applied at a rate of 38 lbs/ac of elemental phosphorus and 80 lbs/ac of elemental nitrogen. The sugar beets are planted April 10^{th}. At the end of June, the soil was cultivated (FURROW-OUT CULTIVATOR), and more fertilizer was applied in the form of elemental nitrogen (40 lbs/ac). The sugar beets are harvested on the same day, October 1^{st}, as the conventional tillage. The same operations and fertilizer application rates were completed for strip tillage as were for reduced tillage, without the vertical till (SINGLE DISK). Under the no-tillage scenario, there is no tillage and only the fertilizer was added to the fields at the same rates as reduced and strip tillage.

Irrigation. Scenarios were created for both surface irrigation with graded furrow, which was assumed to be the conventional method, and center pivot irrigation with a spray nozzle. The irrigation in SWAT-CP is based off of auto irrigation. Auto irrigation waters the crops based on soil moisture. When the field capacity minus the soil water divided by the field capacity was greater than the stress threshold (i.e. 40%), irrigation would be applied. The amount of water applied per irrigation event was 3.5 inches (90mm) for surface irrigation and 1 inch (25 mm) for center pivot irrigation. The runoff coefficients for surface and center pivot irrigation were 0.4 and 0.03, respectively. It was assumed that there were no nutrients in the groundwater supply.

2.3: Results and Discussion

At the watershed scale, on an average annual basis, the nutrient load reductions seen from each of the conservation management practices varied greatly for each dominant crop rotation (**Table 2.5**). Due to the large number of fields with varying soil and weather characteristics along with the multitude of different conservation management practices tested, this variation was expected. There were limitations to modeling due to the fact that Kerbel did not have all of the practices tested on it; therefore not all of the practices were calibrated. The loads in baseline conditions for each dominant crop rotation are provided in **Table 2.3**. A pattern can be observed between the nutrient load reductions seen for the different conservation management practices. Switching from surface irrigation (flood) to center pivot irrigation appeared to show the greatest nutrient reduction for all crop rotations. This could be foreseen as in regions with semi-arid climate, the majority of surface runoff which carries nutrients off the field comes from irrigation water. Switching from furrow irrigation to the center pivot sprinkler irrigation, results in much lower volumes of surface runoff which consequently lead to lower yields of nutrients. In more humid areas with higher precipitation where irrigation might not be the primary source of surface runoff, different results may be obtained. Similar results were reported in the Twin Falls irrigation tract in southern Idaho (Bjorneberg et al., 2002).

When looking at the different tillage operations (i.e. conventional (baseline), reduced, strip, and no-tillage) for the applicable crop rotations (i.e. continuous corn, silage corn/winter wheat, and winter wheat/sugar beets/corn), the highest nutrient reduction was seen using the no-tillage operation. This could be explained by maintaining more moisture from a higher amount of residue on the ground which results in higher biological activity (e.g. denitrification). Also, more residue on the ground results in lower volume of surface runoff due to higher interception which consequently results in lower nutrient loads leaving the field. In contrast, Her et al. (2016) in their study of St. Joseph watershed in Indiana, Ohio, and Michigan concluded that no-tillage had the least amount of nutrient reduction. Although their study watershed had a humid climate and poorly draining soils (Her et at., 2016). When implementing the conservation tillage practices, nutrient timing and amount was also considered. Hence, the reductions seen for these practices could be in part due to having two fertilizer applications in smaller quantities in reduced, strip and no-tillage versus one application at a higher quantity under conventional tillage. Combining the tillage operations with center pivot irrigation further enhanced the load reductions (**Figure 2.3**). The total load reductions seen when looking at the SPRB as a whole follow relatively similar patterns to the reductions seen when analyzing the crop rotations on individual fields (**Table 2.4**).

For the grass pasture rotation, when there was no fertilizer added, the percent load reductions seen for total nitrate and TN from the baseline condition exceeded 65% for both the one harvest and three harvest options, and over 40% for TP. Combining the no fertilizer scenario with center pivot irrigation enhanced the reductions seen. Total phosphorus for grass pasture had a total reduction exceeding 90% for both the one harvest and three harvest option, compared to roughly 40% and 71%, respectively, for the no fertilizer scenario.

Similar to previous studies (Cho et al., 2010); TP had the highest load reductions among all crop rotations for all different management practices. This is in part due to phosphorus being primarily transported through sediments. When conservation tillage operations or center pivot irrigation is used, the amount of runoff from fields is reduced substantially, which results in reduction of total sediments and consequently TP. The mean sediment removal efficiency for no tillage is 92 compared to 55 for conservation tillage, further backing up the large reductions seen for TP with the no-tillage scenario (Stang et al., 2016).

Table 2.3: Average annual loads for the baseline condition for each dominant crop rotation within the SPRB

Dominant Crop Rotation	Initial loads for baseline condition (lb/yr)		
	Total Nitrate	**TN**	**TP**
Silage Corn/Winter Wheat	76,240	104,218	31,931
Continuous Corn	909,455	1,067,928	151,547
Alfalfa/Corn	604,330	672,244	114,215
Grass Pasture-One harvest	3,559	3,645	334
Grass Pasture-Three harvests	92,974	93,768	33,284
Silage Corn/Winter Wheat/Sugar beets	63,750	80,485	18,444
Total	1,750,308	2,022,288	349,755

Notes: TN= total nitrogen. TP= total phosphorus.

Table 2.4: Average annual load reductions due to the application of different conservation management for all fields within the SPRB

Scenarios (management practices)	Load Reductions (%) (All Crops)		
	Total Nitrate	TN	TP
Baseline(Surface) to Baseline (Center Pivot)	20.7	24.3	55.6
Baseline(Surface) to Reduced Tillage or No Fertilizer (Surface)	50.5	50.4	67.6
Baseline(Surface) to Strip Tillage (Surface)	54.7	55.2	76.5
Baseline(Surface) to No-Tillage (Surface)	58.0	56.6	77.3
Baseline(Surface) to Reduced Tillage or No Fertilizer (Center Pivot)	60.1	63.7	92.0
Baseline(Surface) to Strip Tillage (Center Pivot)	63.0	67.0	96.2
Baseline(Surface) to No-Tillage (Center Pivot)	65.9	69.8	97.8

Notes: TN= total nitrogen. TP= total phosphorus. Surface= surface irrigation (flood irrigation)/graded furrow. Center Pivot= center pivot irrigation/spray nozzle.

Table 2.5: Average annual load reductions due to the application of different conservation management practices based on dominant crop rotations for the SPRB

Scenarios (management practices)	Dominant Crop Rotation	Load Reductions (%)		
		Total Nitrate	TN	TP
Baseline(Surface) to Baseline (Center Pivot)	Continuous Corn	20.6	24.6	51.3
	Silage Corn/Winter Wheat	30.0	37.2	59.8
	Alfalfa/Corn	20.8	23.1	55.3
	Silage Corn/Winter Wheat/Sugar beets	22.0	27.1	51.4
	Grass Pasture-One harvest	27.8	27.9	55.4
	Grass Pasture-Three harvests	13.4	13.7	74.5
Baseline(Surface) to Reduced Tillage (Surface)	Continuous Corn	18.1	20.8	50.8
	Silage Corn/Winter Wheat	23.7	26.1	40.9
	Silage Corn/Winter Wheat/Sugar beets	27.7	29.2	46.6
Baseline(Surface) to Strip Tillage (Surface)	Continuous Corn	23.4	26.4	59.7
	Silage Corn/Winter Wheat	29.2	32.8	57.0
	Silage Corn/Winter Wheat/Sugar beets	34.7	36.9	60.5
Baseline(Surface) to No-Tillage (Surface)	Continuous Corn	28.7	28.5	57.4
	Silage Corn/Winter Wheat	37.1	38.1	71.2
	Silage Corn/Winter Wheat/Sugar beets	38.5	39.1	69.8
Baseline(Surface) to Reduced Tillage (Center Pivot)	Continuous Corn	33.6	41.0	87.9
	Silage Corn/Winter Wheat	40.5	52.7	88.3
	Silage Corn/Winter Wheat/Sugar beets	46.0	53.1	85.7
Baseline(Surface) to Strip Tillage (Center Pivot)	Continuous Corn	37.0	44.9	93.3
	Silage Corn/Winter Wheat	43.4	56.5	94.3
	Silage Corn/Winter Wheat/Sugar beets	50.2	58.2	92.6
Baseline(Surface) to No-Tillage (Center Pivot)	Continuous Corn	41.8	49.4	95.8
	Silage Corn/Winter Wheat	50.4	62.6	97.6
	Silage Corn/Winter Wheat/Sugar beets	53.8	62.0	96.6
Baseline(Surface) to No Fertilizer (Surface)	Grass Pasture-One harvest	75.3	68.0	39.8
	Grass Pasture- Three harvests	82.8	77.3	70.9
Baseline(Surface) to No Fertilizer (Center Pivot)	Grass Pasture-One harvest	78.9	67.1	96.2
	Grass Pasture- Three harvests	85.4	82.8	90.3

Notes: TN= total nitrogen. TP= total phosphorus. Surface= surface irrigation (flood irrigation)/graded furrow. Center Pivot= center pivot irrigation/spray nozzle.

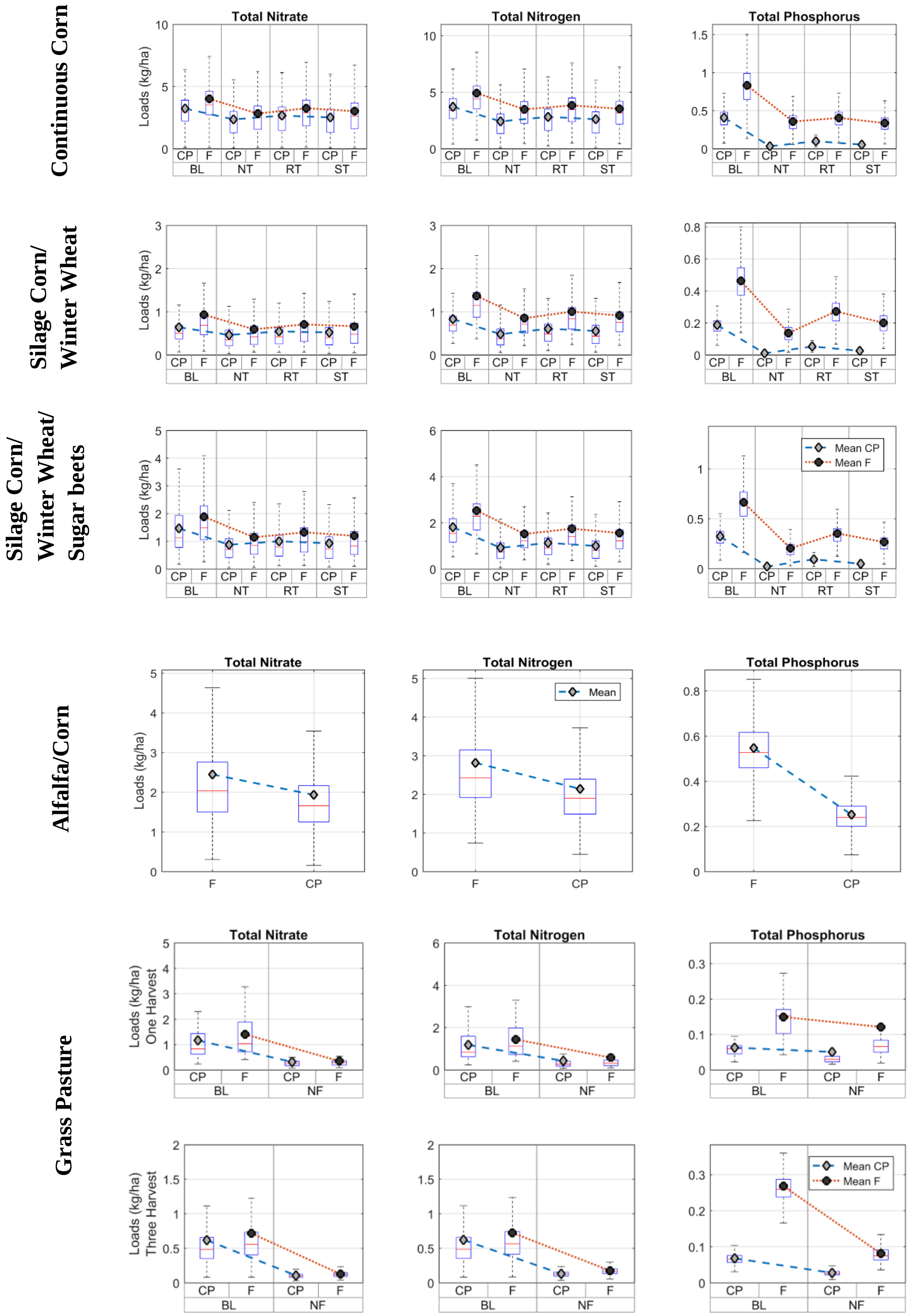

Figure 2.3: Average annual loads and means for each crop rotation and scenario tested in the SPRB

Notes: BL=baseline conditions. NT= no tillage. RT= reduced tillage. ST= strip tillage. F= surface irrigation (flood irrigation)/graded furrow. CP= center pivot irrigation. NF = no fertilizer.

2.4: Summary and Conclusions

The quantification of nutrient loads for the different conservation management practices tested for each dominant crop rotation within the SPRB using eRAMS indicates that the best practice for farmers to implement within the semi-arid basin would be center pivot irrigation with no-tillage operations. Center pivot irrigation had by far the largest nutrient reductions for all crop types. Center pivot irrigation generates less runoff compared to surface irrigation, which in turn reduces the overall edge of field nutrient and sediment loads. Center pivot irrigation is certainly a more expensive option compared to surface irrigation or implementation of different conservation tillage practices. An alternative to center pivot irrigation for farmers who cannot afford the cost would be implementing one of the conservation management practices while also managing the nutrient timing and application rates. No-tillage had the most nutrient reduction, followed by strip tillage and then reduced tillage. For grass pasture, the most effective method was center pivot irrigation with no fertilizer application. As stated before, if center pivot irrigation is not an option, no fertilizer application still showed a relatively higher nutrient reduction. The high quality monitoring data available along with computation capacity of the modeling framework (eRAMS) provided a unique opportunity to conduct this study at a relatively large scale with acceptable accuracy. The results of this study can be used by farmers in semi-arid regions to implement optimal conservation management practices to further enhance nutrient load reductions.

CHAPTER 3 : ASSESSING NUTRIENT MANAGEMENT SCENARIOS FOR THE CACHE LA POUDRE WATERSHED IN COLORADO

3.1: Introduction

Nutrient contamination is one of the leading causes of water body impairments in the United States and throughout the world. Phosphorus and nitrogen cause eutrophication in water bodies which leads to algal blooms and a depletion of oxygen (Elser, et al., 2009; Daly et al., 1997). Phosphorus is a key element in the process, but nitrogen also plays a significant role; therefore, a reduction of total phosphorus and nitrogen in stream, lakes, and reservoirs is needed in order to reduce the acceleration of eutrophication (Elser et al., 2009; Daly et al., 1997). Excessive nutrients within water systems may also lead to health issues, such as reproductive problems and cancer, within individuals (USEPA, 1998; Williams et al., 2014).

A wide range of human activities cause an increase in total nitrogen (TN) and total phosphorus (TP) within water bodies, including nonpoint sources (i.e. fertilizers from agricultural practices and stormwater runoff) and point sources (i.e. outflows from wastewater treatment plants and factories). Nutrient mobilization from agriculture is dependent upon source (i.e. soil, crop, and management) and transport (i.e. runoff, erosion, and channel processes) factors (Heathwaite et al., 2000). In highly urbanized areas, imperviousness increases, leading to an increase in polluted runoff from urban and suburban areas. Wastewater treatment plants play a significant role in nutrient pollution as well, due to a large number of plants lacking the ability to remove nutrients (Suchetana et al., 2016). Therefore, a system level assessment is needed to determine the optimal scenarios to reduce nutrient pollution.

Nutrient standards and regulations aim to control emissions from point and nonpoint sources to reduce the vulnerability of water systems to nutrient pollution. In Colorado, these targets include CDPHE Regulations 31 and 85, which set standards for the TN and TP concentrations that can enter lakes, reservoirs, or streams, or within the effluent of point source contributors, respectively (CDPHE, 2012a; CDPHE, 2012b). The annual median TN and TP concentration for in-stream flows has an allowable exceedance value of 1-in-5 years (CDPHE, 2012a). Regulation 31 pertains to the TN and TP criteria needed for in-stream concentrations in order to protect aquatic life. The TN annual median concentrations cannot exceed 1.25 mg/L for cold water bodies and 2.01 mg/L for warm water bodies, whereas these values for TP are 0.11 mg/L and 0.17 mg/L, respectively (CDPHE, 2012a). Regulation 85 regulates point sources of pollution and states that TP and TN levels need to be monitored in the effluent of these facilities every month for large plants (effluent discharge greater than 1 million gallons per day) and every other month for small plants (effluent discharge less than 1 million gallons per day)(CDPHE, 2012b). The annual median point source effluent concentration cannot exceed 0.7 mg/L and 7 mg/L for TP and TN, respectively (CDPHE, 2012b).

There are a wide variety of strategies that can be implemented to reduce nutrient pollution from WWTPs, urban nonpoint and MS4s, and agricultural systems. Point source polluters usually have the most contribution to in-stream nutrient loads out of all the different sectors, and the technologies adopted can have very high reductions in comparison to others. Even though point source contributors do play a significant role in the overall nutrient contribution, non-point sources also play a large role, especially in parts of the country that are heavily farmed or urbanized, and should play a role in helping to reduce their nutrient contributions. Since Colorado Regulation 31 pertains to in-stream water quality standards, and all sectors contribute to nutrient pollution, in order to meet these standards the most cost effective and equitable solution should be adopted.

The likelihood of adoption for these practices is dependent not only on their environmental benefits but also socioeconomic factors such as cost, maintenance, and equity between sectors. Incorporating these indicators into an analysis provides a more realistic assessment of adoption (Hoque et al., 2016). The studies that have focused on these indicators (Asefa et al., 2014; Fowler et al., 2003; Kasprzyk et al., 2012; Kasprzyk et al., 2011; Walker et al., 2004) have not incorporated different scenarios for all sectors on a watershed scale.

The overall goal of this study was to assess nutrient management scenarios at the system level for the Cache la Poudre watershed in Colorado. The objectives included: 1) determine a methodology that could be used to quantify nutrient load contributions from each sector at the watershed scale; 2): determining delivery ratios for each sector based on the ambient nutrient loads at the outlet of the watershed; 3): assess the cost, equity, and water quality effects of conservation management practices, BMPs, wastewater treatment technologies, and water conservation practices.

3.2: Methods

3.2.1: Overall Framework for Assessment of Water Quality Control Measures

A system level analysis requires that all sectors be taken into consideration and included in the assessment. The sectors include urban stormwater, irrigated agriculture, WWTP's, and natural background contributions from groundwater and forest and rangeland. Different water quality control strategies were tested within each sector using models in order to get nutrient loads (i.e. TN and TP) in compliance with regulatory standards. In Colorado, the in-stream water quality standards are set by Regulation 31 in order to maintain ecological health. Due to ambient water quality loads exceeding regulatory standards, different indicators were taken into consideration, including TN/TP loads, delivery ratios for each sector, cost of each practice, cost per unit of nutrient removed, and a Gini index factor relating to the equity between each sector, in order to determine the most cost effective and equitable way to reduce in-stream nutrient loads to within an acceptable range for water quality standards. The analysis was performed over a 14 year time period (i.e. 2002-2015) for the entire extent of the Cache la Poudre watershed in Colorado (**Figure 3.1**).

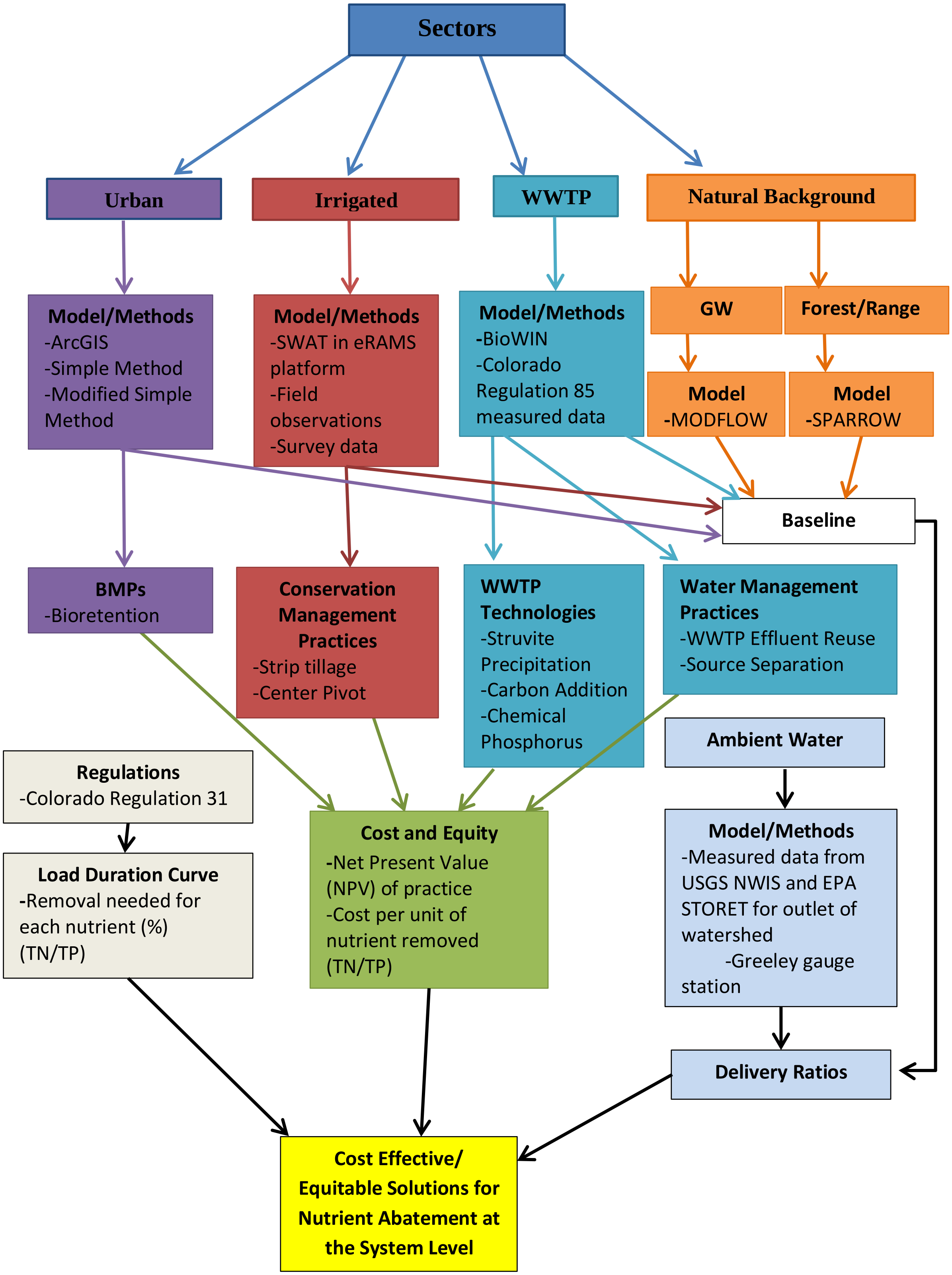

Figure 3.1: System Level Analysis Diagram of Cache la Poudre Watershed

3.2.2: Data and Modeling Analyses to Quantify the Facility-Level or Edge-of- Field Contribution

3.2.2a: Water Management Practices and Wastewater Treatment Technologies

In the study area, there are a total of 13 permitted facilities of which 6 facilities are Publicly Owned Treatment Works (POTW) with a permitted capacity greater than 1 million gallons per day (MGD). Two of the facilities are industrial wastewater treatment facilities, 2 facilities are seasonal camp facilities, and the remaining 4 facilities are permitted between 0.035-0.75 MGD. Baseline conditions were determined based on samples taken from each facility in accordance with Regulation 85 collected in 2014 and 2015. Loads were estimated for the years 2002-2015 by interpolating based on 2000 and 2010 population census data and the baseline annual nutrient load of each facility. Modeling efforts were performed on POTW with a permitted capacity greater than 1 MGD and included the evaluation of three different water management practices and three different wastewater treatment plant technologies to determine the impacts these practices could have on effluent nutrient loads (**Table 3.1)**.

Table 3.1: Water Management and Wastewater Treatment Scenarios

Sector	Evaluation Number	Practice or Technology
Water Management	1	Source Separation – 20% Household Adoption
	2	WWTF Effluent Reuse – 50% Effluent Flow during Irrigation Season
WWTF Treatment Technologies	3	Carbon Addition – 20% increase in COD/TN
	4	Chemical Phosphorous – 0.5 mg/L effluent concentration
	5	Struvite Precipitation – 80% Process Efficiency

Water Management Practices

To estimate the impacts of effluent nutrient loads with the implementation of the identified water management practices, regression equations were developed based on previous BioWin process modeling completed evaluating these practice impacts at the City of Boulder (Hodgson et al., 2017a). In this study, the impacts on the effluent nutrient concentrations from each water management practice were normalized based on the baseline conditions and then fit to a polynomial regression. Based on this polynomial regression, the impact of each practice was quantified and evaluated at the facilities in the study watershed.

Wastewater Treatment Facilities

Similarly to water management, BioWin modeling was used to determine how the incorporation of different wastewater treatment technologies could impact effluent nutrient loads. The process was more extensive than before, requiring BioWin modeling to be performed at several facilities in Colorado and then using this data to incorporate carbon addition, chemical phosphorus addition, and side stream struvite precipitation (Hodgson et al., 2017b). Technologies were modeled individually and at different adoption levels and treatment efficiencies, the results were then normalized to the facilities existing treatment performance, and then a multi-linear regression analysis was performed (**Equation 3.1**) (Hodgson et al., 2017b) to determine how each practice would affect nutrient loads.

$$y = \beta_0 + \beta_1[x] + \beta_2[x^2] + \varepsilon_i \qquad \textbf{Equation 3.1}$$

where y was the effluent load as a function of *x* divided by the base effluent load; *x* was the process efficiency; β was the determined coefficient; and ε was the unexplained noise in the data. This evaluation was performed for each modeled technology to provide estimates of regression coefficients for generalizing the impact to effluent nutrient concentrations (**Table 3.2**).

Table 3.2: Generalized WWTF Technology Relationships

Technology	Variable	Formula
Chem-P	Desired Effluent TP Concentration	TP = 0.5 mg/L
Struvite Precipitation	Process Efficiency	ΔTN = 1 - 0.106x + 0.0377x^2 ΔTP = 1 - 0.6648x + 0.1626x^2
Carbon Addition	% Increase in COD/TN	ΔTN = -1.7936x + 2.7022 ΔTP = -0.9386x + 1.9652

3.2.2b: Urban Stormwater BMPs

Urban stormwater is a non-point source of pollution that has not yet had a regulation passed that sets load restrictions for this sector. However, in Colorado, stormwater is regulated to an extent by the Municipal Separate Storm Sewer System (MS4) permits which are issued by CDPHE for cities with a population larger than 10,000. It is widely known that the change in imperviousness due to urban expansion has caused an increase in runoff quality and quantity over the last few decades. In an attempt to reduce the nutrients and volume of stormwater entering nearby water bodies, MS4s are implementing Best Management Practices (BMPs) such as extended detention basins and bio-retention basins, in urban areas.

The Simple Method (Schueler, 1987) was used to calculate the urban stormwater loads within the Cache la Poudre watershed without the implementation of BMPs, and can be seen in **Equation 3.2**.

$$L = 0.226 * P * Pr * Rv * A * C \qquad \textbf{Equation 3.2}$$

where L was the pollutant load (lbs); P was the precipitation (in); Pr was the fraction of precipitation that produces runoff; Rv was the runoff volume coefficient; A was the drainage area (acres); C was the pollutant concentration (mg/L); and 0.226 represents the unit conversion.

National databases were used to gather the information needed for this analysis including the USGS National Land Cover Database (NLCD) and Parameter-elevation regressions on independent slopes model (PRISM). PRISM provided the annual precipitation data and NLCD provided the land use and percent imperviousness layers. Raster datasets have been developed by NLCD for the years 2001, 2006, and 2011. The assumption was made that the land use and imperviousness data from 2001 would be the most adequate to use when calculating loads for years 2002 and 2003; the 2006 raster would be most adequate for years 2004-2008; and the 2011 raster would be the most adequate to use for years 2009-2015.

Rv was used to take into consideration the amount of precipitation that becomes runoff and was calculated using **Equation 3.3** (Schueler, 1987):

$$Rv = 0.05 + 0.009 * I \qquad \textbf{Equation 3.3}$$

where I was the percent imperviousness. The area was determined by the grid cell size, which in the case of this analysis was 30 x 30 meters, making the drainage area equal to 900 m^2 or 0.22 acres. A Pr value of 0.9 was used for this analysis (Schueler, 1987).

The NLCD land use layer was used to classify the appropriate median runoff concentrations for TN and TP. This data was gathered from a study completed by Wright Water Engineers in Denver, CO for each urban land use classification (i.e. 21-24) for the state of Colorado and can be seen in **Table 3.3** (Dell, 2017).

Table 3.3: Median runoff concentrations with 95th Percentiles for TN and TP for each NLCD urban land use code

		Total Nitrogen		Total Phosphorus	
Land Use	**NLCD Code**	**Median (mg/L)**	**# of Samples**	**Median (mg/L)**	**# of Samples**
Developed Open Space	21	3.76 (1.58-5.83)	7	0.41 (0.22-0.65)	7
Developed Low Intensity	22	4.47 (1.58-13.68)	166	0.47 (0.11-0.65)	211
Developed Medium Intensity	23	2.84 (1.04-7.56)	25	0.40 (0.16-2.08)	43
Developed High Intensity	24	2.84 (0.75-11.20)	191	0.22 (0.03-1.34)	316

When taking into account the possible implementation of BMPs, which were assumed to only have been implemented after 2008, a modified Simple Method was used and can be seen in **Equation 3.4** (Dell, 2017):

$$L = 0.226 * A * P * Pr * Rv * V_r * C^* \qquad \textbf{Equation 3.4}$$

For the modified Simple Method, the volume and concentration reductions, V_r and C^* respectively, seen from the implementation of different BMPs need to be taken into consideration. C^* and V_r were calculated using **Equations 3.5** and **3.6**, respectively (Dell, 2017).

$$C^* = \left(\frac{C_{LU}(1-ETP_{Layer}*0.85)+C_{BMP}*ETP_{Layer}*0.85*(1-\Delta V)}{1-ETP_{Layer}*0.85*\Delta V}\right) * Level\ I\ NLCD\ Reclass \qquad \textbf{Equation 3.5}$$

$$\mathrm{V_r} = 1 - ETP_{Layer} * 0.85 * \Delta V_{BMP} \qquad \textbf{Equation 3.6}$$

where C_{LU} was the median runoff concentration of TN and TP for each urban land use type seen in **Table 3.3** (mg/L); C_{BMP} was the median concentration of TN and TP for each BMP (mg/L); ΔV was the volume reduction seen from the implementation of each BMP (%); 0.85 was the assumed BMP efficiency (%) based on traditional BMP design standards (Guo et al. 2014;

UDFCD 2011); and the Level 1 NLCD reclass was converting any urban land use code (i.e. 21-24) to 1 and all other land use classifications to 0 to ensure only urban loads were being considered. C_{BMP} and ΔV values for the BMPs of interest can be seen in **Table 3.4** (Dell, 2017). The ETP_{layer} was the estimated BMP treatment area, and for extended detention basins was a comparison between the 2006 and 2011 land use data (Dell, 2017). For bio-retention basins, 0.25 and 0.5 were used instead of the ETP_{layer} and analyzed the different adoption percentages of these BMPs.

Table 3.4: BMPs of interest and their respective volume reductions and median TN and TP concentrations

BMP Type	Median Concentrations (mg/L)		Volume Reduction (ΔV)
	TN	TP	
Bio-retention	0.92	0.24	57%
Extended Detention Basin	1.6	0.2	33%

For this analysis, the baseline condition was considered the loads associated with no BMPs present prior to 2008, and extended detention basins being evenly distributed throughout the urban areas of the watershed after 2008. The two practices that were analyzed were if 25% of the urban acres implemented bio-retention basins, or if 50% of the urban acres implemented bio-retention basins.

3.2.2c: Agricultural Conservation Practices

The scenarios developed for modeling were discussed in Chapter 2. For this study, scenarios were developed based on dominant crop, data availability, and general interest. The general interest was to compare the effectiveness of different tillage and irrigation operations on nutrient yields from fields. The baseline scenario was the assumed most common practice currently being employed within the watershed. The irrigation method for each field was known and applied when running the model. From a survey completed in 2011 (Bauder et al., 2013), 33% of the respondents within the Cache la Poudre watershed proclaimed that they used conservation tillage. Therefore, the baseline tillage condition was assumed to be 33% of the fields used conservation tillage, and the remaining 67% of the fields used conventional tillage practices. The combination of scenarios created involved conventional versus strip (conservation) tillage as well as surface (flood) versus center-pivot irrigation.

Different adoption rates were chosen and analyzed for each scenario above the current percent of either conventional tillage or surface irrigation being performed by farmers in the watershed. To determine the potential loads reductions for TN and TP that could be seen from converting current flood-irrigated fields to center-pivot irrigation, flood- irrigated agricultural fields were randomly selected within the watershed whose acres totaled the selected adoption percentage (i.e. 10%, 25%, 50%, and 75% of irrigated acres), and then the new loads were summed for the entire extent of the watershed per year (i.e. 2002-2015). The fields chosen were assumed to have conventional tillage practices being used on them. This process was repeated 100 times in order to get a distribution of results, and then averaged for every year. A similar process was completed for the scenario looking at the adoption of strip (conservation) tillage practices. Actual irrigation methods for all fields were used when running the analysis. A random selection of fields currently employing conventional tillage practices were chosen and converted to strip (conservation) tillage. This was done at 10% increments above the 33% baseline acreage value, up to a total of 73% of fields using strip (conservation) tillage. This process excluded the fields with alfalfa and grass pasture since tillage scenarios were not modeled for these crop rotations, yet the loads for these fields were still accounted for in the total nutrient contribution from irrigated agriculture.

3.2.2d: Natural Background

Groundwater Return Flows

TN and TP exist in the watershed naturally, therefore these loads need to be accounted for, and come from groundwater, forest and rangeland, and atmospheric deposition. When determining in-stream loads pertaining to groundwater, well data along with the USGS Modular Finite Difference Flow Model (MODFLOW) (Niswonger et al., 2011) were used. MODFLOW is a model that takes into account stream and aquifer (South Platte Alluvial aquifer) interactions to estimate the in-stream nutrient levels coming from groundwater. There was no data available for the amount of TP contained in the groundwater, and therefore was not used within the analysis. The MODFLOW model did not have the capability to model the portion of the aquifer that extends into Poudre Canyon, and was only modeled through the year 2012. An average load was used for the remaining three years of the study (i.e. 2013-2015).

Forest/Rangeland

The estimated nutrient load contributions from forest and rangeland were determined using the USGS Spatially Referenced Regression on Watershed Attributes (SPARROW), which estimates the nutrient contributions from each sector (i.e. point source, fertilizer, livestock, atmospheric, non-agricultural) and then determines the nutrient loads for non-agricultural areas and uses that weighted value as the forest and rangeland contribution (Schwarz et al., 2006). SPARROW data was only available for the year 2012, therefore an assumption was made that this value was constant throughout the years of the analysis.

Atmospheric Deposition

Nutrient loads pertaining to atmospheric deposition were not included in this analysis. Future studies should include this value in order to get a more complete assessment of the natural background loads entering a system.

3.2.2e: Ambient Water Quality using LOADEST

Monitoring stations have been implemented around the country by USGS and the EPA that measure flow and nutrient data within rivers. The data from these stations were obtained from USGS NWIS and EPA STORET. Since the analysis was for the entire watershed as a whole, the gauge station of interest was the outlet of the Cache la Poudre watershed, which was located in Greeley, CO (USGS Site Number 06752500; STORET Site Number C0040258-D/S). The flow and nutrient data were extracted from each source and combined into one file. LOADEST, which is a load estimator model developed by the USGS that uses regression equations to fill in missing data points (Runkel et al., 2004), was then used to determine the annual TN and TP in-stream loads for the years 2002-2015.

3.2.3: Estimate Delivery of Loads from Sectors to the Watershed Outlet by Sector

The LOADEST estimated in-stream loads, along with the modeled baseline loads, were used to determine delivery ratios for each sector. The delivery ratios were used to quantify the amount of load from each sector that would reach the outlet of the watershed. In order to determine exact delivery ratios for each sector, a more complex distributed model would be needed to account for the variety of factors that affect how nutrients were transported in the environment. The total sector contribution to the in-stream load at the outlet of the watershed was determined by multiplying the annual modeled load by its representative delivery ratio. The error between this value and the measured ambient nutrient load at Greeley was then minimized using the least squares method. The relative error was calculated by subtracting the simulated nutrient load contributions from each sector after applying the delivery ratios from the observed nutrient load at Greeley and then dividing this value by the observed nutrient load at Greeley. For the purpose of this analysis, typical ranges seen within the literature were used for each sector to constrain the ratios to realistic values (Motallebi et al., 2017; Sprague et al., 2000). The delivery ratios that were generated from this method were the assumed delivery ratios for each sector.

3.2.4: Cost Analysis and Gini Index

The net present value (NPV) of the installation and maintenance cost for each practice/technology (*i*) was determined using **Equations 3.7** and **3.8**:

$$NPV = \sum_i^I [MC + RC + FC_i] \qquad \textbf{Equation 3.7}$$

$$FC_i = \frac{r(PV)}{1-(1+r)^{-n}} \qquad \textbf{Equation 3.8}$$

where *FC* denotes the fixed cost of installation; *r* was the interest rate; PV was the present value of the piece of equipment, etc. that was purchased for the practice being tested; n is the number of periods (25); I was all of the equipment needed for the implementation of that practice; MC were the yearly maintenance costs; RC were the irregular costs that could happen sporadically throughout the year (i.e. new motor costs). An interest rate of 4.3 percent was assumed, which reflects values seen within the literature (Nordhaus, 2007).

Another cost of particular interest was the per-unit cost of nutrient removed from the implementation of different conservation practices within each sector. The per-unit cost reflects the cost associated with how much TN/TP was removed from the implementation of each practice from baseline conditions. **Equation 3.9** was used when calculating these costs.

$$C = \frac{NPV}{\sum N} \qquad \textbf{Equation 3.9}$$

Where C was the total cost per pound of nitrogen or phosphorus reduced for the practice of interest (unit: $/lb of TN/TP reduced); NPV was the net present value of the practice which was discussed above (unit:$); and N was the amount of nitrogen or phosphorus removed over the project life from baseline conditions due to the implementation of each practice (unit: lb of TN/TP reduced).

The Gini index was used to determine the equity between sectors when determining the optimal scenarios for nutrient abatement (Milanovik, 1994). The Gini index was quantified by taking 10% increments of the total reduction needed (lbs) for each nutrient and determining the most cost effective solution to obtain that reduction. The reduction that could be achieved out of the possible scenarios was subtracted from the total nutrient contribution from that sector with baseline conditions and then was divided by the total sector contribution to determine the percent contribution. The percent contribution for each increment was then divided by the total percent contribution to determine the Gini index. A completely equitable solution, where all sectors were reducing their nutrient load equally based on their contributions, would have a Gini index of 1.0.

3.2.5: Study Watershed

The Cache la Poudre (CLP) watershed located in northeastern Colorado will be the focus of this case study, with a drainage area of 1,208,840 acres (4892 km^2) (**Figure 3.2**). Within this area, approximately 80% of the land was considered to be natural land cover, including grasslands, wetlands, open water, or wetlands. The remaining 20% was non-natural such as developed areas, pasture/hay, or cultivated crops, all of which contribute to nutrient pollution. A majority of the soils are well drained with small segments falling into the other categories for the central and eastern portions of the watershed. The south western portion of the watershed was a combination of drainage types, yet most soils were excessively or somewhat excessively drained.

The average annual temperature was between 48 and 51 degrees Fahrenheit, yet can reach upwards of 100 degrees Fahrenheit in the summer and in the winter temperatures can easily drop below zero (Cache la Poudre, 2009). The average annual precipitation for the watershed was 12 to 18 inches, yet can range between 6 and 29 inches (Cache la Poudre, 2009). A total of 13 WWTPs discharge into the surrounding rivers. There were 123,000 acres of irrigated agricultural fields. In the Poudre Canyon within the CLP watershed, there were relatively pristine conditions due to minimal human impacts, and then the water quality begins to degrade further downstream due to a gradient of anthropogenic activities. A majority of the WWTP's, urban areas, and irrigated agricultural fields were condensed into the southwest portion of the watershed, relatively close to the outlet of watershed, causing an excess of in-stream nutrients, and thus regulations have been exceeded. All sectors contribute to TN and TP pollution; therefore, it was necessary to include all sectors when establishing possible solutions for nutrient abatement.

Current water quality conditions were assessed using load duration curves (LDCs) generated on the eRAMS platform for the Greeley gauge station. The LDCs took the modeled nutrient loads from LOADEST, flow data, and regulatory nutrient concentration values to generate curves that depict how often the water quality falls out of compliance with standards. Boxplots were shown on the graph for each hydrologic condition (i.e. high flow, moist conditions, mid-range flow, dry conditions, and low flow), and the median value was used to calculate the percent reduction needed for each nutrient to meet regulatory standards. Scenarios were then determined by putting together practices from each sector that would meet the generated percent reduction. Scenarios were suggested for implementation based on their cost effectiveness and equitability.

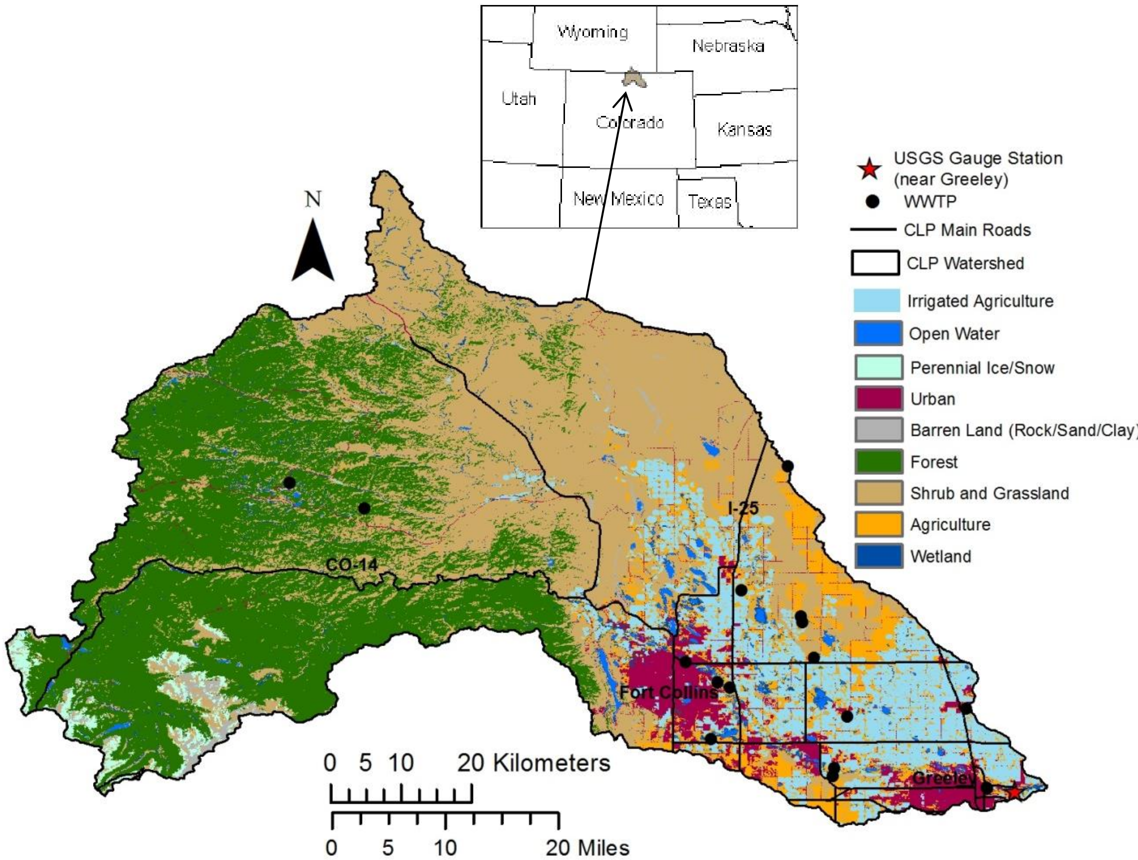

Figure 3.2: Map depicting land use and location of the CLP watershed

3.3: Results and Discussion

The results of the analysis depict the nutrient load contributions from each sector (i.e. natural background, irrigated agriculture, urban stormwater, and wastewater treatment plants) with the assumed baseline conditions and for each practice that was tested. The sectors were analyzed individually, as well as combined. The loads associated with each sector were compared against the Greeley gauge station loads to determine delivery ratios from each sector, as well as to determine the possible scenarios for adoption to be in compliance with Regulation 31. Thusly, the cost and equitability of these scenarios were also looked into in order to get an understanding of the likelihood of adoption by stakeholders within each sector. It was found that TN reductions needed for regulations could be achieved through the adoption of carbon addition, WWTP effluent reuse, 10% adoption of strip tillage, and a 25% adoption of bio-retention basins for a total of roughly $6,000,000. Whereas the TP reduction needed for regulations for all hydrologic conditions could not be achieved with any combination of the practices looked into, however 2 out of the 3 reductions could be achieved from the adoption of Chem-P, WWTP effluent reuse, 10% adoption of strip tillage, and 25% adoption of bio-retention basins for roughly $11,000,000. Further research would be needed to determine a scenario that could achieve a 70% TP reduction and 40% TN reduction simultaneously at the outlet, which was needed at the system level to be in compliance with regulatory standards. This would entail more practices to be tested within each sector, such as the possibility of combining different WWTP technologies.

3.3.2 Observed Load Duration Curves at the Outlet of the Watershed

Regulatory standards were used to determine the potential scenarios for nutrient abatement when taking into consideration all sectors and costs for the CLP watershed. As mentioned previously, Regulation 31 sets standards for in-stream water quality to maintain ecological health. The load duration curves (LDCs) for the years 2002-2015 associated with the criteria set by this regulation for TN and TP can be seen in **Figures 3.3 and 3.4.** For both TN and TP, the loads exceeded regulatory standards for different hydrologic conditions throughout the year; therefore different scenarios for ways to reduce nutrient load contributions from the different sectors were established. The total load reductions needed from these scenarios (**Table 3.5**) were established using the LDCs for each nutrient.

Table 3.5: Nutrient load reductions needed for each nutrient and hydrologic condition to stay in compliance with Regulation 31

	Nutrient Load Reduction Needed (%)				
Nutrient	**High Flow**	**Moist Conditions**	**Mid-Range Flows**	**Dry Conditions**	**Low Flow**
TN	N/A	35	N/A	40	N/A
TP	25	70	N/A	53	N/A

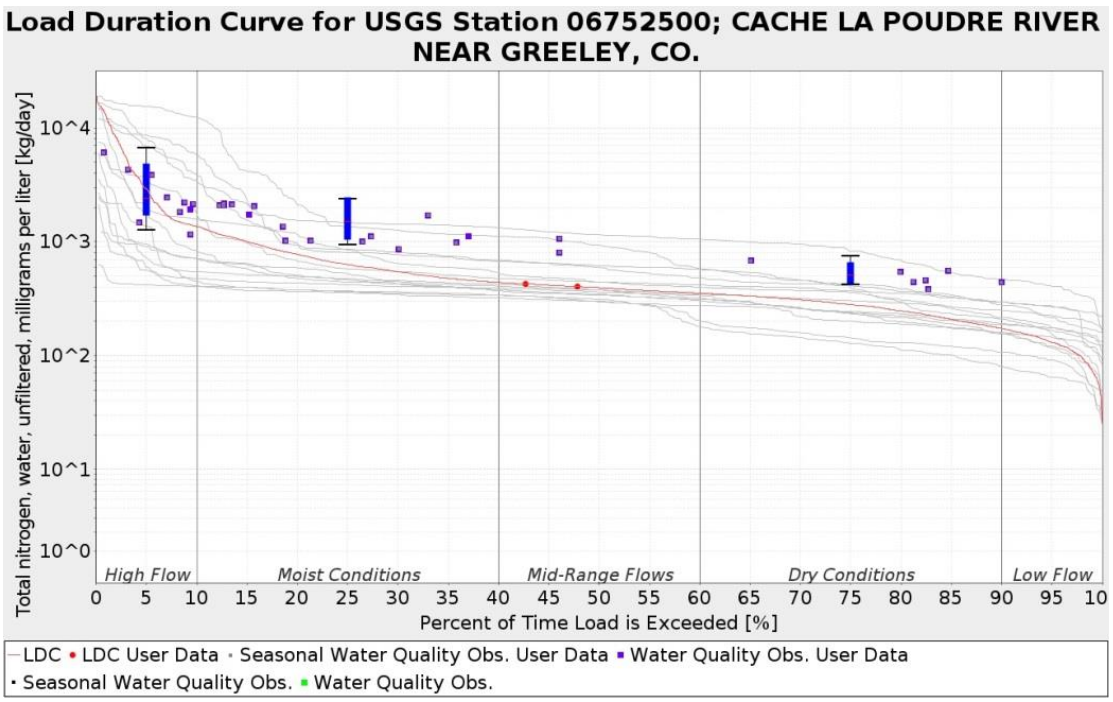

Figure 3.3: TN load duration curve for the Greeley, CO USGS Gauge Station based on Regulation 31 (warm water) river and stream standards for the years 2002-2015

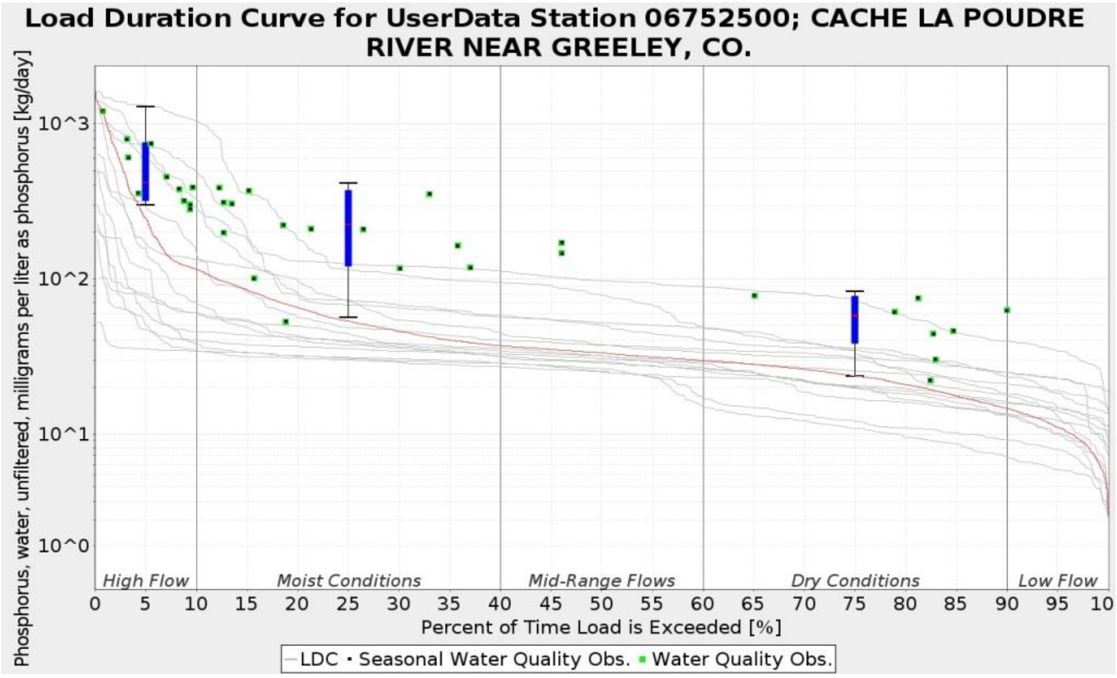

Figure 3.4: TP load duration curve for the Greeley, CO USGS Gauge Station based on Regulation 31 (warm water) river and stream standards for the years 2002-2015

3.2.3: Baseline Nutrient Loads by Sector

The models that were used to calculate nutrient loads from each sector determined the loads at the source. In order to be able to compare the loads from the Greeley gauge station to each sector and determine the optimal ways to reach the nutrient load required to be in compliance with Regulation 31, delivery ratios were needed. Delivery ratios determine how much of the load at the source will reach the outlet for each sector. The observed nutrient loads at the Greeley gauge station were used in conjunction with the modeled values to calculate delivery ratios from each sector (**Table 3.6**).

Table 3.6: Delivery ratios and the representative nutrient load from each sector that will reach the Greeley gauge station (outlet of watershed)

	Average Annual Total Nitrogen		Average Annual Total Phosphorus	
Source	**Delivery Ratio (dimensionless)**	**Nutrient load that reaches Greeley gauge station (lb/yr)**	**Delivery Ratio (dimensionless)**	**Nutrient load that reaches Greeley gauge station (lb/yr)**
Irrigated Agriculture	0.53	112,497	0.33	13,273
WWTPs	0.70	681,089	0.55	161,623
Urban SW	0.60	155,916	0.20	5,851
Forest and Rangeland	0.20	61,943	0.05	1,767
Groundwater	0.14	39,049	N/A	N/A
Total		**1,050,497**		**182,514**
Gauge Station		**1,046,720**		**148,500**
RE (%)		**-0.36**		**-22.9**

The baseline loads at the source and outlet of the CLP watershed can be seen in **Figures 3.5-3.8.** A majority of the TN and TP that reaches the outlet comes from WWTPs, followed by stormwater and then agriculture. These values are important to take into consideration when determining how equitable each scenario was for nutrient abatement at the watershed scale.

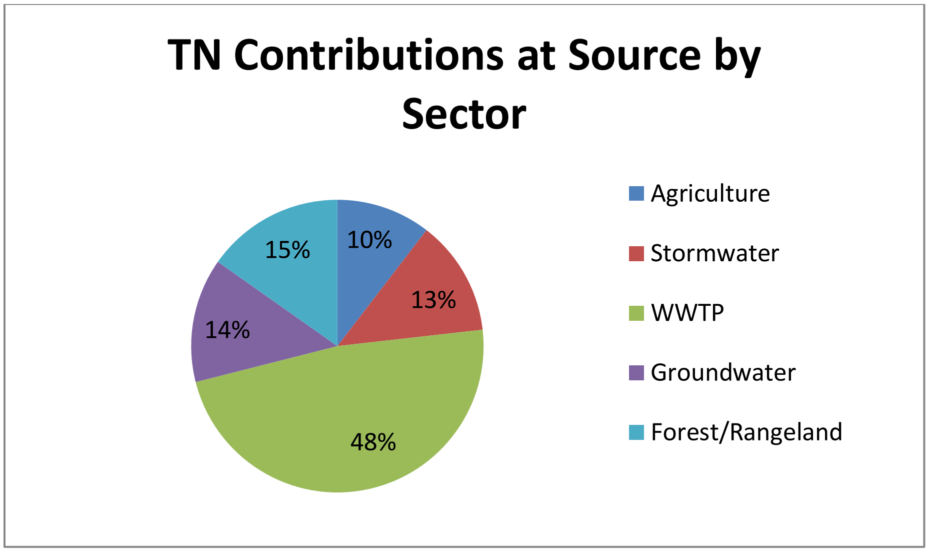

Figure 3.5: Total nitrogen contributions at the source by each sector in the CLP watershed

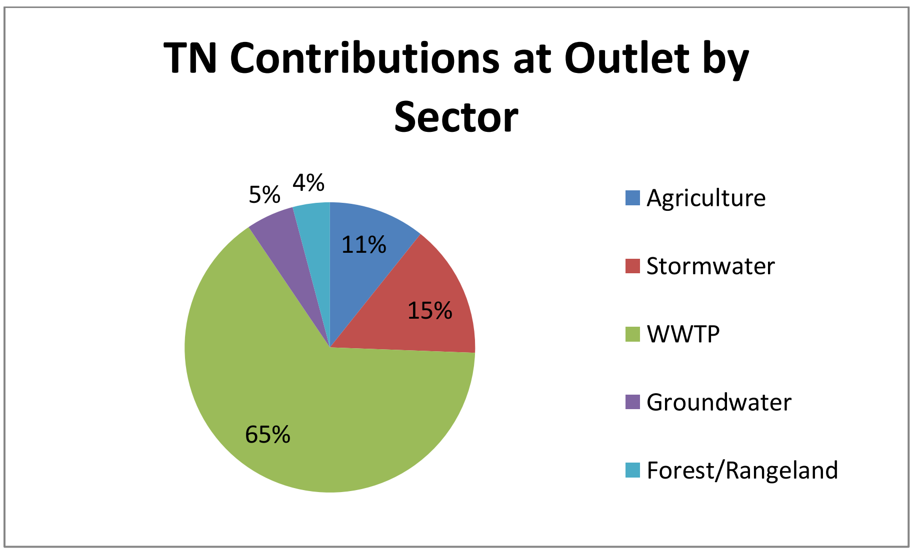

Figure 3.6: Total nitrogen contributions at the outlet by each sector in the CLP watershed

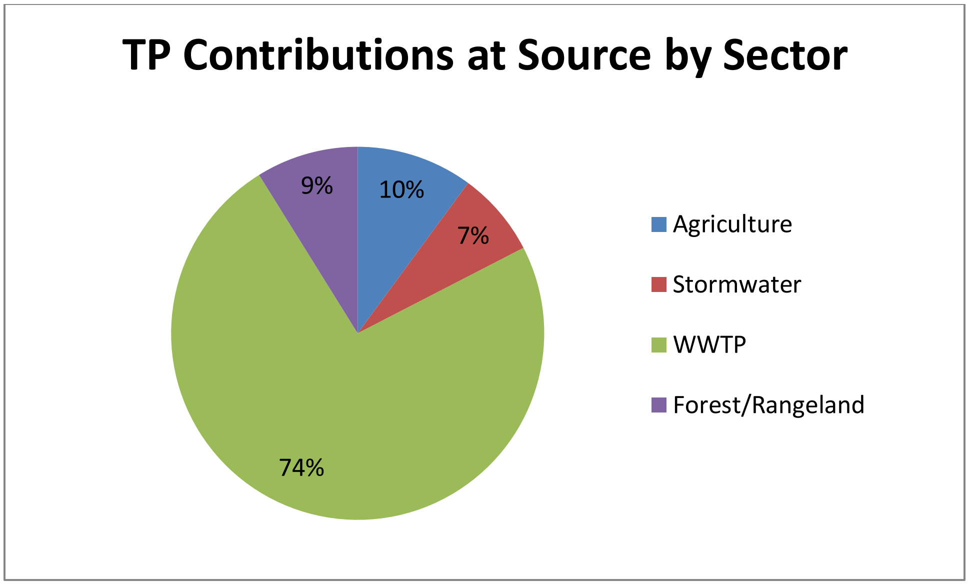

Figure 3.7: Total phosphorus contributions at the source by each sector in the CLP watershed

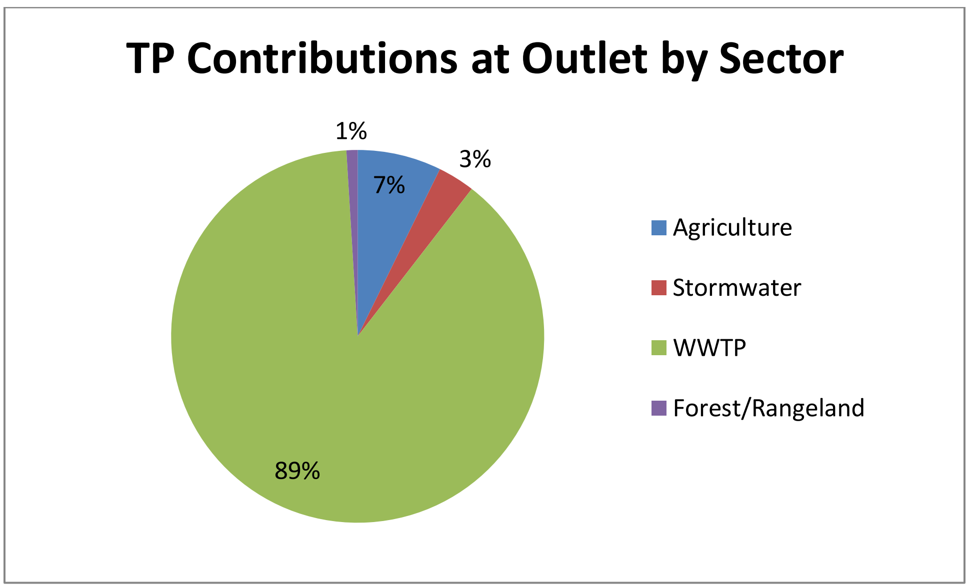

Figure 3.8: Total phosphorus contributions at the outlet by each sector in the CLP watershed

3.3.3: Reductions of Loads at Source and Outlet of Watershed from each Sector

3.3.3a: Agricultural Conservation Practices

Irrigated agriculture contributions were directly related to the adoption rates of center pivot irrigation and strip tillage; the higher the percent adoption, the lower the average annual

TN/TP contribution (**Tables 3.7 and 3.8**). There were a total of 122,737 irrigated acres within the Cache la Poudre watershed, of which 90,419 acres were currently utilizing flood irrigation. The reductions seen when more acres were converted to center pivot irrigation make sense due to center pivot irrigation being more efficient than surface irrigation and requiring less water overall. This in turn was similar to the strip tillage scenario. As mentioned in the methods section, pasture and alfalfa were not selected in the analysis due to these crops not having tillage operations performed on them. Therefore, there was a remaining 60,209 acres of irrigated agriculture that could be converted to utilizing strip tillage. Strip tillage had less tillage operations applied to the field and a higher crop residue on the ground, which ultimately minimized runoff and reduced the nutrient load contributions from irrigated agriculture.

Table 3.7: Average annual nutrient loads for irrigated agriculture based on strip tillage adoption rates and the baseline condition

Strip Tillage Adoption				
Percent Adoption	**Average Annual TN at Source (lb/yr)**	**Average Annual TN at Outlet (lb/yr)**	**Average Annual TP at Source (lb/yr)**	**Average Annual TP at Outlet (lb/yr)**
Baseline	212,258	112,497	40,222	13,273
10% adoption	206,808	109,608	38,359	12658
20% adoption	201,384	106,733	36,550	12061
30% adoption	196,064	103,914	34,715	11456
40% adoption	190,558	100,995	32,899	10857

Table 3.8: Average annual nutrient loads for irrigated agriculture based on center pivot irrigation adoption rates and the baseline condition

Center Pivot Irrigation Adoption				
Percent Adoption	**Average Annual TN at Source (lb/yr)**	**Average Annual TN at Outlet (lb/yr)**	**Average Annual TP at Source (lb/yr)**	**Average Annual TP at Outlet (lb/yr)**
Baseline	230114	121,960	46253	15,264
10% adoption	225765	119655	43957	14506
25% adoption	219180	116166	40514	13369
50% adoption	208530	110521	34797	11483
75% adoption	197613	104735	29042	9584

The percent nutrient reduction seen from the baseline condition reached an upwards of 38% for total phosphorus and roughly 14% for total nitrogen when using the highest percent adoption (i.e. 75%) for center pivot irrigation (**Figure 3.9**). The percent reductions for total phosphorus and total nitrogen were less when converting to strip tillage operations, but still reached values of around 18% and 10%, respectively (**Figure 3.10**).

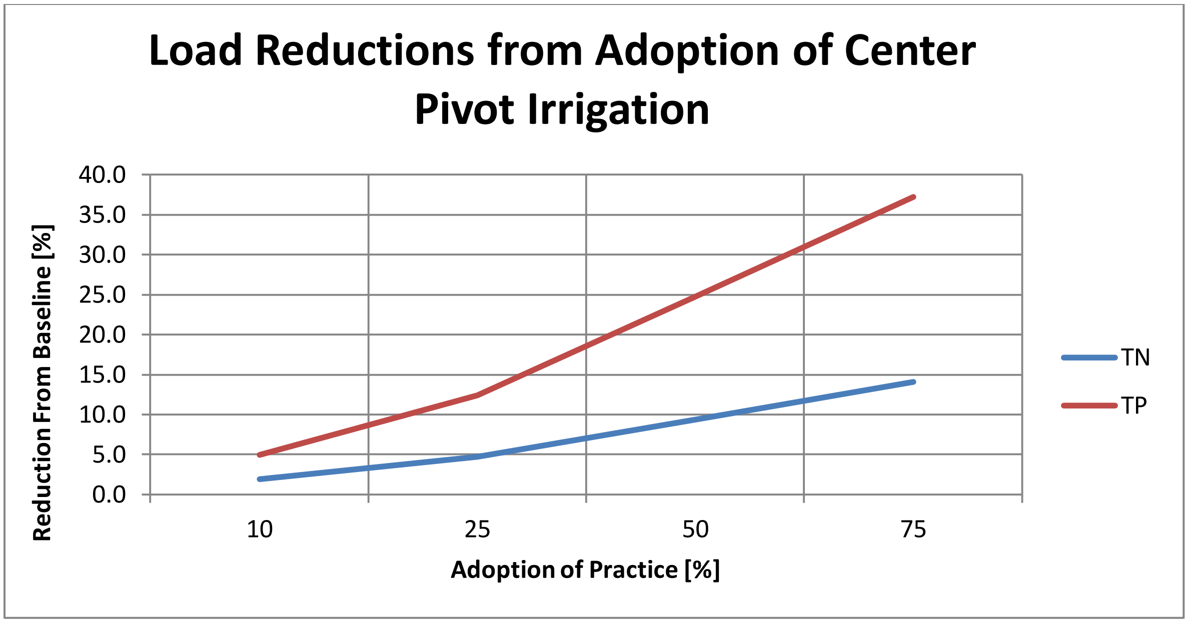

Figure 3.9: Percent nutrient load reductions from the baseline condition for center pivot irrigation adoption rates

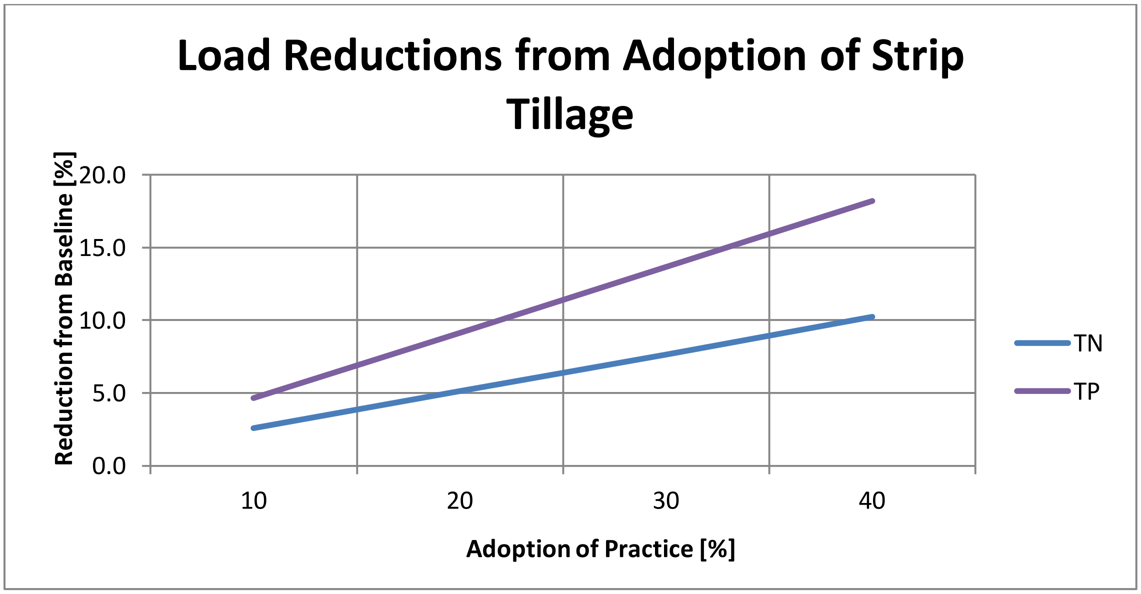

Figure 3.10: Percent nutrient load reductions from the baseline condition for strip tillage adoption rates

3.3.3b: Water Management Practices and Wastewater Treatment Technologies

The three wastewater treatment plant technologies would be used to target a specific nutrient for removal, and any other reductions were an added benefit (**Table 3.9**). Struvite precipitation and chemical phosphorus targeted phosphorus, whereas carbon addition targeted nitrogen. The water management practices had significant variations in nutrient load reductions between the two nutrients. Total phosphorus saw minimal reductions from the incorporation of both management practices in comparison to total nitrogen. Total nitrogen had the greatest reductions seen from carbon addition, with an annual reduction around 40% (**Figure 3.11**). Chemical phosphorus showed a 50% reduction in total phosphorus loads on an annual basis, which outweighed all the other options drastically overall (**Figure 3.12**).

Table 3.9: Average annual nutrient loads from WWTPs for baseline conditions and the implementation of different wastewater technologies and water management practices

Practice/ Technology	Average Annual TN at Source (lb/yr)	Average Annual TN at Outlet (lb/yr)	Average Annual TP at Source (lb/yr)	Average Annual TP at Outlet (lb/yr)
Baseline	972,984	681,089	293,859	161,623
Wastewater Treatment Technologies				
Struvite Precipitation	921,281	644,897	216,148	118,882
Carbon Addition	589,407	412,585	264,590	145,525
Chem-P	972,984	681,089	146,276	80,452
Water Management Practices				
Source Separation	739,971	517,980	269,193	148,056
Effluent Reuse	813,773	569,641	263,779	145,079

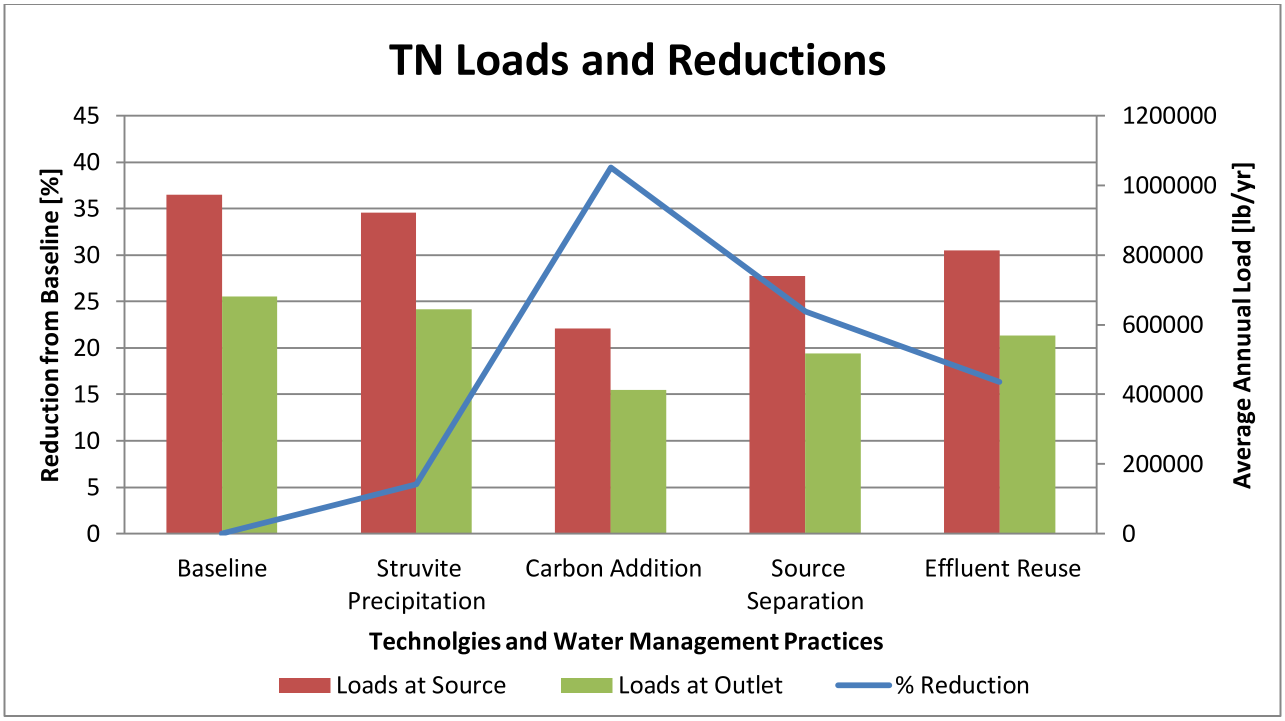

Figure 3.11: Total nitrogen loads and percent reductions seen from the implementation of different wastewater technologies and water management practices

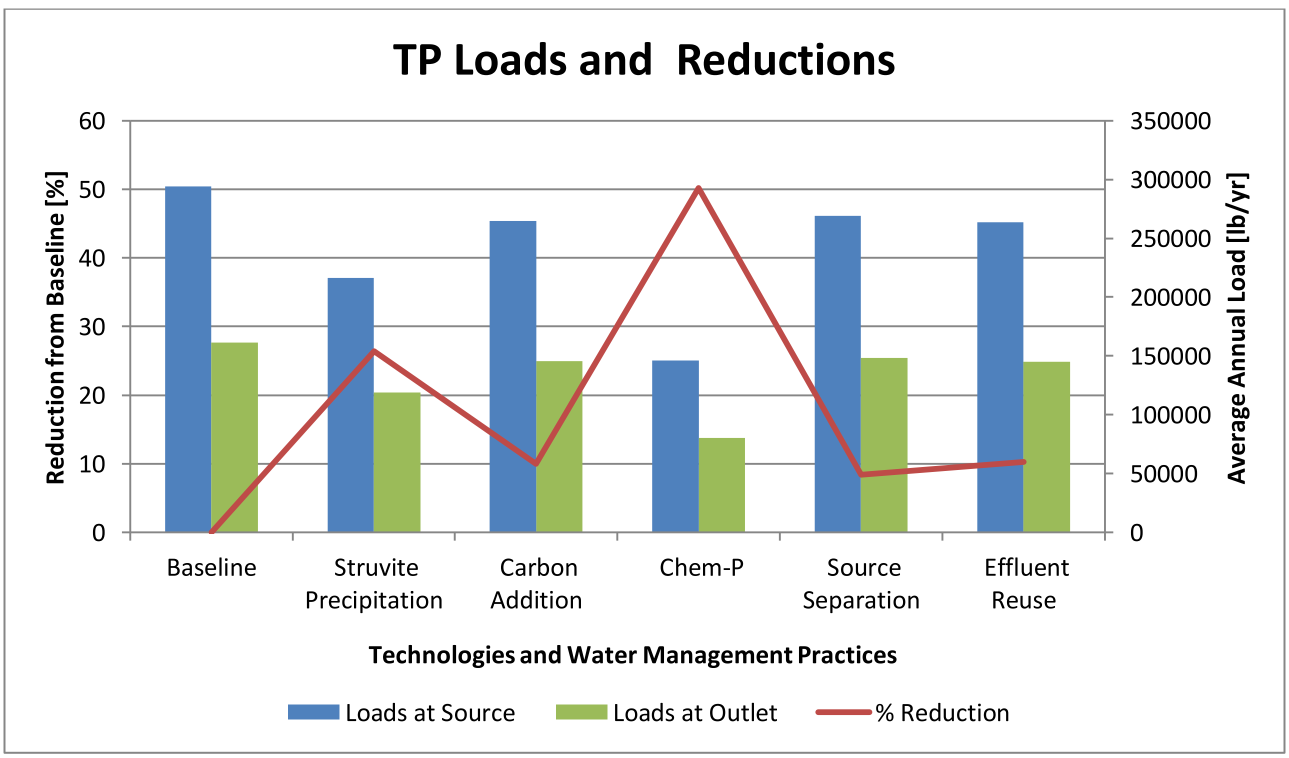

Figure 3.12: Total phosphorus loads and percent reductions seen from the implementation of different wastewater technologies and water management practices

3.3.3c: Urban Stormwater BMP's

As mentioned earlier, the baseline condition for urban stormwater was the assumption that no BMPs were implemented prior to 2008, and extended detention basins were evenly distributed throughout urban areas after 2008. The percent adoption of bio-retention basins entailed that 25% or 50% of the urban acres would implement bio-retention basins. Bio-retention basins produced a higher volume reduction than extended detention basins and lowered the median nutrient concentrations for TN and TP, which resulted in lower average annual loads (**Table 3.10**). An adoption rate of 25% for bio-retention basins resulted in loads reductions around 10% and 8% for total nitrogen and total phosphorus, respectively (**Figure 3.13)**. The loads reductions increased to around 21% for total nitrogen and 18% for total phosphorus when the adoption rate for bio-retention basins were 50% of the urban acres (**Figure 3.13**).

Table 3.10: Average annual nutrient loads from urban stormwater for baseline conditions and the adoption of bio-retention basins

Percent Adoption	Average Annual TN at Source (lb/yr)	Average Annual TN at Outlet (lb/yr)	Average Annual TP at Source (lb/yr)	Average Annual TP at Outlet (lb/yr)
Baseline	259,860	155,916	29,255	5,851
25% Adoption	233,816	140,290	26,809	5,362
50% Adoption	205,127	123,077	24,100	4,820

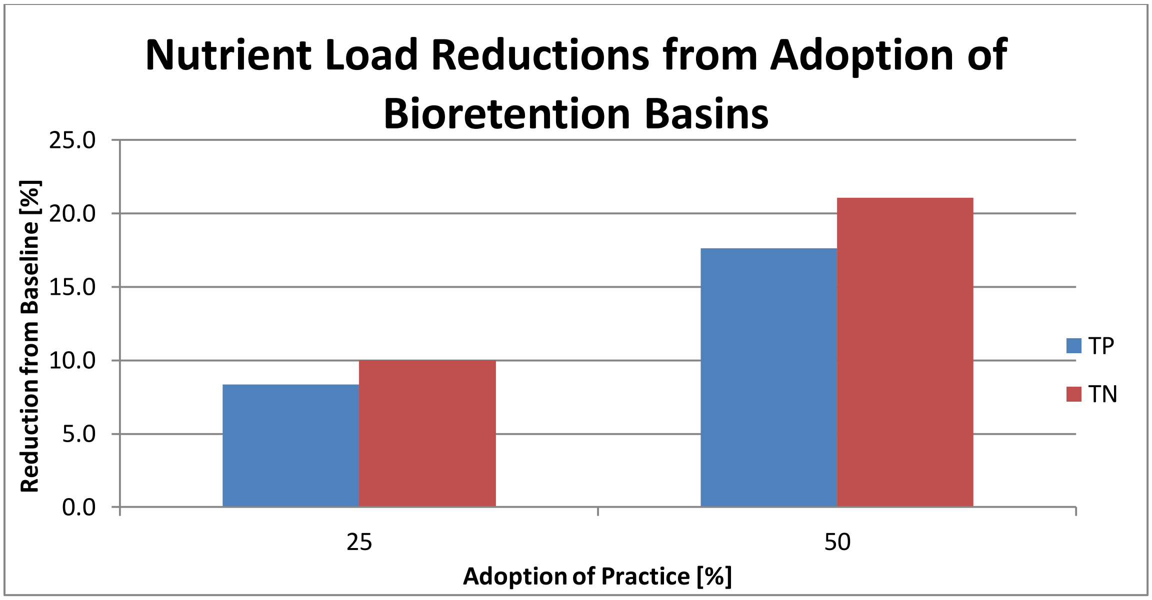

Figure 3.13: Percent nutrient reductions seen from the implementation of bio-retention basins at the selected adoption percentages

3.3.3d: Natural Background

Different practices to reduce the nutrient load contributions from natural background sources were not taken into consideration, but still needed to be accounted for when doing a system level analysis. The average annual TN and TP contributions from these sources (i.e. groundwater and forest and rangeland) can be seen in **Table 3.11**.

Table 3.11: Average annual nutrient load contributions from natural background sources

Practice	Average Annual TN at Source (lb/yr)	Average Annual TN at Outlet (lb/yr)	Average Annual TP at Source (lb/yr)	Average Annual TP at Outlet (lb/yr)
Groundwater	279,120	55,824	0	0
Forest and Rangeland	309,731	43,362	35,336	1,767

3.3.4: System Level Scenarios to meet Regulatory Standards

As previously discussed, the warm water in-stream water quality standards (Regulation 31) for Colorado at the outlet of the CLP watershed were being exceeded, and needed to be reduced by 40% for TN and 70% for TP. The overall load reductions that could be seen within the CLP watershed from the implementation of different practices from each sector and the representative costs associated with those practices can be seen in **Table 3.12**. When trying to determine the most cost effective scenario to reduce TN and TP to be within regulatory standards, one sector alone could not produce these reductions, therefore combinations of practices from different sectors needed to be considered.

Table 3.12: Nutrient loads and reductions at the outlet from the implementation of each practice for each sector and their associated costs

Sectors and Practices	Average TN Load (lb/yr)	Average TP Load (lb/yr)	TN Reduction (%)	TP Reduction (%)	$/lb of N removed	$/lb of P removed	Cost ($/yr)
			Irrigated Agriculture Conservation Practices				
Center Pivot Irrigation (10% adoption)	119655	14506	1.9	5.0	$770	$2,343	$1,775,838
Center Pivot Irrigation (25% adoption)	116166	13369	4.8	12.4	$726	$2,222	$4,208,293
Center Pivot Irrigation (50% adoption)	110521	11483	9.4	24.8	$733	$2,219	$8,388,120
Center Pivot Irrigation (75% adoption)	104735	9584	14.1	37.2	$718	$2,177	$12,366,938
Strip Tillage (10% adoption)	109608	12658	2.6	4.6	$14	$67	$41,474
Strip Tillage (20% adoption)	106734	12061	5.1	9.1	$14	$68	$82,954
Strip Tillage (30% adoption)	103914	11456	7.6	13.7	$14	$68	$124,421
Strip Tillage (40% adoption)	100996	10857	10.2	18.2	$14	$69	$165,901
			Urban Stormwater				
Bioretention basin (25% adoption)	140290	5362	10.0	8.4	$22	$726	$355,300
Bioretention basin (50% adoption)	123077	4820	21.1	17.6	$21	$688	$709,675
			Wastewater Treatment Plants and Technologies				
Struvite precipitation (80%)	644897	118882	5.3	26.4	N/A	$7.5	$319,617
Carbon Addition (7.0)	412585	145525	39.4	10.0	$21.55	N/A	$5,786,118
Chemical P (0.5)	681089	80452	0.0	50.2	N/A	$10.65	$864,424
			Water Management Practices				
Source separation	517980	148056	23.9	8.4	$11.91	$143.25	$1,943,427
WWTP effluent reuse	569641	145079	16.4	10.2	$40.12	$270.26	$4,471,294

All of the different scenarios cost and nutrient reductions, both individual (large circles) and combinations of practices from the different sectors (small circles), for both TN and TP can be seen in **Figures 3.14-3.15**. The non-dominated solutions that were analyzed further to determine the optimal nutrient abatement strategies for the CLP watershed were circled. These scenarios had the most nutrient reduction for the lowest cost. The most cost effective scenarios pertaining to the reductions needed to sustain ecological health in the river (**Table 3.12**) can be seen in **Table 3.13**. It was assumed that WWTPs could only implement one of the wastewater technologies and each of those technologies could be combined with WWTP effluent reuse; and that source separation could only be applied on its own. For TP, the 70% reduction needed during moist conditions could not be obtained from any scenario tested in this analysis at the outlet of the watershed. Therefore, the most cost effective scenario to meet the next highest reduction (i.e. 53% for dry conditions) for TP was determined. Graphs depicting the cost versus the percent nutrient reduction for each practice within each sector can be seen in **Figures B.3 and B.4**.

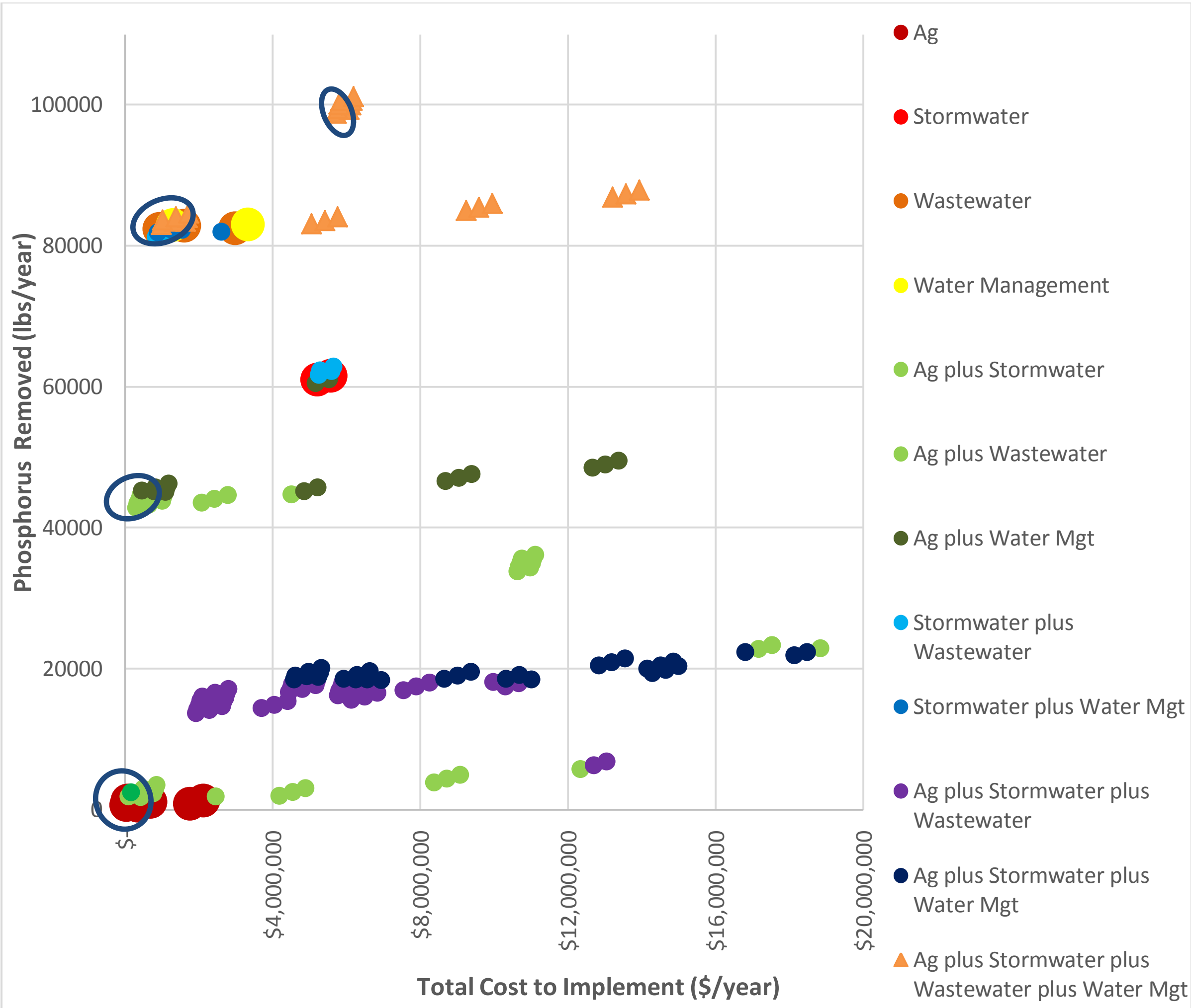

Figure 3.14: Pounds of phosphorus removed versus total cost to implement for all scenarios

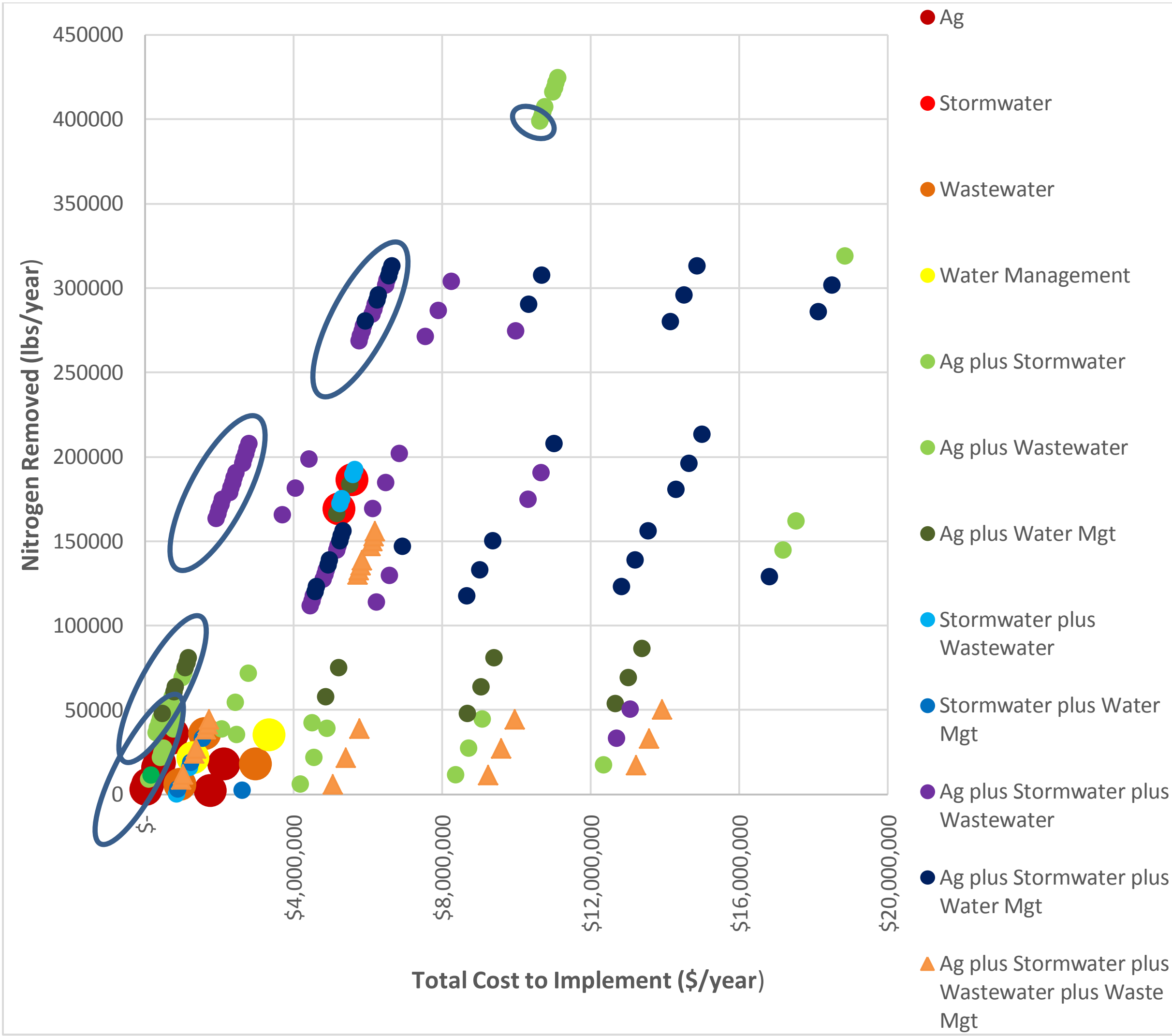

Figure 3.15: Pounds of nitrogen removed versus total cost to implement for all scenarios

Table 3.13: Cost effective scenarios for reducing TP and TN to meet Regulation 31 standards

Scenario	Practices	Total TP Reduction (%)	Total TN Reduction (%)	Cost ($/yr)	Regulation 31
1	**Chem-P; 25% adoption of bio-retention basin; 10% adoption of strip tillage**	55	14	$10,654,186	Satisfies TP standard
2	**WWTP effluent reuse Carbon addition; 25% adoption of bio-retention basin; 10% adoption of strip tillage**	19	42	$5,732,493	Satisfies TN standard

The most cost effective scenarios happened to include the contribution of each sector. WWTPs play a significant role in the overall nutrient load contributions for each year, and can greatly reduce their contribution by implementing certain wastewater treatment technologies at a reasonable cost. Due to most of the standards being exceeded during moist conditions, incorporating WWTP effluent reuse during the appropriate months would be beneficial. Center pivot irrigation and source separation had very high costs associated with their implementation. The costs associated with center pivot irrigation did not account for the economic benefits of this technology (e.g. labor costs or increased yields), and therefore could be offset to some level. If these factors were taken into consideration, the overall cost could have been lower and thus had center pivot irrigation be a more cost effective option for nutrient reduction from the agricultural sector. The adoption of Chem-P and WWTP effluent reuse at WWTPs, along with a 10% adoption of strip tillage for agriculture, and a 25% adoption of bio-retention basins for stormwater, satisfied 2 out of the 3 reductions needed (i.e. high flow and dry conditions) for TP to be in compliance with Regulation 31 with a reduction of 54% for a total cost of roughly $11,000,000. The adoption of carbon addition and WWTP effluent reuse at WWTPs, along with a 10% adoption of strip tillage for agriculture, and a 25% adoption of bio-retention basins for stormwater, satisfied all of the reductions needed for TN to be in compliance with Regulation 31 with a total cost of roughly $6,000,000.

To determine how equitable the above scenarios were for each sector, the Gini index for each nutrient and sector were determined (**Table 3.14 and 3.15**). The last row of each table depicts the equitability for the scenarios portrayed in **Table 3.13** to reach the TN/TP removals needed to satisfy Regulation 31 (i.e. 40% for TN; 54% for TP). A completely equitable solution, where all sectors were reducing their nutrient load equally based on their contributions, would have a Gini index of 1.0.The Gini index for each sector when satisfying the removal needed to meet TN standards for Regulation 31 were 1.3 for WWTPs, 0.2 for stormwater, and 0.1 for agriculture. This means that WWTPs were putting in more than their share of the total TN contribution, whereas stormwater and agriculture were putting in less than their share of the total TN contribution. Similarly, this was seen when satisfying removals for TP, where the Gini index for WWTPs were 1.1, 0.2 for stormwater, and 0.1 for agriculture. Slightly more expensive options could be looked into that would make each sectors responsibility more equitable, and therefore could be more likely to be adopted, depending on stakeholder preference.

Table 3.14: Gini Index for each Sector of Interest for TN Removal

Increment to reaching TP Removal (%)	SW (% cont)	SW Gini Index	WWTP (% cont)	WWTP Gini Index	Agriculture (% cont)	Agriculture Gini Index	Most Cost Effective Scenario that Satisfies Reduction (Sectors involved)
0	16.4%		71.7%		11.8%		Baseline
10	13.5%	5.2	74.8%	0	11.7%	1.3	AG+SW
20	14.1%	2.6	74.0%	0.7	11.9%	0.9	AG+SW+WWT
30	19.8%	0.0	65.9%	1.4	14.3%	0.0	WM
40	19.8%	0.0	65.9%	1.4	14.3%	0.0	WM
50	18.5%	0.5	68.2%	1.2	13.3%	0.5	AG+SW+WM
60	22.9%	0.0	60.6%	1.4	16.5%	0.0	WWT
70	22.9%	0.0	60.6%	1.4	16.5%	0.0	WWT
80	19.2%	0.7	64.2%	1.2	16.6%	0.2	AG+SW+WWT
90	25.6%	0.2	54.9%	1.3	19.5%	0.1	AG+SW+WWT+ WM
100	**25.6%**	**0.2**	**54.9%**	**1.3**	**19.5%**	**0.1**	**AG+SW+WWT+ WM**

Note: SW= stormwater, AG= agriculture, WWT= wastewater technology, WM= water management practice, cont= contribution

Table 3.15: Gini Index for each Sector of Interest for TP Removal

Increment to reaching TP Removal (%)	SW (% cont)	SW Gini Index	WWTP (% cont)	WWTP Gini Index	Agriculture (% cont)	Agriculture Gini Index	Most Cost Effective Scenario that Satisfies Reduction (Sectors involved)
0	3.2%		89.4%		7.3%		Baseline
10	4.2%	0	86.1%	1.1	9.6%	0	WWT
20	4.2%	0	86.1%	1.1	9.6%	0	WWT
30	4.2%	0	86.1%	1.1	9.6%	0	WWT
40	4.2%	0	86.1%	1.1	9.6%	0	WWT
50	5.9%	0	80.8%	1.1	13.3%	0	WWT
60	5.9%	0	80.8%	1.1	13.3%	0	WWT
70	5.9%	0	80.8%	1.1	13.3%	0	WWT
80	5.9%	0	80.8%	1.1	13.3%	0	WWT
90	6.5%	0.2	78.0%	1.1	15.5%	0.1	AG+SW+WWT+ WM
100	**6.5%**	**0.2**	**78.0%**	**1.1**	**15.5%**	**0.1**	**AG+SW+WWT+ WM**

Note: SW= stormwater, AG= agriculture, WWT= wastewater technology, WM= water management practice, cont= contribution

3.4: Summary and Conclusions

With water degradation affecting every state in the United States, and the understanding that not one sector alone contributes to these impairments, resulted in the need for a system level analysis that could determine cost effective and equitable ways to reduce nutrient pollution. It was found that TN reductions needed for regulations could be achieved through the adoption of carbon addition, WWTP effluent reuse, 10% adoption of strip tillage, and a 25% adoption of bio-retention basins for a total of roughly $6,000,000. Whereas the TP reduction needed for regulations for all hydrologic conditions could not be achieved with any combination of the practices looked into, however 2 out of the 3 reductions could be achieved from the adoption of

Chem-P, WWTP effluent reuse, 10% adoption of strip tillage, and 25% adoption of bio-retention basins for roughly $11,000,000. Further research would be needed to determine a scenario that could achieve a 70% TP reduction and 40% TN reduction simultaneously at the outlet, which was needed at the system level to be in compliance with regulatory standards.

Further research should look into the uncertainty associated with an analysis of this caliber. These include the resiliency, reliability, and vulnerability of the system, as well as doing a more detailed analysis on equity between sectors. The delivery ratios that were found should also have further investigation applied to them due to the variability that can be seen from watershed to watershed from the complex factors that are associated with determining these values. This method should be tested in other watersheds to determine if the methods can apply to other locations and still maintain reasonably accurate.

CHAPTER 4: CONCLUSIONS

With the effects of nutrient pollution becoming more prevalent around the country, it is important to determine ways that will mitigate this issue. The nutrient loads produced from urban stormwater, WWTPs, irrigated agriculture, groundwater, and forest and rangeland were quantified in order to determine the potential load reductions that could be seen from the implementation of different practices and technologies. The costs associated with each practice were calculated to determine the most cost effective strategies to reducing nutrient load contributions at the system level, as well as a Gini index for equitability between sectors, in order to remain in compliance with Colorado regulations.

The study completed in the South Platte River Basin accomplished the objective of assessing conservation effects of agricultural management practices in irrigated river basins. The results indicated that the most nutrient reduction in the SPRB could be obtained from the implementation of center pivot irrigation with no-tillage operations. For tillage operations, no-tillage had the most nutrient reduction, followed by strip tillage and then reduced tillage. For grass pasture, the most effective method was center pivot irrigation with no fertilizer application. The approach used for this analysis was then used to assess the nutrient load reductions that could be seen in the Cache la Poudre watershed from the adoption of the different conservation practices tested.

The system level analysis for the Cache la Poudre watershed achieved the objective of determining a methodology that could be used to quantify nutrient load contributions from each sector and their associated nutrient load reductions from the implementation of different practices and technologies at the watershed scale. This was done through the use of a variety of models, including the Simple Method, BioWin, SWAT-CP in eRAMS, SPARROW, LOADEST, and MODFLOW. The models were validated through field observations (SWAT-CP), an analysis completed at different WWTPs in Boulder and throughout Colorado (BioWin), an extensive analysis done for Colorado pertaining to urban stormwater loads (The Simple Method), and extensive use within the literature (MODFLOW, SPARROW, LOADEST).

A wide range of reductions from the implementation of the different practices for each sector at the system level were seen. The highest nutrient reduction from WWTPs could be seen from the implementation of Chem-P (i.e. TP) and carbon addition (i.e. TN). The other technologies and practices analyzed had relatively high reductions in comparison to some of other practices that could be adopted by stormwater or agriculture. Center pivot irrigation and strip tillage adoption for irrigated agricultural fields and bio-retention basins for urban stormwater all needed significant adoption percentages to see notable nutrient reductions.

The development of nutrient load duration curves for the outlet of the CLP watershed (i.e. Greeley gauge station) were used to determine how often Regulation 31 standards for in-stream water quality were exceeded. The results indicated that the standards were exceeded for both TN and TP quite frequently, most often during high flow and moist conditions. The reductions seen from the implementation of each practice and the associated costs were used to determine the most cost effective strategies to dealing with this issue. The adoption of strip tillage practices and bio-retention basins, and the implementation of carbon addition or Chem-P were the cheapest options that also had relatively high nutrient reductions for both TN and TP. It was found that TN reductions needed for regulations could be achieved through the adoption of carbon addition, WWTP effluent reuse, 10% adoption of strip tillage, and a 25% adoption of bio-retention basins for a total of roughly $6,000,000. Whereas the TP reduction needed for regulations for all hydrologic conditions could not be achieved with any combination of the practices looked into, however 2 out of the 3 reductions could be achieved from the adoption of Chem-P, WWTP effluent reuse, 10% adoption of strip tillage, and 25% adoption of bio-retention basins for roughly $11,000,000. Further research would be needed to determine a scenario that could achieve a 70% TP reduction and 40% TN reduction simultaneously, which was needed at the system level to be in compliance with regulatory standards.

Overall, this study demonstrates the feasibility of determining nutrient load contributions and potential reductions that could be seen at the system level through the use of models and ambient water quality data. Once the models are developed for the watershed of interest, they can be applied to determine the most cost effective and equitable scenarios to remain in compliance with regulations.

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APPENDIX A: DETAILED DESCRIPTIONS OF EACH SCENARIO TESTED IN SWAT-CP

Appendix A displays the description of each scenario tested for the SPRB in Chapter 2 in **Table A.1**. Included in this table is the dominant cropping systems analyzed, which included: continuous corn, alfalfa-corn, silage corn-winter wheat-sugar beets, grass pasture, and silage corn-winter wheat. The scenarios included different combinations of irrigation (center pivot and surface irrigation), tillage operations (conventional, reduced, strip, and no-tillage), as well as fertilizer rate and timing. **Tables A.2-A.18** includes the exact dates and operations performed, as well as the type and amount of fertilizer applied, for each scenario and crop rotation in the SPRB created by experts in the field.

Table A.1: Description and code for each scenario tested in SWAT-CP within the SPRB

Cropping System	Scenario Code	Scenario
Continuous Corn	SC1-CORN	Conventional tillage with Surface irrigation (baseline)
	SC2-CORN-REDTILL	Reduced tillage with Surface irrigation
	SC3-CORN-STRIPTILL	Strip tillage with Surface irrigation
	SC4-CORN-NOTILL	No tillage with Surface irrigation
	SC1-CORN-CNTRPIV	Conventional tillage with Center pivot irrigation
	SC2-CORN-REDTILL-CNTRPIV	Reduced tillage with Center pivot irrigation
	SC3-CORN-STRIPTILL-CNTRPIV	Strip tillage with Center pivot irrigation
	SC4-CORN-NOTILL-CNTRPIV	No tillage with Center pivot irrigation
Silage Corn-Winter Wheat	SC1-SCORN-WWHT	Conventional tillage with Surface irrigation (baseline)
	SC2-SCORN-WWHT-REDTILL	Reduced tillage with Surface irrigation
	SC3-SCORN-WWHT-STRIPTILL	Strip tillage with Surface irrigation
	SC4-SCORN-WWHT-NOTILL	No tillage with Surface irrigation
	SC1-SCORN-WWHT-CNTRPIV	Conventional tillage with Center pivot irrigation
	SC2-SCORN-WWHT-REDTILL-CNTRPIV	Reduced tillage with Center pivot irrigation
	SC3-SCORN-WWHT-STRIPTILL-CNTRPIV	Strip tillage with Center pivot irrigation
	SC4-SCORN-WWHT-NOTILL-CNTRPIV	No tillage with Center pivot irrigation
Alfalfa-Corn	SC1-ALF-CORN	Conventional tillage with Surface irrigation (baseline)
	SC1-ALF-CORN-CNTRPIV	Conventional tillage with Center pivot irrigation
Silage Corn/Winter Wheat/Sugar beets	SC1-WWCS	Conventional tillage with Surface irrigation (baseline)
	SC2-WWCS-REDTILL	Reduced tillage with Surface irrigation
	SC3-WWCS-STRIPTILL	Strip tillage with Surface irrigation
	SC4-WWCS-NOTILL	No tillage with Surface irrigation
	SC1-WWCS-CNTRPIV	Conventional tillage with Center pivot irrigation
	SC2-WWCS-REDTILL-CNTRPIV	Reduced tillage with Center pivot irrigation
	SC3-WWCS-STRIPTILL-CNTRPIV	Strip tillage with Center pivot irrigation
	SC4-WWCS-NOTILL-CNTRPIV	No tillage with Center pivot irrigation
Grass Pasture	SC1-PASTURE-Oneharvest	Fertilizer application with Surface irrigation (baseline) for HUC's 1009001, 1009002, and 1080010
	SC1-PASTURE-Threeharvests	Fertilizer application with Surface irrigation (baseline) for the rest of the HUC 8's in Colorado disregarding the three mentioned in the ONE harvest category
	SC2-PASTURE-NOFERT-Oneharvest	No fertilizer application with Surface irrigation for HUC's 1009001, 1009002, and 1080010
	SC2-PASTURE-NOFERT-Threeharvests	No fertilizer application with Surface irrigation for the rest of the HUC 8's in Colorado disregarding the three mentioned in the ONE harvest category
	SC1-PASTURE-CNTRPIV-Oneharvest	Fertilizer application with Center pivot irrigation for HUC's 1009001, 1009002, and 1080010

	SC1-PASTURE-CNTRPIV-Threeharvests	Fertilizer application with Center pivot irrigation for the rest of the HUC 8's in Colorado disregarding the three mentioned in the ONE harvest category
	SC2-PASTURE-NOFERT-CNTRPIV-Oneharvest	No fertilizer application with Center pivot irrigation for HUC's 1009001, 1009002, and 1080010
	SC2-PASTURE-NOFERT-CNTRPIV-Threeharvests	No fertilizer application with Center pivot irrigation for the rest of the HUC 8's in Colorado disregarding the three mentioned in the ONE harvest category

Table A.2: Exact dates and inputs into SWAT-CP for Scenario 1 of continuous corn

SC1-CORN				
id	**date**	**operation**	**detail**	**fertilizer amount (lbs/acre)**
1	3/15/2014	Tillage	DEEP RIPPER- SUBSOILER	
2	3/23/2014	Tillage	OFFSET DIS/HEAVDUTY GE19FT	
3	3/23/2014	Tillage	MOLDBOARD PLOW REG GE10B	
4	3/27/2014	Tillage	CULTI-MULCH ROLLER GE18FT	
5	4/14/2014	Nutrient	Elemental Nitrogen	160
6	4/14/2014	Nutrient	Elemental Phosphorous	60
7	4/14/2014	Tillage	BEDDER (DISK)	
8	4/14/2014	Tillage	CULTI-PACKER PULVERIZER	
9	4/30/2014	Planting	Corn	
10	6/24/2014	Tillage	FURROW-OUT CULTIVATOR	
11	11/1/2014	Harvest & Kill		
12	3/23/2015	Tillage	OFFSET DIS/HEAVDUTY GE19FT	
13	3/23/2015	Tillage	MOLDBOARD PLOW REG GE10B	
14	3/27/2015	Tillage	CULTI-MULCH ROLLER GE18FT	
15	4/14/2015	Nutrient	Elemental Nitrogen	160
16	4/14/2015	Nutrient	Elemental Phosphorous	60
17	4/14/2015	Tillage	BEDDER (DISK)	
18	4/14/2015	Tillage	CULTI-PACKER PULVERIZER	
19	4/30/2015	Planting	Corn	
20	6/24/2015	Tillage	FURROW-OUT CULTIVATOR	
21	11/1/2015	Harvest & Kill		

Table A.3: Exact dates and inputs into SWAT-CP for Scenario 2 of continuous corn with reduced tillage

SC2-CORN-REDTILL				
id	**date**	**operation**	**detail**	**fertilizer amount (lbs/acre)**
1	3/23/2014	Tillage	SINGLE DISK	
2	4/13/2014	Tillage	STRIP TILLING	
3	4/13/2014	Nutrient	Elemental Nitrogen	90
4	4/13/2014	Nutrient	Elemental Phosphorous	30
5	4/30/2014	Planting	Corn	
6	6/24/2014	Tillage	FURROW-OUT CULTIVATOR	
7	6/24/2014	Nutrient	Elemental Nitrogen	70
8	11/1/2014	Harvest & Kill		

Table A.4: Exact dates and inputs into SWAT-CP for Scenario 3 of continuous corn with strip tillage

SC3-CORN-STRIPTILL				
id	**date**	**operation**	**detail**	**fertilizer amount (lbs/acre)**
1	4/13/2014	Tillage	STRIP TILLING	
2	4/13/2014	Nutrient	Elemental Nitrogen	90
3	4/13/2014	Nutrient	Elemental Phosphorous	30
4	4/30/2014	Planting	Corn	
5	6/24/2014	Tillage	FURROW-OUT CULTIVATOR	
6	6/24/2014	Nutrient	Elemental Nitrogen	70
7	11/1/2014	Harvest & Kill		

Table A.5: Exact dates and inputs into SWAT-CP for Scenario 4 of continuous corn with no tillage

SC4-CORN-NOTILL				
id	**date**	**operation**	**detail**	**fertilizer amount (lbs/acre)**
1	4/30/2014	Nutrient	Elemental Nitrogen	90
2	4/30/2014	Nutrient	Elemental Phosphorous	30
3	4/30/2014	Planting	Corn	
4	6/24/2014	Nutrient	Elemental Nitrogen	70
5	11/1/2014	Harvest & Kill		

Table A.6: Exact dates and inputs into SWAT-CP for Scenario 1 of alfalfa/corn

SC1-ALF-CORN				
id	**date**	**operation**	**detail**	**fertilizer amount (lbs/acre)**
1	8/10/2009	Tillage	DEEP RIPPER- SUBSOILER	
2	8/12/2009	Tillage	OFFSET DIS/HEAVDUTY GE19FT	
3	8/15/2009	Tillage	MOLDBOARD PLOW REG GE10B	
4	8/17/2009	Tillage	CULTI-MULCH ROLLER GE18FT	
5	8/20/2009	Nutrient	Elemental Phosphorous	125
6	8/20/2009	Nutrient	Elemental Nitrogen	26
7	8/20/2009	Tillage	CULTI-PACKER PULVERIZER	
8	8/25/2009	Planting	Alfalfa	
9	6/1/2010	Harvest		
10	7/5/2010	Harvest		
11	8/15/2010	Harvest		
12	9/30/2010	Harvest		
13	4/15/2011	Nutrient	Elemental Nitrogen	10
14	4/15/2011	Nutrient	Elemental Phosphorous	50
15	6/1/2011	Harvest		
16	7/5/2011	Harvest		
17	8/15/2011	Harvest		
18	9/30/2011	Harvest		
19	4/15/2012	Nutrient	Elemental Nitrogen	10
20	4/15/2012	Nutrient	Elemental Phosphorus	50
21	6/1/2012	Harvest		
22	7/5/2012	Harvest		
23	8/15/2012	Harvest		
24	9/30/2012	Harvest & Kill		
25	3/15/2013	Tillage	DEEP RIPPER- SUBSOILER	
26	3/23/2013	Tillage	OFFSET DIS/HEAVDUTY GE19FT	
27	3/23/2013	Tillage	MOLDBOARD PLOW REG GE10B	
28	3/27/2013	Tillage	CULTI-MULCH ROLLER GE18FT	
29	4/14/2013	Nutrient	Elemental Nitrogen	160
30	4/14/2013	Nutrient	Elemental Phosphorous	60
31	4/14/2013	Tillage	BEDDER (DISK)	
32	4/14/2013	Tillage	CULTI-PACKER PULVERIZER	
33	4/30/2013	Planting	Corn	
34	6/24/2013	Tillage	FURROW-OUT CULTIVATOR	
35	11/1/2013	Harvest		
36	3/23/2014	Tillage	OFFSET DIS/HEAVDUTY GE19FT	
37	3/23/2014	Tillage	MOLDBOARD PLOW REG GE10B	

38	3/27/2014	Tillage	CULTI-MULCH ROLLER GE18FT	
39	4/14/2014	Tillage	BEDDER (DISK)	
40	4/14/2014	Nutrient	Elemental Phosphorous	60
41	4/14/2014	Nutrient	Elemental Nitrogen	160
42	4/14/2014	Tillage	CULTI-PACKER PULVERIZER	
43	4/30/2014	Planting	Corn	
44	6/24/2014	Tillage	FURROW-OUT CULTIVATOR	
45	11/1/2014	Harvest & Kill		

Table A.7: Exact dates and inputs into SWAT-CP for Scenario 1 of grass pasture with one harvest

SC1 –PASTURE-One harvest				
id	**date**	**operation**	**detail**	**fertilizer amount (lbs/acre)**
1	11/15/2014	Planting	Pasture	
2	4/15/2015	Nutrient	Elemental Nitrogen	50
3	4/15/2015	Nutrient	Elemental Phosphorous	40
4	6/25/2015	Nutrient	Elemental Nitrogen	50
5	8/1/2015	Harvest		

Table A.8: Exact dates and inputs into SWAT-CP for Scenario 1 of grass pasture with three harvests

SC1 -PASTURE- Three harvests				
id	**date**	**operation**	**detail**	**fertilizer amount (lbs/acre)**
1	11/15/2013	Planting	Pasture	
2	4/15/2014	Nutrient	Elemental Nitrogen	50
3	4/15/2014	Nutrient	Elemental Phosphorous	40
5	6/25/2014	Nutrient	Elemental Nitrogen	50
6	8/1/2014	Harvest		
8	4/15/2015	Nutrient	Elemental Nitrogen	50
9	4/15/2015	Nutrient	Elemental Phosphorous	40
10	5/15/2015	Harvest		
11	6/25/2015	Nutrient	Elemental Nitrogen	50
12	8/1/2015	Harvest		
13	9/30/2015	Harvest		

Table A.9: Exact dates and inputs into SWAT-CP for Scenario 2 of grass pasture with one harvest

SC2-PASTURE-NOFERT-One harvest			
id	**date**	**operation**	**detail**
1	11/15/2014	Planting	Pasture
2	8/1/2015	Harvest	

Table A.10: Exact dates and inputs into SWAT-CP for Scenario 2 of grass pasture with three harvests

SC2-PASTURE-NOFERT-Three harvests			
id	**date**	**operation**	**detail**
1	11/15/2014	Planting	Pasture
2	8/1/2015	Harvest	
3	5/15/2015	Harvest	
4	9/30/2015	Harvest	

Table A.11: Exact dates and inputs into SWAT-CP for Scenario 1 of silage corn/winter wheat

SC1 -SCORN -WWHT				
id	**date**	**operation**	**detail**	**fertilizer amount (lbs/acre)**
1	3/15/2013	Tillage	DEEP RIPPER- SUBSOILER	
2	3/23/2013	Tillage	OFFSET DIS/HEAVDUTY GE19FT	
3	3/23/2013	Tillage	MOLDBOARD PLOW REG GE10B	
4	3/27/2013	Tillage	CULTI-MULCH ROLLER GE18FT	
5	4/14/2013	Nutrient	Elemental Nitrogen	160
6	4/14/2013	Nutrient	Elemental Phosphorous	60
7	4/14/2013	Tillage	BEDDER (DISK)	
8	4/14/2013	Tillage	CULTI-PACKER PULVERIZER	
9	4/30/2013	Planting	Corn Silage	
10	6/24/2013	Tillage	FURROW-OUT CULTIVATOR	
11	9/14/2013	Harvest & Kill		
13	9/16/2013	Tillage	OFFSET DIS/HEAVDUTY GE19FT	
14	9/17/2013	Tillage	MOLDBOARD PLOW REG GE10B	
15	9/20/2013	Tillage	CULTI-PACKER PULVERIZER	
16	9/25/2013	Nutrient	Elemental Nitrogen	90
17	9/25/2013	Nutrient	Elemental Phosphorous	30
18	9/25/2013	Tillage	BEDDER (DISK)	
19	9/28/2013	Tillage	CULTI-PACKER PULVERIZER	
20	9/30/2013	Planting	Winter Wheat	
21	7/8/2014	Harvest & Kill		

Table A.12: Exact dates and inputs into SWAT-CP for Scenario 2 of silage corn/winter wheat with reduced tillage

SC2-SCORN-WWHT-REDTILL				
id	**date**	**operation**	**detail**	**fertilizer amount (lbs/acre)**
1	3/23/2013	Tillage	SINGLE DISK	
2	4/13/2013	Tillage	STRIP TILLING	
3	4/13/2013	Nutrient	Elemental Nitrogen	90
4	4/13/2013	Nutrient	Elemental Phosphorous	30
5	4/30/2013	Planting	Corn Silage	
6	6/24/2013	Tillage	FURROW-OUT CULTIVATOR	
7	6/24/2013	Nutrient	Elemental Nitrogen	70
8	9/14/2013	Harvest & Kill		
9	9/15/2013	Tillage	SINGLE DISK	
10	9/16/2013	Tillage	STRIP TILLING	
11	9/30/2013	Nutrient	Elemental Nitrogen	50
12	9/30/2013	Nutrient	Elemental Phosphorous	30
13	9/30/2013	Planting	Winter Wheat	
14	4/1/2014	Nutrient	Elemental Nitrogen	40
15	6/24/2014	Tillage	FURROW-OUT CULTIVATOR	
16	7/8/2014	Harvest & Kill		

Table A.13: Exact dates and inputs into SWAT-CP for Scenario 3 of silage corn/winter wheat with strip tillage

SC3-SCORN-WWHT-STRIPTILL				
id	**date**	**operation**	**detail**	**fertilizer amount (lbs/acre)**
1	4/13/2013	Tillage	STRIP TILLING	
2	4/13/2013	Nutrient	Elemental Nitrogen	90
3	4/13/2013	Nutrient	Elemental Phosphorous	30
4	4/30/2013	Planting	Corn Silage	
5	6/24/2013	Tillage	FURROW-OUT CULTIVATOR	
6	6/24/2013	Nutrient	Elemental Nitrogen	70
7	9/14/2013	Harvest & Kill		
8	9/16/2013	Tillage	STRIP TILLING	
9	9/30/2013	Nutrient	Elemental Nitrogen	50
10	9/30/2013	Nutrient	Elemental Phosphorous	30
11	9/30/2013	Planting	Winter Wheat	
12	4/1/2014	Nutrient	Elemental Nitrogen	40
13	6/24/2014	Tillage	FURROW-OUT CULTIVATOR	
14	7/8/2014	Harvest & Kill		

Table A.14: Exact dates and inputs into SWAT-CP for Scenario 4 of silage corn/winter wheat with no tillage

SC4-SCORN-WWHT-NOTILL				
id	**date**	**operation**	**detail**	**fertilizer amount (lbs/acre)**
1	4/30/2013	Nutrient	Elemental Nitrogen	90
2	4/30/2013	Nutrient	Elemental Phosphorous	30
3	4/30/2013	Planting	Corn Silage	
4	6/24/2013	Nutrient	Elemental Nitrogen	70
5	9/14/2013	Harvest & Kill		
6	9/30/2013	Nutrient	Elemental Nitrogen	50
7	9/30/2013	Nutrient	Elemental Phosphorous	30
8	9/30/2013	Planting	Winter Wheat	
9	4/1/2014	Nutrient	Elemental Nitrogen	40
10	7/8/2014	Harvest & Kill		

Table A.15: Exact dates and inputs into SWAT-CP for Scenario 1 of silage corn/winter wheat/sugar beets

SC1-WWSC				
id	**date**	**operation**	**detail**	**fertilizer amount (lbs/acre)**
1	3/15/2011	Tillage	DEEP RIPPER- SUBSOILER	
2	3/23/2011	Tillage	OFFSET DIS/HEAVDUTY GE19FT	
3	3/23/2011	Tillage	MOLDBOARD PLOW REG GE10B	
4	3/27/2011	Tillage	CULTI-MULCH ROLLER GE18FT	
5	4/14/2011	Nutrient	Elemental Nitrogen	160
6	4/14/2011	Nutrient	Elemental Phosphorous	60
7	4/14/2011	Tillage	BEDDER (DISK)	
8	4/14/2011	Tillage	CULTI-MULCH ROLLER GE18FT	
9	4/30/2011	Planting	Corn Silage	
10	6/24/2011	Tillage	FURROW-OUT CULTIVATOR	
11	9/15/2011	Harvest & Kill		
13	9/16/2011	Tillage	OFFSET DIS/HEAVDUTY GE19FT	
14	9/17/2011	Tillage	MOLDBOARD PLOW REG GE10B	
15	9/20/2011	Tillage	CULTI-MULCH ROLLER GE18FT	
16	9/25/2011	Nutrient	Elemental Nitrogen	90
17	9/25/2011	Nutrient	Elemental Phosphorous	30
18	9/25/2011	Tillage	BEDDER (DISK)	
19	9/28/2011	Tillage	CULTI-PACKER PULVERIZER	
20	9/30/2011	Planting	Winter Wheat	
21	7/8/2012	Harvest & Kill		
22	3/1/2013	Tillage	DEEP RIPPER- SUBSOILER	
23	3/2/2013	Tillage	OFFSET DIS/HEAVDUTY GE19FT	
24	3/2/2013	Tillage	MOLDBOARD PLOW REG GE10B	
25	3/10/2013	Tillage	CULTI-MULCH ROLLER GE18FT	
26	4/1/2013	Nutrient	Elemental Nitrogen	120
27	4/1/2013	Nutrient	Elemental Phosphorous	75
28	4/1/2013	Tillage	BEDDER (DISK)	
29	4/1/2013	Tillage	CULTI-PACKER PULVERIZER	
30	4/10/2013	Planting	Sugar beet	
31	5/08/2013	Tillage	FURROW-OUT CULTIVATOR	
32	10/1/2013	Harvest & Kill		

Table A.16: Exact dates and inputs into SWAT-CP for Scenario 2 of silage corn/winter wheat/sugar beets with reduced tillage

SC2-WWSC-REDTILL				
id	**date**	**operation**	**detail**	**fertilizer amount (lbs/acre)**
1	3/23/2011	Tillage	SINGLE DISK	
2	4/13/2011	Tillage	STRIP TILLING	
3	4/13/2011	Nutrient	Elemental Nitrogen	90
4	4/13/2011	Nutrient	Elemental Phosphorous	30
5	4/30/2011	Planting	Corn Silage	
6	6/24/2011	Tillage	FURROW-OUT CULTIVATOR	
7	6/24/2011	Nutrient	Elemental Nitrogen	70
8	9/15/2011		Harvest & Kill	
9	9/15/2011	Tillage	SINGLE DISK	
10	9/16/2011	Tillage	STRIP TILLING	
11	9/30/2011	Nutrient	Elemental Nitrogen	50
12	9/30/2011	Nutrient	Elemental Phosphorous	30
13	9/30/2011	Planting	Winter Wheat	
14	4/1/2012	Nutrient	Elemental Nitrogen	40
15	6/24/2012	Tillage	FURROW-OUT CULTIVATOR	
16	7/8/2012		Harvest & Kill	
17	3/23/2013	Tillage	SINGLE DISK	
18	4/1/2013	Tillage	STRIP TILLING	
19	4/1/2013	Nutrient	Elemental Nitrogen	80
20	4/1/2013	Nutrient	Elemental Phosphorous	38
21	4/10/2013	Planting	Sugar beet	
22	5/08/2013	Tillage	FURROW-OUT CULTIVATOR	
23	6/24/2013	Nutrient	Elemental Nitrogen	40
24	10/1/2013		Harvest & Kill	

Table A.17: Exact dates and inputs into SWAT-CP for Scenario 3 of silage corn/winter wheat/sugar beets with strip tillage

SC3-WWSC-STRIPTILL				
id	**date**	**operation**	**Detail**	**Fertilizer Amount (lbs/acre)**
1	4/13/2011	Tillage	STRIP TILLING	
2	4/13/2011	Nutrient	Elemental Nitrogen	90
3	4/13/2011	Nutrient	Elemental Phosphorous	30
4	4/30/2011	Planting	Corn Silage	
5	6/24/2011	Tillage	FURROW-OUT CULTIVATOR	
6	6/24/2011	Nutrient	Elemental Nitrogen	70
7	9/15/2011	Harvest & Kill		
8	9/16/2011	Tillage	STRIP TILLING	
9	9/30/2011	Nutrient	Elemental Nitrogen	50
10	9/30/2011	Nutrient	Elemental Phosphorous	30
11	9/30/2011	Planting	Winter Wheat	
12	4/1/2012	Nutrient	Elemental Nitrogen	40
13	6/24/2012	Tillage	FURROW-OUT CULTIVATOR	
14	7/8/2012	Harvest & Kill		
15	4/1/2013	Tillage	STRIP TILLING	
16	4/1/2013	Nutrient	Elemental Nitrogen	80
17	4/1/2013	Nutrient	Elemental Phosphorous	38
18	4/10/2013	Planting	Sugar beet	
19	5/08/2013	Tillage	FURROW-OUT CULTIVATOR	
20	6/24/2013	Nutrient	Elemental Nitrogen	40
21	10/1/2013	Harvest & Kill		

Table A.18: Exact dates and inputs into SWAT-CP for Scenario 4 of silage corn/winter wheat/sugar beets with no tillage

SC4-WWSC-NOTILL				
id	**date**	**operation**	**detail**	**fertilizer amount (lbs/acre)**
1	4/30/2011	Nutrient	Elemental Nitrogen	90
2	4/30/2011	Nutrient	Elemental Phosphorous	30
3	4/30/2011	Planting	Corn Silage	
4	6/24/2011	Nutrient	Elemental Nitrogen	70
5	9/15/2011	Harvest & Kill		
6	9/30/2011	Nutrient	Elemental Nitrogen	50
7	9/30/2011	Nutrient	Elemental Phosphorous	30
8	9/30/2011	Planting	Winter Wheat	
9	4/1/2012	Nutrient	Elemental Nitrogen	40
10	7/8/2012	Harvest & Kill		
11	4/10/2013	Nutrient	Elemental Nitrogen	80
12	4/10/2013	Nutrient	Elemental Phosphorous	38
13	4/10/2013	Planting	Sugar beet	
14	6/24/2013	Nutrient	Elemental Nitrogen	40
15	10/1/2013	Harvest & Kill		

APPENDIX B: DETAILED RESULTS FROM CACHE LA POUDRE WATERSHED STUDY

Appendix B depicts the modeled annual nutrient contributions (i.e. TN and TP) from each sector for the years 2002-2015 for the CLP watershed. **Tables B.1 and B.2** are the natural background contributions from groundwater and forest and rangeland for the entire extent of CLP watershed, as well as for just the Poudre Canyon. **Tables B.3 and B.4** are for irrigated agriculture, and include the baseline loads and the load associated with adoption of center pivot irrigation and strip tillage, respectively. **Table B.5** represents the loads associated with urban stormwater for baseline conditions and the adoption of bio-retention basins. **Tables B.6 and B.7** are for WWTPs and include the technologies (Chem-P, carbon addition, and struvite precipitation) as well as water management practices (source separation and WWTP effluent reuse) that were tested. **Table B.8** included the estimated ambient water quality loads generated for the Greeley gauge station using observed water quality data in combination with LOADEST. **Figures B.1 and B.2** show graphical representation of each sectors overall nutrient load contribution with baseline conditions on an annual basis. **Figures B.3 and B.4** show the cost versus the modeled percent nutrient reduction for each practice tested.

Table B.1: Contribution from natural background sources for total phosphorus in the Cache la Poudre watershed

Year	Groundwater (All of Cache la Poudre) (lb/yr)	Forest and Rangeland (All of Cache la Poudre) (lb/yr)	Groundwater (Poudre Canyon) (lb/yr)	Forest and Rangeland (Poudre Canyon) (lb/yr)
2002	0	35336	0	19611
2003	0	35336	0	19611
2004	0	35336	0	19611
2005	0	35336	0	19611
2006	0	35336	0	19611
2007	0	35336	0	19611
2008	0	35336	0	19611
2009	0	35336	0	19611
2010	0	35336	0	19611
2011	0	35336	0	19611
2012	0	35336	0	19611
2013	0	35336	0	19611
2014	0	35336	0	19611
2015	0	35336	0	19611
Average	**0**	**35336**	**0**	**19611**

Table B.2: Contribution from natural background sources for total nitrogen in the Cache la Poudre watershed

Year	Groundwater (All of Cache la Poudre) (lb/yr)	Forest and Rangeland (All of Cache la Poudre) (lb/yr)	Groundwater (Poudre Canyon) (lb/yr)	Forest and Rangeland (Poudre Canyon) (lb/yr)
2002	242050	309731	0	171825
2003	253793	309731	0	171825
2004	257578	309731	0	171825
2005	290529	309731	0	171825
2006	296282	309731	0	171825
2007	292828	309731	0	171825
2008	294803	309731	0	171825
2009	301368	309731	0	171825
2010	283545	309731	0	171825
2011	285410	309731	0	171825
2012	272138	309731	0	171825
2013	279120	309731	0	171825
2014	279120	309731	0	171825
2015	279120	309731	0	171825
Average	**279120**	**309731**	**0**	**171825**

Table B.3: Contribution from irrigated agriculture for baseline conditions and the implementation of center pivot irrigation at the selected adoption methods in the Cache la Poudre watershed

	Total Nitrogen (lb/yr)					Total Phosphorus (lb/yr)				
Year	**Base**	**10% of Acres Adopt**	**25% of Acres Adopt**	**50% of Acres Adopt**	**75% of Acres Adopt**	**Base**	**10% of Acres Adopt**	**25% of Acres Adopt**	**50% of Acres Adopt**	**75% of Acres Adopt**
2002	162234	153712	140580	119684	97793	31010	28596	24966	18952	12929
2003	233058	228890	222659	212409	202037	49875	48039	45297	40707	36105
2004	193553	188929	181798	170255	158559	34066	32287	29647	25243	20802
2005	110694	108313	104813	98947	93081	29414	27804	25391	21366	17321
2006	219760	215510	208802	198385	187710	37300	34205	29555	21865	14140
2007	180973	177433	172008	163282	154297	38188	36020	32765	27384	21903
2008	131196	126955	120439	110012	99322	49496	46856	42864	36269	29649
2009	226870	223301	217893	209167	200045	45181	43422	40788	36406	31981
2010	207086	203265	197710	188459	179179	71821	69611	66301	60792	55266
2011	178588	174008	167118	155913	144467	43982	41866	38693	33427	28108
2012	60499	58230	54819	49391	43814	44823	41129	35595	26382	17172
2013	322143	316462	308097	294190	279984	49544	47167	43603	37679	31681
2014	413930	409356	402556	391747	380368	56817	54345	50614	44488	38292
2015	581002	576332	569227	557567	545922	66023	64044	61104	56190	51238
Average	**230113**	**225764**	**219180**	**208529**	**197613**	**46253**	**43957**	**40513**	**34796**	**29042**

Table B.4: Contribution from irrigated agriculture for baseline conditions and the conversion from conventional to strip tillage at the selected adoption methods in the Cache la Poudre watershed

	Total Nitrogen (lb/yr)					Total Phosphorus (lb/yr)				
Year	**Base**	**10% of Acres Adopt**	**20% of Acres Adopt**	**30% of Acres Adopt**	**40% of Acres Adopt**	**Base**	**10% of Acres Adopt**	**20% of Acres Adopt**	**30% of Acres Adopt**	**40% of Acres Adopt**
2002	151854	148671	145623	142381	139350	28439	27632	26874	26059	25294
2003	222629	219482	216131	213322	209584	43124	41049	39002	36946	34918
2004	159063	148779	138283	127933	117756	30486	29390	28330	27234	26155
2005	103529	101495	99429	97331	95230	25357	24109	22889	21658	20458
2006	175749	162410	149041	135844	122485	34643	33824	33051	32245	31447
2007	150265	140880	131523	122262	113026	33303	31807	30335	28844	27384
2008	121892	118966	116198	113443	110528	43393	41470	39630	37791	35916
2009	212103	207593	203110	198857	193980	38899	36942	35055	33150	31254
2010	210597	211536	212810	214139	214698	61493	58307	55240	52061	48956
2011	156962	150171	143597	137056	130379	36714	34477	32298	30112	27918
2012	56832	55545	54437	53312	52124	41157	40005	38914	37783	36676
2013	281824	269649	256958	244975	232794	42253	39998	37809	35588	33394
2014	375484	364059	352475	340879	329023	48708	46227	43773	41313	38878
2015	592820	596066	599756	603158	606843	55131	51780	48492	45218	41929
Average	**212257**	**206807**	**201384**	**196064**	**190557**	**40221**	**38358**	**36549**	**34714**	**32898**

Table B.5: Contribution from urban stormwater for baseline conditions and the adoption of bio-retention basins in the Cache la Poudre watershed

	Total Nitrogen (lb/yr)			Total Phosphorus (lb/yr)		
Year	**Baseline**	**25% Adoption**	**50% Adoption**	**Baseline**	**25% Adoption**	**50% Adoption**
2002	140540	140540	140540	140540	140540	140540
2003	226094	226094	226094	226094	226094	226094
2004	266054	266054	266054	266054	266054	266054
2005	256657	256657	256657	256657	256657	256657
2006	181046	181046	181046	181046	181046	181046
2007	235680	235680	235680	235680	235680	235680
2008	248126	248126	248126	248126	248126	248126
2009	345846	285762	219011	39038.9	33373	27070.1
2010	261231	215685	165295	29473.8	25180.3	20423.3
2011	299552	247466	189648	33811.5	28898.7	23437.4
2012	164771	136073	104270	18585.2	15879.4	12876.7
2013	330920	273317	209463	37344.1	31912.6	25883.3
2014	321502	264599	202789	36194.7	30895	25059.9
2015	360022	296337	227114	40548.3	34614.4	28076.1
Average	**297692**	**245605**	**188227**	**33570**	**28679**	**23260**

Table B.6: Contribution from wastewater treatment plants for total nitrogen for baseline conditions and the use of different wastewater treatment technologies and water management practices in the Cache la Poudre watershed

	Load (lb/yr)						
Year	**Baseline**	**Struvite Precipitation**	**Carbon Addition**	**Chem-P**	**Indoor Conservation**	**Source Separation**	**Effluent Reuse**
2002	864415	818481	523639	864415	864415	657403	722969
2003	881118	834297	533757	881118	881118	670105	736939
2004	897821	850112	543875	897821	897821	682808	750909
2005	914524	865928	553994	914524	914524	695511	764879
2006	931227	881743	564112	931227	931227	708214	778848
2007	947930	897559	574230	947930	947930	720917	792818
2008	964633	913374	584348	964633	964633	733620	806788
2009	981336	929190	594467	981336	981336	746323	820758
2010	998039	945005	604585	998039	998039	759026	834728
2011	1014742	960821	614703	1014742	1014742	771729	848698
2012	1031445	976636	624821	1031445	1031445	784432	862668
2013	1048148	992452	634940	1048148	1048148	797135	876638
2014	1064851	1008267	645058	1064851	1064851	809838	890608
2015	1081554	1024082	655176	1081554	1081554	822541	904577
Average	**972984**	**921281**	**589407**	**972984**	**972984**	**739971**	**813773**

Table B.7: Contribution from wastewater treatment plants for total phosphorus for baseline conditions and the use of different wastewater treatment technologies and water management practices in the Cache la Poudre watershed

				Load (lb/yr)			
Year	**Baseline**	**Struvite Precipitation**	**Carbon Addition**	**Chem-P**	**Indoor Conservation**	**Source Separation**	**Effluent Reuse**
2002	261070	192029	235066	129954	261070	239156	234346
2003	266114	195740	239608	132465	266114	243777	238874
2004	271159	199451	244150	134976	271159	248398	243402
2005	276204	203161	248692	137488	276204	253019	247931
2006	281248	206872	253235	139999	281248	257640	252459
2007	286293	210582	257777	142510	286293	262262	256987
2008	291337	214293	262319	145021	291337	266883	261515
2009	296382	218003	266861	147532	296382	271504	266044
2010	301427	221714	271403	150043	301427	276125	270572
2011	306471	225425	275945	152554	306471	280746	275100
2012	311516	229135	280488	155065	311516	285368	279628
2013	316561	232846	285030	157576	316561	289989	284157
2014	321605	236556	289572	160087	321605	294610	288685
2015	326650	240267	294114	162599	326650	299231	293213
Average	**293859**	**216148**	**264590**	**146276**	**293859**	**269193**	**263779**

Table B.8: Annual nutrient loads for the outlet of the CLP watershed (Greeley gauge station)

Year	Greeley In-stream load (TN) (lb/yr)	Greeley In-stream load (TP) (lb/yr)
2002	624198	58627
2003	700176	75235
2004	699266	78442
2005	886505	116156
2006	751635	84128
2007	783513	96460
2008	825848	104150
2009	1055947	159291
2010	1377877	219149
2011	1371388	228501
2012	830135	96956
2013	1087247	163581
2014	1764384	305419
2015	1895961	295890
Average	**1046720**	**148499**

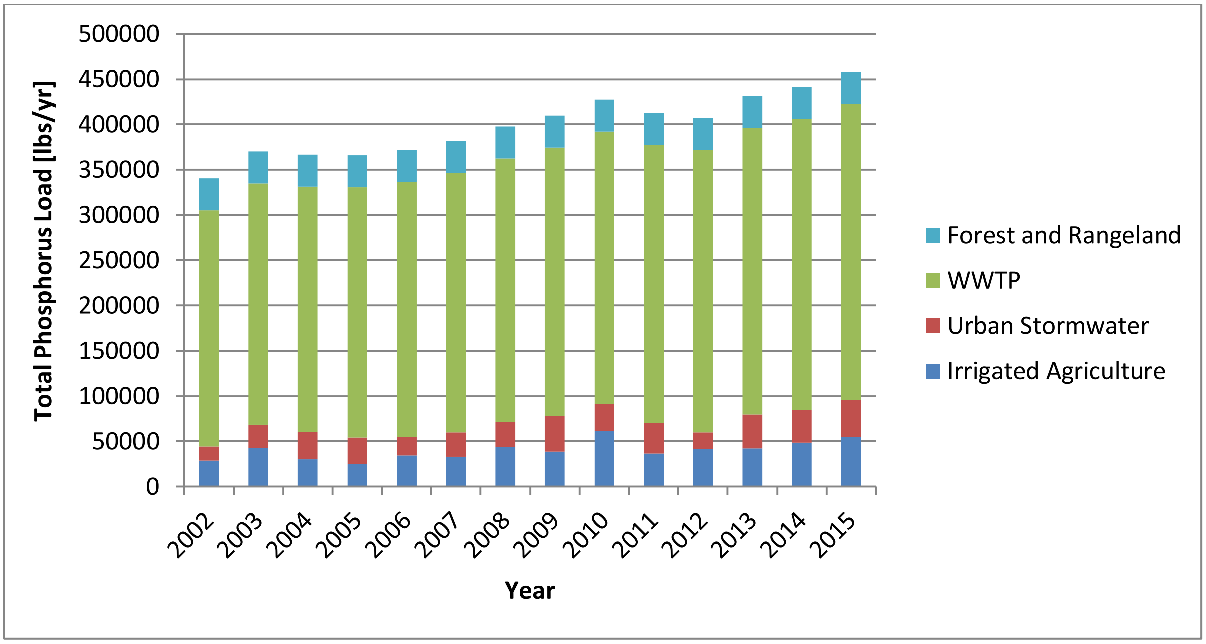


Figure B.1: TP load contributions from each sector at the source for the Cache la Poudre watershed from 2002-2015

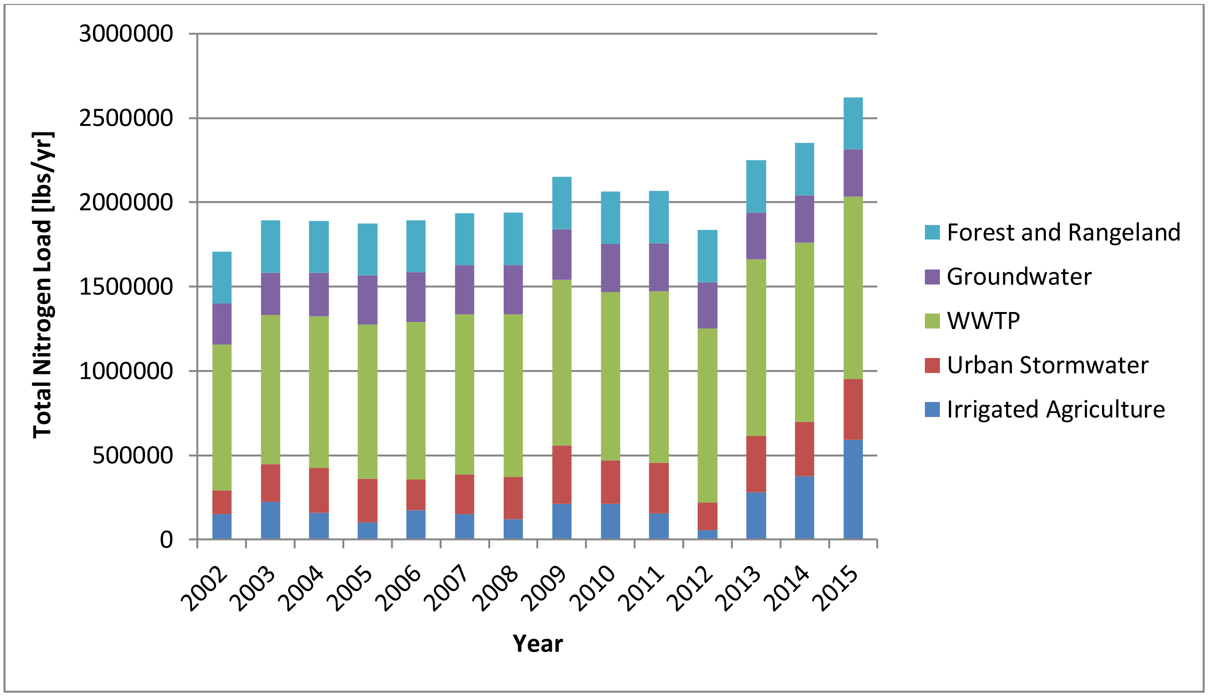
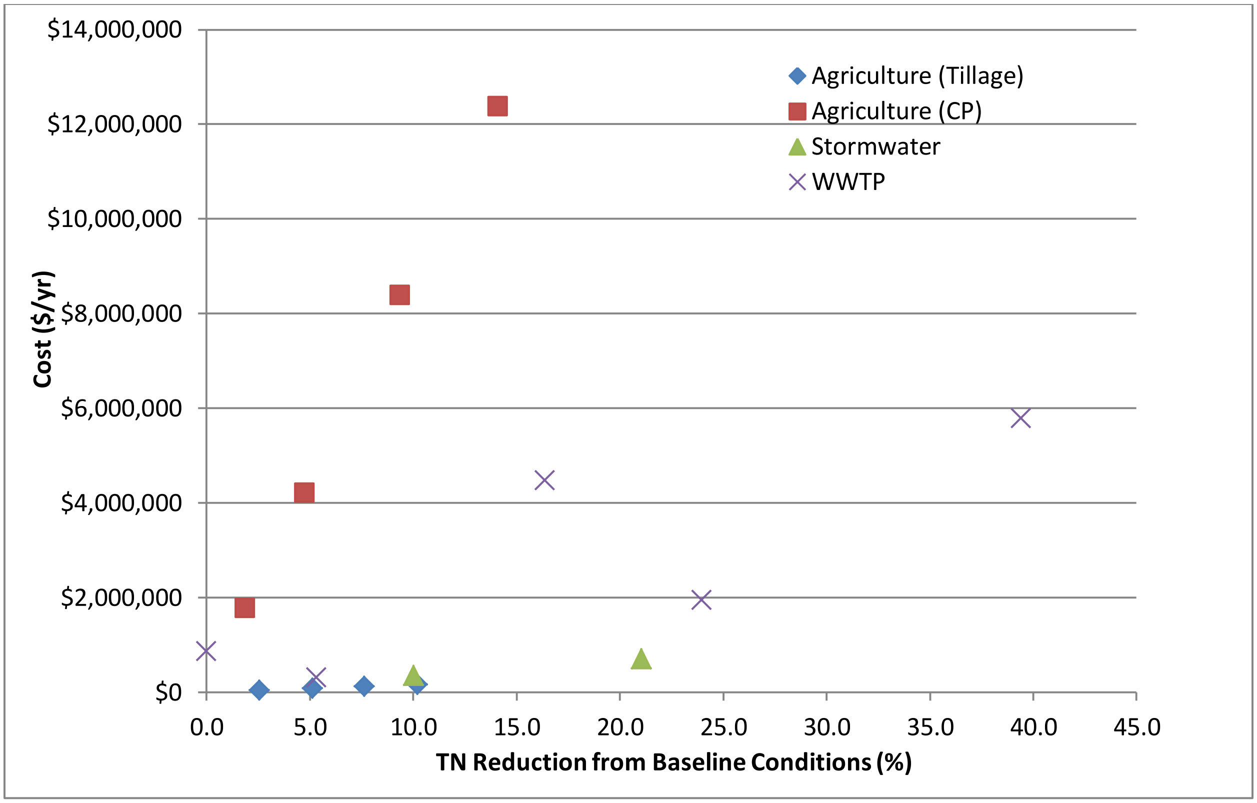
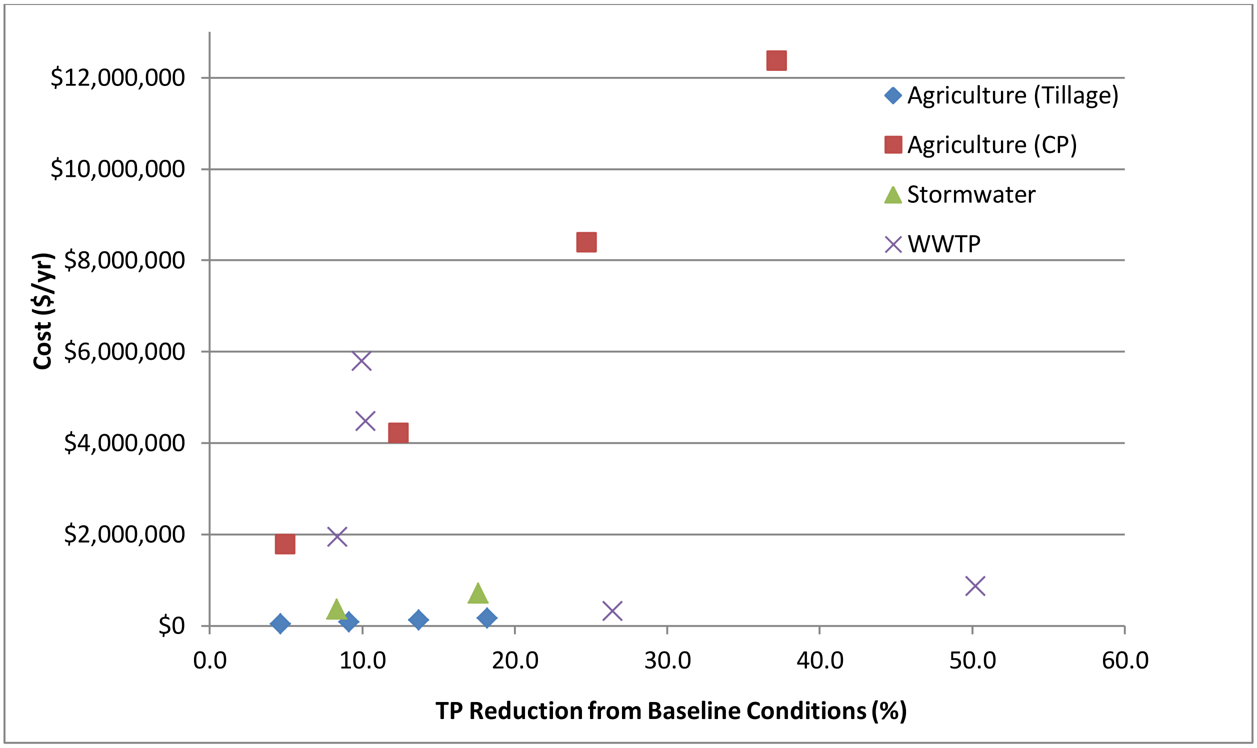


Figure B.2: TN load contributions from each sector at the source for the Cache la Poudre watershed from 2002-2015



Note: CP= center pivot irrigation

Figure B.3: TN reduction seen from each practice within each sector and its associated cost at the source



Note: CP= center pivot irrigation

Figure B.4: TP reduction seen from each practice within each sector and its associated cost at the source