THESIS

GEOSPATIAL ANALYSIS OF WATER AND NUTRIENT TRANSPORT IN TWO NORTHERN COLORADO MIXED-LANDUSE WATERSHEDS

Submitted by

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ABSTRACT

GEOSPATIAL ANALYSIS OF WATER AND NUTRIENT TRANSPORT IN TWO NORTHERN COLORADO MIXED-LANDUSE WATERSHEDS

This study examines the effect of different sources, transport pathways, and hydrologic regimes on phosphorus concentrations along a pristine-urban-agricultural gradient. A total of 48 sampling locations were monitored to characterize total phosphorus concentrations in the Cache la Poudre River Watershed in Northern Colorado. The comprehensive design of sampling locations aimed to capture the influence of anthropogenic activities and geospatial heterogeneity. Samples were collected at seven points in time with distinct climatic and hydrologic characteristics from April 2010 to February 2011. A geographic information system (GIS) was used to measure the overland, irrigation ditch, and stream/river distances from the sources to sampling locations. Analysis of variance, non-linear regression, and multiple linear regression models were used in combination to explore the co-variation of phosphorus concentrations with capacities of upstream WWTPs and CAFOs, along with other geospatial factors. It was evident, under all hydrologic conditions, that phosphorus concentrations downstream from WWTPs were significantly higher than the concentrations upstream of the facilities. Transport from WWTPs governed phosphorus concentrations in surface water during dry and low flow conditions, whereas contribution of CAFOs was significant during rainfall events. The total flow distance (a function of overland, irrigation ditch, and stream/river distances) from CAFOs to the sample locations was strongly associated with phosphorus concentrations during precipitation events. The results of this study provide the foundation for creating a decision support system for water quality analysis, monitoring, and management in the Poudre River basin and other similar mixed-land use watersheds.

After examining the Poudre River watershed, a thorough investigation of Boxelder Creek basin was executed. The objectives were to gain an understanding of the geospatial heterogeneity and hydrologic complexity of the watershed using available data, aerial photography, and ground truthing and to develop a model that could accurately simulate the hydrology and nutrient routing in the watershed. Modeling the system using a simplified method for irrigation produced simulated results that were inconsistent with observed flow measurements. These results seem to indicate that irrigation ditches play a vital role in the hydrologic cycle of the basin. Previous studies indicate that watersheds in the study region can be accurately modeled; and although stream flow was not adequately simulated, the model did perform better when estimating total phosphorus concentrations. Therefore, future studies attempting to model basins containing irrigation ditches, like Boxelder Creek basin, should incorporate methods for representing the channels and their various interactions with the natural system. Routing irrigation canals through the watershed, along with irrigation and manure application methods described in this study, should improve the feasibility of modeling the heterogeneity of mixed landuse watersheds.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Environmental Impacts of Phosphorus

Environmental degradation from nutrient pollution, specifically phosphorus, consistently ranks as one of the top water quality issues in the U.S. (Carpenter et al., 1998). Excess phosphorus loading can lead to water quality problems such as hypoxia and eutrophication (Carpenter et al., 1998). While the population of the world continues to grow, land use and development will play an increasingly important role in water quality. Contaminant concentrations have been shown to increase with increased urban and agricultural inputs as water flows through mixed-use landscapes (USGS, 2000; Kang et al., 2010; Toor et al., 2008). Although previous studies have shown the impacts of differing landscapes on the watershed scale, they have not attempted to correlate the magnitude of phosphorus concentrations with the characteristics of the sources (e.g. number of cattle in a CAFO).

1.2 Point Sources of Phosphorus

Two of the largest contributors of phosphorus in Northern Colorado watersheds are thought to be wastewater treatment plants (WWTPs) and CAFOs, and both are considered a major source of nutrients, contaminants, and environmental degradation in riparian zones and surface water in many agricultural areas (Hooda et al., 2000; Letson and Gollehon, 1996; McMurry et al., 1998; US General Accounting Office, 1995). Establishing a correlation between source density (number of animals or wastewater flow) when weighted for distance (overland, irrigation ditch and river) will improve the viability and effectiveness of watershed-scale studies when looking at the occurrence, fate, and transport of phosphorus. It is not enough to delineate and quantify land use area (e.g. Kang et al., 2010) since the source density within that land use must be identified, quantified, and correlated to water quality parameters.

Some studies have called for increased regulation of CAFOs and/or downsizing to decrease the environmental impact of this source of pollutants CAFO (Centner, 2003). However, with a continually increasing population, CAFOs remain the most economically efficient and productive form for producing meat and other animal products. Since the contaminant transport pathways associated with CAFOs are not understood completely, it is important to look into transport mechanisms for contaminants, such as irrigation ditches and runoff associated with hydrologic events, especially in semi-arid areas where natural tributaries are not as prevalent.

1.3 Irrigation Canals as Transport Mechanisms

The abundance of irrigation canals and the absence of small streams in the Poudre River watershed creates a unique situation to study this aspect of phosphorus transport. It is thought that irrigation canals and ditches have made substantial changes to the hydrology and associated phosphorus transport within the Poudre River watershed and studies elsewhere have shown that irrigation has a significant impact on the processes of recharging alluvial aquifers and transporting contaminants into ground water (Böhlke et al., 2006). Studies have also focused on factors influencing irrigation water quality and quantity (Causapé et al., 2004), but no studies have actually quantified the impacts of irrigation ditch distance and location on phosphorus transport to rivers.

1.4 Temporal Hydrologic Variations

Temporal hydrologic variations can have significant impacts on the occurrence and transport of phosphorus to and in surface water. Research has shown significant increases in phosphorus fluxes during rainfall events and phases of retention and mobilization throughout seasonal dry and wet periods, respectively (Brunet and Astin, 1998). Other studies have suggested increases in chemical/physical pollutant concentrations in streams as precipitation and runoff inputs increase (Chang and Carlson, 2005). However, no study has represented these phenomena over such a large area with as many sampling sites as shown in this research.

This paper also considers other factors such as irrigation ditch flow rate, river flow rate, precipitation, and snow melt to characterize how hydrologic regimes impact the fate and transport of phosphorus in a mixed-land use watershed. It is important to recognize the sources (agricultural and urban) and fate of phosphorus in the watershed to help policy makers determine the best methods for managing the waterways and protecting the public's health.

1.5 Modeling Water and Nutrient Loadings in Mixed-Land Use Watersheds with SWAT

Hydrologic and nutrient modeling with tools such as the Soil and Water Assessment Tool (SWAT) are increasingly recognized as an important tool for improved understanding of the processes involved in generation of freshwater resources, as well as prediction of the potential impacts from urban and agricultural activities on such supplies. (Neitsch et al., 2005; Pohlert et al., 2005; Praskievicz and Chang, 2009; Sharpley et al., 2002) While high resolution water quality studies are critical for increasing current understanding of water and nutrient transport within a watershed, it is also important to develop physical models that can accurately simulate water and nutrient loading. Field assessment of water quantity and quality parameters can be time and money intensive. Models can often provide a more efficient means of evaluating water and nutrient parameters throughout a watershed (Sharpley et al., 2002). Models like SWAT can also be used to forecast management, anthropogenic, and climate change impacts on water quantity and quality. A study by Foy (2009) showed the viability of using SWAT to model the impacts of climate change on headwater basins in Colorado. One of the basins included in this study was the Upper Cache La Poudre (Poudre) River.

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CHAPTER 2: GEOSPATIAL ANALYSIS OF THE OCCURRENCE AND TRANSPORT OF PHOSPHORUS IN THE CACHE LA POUDRE RIVER BASIN IN NORTHERN COLORADO

2.1 Introduction

According to Dubrovsky et al. (2010), concentrations of nutrients have remained the same or increased since the early 1990s in many streams across the Nation despite Federal, State, and local efforts to control point and non-point sources and transport of nutrients. Because of this, the U.S. Environmental Protection Agency (USEPA) has reaffirmed its commitment to collaborating with states to reduce nutrient loadings to our nation's surface waters (Stoner, 2011). Many states, including Colorado, are now in the process of developing numeric nutrient criteria targeted at different categories of water bodies (Colorado Nutrient Coalition, 2010). Nutrient standards must be realistic, informed by scientific research and understanding and ultimately managed and monitored on a continual basis (Dubrovsky et al., 2010). In addition, changes in nutrient concentrations over space and time in surface water can be determined by catchment characteristics (e.g. waste water treatment plants (WWTPs) and confined animal feeding operations (CAFOs)); natural climatic changes; and land use changes due to population growth, increased food production, and changes in industry (Osborne and Wiley, 1988; Arheimer and Lidén, 2000; Schaefer and Alber, 2007; Stutter et al., 2008; Dubrovsky et al., 2010). These types of changes necessitate comprehensive, watershed-scale water quality surveys with fine spatial resolution carried out over multiple seasons and varying hydrologic events.

New water quality standards are imminent, and current literature does not offer a clear understanding of phosphorus initiation and dissemination. Few watershed-scale studies have addressed phosphorus distribution with a high spatial resolution simultaneously with multiple geospatial, anthropogenic, and temporal factors. Geospatially, the Cache La Poudre River (hereafter referred to as Poudre River) watershed in the semi-arid front range of Colorado provides a unique, mixed-land use watershed containing a pristine-urban-agricultural gradient ideal for studying nutrient occurrence and transport. Agricultural and urban land use has often been linked to nutrient apportionment in surface waters (Carpenter et al., 1998; Tippett et al., 1993). However, according to Arheimer and Lidén (2000), land use was not enough to correlate any significant agricultural influence to most nutrient species, including phosphorus. More research must be completed on the relationship between the actual origins of phosphorus with concentrations found in watersheds.

Waste water treatment plants (WWTPs) and confined animal feeding operations are two well documented sources of nutrients in the aquatic environment (Bradford et al., 2008; Carpenter et al., 1998; Haggard et al., 2001; Marti et al., 2004; Miller et al., 2004; USEPA, 2008). Despite ongoing control measures initiated by government legislation (e.g. Clean Water Act (CWA) in 1972), water inputs from WWTPs continue to increase nutrient availability in streams (Haggard et al., 2001; Marti et al., 2004). According to Marti et al. (2004), the effect of effluent on nutrient loads can be magnified by low flow conditions in streams located in semiarid areas. At the same time, the continuous and stationary nature of discharges from these point sources makes them relatively simple to measure and regulate (Carpenter et al., 1998). Therefore, it is important to include both urban and agricultural anthropogenic sources when analyzing nutrient inputs on a watershed scale, especially in a mixed-landuse watershed like the Poudre River. Confined animal feeding operations (CAFOs) are also classified as point sources in the CWA (USEPA, 2008). However, due to multiple seasonal and spatial factors, CAFOs are important nutrient sources that must not be ignored in regional- and watershed-scale analyses. Precipitation events can produce runoff from CAFOs that contains chemical constituents which can impair nearby surface waters (Miller et al., 2004). After runoff containing elevated nutrient levels flows into rivers, streams, and/or irrigation canals, it has the potential to be used downstream to irrigate cropland, thus elevating soil nutrient levels (Miller et al., 2004). In addition, manure and manure-contaminated wash, lagoon, and catch-basin runoff water produced by CAFOs is a major source of natural fertilizer to adjacent cropland (Bradford et al., 2008). Because this study is just the first step towards a more thorough investigation of phosphorus occurrence and transport in the Poudre River, only anthropogenic influences were considered. Other landscape factors such as soil, slope, and irrigated cropland were not included, but will be incorporated in the next chapter of this study, which includes a more thorough spatial model. Also, since CAFOs are classified as point sources, data and information relevant to this study are easier to obtain. The novelty of this research lies in the high resolution field data used in conjunction with measured geospatial factors and anthropogenic sources to explicitly analyze phosphorus in the Poudre River watershed using linear and non-linear regression methods.

Non-linear tree regression and multiple linear regression analyses have been used in a number of previous studies for empirical analysis of spatial nutrient availability and variability (Arheimer and Liden, 2000; Haggard et al., 2003; Lang et al., 2010; May and Sivakumar, 2008, 2009; Michaelides et al., 2009; Passeport and Hunt, 2009; Taddy et al., 2011). The use of partition trees to represent input-output relationships is a classic nonparametric modeling technique (Taddy et al., 2011). Although partitioning is a rough modeling tool, trees are often better suited to real-world applications than other "more sophisticated" alternatives (Taddy et al., 2011). Regression trees have been used to determine the impacts of land use changes on soil and water quality (Michaelides et al., 2009; Plieninger and Schaar, 2008). The variability and complexity of the Poudre River watershed provide a unique environment to use nonlinear tree regression analysis to determine what anthropogenic sources and transport mechanisms in the basin have the greatest impact on phosphorus concentrations for differing hydrologic condition. Along with non-linear tree regression, multiple linear regression analysis is common for empirical analysis of spatial variability in nutrient occurrence and transport. However, most studies on spatial variability only focus on single factor analysis or include limited datasets (Arheimer and Liden, 2000). As mentioned previously, current literature involving the correlation between nutrients and land use characteristics is inconclusive for phosphorus. Therefore, it is important to use these regression analyses along with other geospatial factors to try to better understand phosphorus dissemination in a mixed land use environment.

The objectives of this study were (i) to conduct a comprehensive, high resolution analysis of phosphorus distribution in the Poudre River watershed where WWTPs and CAFOs are present, (ii) contrast the effects of different hydrologic regimes on phosphorus concentrations in the watershed, and (iii) explain the variability of phosphorus concentrations along the Poudre River and throughout the watershed based on anthropogenic point source capacities (CAFOs) average annual discharges (WWTPs) and geospatial characteristics.

2.2. Methods

2.2.1 Site Location and Description

The Poudre River River watershed in Northern Colorado is an ideal system to identify urban and agricultural impacts on water quality. The pristine-urban-agricultural gradient in the watershed can be characterized by four regions: pristine, predominantly forested region; agricultural tributaries, urban settings; and mixed urban/agricultural influenced region. The dominant phosphorus sources in the urban region are WWTPs whereas CAFOs dominate the agricultural landscape. The 2732-km^2 watershed is contained in the semi-arid front range of Colorado and has minimal natural tributaries. Ditches are used extensively for irrigation and inputs to the river are predominantly point sources in the urban landscape and nonpoint *and* point sources in the agricultural areas outside of Fort Collins (Kim and Carlson, 2006).

Figure 2.1 shows the predominant WWTPs and CAFOs as well as the land uses within the watershed. The river is fed by snowmelt with minimal anthropogenic influences and originates near the Continental Divide in the forested Rocky Mountain National Park. The Poudre River River flows through steep mountainous terrain for approximately 69 km (43 miles) before entering the city of Fort Collins. After traveling through Fort Collins, the river moves through approximately 72 km (45 miles) of a predominately agricultural landscape before joining the South Platte River in Greeley, CO (Yang and Carlson, 2003).

2.2.2 Geospatial Factors

Elevation and hydrography data for the Poudre River Watershed were obtained from the U.S. Geological Survey data warehouses. The National Elevation Dataset 1/3 Arc-Second data for the watershed were used to characterize the terrain. The National Hydrography Dataset High Resolution data were used to identify irrigation ditches, canals, rivers, streams, ponds, and dams in the watershed. The location information and capacity values for all WWTPs and CAFOs in the watershed were collected from the U.S. Environmental Protection Agency Facility Registry System (FRS).

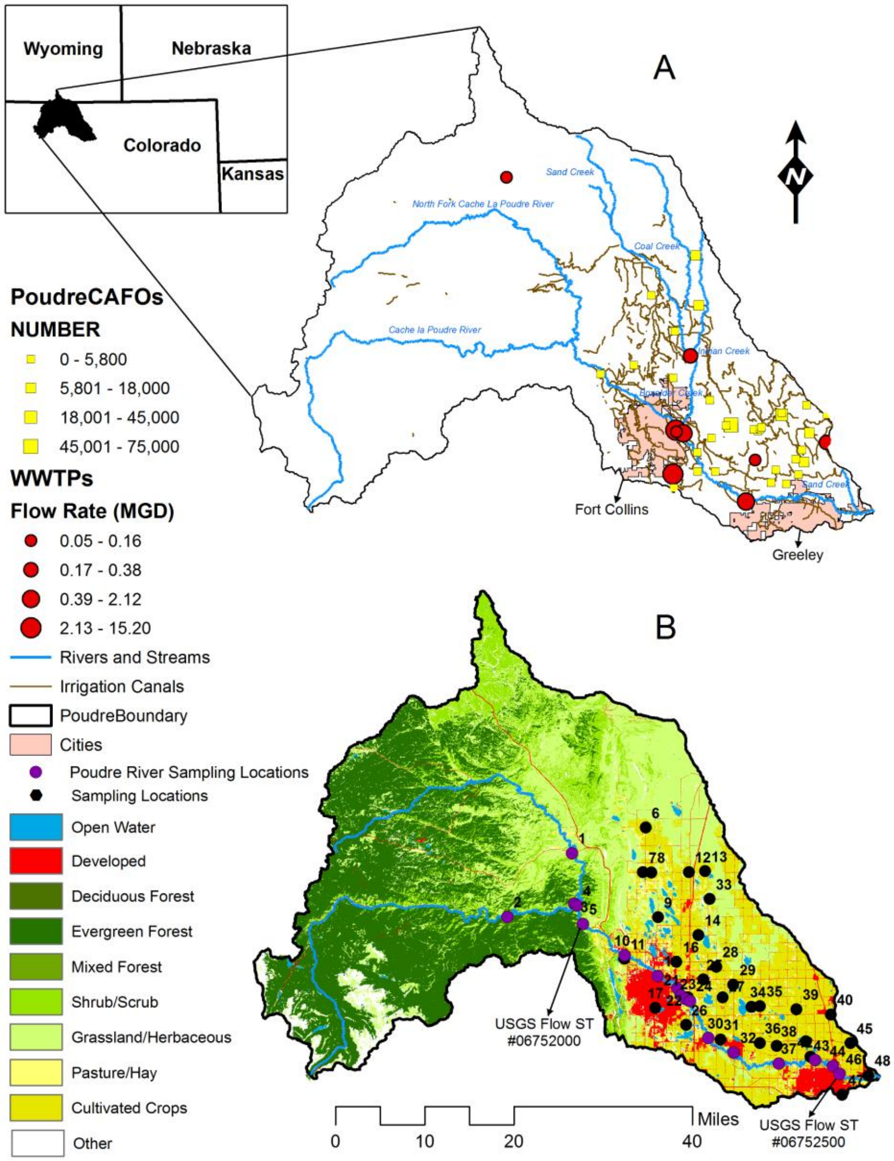


Figure 2.1: (A) Map of the study region showing the Poudre River, CAFOs and WWTPs (B) Map of sampling locations with land use indicated.

This study presents a method for explaining river water quality throughout seasonal hydrologic conditions. Several studies have linked land-use type and/or human and animal population variables with water quality parameters, including phosphorus (Kang et al., 2010; Russell et al., 2008; Schaefer and Alber, 2007). However, some of these methods are rigorous and include multiple input variables. To explain the variability of phosphorus concentrations along the Poudre River and throughout the watershed, a simpler method was constructed. To gain a better understanding of the transport of phosphorus, the Terrain Analysis toolbox in ESRI ArcGIS 9.3 (Redlands, CA, USA) was used to measure overland distance (CAFOs only), canal (or irrigation ditch) distance (CAFOs only), and stream (and/or river) distance from WWTPs and CAFOs to each sample location. To determine overland distance, the cost-surface analysis was used to calculate the distance from each CAFO to the nearest receiving surface water along the flow path. Similarly, irrigation ditch and river distances from WWTPs and CAFOs to each sampling location were calculated. While WWTPs are discharged directly into streams, irrigation ditch and river distances for CAFOs were determined at the points where overland flow entered the bodies of water. For each sampling location situated downstream from a WWTP and/or CAFO, a total flow path was calculated by adding each contributing geospatial factor.

2.2.3 Sample Collection and Analysis

Forty-eight sampling locations were strategically monitored throughout the watershed to capture a range of influences from CAFOs and WWTPs (see Figure 2.1, Panel b). Sample sites were allocated among pristine, agricultural, urban, and mixed urban/agricultural land use areas. Within these land use areas, samples were collected from irrigation ditches, streams, and the Poudre River. Another important consideration in the placement of sampling sites was based on canal/river distance from anthropogenic sources (WWTPs and CAFOs) and the million gallons per day (MGD) of effluent and number of animals that impacted each location. In order to determine the background concentration, five sites within the pristine portion of the watershed were monitored. Three additional sites in cropland areas with no WWTPs or CAFOs were also included.

Table 2.1 presents seven unique climatic and hydrologic conditions between April 2010 and February 2011 when samples were collected. Since one of the objectives of this study was to determine how different hydrologic conditions impact phosphorus concentrations in the Poudre River, streams, and irrigation ditches, the timing of sampling events were designed to reflect conditions before mountain snowmelt, during snowmelt/runoff, after snowmelt, during a rainfall event, during the peak irrigation season, the end of irrigation season, and the winter months with no irrigation which typically coincides with low flow conditions. Figure 2.2a illustrates the flow classification of the sampling events based on flow observations at an upstream location at the mouth of the canyon (USGS # 06752000), and a downstream location immediately upstream of the confluence of the Poudre River with the South Platte River (USGS # 06752500). The locations of these two sites are depicted in Figure 2.1b. Figure 2.2b contains the average snow water equivalent curve based on observed data at two SNOTEL sites located within the study watershed.

Table 2.1: Hydrologic description of sampling events.

Event Number	Event Date	Upstream Flow ST 06752000 (m^3/s)	Downstream Flow ST 06752500 (m^3/s)	Average[1] SWE[2] (mm)	Average[3] Irrigation (m^3/s)	Antecedent 3-Day Rainfall[4] (mm)
1	4/23/2010	4.64	13.96	571.5	1.26	58.4
2	5/19/2010	26.9	24.15	706.1	0.71	14
3	6/4/2010	55.5	24.44	424.2	3.85	0
4	6/18/2010	60.32	60.6	0	1.19	0
5	7/16/2010	13.54	2.09	0	2.1	0
6	9/17/2010	1.16	1.73	0	0.7	0
7	2/22/2011	0.33	2.15	494.03	0	0

[1] Average of Deadman Hill, Hourglass Lake, and Long Draw Reservoir SNOTEL Stations
[2] SWE: Snow Water Equivalent
[3] Average of all monitored irrigation canals in Poudre River Watershed
[4] Average of Fort Collins, CO and Greeley, CO

The first sampling event occurred on April 23, 2010, while snowpack was still increasing and Poudre River flow rates averaged approximately 5.01 (4.64 at ST 06052000 and 13.96 at ST 06752500) cubic meters per second (m^3/s) according to USGS flow monitoring data (U.S. Geological Survey, 2010). Sampling for this date also followed a 58.4 millimeters (mm) rain event (average rainfall recorded for Fort Collins and Greeley, CO on these dates). The second set of samples was taken on May 19, 2010 at the height of snowpack prior to peak runoff. Average river flow rates for this date reached nearly 25.5 m^3/s and the average cumulative 7-day rainfall for Fort Collins and Greeley was 14.0 mm. The third sampling event was on June 4, 2010 in the middle of snowmelt and runoff when average flow rates in the river were near 28.32 m^3/s, no rainfall had occurred and

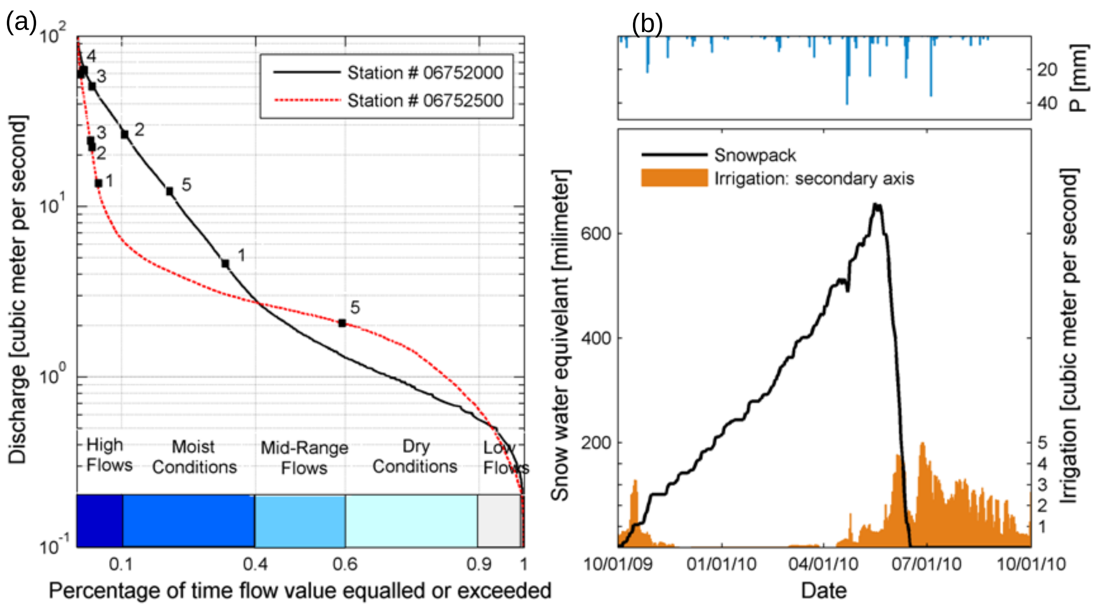


Figure 2.2: (a) Flow duration curves for the Poudre River at the mouth of the canyon near Fort Collins, CO (ST # 0675000) and near Greeley, CO (ST # 06752500) with sampling events indicated, (b) SNOTEL snow water equivalent curve for sites contained in the Poudre River watershed, mean flow rate for the major irrigation ditches in the Poudre River watershed, and the mean rainfall for Fort Collins and Greeley, CO.

water in the major irrigation ditches was flowing at an average rate of 3.85 m^3/s. Samples for the fourth event were taken on June 18, 2010 when all snow had melted and runoff was at its peak. River flow rates for this date averaged over 42.48 m^3/s. This sampling event also occurred 4 days after 48.3 mm of rain fell in Fort Collins, CO and 94.0 mm of rain fell in Greeley, CO. The fifth sampling event took place July 16, 2010. This sampling event was characterized by intense agricultural irrigation, low river flows downstream and no recent precipitation. As shown in Figure 2.2a, during the fifth sampling event flows upstream in the Poudre River were classified under moist conditions, while flows downstream near Greeley were near dry conditions. This could be due to the absence of a significant rainfall event for more than a month and/or significant irrigation diversions upstream. Samples for the sixth and seventh sampling events were obtained September 17, 2010 and February 22, 2011, respectively. The growing season in northern Colorado begins to come to a close in September, which is reflected in the decreasing average irrigation flow value of 0.7 m^3/s. In addition, flows in the river only increase slightly between upstream and downstream gaging stations. This is most likely due to the small amount of irrigation that continues to occur before the first frost. Hydrologic conditions during the final sampling event included no precipitation, no irrigation, increasing snowpack, and low flow conditions in the Poudre River.

A minimum of three samples (total volume of 500 milliliters) were taken at each site across the width of the river or canal. The samples were collected in acid washed Nalgene bottles and stored at 4ºC. Prior to the total phosphorus analysis, samples were pre-filtered and brought to room temperature. An acid persulfate digestion method (USEPA, 1992; Hach method 8190) was used with a 0.06-3.5 mg/L range TP test set

(Hach Company, Loveland, CO). For samples outside this range, the Molybdovanadate method with acid persulfate digestion (USEPA, 1992; Hach method 10127), which can measure a range of 1-100 mg/L, was used. TP analyses were completed within a week of the sampling date.

2.2.4 Data Analysis

The aqueous samples were collected and measured for total phosphorus and other water quality characteristics. Variation among hydrologic events was determined with an analysis of variance (ANOVA) in Matlab R2009b. In order to better understand the importance of sampling site location in relation to anthropogenic sources, an ANOVA was also used to compare sites located in the pristine, urban (downstream from WWTPs), agricultural (downstream from CAFOs), and mixed-urban/agricultural (downstream from WWTPs *and* CAFOs) landscapes.

Impending state water quality standards necessitate a better understanding of nutrient dynamics in surface water bodies. While the high-resolution data obtained in this study were instrumental in understanding phosphorus occurrence and transport throughout the watershed, a closer look at the river was also needed. A noticeable change in phosphorus concentration occurred 55 km (34 miles) from the confluence with the South Platte. Therefore, the 17 data points along the Poudre River were separated at this point 55 km (34 miles) from the confluence into upstream; and downstream data sets and a separate analysis of variance were used to measure the variability of these two regions.

The variability and complexity of the data required a nonlinear tree regression analysis to determine what anthropogenic sources and transport mechanisms have the greatest impact on phosphorus concentrations throughout the watershed and along the river for each hydrologic condition. The nonlinear tree regression ranked the top variables affecting phosphorus concentrations. Variables included in this analysis were CAFO Capacity, WWTP Capacity (representing average annual discharge), CAFO Overland Distance, CAFO Canal Distance, CAFO Stream (and/or river) Distance, and WWTP Stream (and/or river) Distance. While all of these variables were used when performing regression analyses for the watershed as a whole, "Total Distances" were calculated for river samples by adding CAFO overland, canal, and river distances. The same variables were used for the multiple linear regression analysis. The multiple linear regression analysis was used for all 48 watershed samples and for the Poudre River samples to determine how well the top variables estimated phosphorus concentrations throughout the watershed and in the river. The anthropogenic and spatial variables listed above were obtained using the methods described in Section 2.2.2. In addition, these variables were used directly or with inverse distance weighting in both the nonlinear and linear regressions. Inverse distance weighting was calculated using equation 2.1.

Equation 2.1

$$IDW = \frac{\sum_{j}^{n} \frac{Capacity_j}{distance_j}}{\sum_{j=1}^{n} \frac{1}{distance_j}}$$

Capacities for CAFOs could be inverse distance weighted by overland, canal, or stream distances (or total distance for river samples), but WWTP capacities could only be inverse distance weighted by stream distances.

2.3 Results and Discussion: Watershed-Scale Analysis of the Poudre River Basin

A novel approach for determining watershed-scale impacts of anthropogenic sources of contamination was developed and used in the Poudre River watershed in Northern Colorado. This method includes WWTP and CAFO capacity and geospatial information of sources to obtain occurrence and transport information for phosphorus. In the following sections, the impacts of hydrologic events on phosphorus concentrations are discussed. Geospatial factors influencing the transport of phosphorus, including irrigation ditches, are also analyzed and presented. A regression model for determining expected P concentrations in the Poudre River and surrounding watershed based on capacity and location relative to sampling stations is also described.

2.3.1 Temporal Variability of TP Concentrations under Varying Hydrologic Regimes

An ANOVA was performed to determine the differences among samples collected from all of the sampling sites during the five hydrologic sampling periods and the results are shown in Figure 2.3. Phosphorus values for the first samples (taken during 58.4 mm rainfall event) ranged from 0.080 milligrams per liter (mg/L) total phosphorus (TP) to 2.1 mg/L TP. For the second sampling event, phosphorus values ranged from 0.090 mg/L TP to 1.0 mg/L TP. The third sampling event yielded data ranging from 0.12 mg/L TP to 1.0 mg/L TP, fourth sampling results yielded phosphorus values ranging from 0.075 mg/L TP to 0.79 mg/L TP with two outliers (1.3 and 1.7 mg/L TP), and samples taken during the fifth sampling event ranged from 0.11 mg/L TP to 3.1 mg/L TP with one outlier (3.9 mg/L TP). Samples collected in September and February produced similar results to those collected during the second, third, and fourth sampling events. Samples collected during the sixth sampling contained TP ranging from 0.085 mg/L to 0.90 mg/L with four outliers ranging from 1.0 mg/L to 6.3 mg/L. The final sampling event yielded aqueous samples with TP values ranging from 0.09 mg/L to 0.41 mg/L with four outliers ranging from 0.80 mg/L to 1.5 mg/L. As shown in the figure, results from the analysis of variance indicated that the first and fifth sampling events were statistically different from the other five sampling events with a *p value* = 1.7e-5, while sampling events 2, 3, 4, 6, and 7 were not statistically different.

These results show the impacts of different hydrologic regimes on the occurrence and transport of phosphorus concentrations in surface water. The average annual precipitation for the semi-arid study area is approximately 381 mm per year (NOAA, 1996). In this study a 58.4 mm rainfall event was captured in the first sampling event. Significantly higher phosphorus concentrations (p-value = 1.7e-5) found in the samples taken the day of the rainfall event suggest how precipitation, and hence runoff, can increase phosphorus concentrations in agricultural areas where CAFOs are prevalent. Similar results were reported by Arheimer and Lidén (2000), who found positive correlations between phosphorus fractions and variables describing recent runoff or precipitation events in agricultural catchments. The fourth sampling event was also taken after a rainfall event but occurred at a different point in the hyetograph (four days after rainfall). As shown in

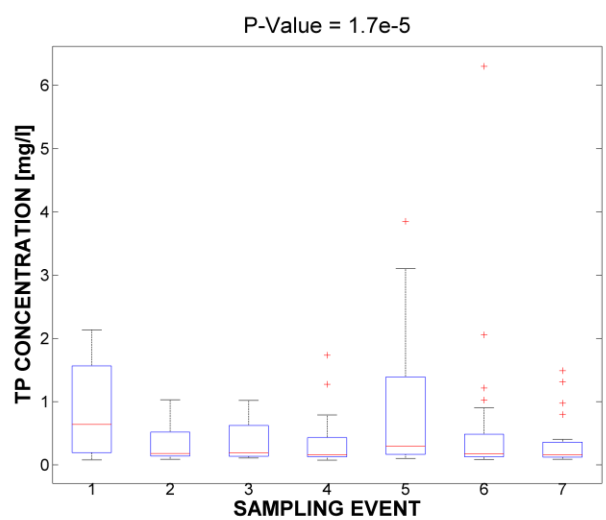


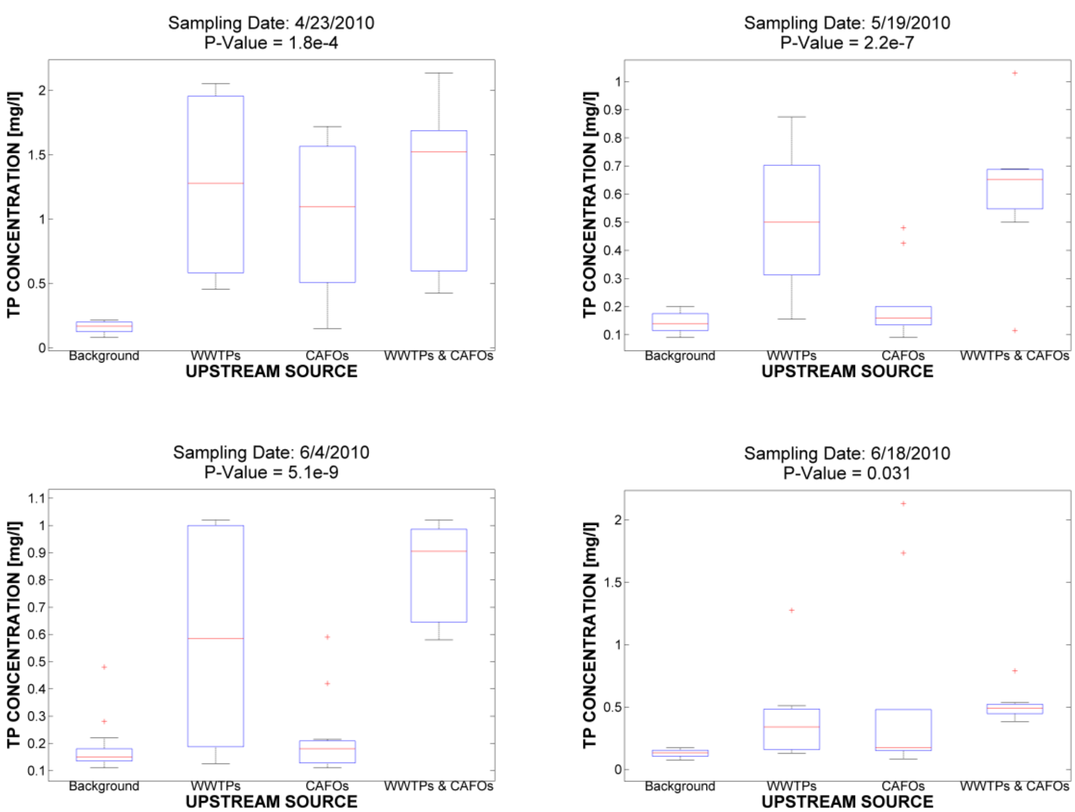
Figure 2.3: Analysis of variance for testing the differences between samples collected during different hydrologic regimes (boxes and whiskers represent 25%, 50%, and 75% quartiles and outliers).

Figure 2.3, samples from this event did not show statistically higher phosphorus concentrations. This suggests that in order to capture non-point source impacts on surface water due to excess runoff during precipitation events, samples must be obtained during or immediately after precipitation events. This is an important finding with respect to sampling plans because it shows the importance of timing when monitoring surface water quality.

The fifth sampling event also showed elevated phosphorus concentrations. As presented in Table 2.1, the most striking difference between the first and fifth sampling events and the second, third, and fourth sampling events was the average flow in the Poudre River. Average river flows for the first and fifth samples were 5.01 m^3/s and 4.08 m^3/s, respectively, while the lowest average river flow for these other three events was 25.0 m^3/s. Since phosphorus was measured using concentrations (in mg/L), low flows and the lack of dilution for point sources could help explain significantly higher P levels during the fifth sampling event. However, low flows were also present during the sixth and seventh sampling events. More irrigation was occurring in July as evident in the difference between upstream and downstream flow and the higher average irrigation value of 2.1 m^3/s. It appears that low flow conditions in combination with irrigation activities produce elevated TP values throughout the watershed. This agrees with results produced by Arheimer and Lidén (2000), which found that phosphorus concentrations were elevated during flow increases at low-flow conditions and diluted as the wetness in the catchment increased. This could help explain why phosphorus concentrations for the sixth and seventh sampling events were not also significantly higher. Low flow conditions result in elevated phosphorus concentrations when irrigation and precipitation increase the flow into the system, thereby transporting nutrients from anthropogenic sources to nearby water bodies and then to the river.

An ANOVA was also used to determine how WWTPs and CAFOs impact phosphorus concentrations in downstream sampling locations. Using ArcGIS 9.3 (Redlands, CA, USA), irrigation ditch, river, and stream sampling locations were categorized based on their proximity to phosphorus sources in the watershed. Sampling sites were located directly downstream of background sources of phosphorus (no WWTP or CAFO influence), WWTPs only, CAFOs only, or WWTPs and CAFOs. Figure 2.4 contains ANOVA plots for each sampling event.

Wastewater treatment plants appear to have the greatest impact on downstream phosphorus concentrations for most sampling dates. Confined animal feeding operations appear to have the greatest effect on water quality during and following precipitation, as shown by the ANOVA of the 4/23/2010 sampling event. Due to its lack of irrigation and precipitation, the final sampling event (2/22/2011) was considered the "control" for this study. The ANOVA for this sampling event seems to support this assumption. For the final sampling event, TP concentrations were significantly higher downstream from WWTPs than at any other location, including downstream from both WWTPs and CAFOs. Winter months are characterized by low flow conditions and no agricultural irrigation. These factors combined with no precipitation allow WWTP effluent to have a greater impact on water quality throughout the watershed. Additionally, CAFOs alone only had a statistically significant effect on downstream water quality during the first sampling event. However, TP concentrations were elevated in samples collect from locations located directly downstream from CAFOs *and* WWTPs for all sampling events. It cannot be automatically inferred that these higher TP concentrations are primarily due to WWTPs for two reasons. First, sample locations classified as downstream from WWTPs only are much closer to the largest WWTPs in the watershed than sample locations classified as downstream from WWTPs and CAFOs. Processes such as attenuation can occur downstream, which can lessen a source's impact on TP concentrations in the river. Second, locations classified as downstream from WWTPs and CAFOs are actually located closer to larger CAFOs than those classified as downstream from only CAFOs. As shown in Figure 2.1, most of the CAFOs in the Poudre River watershed are located in the lower portion of the watershed between Fort Collins and Greeley. Therefore, many of the sample locations downstream from the major CAFOs are also downstream from the WWTPs in Fort Collins. More analysis was needed to more thoroughly decipher anthropogenic TP contributions along the Poudre River.



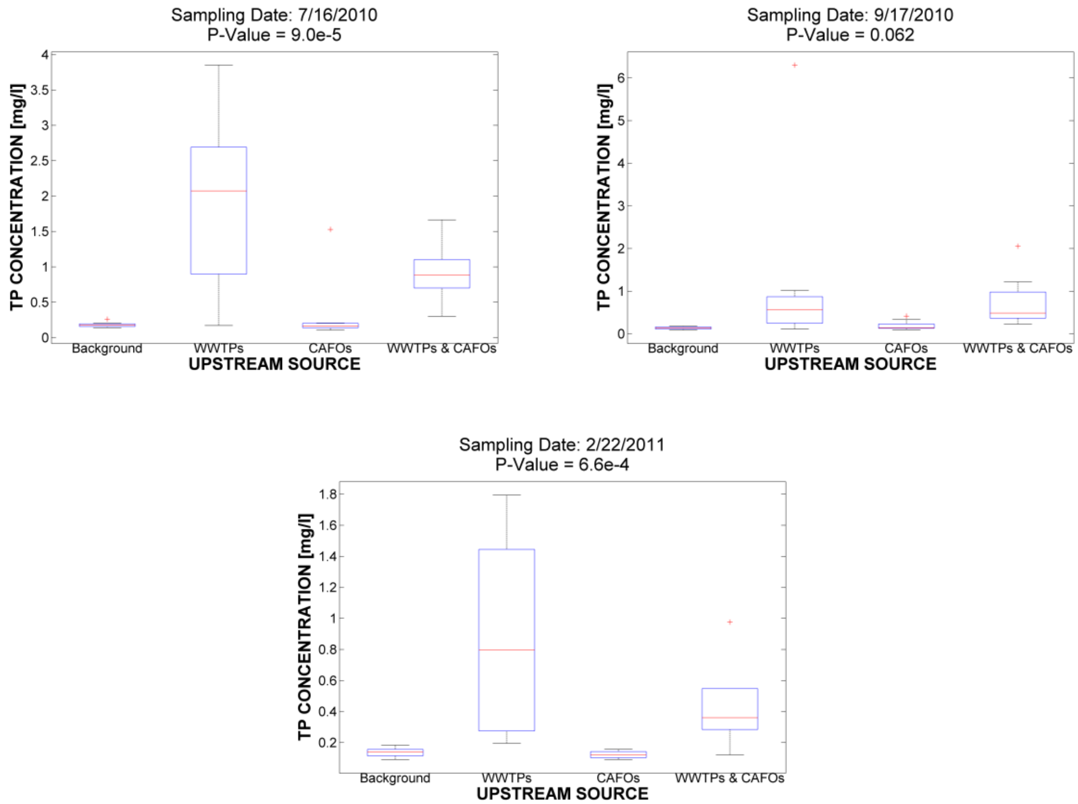


Figure 2.4: Analysis of variance depicting the impact of upstream anthropogenic sources on downstream phosphorus concentrations.

2.3.2 Key Anthropogenic and Geospatial Factors

2.3.2.1 Tree Regression Analysis

Due to the complexity of the geospatial setting in the Poudre River watershed, a regression tree analysis was used to determine the most important factors for determining phosphorus concentrations in the watershed. The non-linear regression method partitions the space into smaller, more manageable regions that make up each branch of the tree. This analysis gives insight into the components that affect phosphorus concentration the most for each hydrologic condition. The results for all of the sampling events are shown in Table 2.2 with the ranking of significance for each component.

Table 2.2: Summary of principal anthropogenic and spatial factors affecting phosphorus concentration along the Poudre River River for each sampling event.

Date	Factor Significance		
	Primary	Secondary	Tertiary
4/23/2010	CAFO Capacity	CAFO Canal Distance	WWTP Capacity
5/19/2010	WWTP Stream Distance	CAFO Capacity IDW[1] Overland Distance	CAFO Stream Distance
6/4/2010	WWTP Stream Distance	WWTP Capacity	CAFO Stream Distance
6/18/2010	CAFO Capacity IDW Overland Distance	CAFO Canal Distance	CAFO Stream Distance
7/16/2010	WWTP Capacity IDW Stream Distance	CAFO Capacity IDW Ca-nal Distance	CAFO Overland Distance
9/17/2010	CAFO Capacity	WWTP Capacity IDW Stream Distance	CAFO Stream Distance
2/22/2011	CAFO Canal Distance	WWTP Capacity	CAFO Stream Distance

[1] Inverse Distance Weighted

As shown in Table 2.2, the most important variable impacting phosphorus concentrations for the first sampling (precipitation event) was CAFO capacity. For the fifth sampling taken during low river flow conditions and irrigation, the most important variables were WWTP capacity and CAFO capacity inverse distance weighted (IDW) with stream and canal distance, respectively. It appears that unless there is a precipitation event, WWTP capacity will determine the TP concentration in the system, while CAFO capacity and irrigation canal distance will determine TP during precipitation events. This could also explain the outcome of the fourth sampling event's tree regression, which shows all CAFO variables to be most important. Sampling for this event occurred four days after a rain fell throughout the watershed. Unlike the first and fourth sampling events, the sixth sampling event did not occur during or after a precipitation event, but the tree regression analysis determined CAFO capacity to be the most significant factor. One would expect this event to produce similar results as the seventh sampling event due to similar hydrologic characteristics for both sampling days. While WWTP capacity IDW with stream distance was of secondary importance for the sixth sampling event, it is unclear why CAFO capacity was of primary importance. The only reasoning could be found in the difference between upstream and downstream flow, as outlined in Table 2.1. During the sixth sampling event, flow was greater at the downstream gauge in Greeley. This is similar to the first and fourth sampling events, where greater flow was likely due to runoff from the precipitation events. However, for the sixth sampling events, higher flow downstream was probably caused by return flows from irrigation, maximizing inputs from agricultural point sources. Similarly, the final sampling event yielded CAFO canal distance as the most important variable and WWTP capacity as the secondary factor. The initial assumption that the final sampling event could serve as the "control" for this study was only supported by the secondary factor in the tree regression analysis (WWTP capacity).

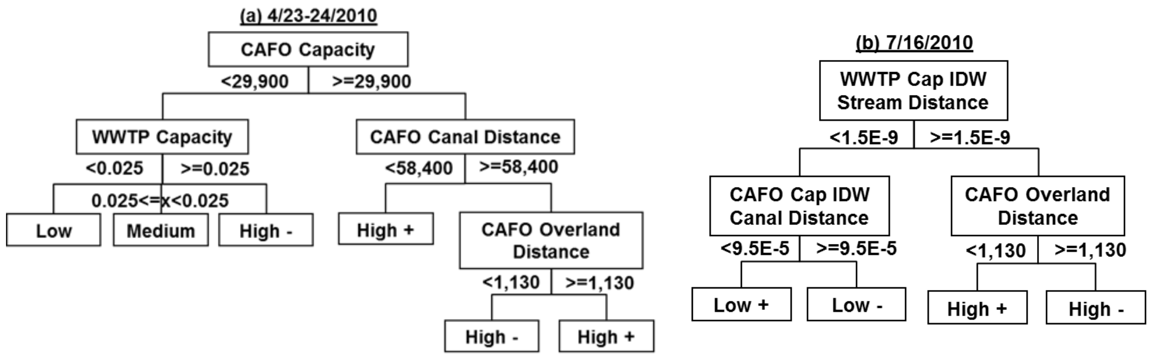


Figure 2.5: Regression tree analysis for the 4/23/2010 (precipitation event) and 7/16/2010 (end of runoff and middle of irrigation period sampling events, where Low = 0.2 mg/L TP, Medium = 0.2-0.4 mg/L TP, High- = 0.4-1 mg/L TP, and High+ > 1 mg/L TP.

Figure 2.5 contains the regression trees for the first and fifth sampling events that produced significantly higher phosphorus concentrations. In the presence of rainfall, agricultural point sources have a greater influence on phosphorus concentrations. As the number of animals impacting a location increases, the importance of geospatial factors (e.g. irrigation ditch/canal and overland distance) also increases as shown in Figure 2.5a. As the number of animals impacting a location decreases, the importance of urban point sources (WWTPs) increases. The fifth sampling event also produced high concentrations of phosphorus, but these results were not due to rainfall. These significantly higher concentrations are likely due to irrigation and low flow conditions decreasing the WWTP dilution effect. Therefore, it may be inferred that hydrologic events contributing to the occurrence of significantly higher phosphorus levels in surface water include precipitation, low flow conditions, and irrigation in semi-arid areas where natural tributaries are rare and man-made irrigation ditches dominate the landscape.

2.3.2.2 Multiple Linear Regression Analysis

The nonlinear tree regression was used to rank critical anthropogenic and spatial factors impacting phosphorus concentrations in the Poudre River basin. Furthermore, a multiple linear regression was used to determine how well these key factors explain total phosphorus concentrations. As in the tree regression analysis, spatial distances were used directly or to inverse distance weight anthropogenic factors in the multiple linear regression equations in order to obtain the best coefficient of determination.

The most important variables for the first sampling event according to the tree regression analysis were CAFO capacity, CAFO canal distance, and WWTP capacity. These three variables along with WWTP stream distance provided the highest R^2 values in the multiple linear regression (MLR) analysis (Equation 1, Table 2.3). These four values alone with no inverse distance weighting gave R^2=0.59. When CAFO overland distance and CAFO stream distance were added, the R^2 value increased slightly to 0.60.

Table 2.3: Multiple linear regression equations for each sampling event using critical anthropogenic and spatial factors obtained from the nonlinear tree regression analysis.

Sampling Event/ Equation No.	MLR Equation	Coefficient of Determination
1	$y = a_0 + a_1 \sum_{j=1}^{n} C_{j,CAFO} + a_2 \sum_{j=1}^{n} C_{j,WWTP} + a_3 \sum_{j=1}^{n} d_{j,CAFO_{OL}} + a_4 \sum_{j=1}^{n} d_{j,CAFO_{Canal}} + a_5 \sum_{j=1}^{n} d_{j,CAFO_{Stream}} + a_6 \sum_{j=1}^{n} d_{j,WWTP_{Stream}}$	0.60

2	$y = a_0 + a_1 \sum_{j=1}^{n} C_{j,WWTP} + a_2 \frac{\sum_{j=1}^{n} \frac{C_{j,CAFO}}{d_{j,OL}}}{\sum_{j=1}^{n} \frac{1}{d_{j,OL}}} + a_3 \sum_{j=1}^{n} d_{j,CAFO_{Canal}} + a_4 \sum_{j=1}^{n} d_{j,CAFO_{Stream}} + a_5 \sum_{j=1}^{n} d_{j,WWTP_{Stream}}$	0.72
3	$y = a_0 + a_1 \sum_{j=1}^{n} C_{j,WWTP} + a_2 \frac{\sum_{j=1}^{n} \frac{C_{j,CAFO}}{d_{j,Canal}}}{\sum_{j=1}^{n} \frac{1}{d_{j,Canal}}} + a_3 \sum_{j=1}^{n} d_{j,CAFO_{OL}} + a_4 \sum_{j=1}^{n} d_{j,CAFO_{Stream}} + a_5 \sum_{j=1}^{n} d_{j,WWTP_{Stream}}$	0.84
4	$y = a_0 + a_1 \frac{\sum_{j=1}^{n} \frac{C_{j,WWTP}}{d_{j,Stream}}}{\sum_{j=1}^{n} \frac{1}{d_{j,Stream}}} + a_2 \frac{\sum_{j=1}^{n} \frac{C_{j,CAFO}}{d_{j,OL}}}{\sum_{j=1}^{n} \frac{1}{d_{j,OL}}} + a_3 \sum_{j=1}^{n} d_{j,CAFO_{Canal}} + a_4 \sum_{j=1}^{n} d_{j,CAFO_{Stream}}$	0.59
5	$y = a_0 + a_1 \frac{\sum_{j=1}^{n} \frac{C_{j,WWTP}}{d_{j,Stream}}}{\sum_{j=1}^{n} \frac{1}{d_{j,Stream}}} + a_2 \frac{\sum_{j=1}^{n} \frac{C_{j,CAFO}}{d_{j,Canal}}}{\sum_{j=1}^{n} \frac{1}{d_{j,Canal}}} + a_3 \sum_{j=1}^{n} d_{j,CAFO_{OL}} + a_4 \sum_{j=1}^{n} d_{j,CAFO_{Stream}}$	0.65
6	$y = a_0 + a_1 \frac{\sum_{j=1}^{n} \frac{C_{j,WWTP}}{d_{j,Stream}}}{\sum_{j=1}^{n} \frac{1}{d_{j,Stream}}} + a_2 \sum_{j=1}^{n} C_{j,CAFO} + a_3 \sum_{j=1}^{n} d_{j,CAFO_{OL}} + a_4 \sum_{j=1}^{n} d_{j,CAFO_{Canal}} + a_5 \sum_{j=1}^{n} d_{j,CAFO_{Stream}}$	0.95
7	$y = a_0 + a_1 \sum_{j=1}^{n} C_{j,WWTP} + a_2 \frac{\sum_{j=1}^{n} \frac{C_{j,CAFO}}{d_{j,OL}}}{\sum_{j=1}^{n} \frac{1}{d_{j,OL}}} + a_3 \sum_{j=1}^{n} d_{j,CAFO_{Canal}} + a_4 \sum_{j=1}^{n} d_{j,CAFO_{Stream}} + a_5 \sum_{j=1}^{n} d_{j,WWTP_{Stream}}$	0.30

Equation 1 shows that all variables were used with no inverse distance weighting. Table A.2 in the appendix shows the relative importance of each variable when added one by one into the MLR equation. The order that each variable was added into the equation was based on the tree regression results. When only CAFO capacity was used, R^2=0.34.

The next variable added was CAFO canal distance, which produced an R^2 value of 0.41. The coefficient of determination did not increase significantly again until WWTP stream distance was added (R^2=0.59). According to the tree regression, WWTP capacity was the third most important variable, however the MLR suggests that WWTP stream distance is more important. However, it could just be that the *combination* of these variables that produces the higher regression coefficient. As mentioned previously, all variables had to be used separately in the MLR equation with no inverse distance weighting. This could be explained as the distances indicating source areas rather than sink areas due to the confounding nature of stream distance with overland runoff. Attenuation of phosphorus cannot occur due to mixing and continual inputs from runoff as the water flows downstream. This is also supported by Figure 2.7 in section 2.4.1, which shows minimal attenuation downstream.

According to the tree regression analysis, WWTP stream distance, CAFO capacity inverse distance weighted with overland distance, and CAFO stream distance were the three most critical variables for the second sampling event. This was supported by the MLR analysis. The final variables used are shown in Equation 2. Table A.2 in the appendix shows that the R^2 value only notably increased when each of these three variables were added. R^2 values ≥ 0.7 were only found when CAFO canal distance and CAFO stream distance were used directly and CAFO capacity was inverse distance weighted with CAFO overland distance in the regression equation. It made no difference whether or not WWTP stream distance was direct or used in inverse distance weighting, but the highest coefficient of determination was obtained when WWTP stream distance was a separate variable and not used to inverse distance weight WWTP capacity.

WWTP stream distance, WWTP Capacity, and CAFO stream distance were presented as the most critical anthropogenic and spatial variables for the third sampling event by the non-linear tree regression. This was supported by the MLR analysis (Equation 3). When only WWTP stream distance was used, R^2=0.69; and when WWTP capacity was included in the regression equation, coefficients of determination were above 0.75.

The most important variables impacting phosphorus concentrations in the fourth sampling event were CAFO capacity inverse distance weighted with overland distance, CAFO canal distance, and CAFO stream distance. These variables did not agree with the multiple linear regression analysis (Equation 4). WWTP capacity needed to be inverse distance weighted with WWTP stream distance in order for the R^2 value to be above 0.50. As shown in Table A.2 in the appendix, the top three variables according to the tree regression only produced an R^2=0.31. The coefficients of determination were achieved when CAFO canal distance was input directly into the regression equation and when CAFO capacity was direct or inverse distance weighted by overland distance, which is similar to the results of the first, precipitation-driven sampling event. However, it was not until the WWTP variable was input into the equation that R^2 increased to 0.59.

WWTP capacity, CAFO capacity, and CAFO canal distance were the most significant factors in the tree regression analysis for the fifth sampling event. The multiple linear regression analysis also seemed to indicate that this event was dominated by WWTP activity. Only when WWTP capacity was inverse distance weighted were R^2 values $\geq$0.60. The highest regression coefficient, R^2=0.65, was obtained when CAFO capacity was inverse distance weighted with CAFO canal distance (Equation 5). As shown in Table A.2 in the appendix, obtaining a suitable coefficient of determination (R^2=0.65) depended on all variables being included in the regression equation. This sampling event produced the same three most important variables as the first sampling event. However, inverse distance weighting was used for the regression analysis while it was not used for the data produced from sampling during a precipitation event. It appears that during low flow conditions with no rainfall, attenuation of phosphorus occurs downstream from the source.

The most significant factors for determining phosphorus concentration for the sixth sampling event were CAFO capacity, WWTP capacity inverse distance weighted with stream distance, and CAFO stream distance. The multiple linear regression analysis supported these results. When only CAFO capacity was used in the MLR equation, the R^2 value equaled 0.85. The coefficient of determination then steadily increased with the addition of each variable until it reached 0.95 with all variables added into the equation (see Table A.2, appendix). The sixth sampling event produced the highest overall coefficient of determination.

According to the tree regression analysis, CAFO canal distance, WWTP capacity, and CAFO stream distance were the primary, secondary, and tertiary factors for the seventh sampling event, respectively. This was not supported by the MLR analysis. In fact, MLR was an inadequate method for predicting phosphorus concentrations throughout the Poudre River Basin for the final sampling event. The highest coefficient of determination that could be achieved with the available anthropogenic and geospatial variables was $R^2=0.30$.

2.4 Results and Discussion: Phosphorus Concentrations along the Poudre River

While a comprehensive, watershed-scale survey with fine spatial resolution is important for studying and understanding water quality dynamics across space and time, it is also just as critical to take a closer look at the main channel of the system. As numerical water quality standards are developed and published, the focus will shift to major surface water bodies like the Poudre River. For this reason, the statistical methods that were used for the entire watershed (analysis of variance, nonlinear tree regression, and multiple linear regression) were also used to analyze the seventeen samples taken from the Poudre River, including the north and south forks (see Figure 2.1b).

2.4.1 Spatial Variability: Comparing Upstream and Downstream TP Concentrations

A statistically significant difference of measured phosphorus concentration occurred upstream and downstream from the point where the effluents from three major WWTPs enter the Poudre River for all hydrologic events, as shown in Figure 2.6. The three WWTPs include Boxelder Sanitation District (2.1 MGD average flow), Drake Water Reclamation Facility (15.2 MGD average flow) and South Fort Collins Sanitation District (2.8 MGD average flow) and, combined, are the largest point source contributors of phosphorus on the Poudre River. The average monthly flow of the gross effluent from each WWTP was used for the analysis (USEPA 2010). The gross effluent from each WWTP remained relatively consistent during the sampling period.

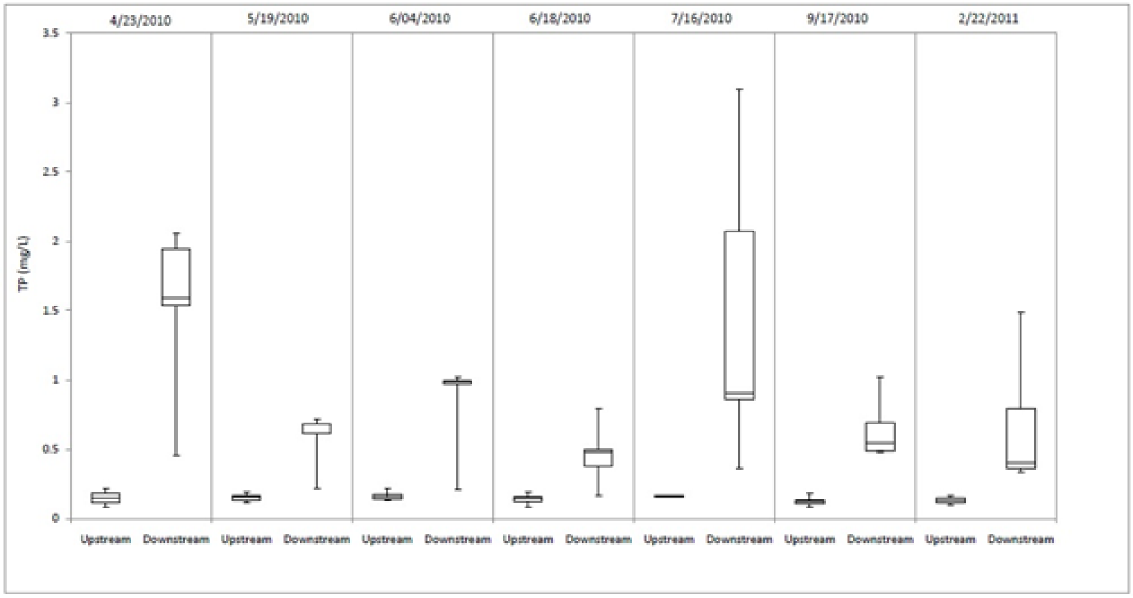


Figure 2.6: Total phosphorus concentration measured along the Poudre River for all five hydrologic events. Each event is divided by samples taken upstream and downstream from significant WWTP influence.

Figure 2.6 illustrates that the variability in the upstream phosphorus concentration is marginal. An average of 0.15 ± 0.065 mg/l was measured for all of the upstream samples and this value is assumed to be the background phosphorus concentration on the Poudre River, which is consistent with the mean total phosphorus concentration of stream water in the continental U.S. of 0.13 mg/l (Smith et al., 1999). The upstream region is predominantly a pristine region with limited urban and agricultural influence.

While slightly more variation was observed in the downstream data sets corresponding to events two, three, four, six, and seven, events one and five exhibited highest variation in the downstream phosphorus concentration. The first sampling event was influenced by precipitation, which maximizes phosphorus mobilization and inhibits natural attenuation. Event five was characterized by low flows, which minimize phosphorus mobilization and promotes natural attenuation, and irrigation, which may allow phosphorus from CAFOs to be transported back to the river.

The natural attenuation, which occurs in the fifth, sixth, and seventh sampling events, can be seen in Figure 2.7, as the phosphorus concentration decreases as the distance from sources increases. These observations are similar to other studies in WWTP impacted streams (House and Denison, 1998; Haggard et al ., 2001), where bed-sediments were responsible for removing some water column phosphorus during low flow conditions. Furthermore, the influence of CAFOs appears to be greatest during the precipitation event (4/23/2010), highlighting the temporal importance of capturing nonpoint sources. Events five, six, and seven also showed the impact of CAFOs, where phosphorus concentrations decrease until the river is impacted by a large number of CAFO animals. This may be due to the low flow conditions, especially for events six and seven, or an increased return flow from irrigation canals promoting phosphorus transport (7/16/2010). The impact of CAFOs on water quality was also seen in the first sampling event, but attenuation was not achieved due to mixing from the rain event and continual inputs from runoff as the water flows downstream. Despite an apparent CAFO influence for the first and fifth hydrologic events, the three WWTPs dividing upstream and downstream data sets appear to have the greatest influence on phosphorus concentrations on the Poudre River.

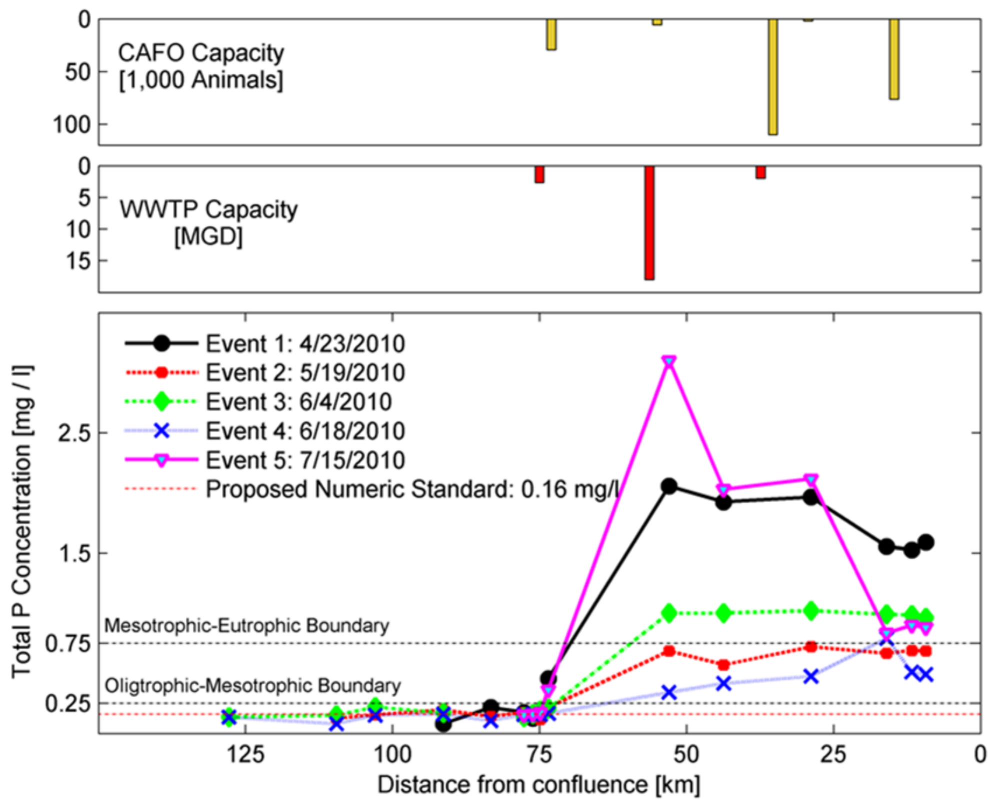


Figure 2.7: The phosphorus concentration along the Poudre River (for the first five sampling events) as a function of the distance from the confluence of the river, with the WWTP and CAFO influence points shown, for all events. The WWTP and CAFO influence indicates the point where the river is influenced and does not show the cumulative capacity. Boundary values obtained from USEPA (2010).

In contrast, the higher flow events (events 2, 3 and 4) do not appear to be influenced by the distance from the source. For example, event three in Figure 2.7 shows two distinctly and consistently different phosphorus values upstream and downstream from the WWTPs. For this event the phosphorus concentration in the river substantially increased where major WWTP effluents discharge to the river, and then remained relatively unchanged flowing downstream. Overall, these three sampling events have lower phosphorus concentrations due to increased dilution. This may suggest low-flow conditions generally have higher phosphorus concentrations due to a lack of dilution and natural phosphorus attenuation reduces the downstream concentration. Furthermore, high flow conditions limit downstream attenuation, and dilution reduces in-stream phosphorus concentrations.

In this study region both CAFOs and WWTPs impact phosphorus concentrations in the Poudre River. For example, the largest increase in phosphorus concentration occurs 53 km from the confluence. This sample location experiences the highest WWTP influence (18 MGD average flow) and the third highest CAFO influence (154,000 animals). Since a smaller increase of phosphorus concentration occurs under the influence of a much higher CAFO influence (76,550) and no WWTP influence, it may indicate WWTP influence dominate the downstream phosphorus concentration of the river.

2.4.2 Key Anthropogenic and Geospatial Factors

2.4.2.1 Tree Regression Analysis

Just as in section 2.3.2, a regression tree analysis was used to determine the most important factors for determining phosphorus concentrations along the Poudre River. This analysis gives insight into the components that affect phosphorus concentration the most for each hydrologic condition. The method for incorporated the geospatial distances into the regression equations was modified for analyzing the river phosphorus data. For the entire watershed, distances were used separately, whether directly or to inverse distance weight CAFO or WWTP capacity. To analyze CAFO impacts on occurrence and transport of phosphorus in the river, overland, canal, and stream distances were added together for one "total distance", or flow path, from the animal facility to the river. For WWTPs, distance was not used directly but only to inverse distance weight WWTP capacity. In the watershed-scale study, when stream distances were used directly in the regression equations, they implied source areas rather than sink areas due to the confounding nature of stream distance with overland runoff. Since WWTPs discharge into streams and rivers at a single location, using stream distance directly, without inverse distance weighting, seemed inaccurate when taking a closer look at phosphorus inputs and transport along the main river channel. The results for all of the sampling events are shown in Table 2.4 with the ranking of significance for each component.

Table 2.4: Summary of principal anthropogenic and spatial factors affecting phosphorus concentration along the Poudre River for each sampling event.

	Factor Significance	
Date	Primary	Secondary
4/23/2010	CAFO Capacity	
5/19/2010	CAFO Capacity	
6/4/2010	CAFO Capacity	WWTP Capacity
6/18/2010	CAFO Capacity	WWTP Capacity
7/16/2010	CAFO Capacity	
9/17/2010	CAFO Capacity	WWTP Capacity
2/22/2011	WWTP Capacity IDW[1] Total Distance	CAFO Capacity IDW Total Distance[2]

[1] Inverse Distance Weighted
[2] Total Distance = Overland Distance (CAFO only) + Irrigation Ditch Distance + River/Stream Distance

As shown in Figure 2.8 and Table 2.4, the most important variable impacting phosphorus concentrations for the first sampling (precipitation event) was CAFO capacity. The tree regression analysis produced similar results for all other sampling events except for the seventh sampling event. For the final sampling, taken during low river flow conditions, no irrigation, and no precipitation, the most important variables were WWTP capacity inverse distance weighted with the total distance, which is the distance the water flows from the source to the sampling location. These results differ from the outcomes of the watershed-scale study and contradict conclusions drawn from Figure 2.7. One shortcoming of this study was that the number of sample points was much greater than the number of flow monitoring stations along the river and throughout the watershed. This prevented the determination of load calculations, which could have given even more insight into these discrepancies. Regardless, the results for the river samples seem straightforward and simplified. It appears that unless there is a precipitation event or irrigation, WWTPs will determine the TP concentration in the river, while CAFO capacity is of primary importance during irrigation season and rainfall events.

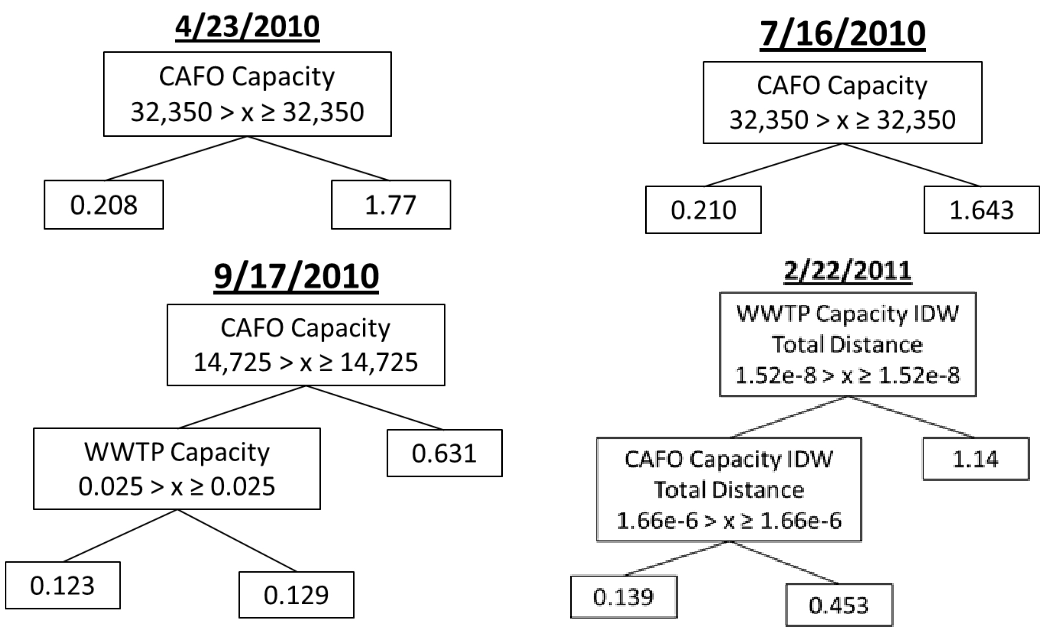


Figure 2.8: Regression tree analysis for the 4/23/2010 (precipitation event) and 2/22/2010 (winter dry period) sampling events, where CAFO Capacity values are in number of animals, WWTP capacity is in MGD, IDW values are capacity/distance in meters, and TP values in branches are in mg/L.

In the presence of significant rainfall and during irrigation season, CAFOs have a greater influence on phosphorus concentrations. As the number of animals impacting a location increases, TP concentrations also increase, as shown in Figure 2.8 for the first, fifth, and sixth sampling events. As the number of animals impacting a location decreases, the importance of point sources (WWTPs) increases (9/17/2010 sampling event). These results are similar to those described in section 2.3.2 for sampling event 1. They differ in that CAFO capacity is the most important variable for the 7/16/2010 sampling event and WWTP Capacity IDW with total distance is the primary factor for the sampling event that occurred on 2/22/2011. However, the results for the seventh sampling event in Figure 2.8 and Table 2.2 support the use of using a winter sampling event as a control, and the multiple linear regression analysis could give more insight into the validity of using geospatial variables for predicting river aqueous phosphorus concentrations.

2.4.2.2 Multiple Linear Regression Analysis

Multiple linear regression methods were used to determine how well key anthropogenic and spatial factors explain total phosphorus concentrations along the Poudre River. As in the tree regression analysis, spatial distances were added together for CAFOs and only used directly for WWTPs in the multiple linear regression equations in order to obtain the best coefficient of determination.

The most important variable for the first sampling event according to the tree regression analysis was CAFO capacity. This variable along with CAFO total distance and WWTP capacity provided the highest coefficient of determination in the multiple linear regression (MLR) analysis (Equation 1, Table 2.3). These three values alone with no inverse distance weighting gave R^2=0.99.

Table 2.5: Multiple linear regression equations for each sampling event using critical anthropogenic and spatial factors obtained from the nonlinear tree regression analysis.

Sampling Event/ Equation No.	MLR Equation	Coefficient of Determination
1	$y = a_0 + a_1 \sum_{j=1}^{n} C_{j,CAFO} + a_2 \sum_{j=1}^{n} d_{j,CAFO} + a_3 \sum_{j=1}^{n} C_{j,WWTP}$	0.99
2	$y = a_0 + a_1 \sum_{j=1}^{n} C_{j,CAFO} + a_2 \sum_{j=1}^{n} C_{j,WWTP}$	0.98
3	$y = a_0 + a_1 \sum_{j=1}^{n} C_{j,CAFO} + a_2 \sum_{j=1}^{n} C_{j,WWTP}$	0.96
4	$y = a_0 + a_1 \sum_{j=1}^{n} C_{j,CAFO} + a_2 \sum_{j=1}^{n} d_{j,CAFO} + a_3 \sum_{j=1}^{n} C_{j,WWTP}$	0.95
5	$y = a_0 + a_1 \sum_{j=1}^{n} C_{j,CAFO} + a_2 \sum_{j=1}^{n} C_{j,WWTP}$	0.93
6	$y = a_0 + a_1 \sum_{j=1}^{n} C_{j,CAFO} + a_2 \sum_{j=1}^{n} C_{j,WWTP}$	0.73
7	$y = a_0 + a_1 \frac{\sum_{j=1}^{n} \frac{C_{j,CAFO}}{d_{j,CAFO_{Total}}}}{\sum_{j=1}^{n} \frac{1}{d_{j,CAFO_{Total}}}} + a_2 \frac{\sum_{j=1}^{n} \frac{C_{j,WWTP}}{d_{j,WWTP_{Total}}}}{\sum_{j=1}^{n} \frac{1}{d_{j,WWTP_{Total}}}}$	0.66

Equation 1 shows that all variables were used with no inverse distance weighting. Table A.2 in the supplementary material shows the relative importance of each variable when added one by one into the MLR equation. The order that each variable was added into the equation was based on the tree regression results. When only CAFO capacity was used, R^2=0.42. The next variable added was CAFO total distance, which produced a coefficient of determination of 0.69. R^2 then increased to 0.99 when WWTP capacity was added. According to the tree regression, CAFO capacity was the only important variable, however the MLR suggests that CAFO total distance and WWTP capacity are also important. However, it could just be that the *combination* of these variables is what produces the higher regression coefficient. As mentioned previously, all variables had to be used separately in the MLR equation with no inverse distance weighting. As for the entire watershed, attenuation of phosphorus cannot occur due to mixing and continual inputs from runoff as the water flows downstream.

According to the tree regression analysis, CAFO capacity was also the only critical variable for the second and fifth sampling events. This was supported by the MLR analysis for the second sampling event, but not for the fifth. The final variables used are shown in Equations 2 and 5 include only CAFO capacity and WWTP capacity. For the second sampling event, an R^2 value of 0.70 was achieved with only CAFO capacity. When WWTP capacity was added, $R^2 = 0.98$. Alternatively, when only CAFO capacity was included in the MLR analysis for the sampling event occurring on 7/16/2010, $R^2 = 0.03$ (Table A.2, appendix), but when WWTP capacity was added, R^2 increased to 0.93.

For the third, fourth, and sixth sampling events, CAFO capacity was again identified as the primary factor, and WWTP capacity was named the secondary factor by the tree regression analysis. These results seemed to agree with the MLR analysis. However, for the fourth sampling event (6/18/2010), CAFO total distance had to be added to the equation directly for the R^2 value to surpass 0.90 (R^2=0.95). These results are similar to the results from the first sampling event. As stated previously, this sampling event also took place after a rain event. Although the precipitation event occurred four days before samples were collected, the MLR results suggest that geospatial factors (overland distance, irrigation ditch distance, and stream/river distance) continue to transport phosphorus to the river four days after precipitation.

The final sampling event, which took place 2/22/2011, was the only date that the nonlinear tree regression analysis did not indicate CAFO capacity as the primary factor for TP concentrations in the Poudre River. Instead, WWTP capacity inverse distance weighted (IDW) with total distance was the primary factor, while CAFO capacity IDW with total distance was the secondary factor. When only WWTP capacity IDW with total distance was included in the MLR equation, R^2=0.59 (Table A.2, appendix). In fact, WWTP capacity needed to be IDW with total distance in order for the R^2 value to be at or above 0.59. After adding CAFO capacity IDW with total distance, R^2=0.66. This coefficient of determination more than doubled the R^2 value determined in the watershed-scale study for this date (R^2=0.30). One reason for this could be the fact that irrigation ditches do not transport water during the winter months. Some of them are big enough to store water, but most of ditches were dry on this date of sample. Therefore, a complete data set could not be obtained for the entire watershed. However, all 17 river samples were obtained and analyzed, which provided a complete data set and better model for predicting phosphorus concentrations in the river. This was the only sampling event for the river analysis in which inverse distance weighting was used for the regression analysis. This supports the conclusion that during dry, low flow conditions with no rainfall and no irrigation, attenuation of phosphorus occurs downstream from the source.

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CHAPTER 3: FEASIBILITY OF USING THE SOIL AND WATER ASSESSMENT TOOL (SWAT) TO MODEL THE GEOSPATIAL HETEROGENITY OF BOXELDER CREEK BASIN

3.1 Introduction

Hydrologic and nutrient modeling with tools such as the Soil and Water Assessment Tool (SWAT) have increasingly been recognized as an important tool for improved understanding of the processes involved in generation of freshwater resources, as well as prediction of the potential impacts from urban and agricultural activities on such supplies. (Neitsch et al., 2005; Pohlert et al., 2005; Praskievicz and Chang, 2009; Sharpley et al., 2002) While high resolution water quality studies are critical for increasing current understanding of water and nutrient transport within a watershed, it is also important to develop physical models that can accurately simulate water and nutrient loading. Field assessment of water quantity and quality parameters can be time and money intensive. Models can often provide a more efficient means of evaluating water and nutrient parameters throughout a watershed (Sharpley et al., 2002). Models like SWAT can also be used to forecast management, anthropogenic, and climate change impacts on water quantity and quality. A study by Foy (2009) showed the viability of using SWAT to model the impacts of climate change on headwater basins in Colorado. One of the basins included in this study was the Upper Cache La Poudre (Poudre) River.

Figure 3.1 shows time series and other statistical plots comparing SWAT stream flow simulations with naturalized stream flows in the Upper Poudre River watershed. While not included in the study by Foy (2009), these plots describe how hydrologic variables in the front range of Colorado can be adequately modeled using SWAT. Boxelder Creek basin is the area of concern for this study and will be described more thoroughly in the following sections. Boxelder creek is a tributary of the Poudre River but is located in the lower portion of the watershed, outside of the study area described by the data in Figure 3.1. While SWAT has sufficiently modeled the upper section of the Poudre River, it is important to determine if the lower section, which includes a mixed land-use landscape and anthropogenic activities, can be modeled.

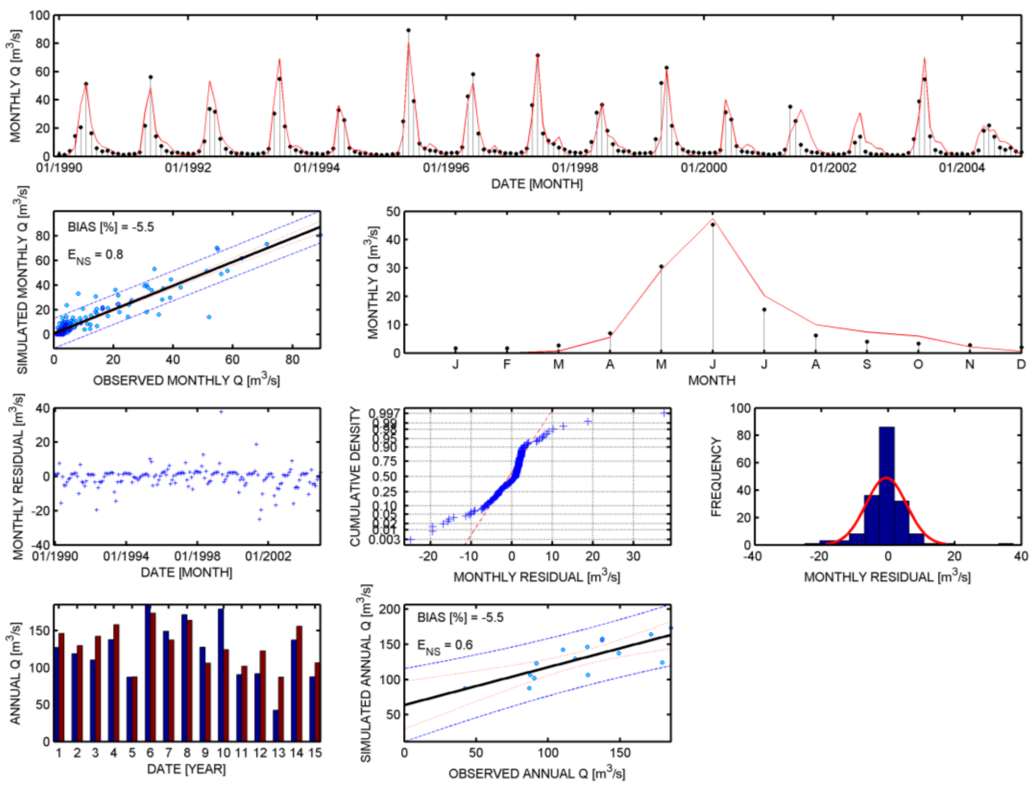


Figure 3.1: A time series and other statistical plots comparing SWAT stream flow simulations with naturalized stream flows in the Upper Poudre River watershed.

The first objectives of this study were to gain a better understanding of water and nutrient interactions in the lower portion of the Poudre River watershed by executing a thorough investigation of Boxelder Creek basin using using available data, aerial photography, and ground truthing. The second objective was to determine the feasibility of using SWAT to develop a model that could capture the spatial and hydrologic heterogeneity of the study basin and simulate water and nutrient routing in the watershed.

3.2 Study Basin

Boxelder Creek is a tributary of the Cache La Poudre (Poudre) River. The basin surrounding Boxelder Creek is 739 km^2 (285 mi^2) in area and spans two states, located primarily in northern Colorado with a small portion extending into southeastern Wyoming. Boxelder Creek originates in the mountainous terrain of southeastern Wyoming and flows southeast through a small portion of the Great Plains and the Front Range municipalities of Wellington and Fort Collins before reaching its confluence with the Poudre River.

The Boxelder Creek basin was chosen for this study because it exhibits similar geospatial heterogeneity as the Poudre River Basin but at a smaller, more manageable scale. Figure 3.2 presents the anthropogenic and geospatial characteristics of the study basin. The basin contains one beef animal feeding operation (AFO) (registered capacity = 150 animals (maximum capacity = 700), CDPHE, personal communication, 2011), one beef confined animal feeding operation (CAFO) (registered capacity = 18,000 animals, CDPHE, personal communication, 2011), and three dairy CAFOs (registered capacity ranging from 2,200 to 7,000 animals, CDPHE, personal communication, 2011). Two waste water treatment plants (WWTPs) discharge into Boxelder Creek. The Town of

Wellington Water Reclamation Facility is located directly south of Wellington and has an average annual discharge flow rate of 0.45 million gallons per day (MGD). Boxelder Sanitation District, located in Northeastern Fort Collins near the intersection of Prospect Road and I-25, discharges 1.5 MGD into Boxelder Creek approximately 91.4 m (100 yds) above the confluence with the Poudre River. Some of the sampling locations from the Poudre River study (Chapter 1) were within the study basin and are shown in Figure 3.2. Phosphorus data from these locations were used for model validation.

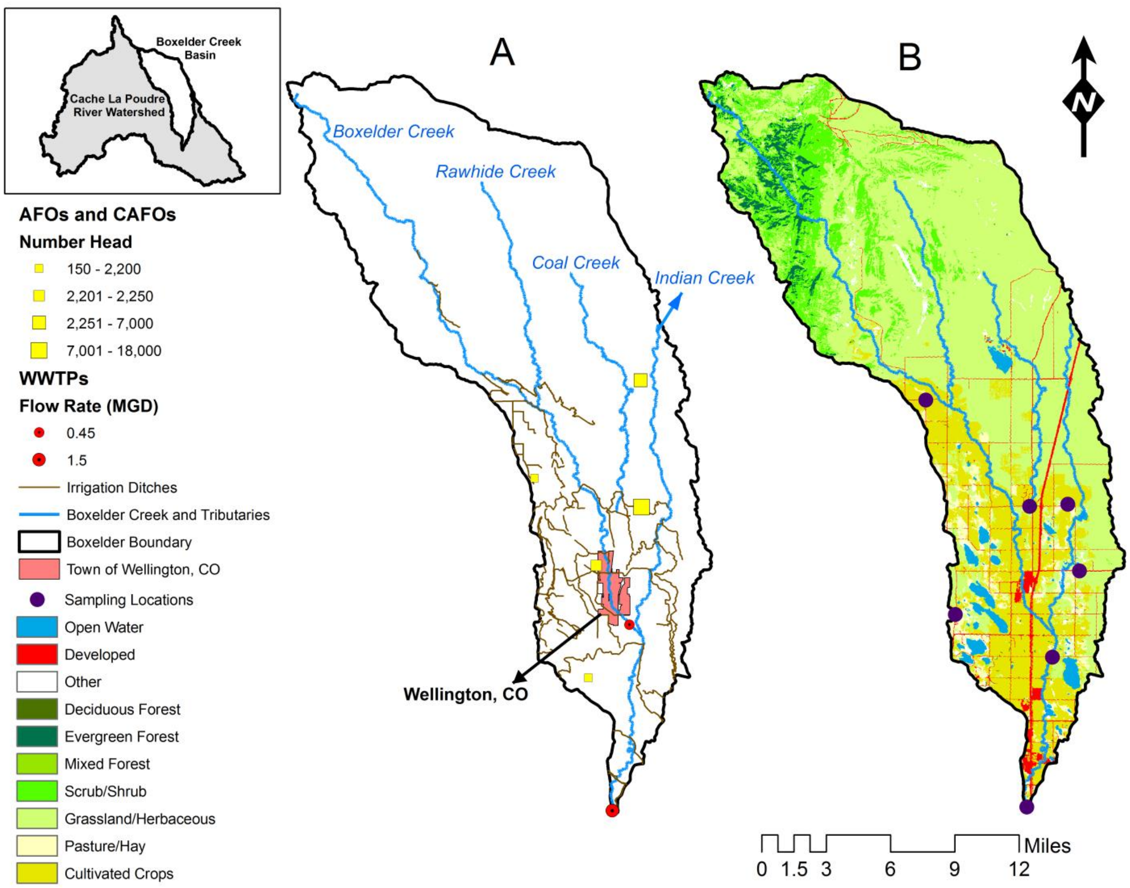
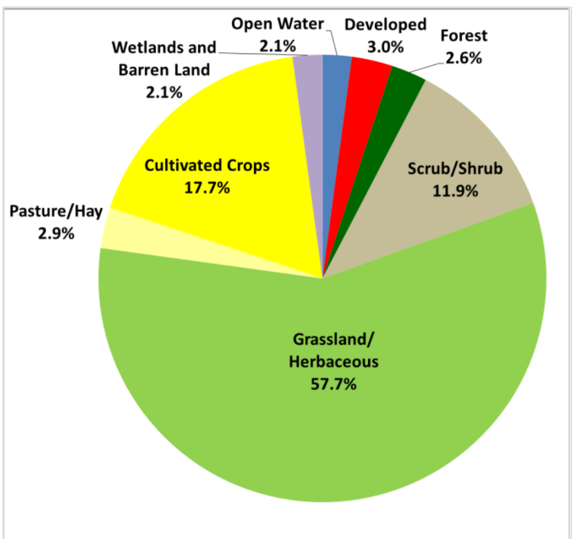


Figure 3.2: (A) Map of the study region showing Boxelder Creek and its tributaries, irrigation ditches, CAFOs, and WWTPs (B) Map of the Boxelder Creek basin showing sampling locations and NLCD 2001 land use classifications.

3.2.1 Land Cover/Land Use

The land cover distribution within the Boxelder Creek basin was described in Figure 3.2a using 2001 National Land Cover Data (NLCD 2001) and in Figure 3.2b (and the SWAT model) with the National Agricultural Statistics Service (NASS) 2008 Cropland Data Layer. Because of its location in the Front Range of Colorado and mostly moderate elevation, the basin is comprised mostly of grassland/herbaceous land cover, cultivated crops, scrub/shrub land. The majority of land employing cultivated crops consists of corn, wheat, and alfalfa.



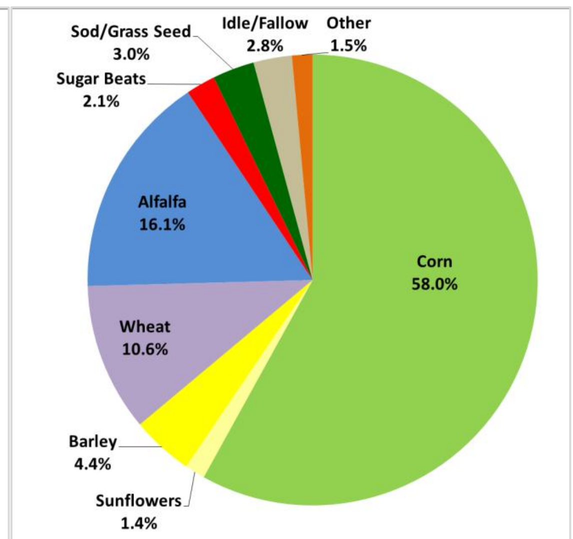


Figure 3.3: (A) Distribution of land cover in the Boxelder Creek basin, computed from NLCD 2001 (B) Distribution of cultivated crops in the study basin, computed from NASS 2008.

3.2.2 Soil

The dissemination of soil within the study basin was defined using the SSURGO Database. The percent land area defined by each hydrologic soil group is shown in Figure 3.4. The hydrologic soil group is a classification which refers to the drainage potential of a soil. Soils in group A have low runoff potential when thoroughly wet and typically have less than 10% clay and more than 90% sand or gravel. Group B soils have moderately low runoff potential when thoroughly wet and normally consist of 10-20% clay and 50-90% sand. Soils in group C have moderately high runoff potential when thoroughly wet and typically consist of 20-40% clay and less than 50% sand. Group D soils have high runoff potential when thoroughly wet, and usually consist of greater than 40% clay and less than 50% sand (NRCS, 2007). Soils in the study area are mostly classified as group B soils. In fact, almost 65% of the soil over the total land area of the watershed is defined in the Barnum series, which consists of very deep, well drained soils formed in calcareous alluvium from red bed sediments. Barnum soils are typical in areas with vegetation, wildlife habitat, and irrigated farmland (NCSS, 2005).

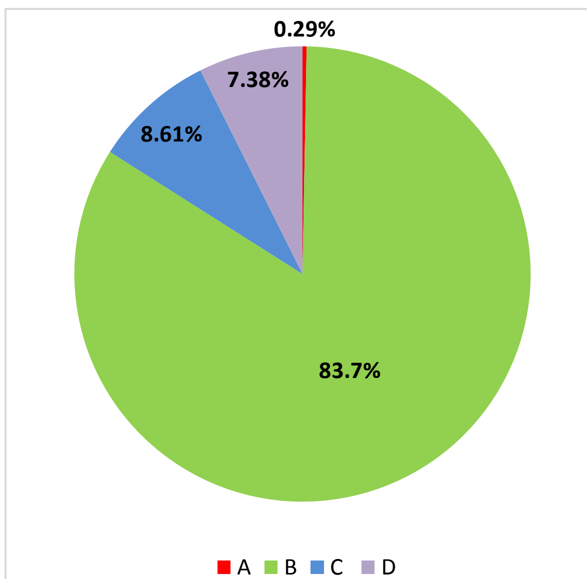


Figure 3.4: Distribution of soil, as represented by hydrologic soil groups (A, B, C, and D), in Boxelder Creek Basin.

3.3 Data Collection and Processing

In order to construct a base Soil and Water Assessment Tool (SWAT) model for the Boxelder Creek Basin, elevation and hydrography data for the Boxelder Creek Basin were obtained from the U.S. Geological Survey data warehouses. A 30-meter Digital Elevation Model (DEM) from the U.S. Geological Survey (USGS) National Elevation Dataset was used to characterize the terrain. The National Hydrography Dataset High Resolution data were used to identify irrigation ditches, canals, rivers, streams, ponds, and dams in the watershed and the watershed boundary (HUC 10, 1019000709). The location information and capacity values for all WWTPs and CAFOs in the watershed were collected from the U.S. Environmental Protection Agency Facility Registry System (FRS) and the Colorado Department of Public Health and the Environment (CDPHE) Environmental Agriculture Program, respectively. Land use data was obtained from the U.S. Department of Agriculture National Agricultural Statistics Service (NASS) CropScape – Cropland Data Layer. The USDA Natural Resource Conservation Service (NRCS) Soil Survey Geographic (SSURGO) Database provided the soil shapefile and information for the study region, and climate data was obtained from the National Climate Data Center (NCDC), the Colorado Agricultural Meteorological Network (CoAgMet), and the NRCS National Weather and Climate Center SNOTEL sites.

Some important aspects of the heterogeneity of the Boxelder Creek basin include the irrigated fields and the structures that divert and carry water for irrigation. The study region contains over 110 km^2 (27,247 acres) of irrigated cropland. The Colorado Decision Support System provided ArcGIS shapefiles for irrigated fields (2005), decreed wells, diversion structures, and irrigation ditches in the study basin. Figure 3.5 shows the complexity of this system, where water is, in some places, diverted from the Poudre River and carried into the basin by irrigation canals that do not necessarily adhere to

NHD boundaries. The figure also shows the fields that receive the water from the irrigation ditches and/or decreed groundwater wells.

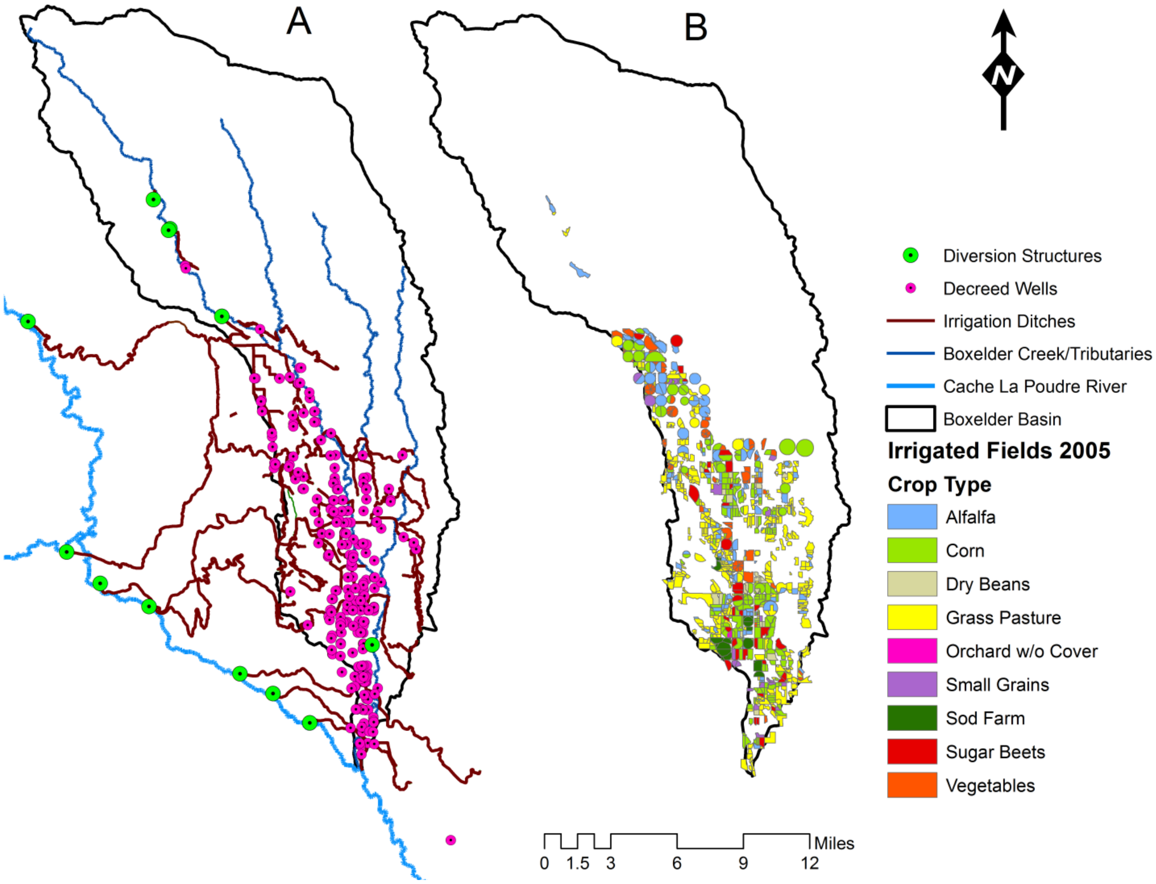


Figure 3.5: (A) Schematic showing the sources and transport of water for irrigating cropland in the Boxelder Creek Basin (B) The 2005 irrigated fields layer for the study area, including crop type.

After the data sets were collected, they were imported into ArcGIS 9.3 (Redland, CA, USA) and extracted by mask (rasters) or clipped (vectors) to the Boxelder HUC 10 boundary, and the 2005 irrigated fields layer and 2008 NASS land use layer were merged together to create one comprehensive land use layer.

3.4 Water Sources, Use, and Administration on the Poudre River

In order to develop a realistic model that captures the natural, agricultural, and engineered aspects of the watershed, a better understanding of water sources, uses, diversions, and transfers was needed. A meeting was set up with District 3 (Poudre River) Water Commissioner George Varra. Mr. Varra conducted a tour on June 23, 2011 of the Upper Poudre River and the major diversion structures and irrigation ditches that divert and transport water to the eastern agricultural regions of the watershed. Understanding the Poudre River system was important for developing a model for the Boxelder Creek basin because the river is a major source of water for irrigation in the basin and the rules that govern water administration for the Poudre River should also apply to Boxelder Creek. Figure 3.5 shows the diversion structures and irrigation ditches that are tied to irrigated fields in the Boxelder Creek Basin. Seven structures divert water from the North Fork and Main Stem of the Poudre River, and five structures divert water from Boxelder Creek to much smaller irrigation ditches within the basin. The main goal of the tour was to better understand the protocol and management of water use and transport within the Upper Poudre Basin, and hence Boxelder Creek, so as to create a more effective model.

The Poudre River is administered by decree, and decrees are ranked by the year that they are established and then by number based on application date. The oldest right on the Poudre River is Yeager Ditch (established 6/1/1860). Changes to decrees, or water rights, must be settled in the water court of each district. If the river is flowing at 2600 cfs (73.6 cfs) or greater, all decrees are satisfied (requirement was once 3600 cfs (102 cms), but agriculture is steadily deteriorating in the Poudre River watershed). Water in the Poudre River Basin comes from three sources: native Poudre water (snowmelt, rain), Colorado-Big Thompson (C-BT) system water, and other transbasin supplies. Annual volume and average daily flows of native Poudre Water vary from year to year. The average annual flow is approximately 300,000 acre-feeet (AF). The highest annual flow was 700,000, recorded in 1983, and the lowest year (2002) saw a flow of 100,000 AF. In addition, two thirds of this annual volume is typically recorded in a two-month period between mid-May and mid-July. Lack of water in the late winter months and extreme variability in the supply from year to year led to the construction of reservoirs to re-time water to supply irrigation and municipal demands throughout the entire year (or growing season). Horsetooth reservoir releases on average approximately 60,000 AF to the Poudre River every year. Releases are made from April through October with most occurring in the later summer irrigation period. Transbasin diversions come from four sources: the Colorado River via Grand River Ditch, the Laramie River thru the Larami-Poudre Tunnel and the Wilson Supply Ditch, and the Michigan River by the Michigan Ditch. Users of the Poudre River water include agricultural, municipal, industrial, recreational, and environmental consumers. Agricultural users consume about 85% of the decreed water each year. The top (senior) 100 users on the Poudre River have priority, and 19 diversions along the Poudre River divert water for these users. Of the companies that operate these 19 decision points, four maintain the largest irrigation systems in the watershed, and three of these systems serve the irrigated fields in the Boxelder Creek Basin (North Poudre Irrigation District, Water Supply and Storage, and Larimer and Weld Irrigation District). Two types of decrees are administered on the Poudre Rive in two different seasons. A direct flow decrees is diverted from the river and is immediately put to beneficial use. Direct flow season is typically from mid-April to the end of October. Water for direct use is measured at the diversion of the river using a Parshall flume and a Stephens recorder (see figures 3.5C and 3.5E).

Figure 3.6: (A) Poudre River along Highway 14 near the mouth of the canyon, downstream of the North Poudre Diversion Structure (B) North Poudre Diversion

Structure on Highway 14, northwest of Fort Collins, CO (C) Stephens recorder measuring flow at the North Poudre Diversion Structure gaging station. (D) Diverted water flowing to the North Poudre Supply Canal (a.k.a Munroe Canal) (E) Twenty-foot Parshall flume measuring flow on the Hanson Supply Canal. (F) Hanson Supply Canal transporting water from Horsetooth Reservoir to the Poudre River.

Reservoir storage season is from November to April. Storage decrees are usually junior to direct flow decrees on the Poudre River. Reservoir water is measured at the point of entry with a staff gage. The top 100 water users are numbered in order of priority of water right from 1 to 100 (1 having the highest priority). The amount of water in the river determines the number of users that can divert water. As flow increases, more water rights come into priority. As flow decreases, only as many users can divert as the river can supply water. The water commissioner starts at the top of the list of 100 users and administers water until the flow available for that day is consumed. In order to determine the amount of Poudre River water available for diversion each day, the river commissioner checks the Canyon Gage at the mouth of the Poudre River (USGS 06752000) every morning at 5:00 am.

Exchanges are also common along the Poudre River; however they are normally junior to most other water rights. An exchange can only occur with no injury to another water right and allows an upstream user to divert water a downstream user would otherwise receive. An example of a river exchange was described by Mr. Varra on the tour of the Poudre River and is represented in Figure 3.6 by site photographs. The North Poudre Irrigation Company (NPIC) owns the first major irrigation diversion structures on the Poudre River (one on the main stem and one on the north fork). The NPIC is also the largest shareholder of Horsetooth Reservoir water in the Poudre River Basin with 40,000 shares (1 share of Horsetooth water = 1 AF). For an exchange to occur there must be a live stream between the ditch and the reservoir outlet to the river. An irrigation company like NPIC diverts water from the river upstream to an irrigation ditch (as shown in Figure 3.6D). Then an equal amount of water is released to the river from a downstream reservoir (Figures 3.6E and 3.6F)

3.5 Ground Truthing and Data Validation

While analyzing NHD High data and comparing the flowlines labeled as canals (irrigation ditches) and artificial paths with the CDSS canals shapefile, discrepancies were found. Where canal segments existed in the NHD High data, they were not included in the CDSS data and vice versa. A world imagery basemap was imported into ArcGIS 9.3 in order to validate NHD High and/or CDSS canal data by comparison with existing flowlines represented by aerial photography. While some questionable areas were validated using aerial photography, more problem areas were discovered. It was unclear in some parts of the basin whether natural stream segments still existed, and the interactions between irrigation ditches and Boxelder Creek appeared ambiguous in some places. In order to validate and simplify the flowline dataset for an accurate model of Boxelder Creek Basin, two ground-truthing expeditions took place on July 7 and 12, 2011. While multiple sites were analyzed, only three case studies are presented in this section as examples of the issues that arise when trying to model a basin that has been augmented by man-made irrigation ditches. The tour of the Upper Poudre River gave some insight as to how irrigation canals interact with naturally occurring water channels. Figure 3.7 shows the three locations along Boxelder Creek that were visited and are presented here as case studies. When the flowlines are placed in ArcGIS 9.3, they appear to intersect naturally, which is how a modeling tool like SWAT would consider them. One goal of ground truthing was to see if these locations truly behave as they are presented in ArcGIS.

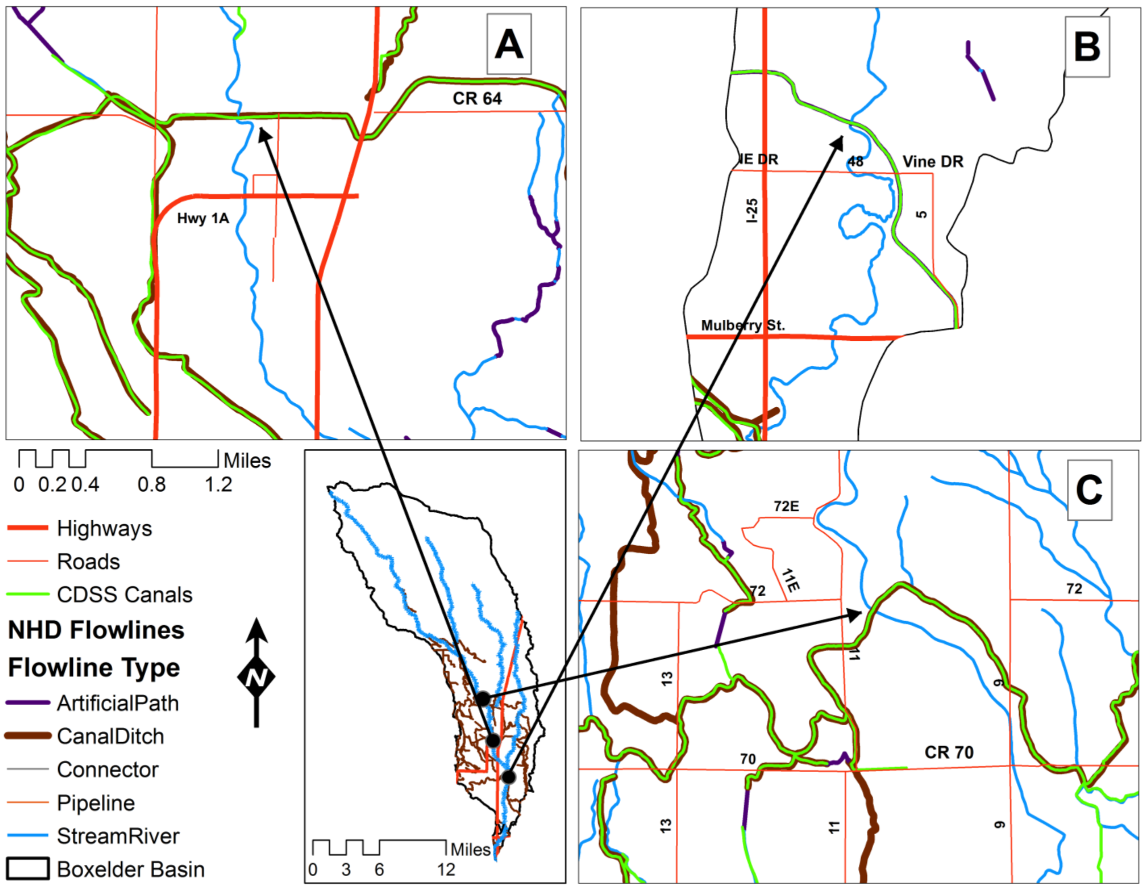


Figure 3.7: (A) Boxelder Creek at intersection with Poudre Valley Canal and County Road (CR) 64, corresponding to Figure 3.8 (B) Intersection of Boxelder Creek with Larimer Weld Canal north of Vine Drive, same location as shown in Figure 3.9 (C) Boxelder Creek at crossing with North Poudre Supply Canal, just north of CR 70, corresponding to Figure 3.10.

Exploring the intricacies of the basin on the ground proved very useful in understanding the dynamics of water transport throughout the basin. Figure 3.8 shows a location in

Wellington, CO (visited 7/7/2011) where Boxelder Creek intersects County Road 64 and the Poudre Valley Canal (also shown in Figure 3.7a). At this location, culverts allow Boxelder Creek to flow uninhibited under the county road, but once on the other side, the creek has no interaction with the canal as the canal is piped across the creek bed. However, a head gate was located near the inlet of the pipe. Water from the canal could enter the creek at this point, but this is not a gaged diversion structure. Therefore, no record could exist of water transfers from the canal to the creek. This type of unnatural situation could prove difficult to model because when flowlines intersect in a GIS interface, an assumed interaction takes place where the waters combine based on elevation and mixing. If all canals in this system are piped across the natural stream and creek channels, then one solution could be to eliminate the canals altogether and irrigate the agricultural fields with groundwater and sources outside the watershed. However, more investigation needed to be completed to determine whether piping canals across the creek was a common practice.

(A) (B)


(C)

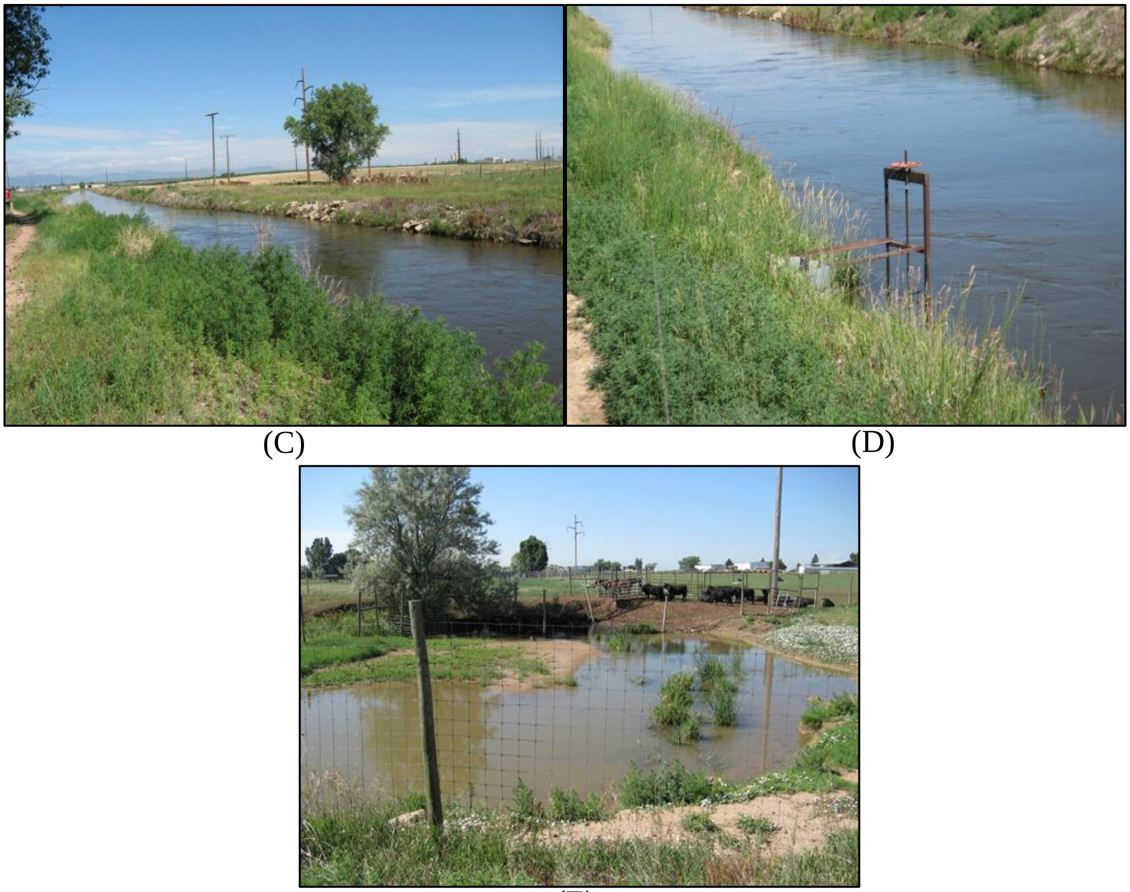

(D)


(E)

Figure 3.8: Boxelder Creek at intersection with Poudre Valley Canal and County Road (CR) 64. (A) Boxelder Creek flowing south from the north side of CR 64 (B) The south side of CR 64 where Poudre Valley canal is piped over Boxelder Creek (C) Boxelder Creek flowing under Poudre Valley Canal (D) Poudre Valley Canal flowing east into pipe inlet, where there appears to be a head gate that can release water from the canal into Boxelder Creek (E) Poudre Valley Canal near intersection with Boxelder Creek.

The pictures in Figure 3.9 help describe the intersection of Boxelder Creek and the Larimer and Weld Canal (Eaton Ditch). An obvious swale was visible on the north side of the canal, but no water was visible due to the vegetation. Instead of being piped across, the canal (which can has a capacity of 700 cfs) runs perpendicularly through where the creek bed should be according to the GIS data (Figure 3.7b). Berms on either side of the canal also appear to prevent water from flowing directly into the canal. However, Figure 3.9d shows a head gate on the south bank of the canal where Boxelder Creek would cross the canal. In addition, a site was checked just north of this location where Boxelder Creek meets a small, unnamed canal. No pictures are included here, but water was observed in the creek at this upstream location, and a head gate on the creek appeared to be diverting water to the irrigation ditch. The head gate shown below may be used to administer some type of exchange, diverting water back into Boxelder Creek that was taken out at the upstream location. An outlet connected to the head gate could not be seen due to fencing on the south side of the canal (Figure 3.9e). Figure 3.9e also shows an additional complication for modeling water quality. While CDPHE provides records of AFOs and CAFOs in the watershed, no statistics were available at the basin-level for grazing cattle on pastures. At this location, seepage from the canal and/or releases from the head gate created an enlarged creek flow path or small pond. While it is hard to see in the photo, cattle are standing under the shade where the "pond" outlets into the reemerging creek bed. A limitation of this study was the inability to quantify and model these types of scenarios within the basin.

(A) (B)


(C) (D)

(E)

Figure 3.9: Intersection of Boxelder Creek and Larimer and Weld Canal (a.k.a. Eaton Ditch). (A) A swale on the north side of Larimer and Weld Canal where Boxelder Creek should be (B) Close-up of the swale (Boxelder Creek) (C) Larimer and Weld canal upstream, flowing west to east (D) A head gate at the point where Boxelder Creek should cross the canal (E) Cattle and horses on the south side of the canal where Boxelder Creek should be, according to GIS.

The third location of interest along Boxelder Creek was located north of CR 70 at the intersection with the North Poudre Supply Canal. Figures 3.10a and 3.10b show the canal and the creek just above their confluence. At the confluence, a large head gate impeded the flow of the creek (Figures 3.10c and 3.10d). Downstream from the head gate, the canal seemed unchanged while the creek appeared very much reduced.

However, the volume of the creek may have only appeared larger upstream due to back flow caused by the head gate. Regardless, this site presents another interesting scenario to describe in the model of the creek basin.

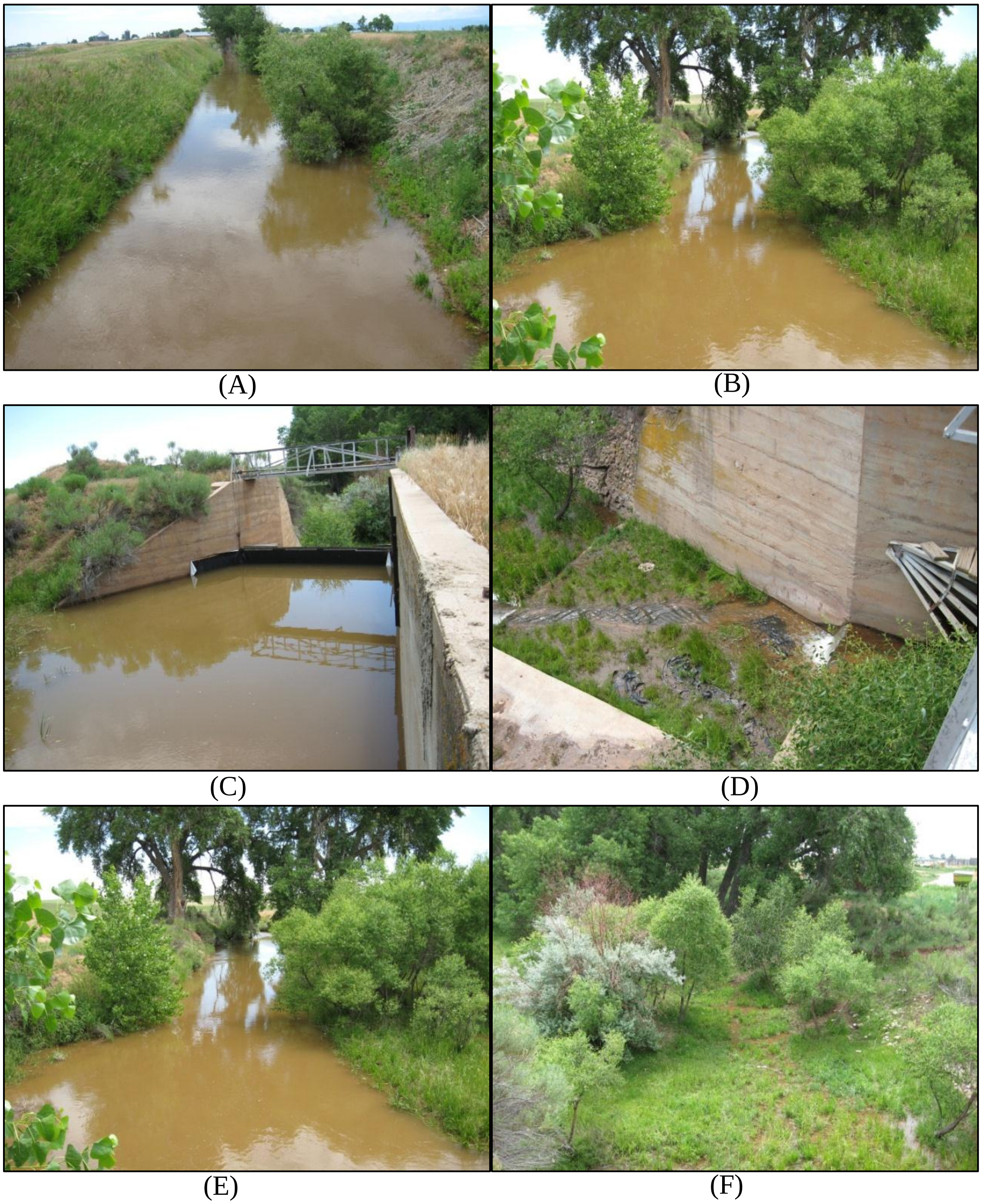


Figure 3.10: Boxelder Creek at crossing with North Poudre Supply Canal, just north of CR 70. (A) Poudre Valley Canal flowing northeast toward Boxelder Creek (B) Boxelder

Creek flowing southeast toward the canal (C) Head gate at intersection of the creek and the canal, acting as a dam along the flow path of the creek (D) The other side of the head gate where a small amount of water is seeping under the structure and flowing into the creek channel (E) The canal downstream of the head gate structure (the creek crosses from left to right in the picture) (F) Boxelder Creek downstream of its confluence with North Poudre Supply Canal.

Additional information was collected at other sites throughout the basin. At one location west, also on CR 70, just west of Interstate 25, a subbasin appeared to have two natural streams exiting at the outlet, and a canal appeared to loop in and out of the outlet, intersecting both streams. In reality, one of the streams did not exist, and the other stream was dry but had a substantial riparian zone. The canal cut through a large center pivot field, and the intersection of the canal and stream was not visible from the road. Indian Creek Reservoir, near the junction of CR 70 and CR 3, appeared to have two inlets and two outlets according to the NHD shapefiles. The in situ investigation determined that the natural inlet and outlet did not exist, while the irrigation ditch inlet and outlet did exist. Finally, some locations on the main stem of Boxelder Creek were found with no water in the channel. However, water was present in the headwaters, which could indicate that Boxelder Creek is a losing stream. These findings as well as other information gathered from data analysis, aerial photography, and field trips were considered in the development of the SWAT model.

3.6 SWAT Model Development

3.6.1 Constructing the Base Model

The SWAT extension for ArcGIS, ArcSWAT Interface for SWAT 2009 was used for the Boxelder Creek Basin model development. The ArcSWAT ArcGIS extension is a graphical user interface for the SWAT model (Winchell et al., 2007). SWAT was developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions (Winchell et al., 2007). As described in previous sections, the necessary geospatial and point source data were collected and modified based on data validation and model requirements. The input data are outlined in Table 3.1

Table 3.1 – Input data for ArcSWAT 2009.

Data Type	Description	Access
Topography	30-m DEM	http://seamless.usgs.gov/ - July, 2010
Land cover	NASS 2008	http://nassgeodata.gmu.edu/CropScape/ - March, 2011
Soil	SSURGO	http://soildatamart.nrcs.usda.gov/ - March, 2011
Climate	SNOTEL; NCDC; CoAgMet	http://www.wcc.nrcs.usda.gov/snow/ - June, 2011; http://www.ncdc.noaa.gov/oa/ncdc.html – June, 2011; http://climate.colostate.edu/~coagmet/rawdata_form.php – June, 2011
Hydrography	NHD - High	http://viewer.nationalmap.gov/viewer/ - February, 2010
Irrigation	CDSS Data	http://cdss.state.co.us/DNN/SouthPlatte/tabid/58/Default.aspx – February, 2011
Point Sources	CAFOs	Personal communication, CDPHE Environmental Ag Program, - February, 2010
	WWTPs	http://www.epa-echo.gov/cgi-bin/effluentsquery.cgin - February, 2010

After updating the soils database (“SWAT2009usersoils”) in Microsoft Access to include SSURO soil classifications for Colorado and Wyoming, a new SWAT project was created in ArcGIS 9.3. First, the 30-meter DEM and HUC 10 NHD boundary were added to the ArcGIS data frame. The spatial analyst tool was used to convert the basin boundary shapefile into a raster mask. The next step was to delineate the initial stream network, as well as the watershed as a whole and subbasins. Due to the complexities presented by irrigation canals and the time frame in which the model needed to reach completion, burning in the NHD flowlines with irrigation canals was not feasible. Instead, reaches were distributed throughout the basin with DEM delineation, and a method for irrigating cropland without the ditches is described in following sections. Stream networks were defined based on a drainage area threshold of 100 hectares (Ha). Point sources were placed on the main stem of Boxelder Creek where the two WWTPs are located (Figure 3.2a), and outlets were added at HUC 12 subbasin outlets and at the locations of monitoring stations for comparison of measured and predicted flows and concentrations. Additional outlets were placed within the basin to assure that all stream segments were captured in the watershed delineation. The basin was delineated by its outlet. After watershed delineation, some of the stream reaches did not stay within the boundary at the base of the basin. In order to keep the flow lines within the basin at this location, the DEM had to be modified along the boundary. A new shapefile was created and added to the SWAT project. Then the editor tool was used to draw a polygon the closely fit the portion of the boundary that needed to be elevated. An elevation field (double) was added to the attribute table of the new polygon, and the field calculator was used to set the elevation equal to 20 m. The polygon was then converted to a raster using spatial analyst and reclassified, for the whole area of the DEM. Finally, the DEM and the new raster were added together using the raster calculator, and the data was exported and saved as a grid. After the DEM modification was complete, the stream, watershed, and subbasin delineation was repeated. All stream reaches remained inside the basin boundary, and geomorphic parameters were then calculated for each subbasin and reach. Subbasins are further divided into hydrologic response units (HRUs), which are areas with unique combination of land use, management, and soil attributes. Subdividing the watershed into areas of unique land use and soil combinations enables the model to reflect differences in hydrologic conditions, sediment and nutrient loading, runoff, and land management (Winchell, 2007). Land use, soil, and slope characterization for the basin were performed using commands from the HRU Analysis menu in ArcSWAT (Winchell, 2007). The land use/land cover attributes for the basin were characterized by the merged NASS 2008/CDSS 2005 Irrigated Fields grid, and the SSURGO Database provided the soil attributes. Four slope classes were used in the HRU delineation. Slope classes included 1-4%, 4-7%, 7-10%, and 10-9999%. After the land use, soil, and slope datasets were imported and overlaid, the distribution of HRUs was determined. Multiple HRUs were created for each subbasin. The number of HRUs in a subbasin is determined by the number of unique combinations of soil and land use that are present, and the size of HRUs can be controlled by implementing threshold values for land use, soil classes, and slope classes. Threshold levels are used to eliminate minor land uses in each subbasin (Winchell, 2007). Land uses that cover a percentage of the subbasin area less than the threshold level are eliminated. Similarly, soils that cover less than the percentage threshold within a land use area and minor slope classes within a soil on a specific land use area are eliminated (Winchall, 2007). Once land use, soil, and slope classes are eliminated, the area remaining for each is reapportioned so that 100% of the

HRU area is modeled. A threshold of 5% was used for each HRU-determining variable, but exemptions were made for land uses containing specific cultivated crops. Exemptions allow certain land uses to be included in an HRU even if the extent of the land use type is below the threshold. Exempt land uses/crop types include corn, orchards, winter wheat, alfalfa, soy beans, sugar beets, onions, and smooth bromegrass.

After the HRU distribution was defined, weather data was imported into the basin simulation. Daily measurements of precipitation, minimum temperature, and maximum temperature readings from stations within and near Boxelder Creek basin were used in this model, and the sources of the climate data are available in Table 3.1. Weather stations were loaded into ArcSWAT, and the Weather Data Definition tool was used to assign weather data to each subbasin. A climate station was assigned to each subbasin based on its proximity to the subbasin, length of record, and completeness of dataset.

3.6.2 Irrigating Cultivated Crops

During watershed and HRU delineation, 110 subbasins were defined containing 928 unique HRU classifications. Of the 110 subbasins, 46 intersected irrigated fields and contained 750 HRUs. In SWAT irrigation is applied at the HRU level automatically in response to soil water deficit or manually with user-specified scheduling. Auto-application of irrigation was used in this model. Automatic irrigation does not require as many input parameters as manual irrigation, but a few variables must be specified, including the month and day of irrigation initialization, a water stress threshold that triggers irrigation, the source of irrigation, and the location of the source (Neitsch et al., 2005). Planting and harvesting dates for continuous corn, soybeans, and wheat were provided for each county in Colorado by the USDA (USDA, 2008; USDA, 2009; USDA, 2010a). Usual planting and harvesting dates for all other continuous crops and pasture were described for each state by the USDA Agricultural Handbook (USDA, 2010b). Planting dates for continuous corn and continuous soybeans occurred on May 20th, and the crops were both harvested on November 10th (USDA, 2008; USDA, 2009). Winter wheat was planted around October 10th, and harvesting was simulated to begin in July (USDA, 2010a). Continuous pasture and alfalfa were planted August 10th and harvested May 15th, July 10th, and September 15th (USDA, 2010b).

Automatic irrigation is initialized based on crop water stress or soil moisture depletion. The water stress threshold is a fraction of potential plant growth (Neitsch et al., 2005). Anytime actual plant growth falls below the user-specified threshold, the model will automatically apply water to the HRU until the soil reaches field capacity if enough water is available in the source (Neitsch et al., 2005). Neitsch et al. (2005) recommends a water stress threshold between 0.90 and 0.95, and a threshold of 0.95 was used for this model.

Water applied to an HRU is obtained from one of five types of water sources: a reach, a reservoir, a shallow aquifer, a deep aquifer, or a source outside the watershed (Neitsch et al., 2005). The model also needs the location of the reach or groundwater well, which is input as the number of the subbasin in which the source is located (Neitsch et al., 2005). In order to determine the source of irrigation for each HRU and the location of each source, a map was created in ArcGIS 9.3 containing the subbasins and HRUs created during SWAT delineation, the 2005 CDSS irrigated fields layer, and the diversion structures and decreed wells layer from CDSS. At database was created in Excel, starting with a list of subbasins that contain irrigated fields. Subbasins were selected one by one, and the “Select by Location” tool in ArcGIS was used to select HRUs within the designated subbasin. The 2005 irrigated fields layer was placed over the HRU layer to determine which HRUs were irrigated. The HRU attribute table was then opened and made to reveal the selected features within the subbasin being analyzed. Each individual HRU was selected and highlighted within the data frame. If the highlighted HRU contained irrigated fields, the “Identify” tool in ArcGIS was used to open the attribute information of the fields within the HRU. The irrigated-fields layer contains irrigation source information in the form of surface water and/or groundwater structure identifier labels. The CDSS gives each diversion structure and decreed well a unique ID number. If a diversion structure and/or decreed well was used to supply irrigation to an irrigated parcel within the HRU, these ID numbers were used to locate the structure. Once the structure was located, the irrigation source type (surface water or groundwater) and location (reach number for diversions and subbasin number for wells) were recorded for each HRU. Many of the irrigated fields received water from the structures diverting water off of the Poudre River (See Figure 3.5), and decreed wells were also located outside the boundary of the basin. When this was the case, water was simply taken from a source “outside the basin” and applied to the HRU. One HRU could have one or multiple irrigation sources from one or more locations. Figure 3.10 shows the process of determining source type and location for each irrigated HRU.

According to the developers of the Colorado Decision Support System (CDSS), the state assumes that irrigated fields with both surface and ground water rights will use decreed surface water amounts to exhaustion and then supplement with groundwater (Sobieski, personal communication, 2011). This criterion was used in the SWAT model and is described in the decision tree in Figure 3.11. Irrigation was auto-applied until crop requirements were met. For HRUs containing fields that utilized both surface and ground water, surface water was used first, and then ground water was applied if needed. A more accurate model would not only incorporate the crop water requirement but also the amount of water available for irrigation from sources within the basin. As described in Section 3.4, the amount of surface water available for irrigation varies throughout the year and may not always be sufficient to supply all priority users. In addition, ground water wells have pumping limitations specified by their decreed water right. If these limitations were incorporated into the model, irrigation would be applied until the crop requirement was met *or* until the decreed water was exhausted. The latter methodology was not incorporated into this model but could be included in future studies with the help of CDSS diversion records and decreed well permits.

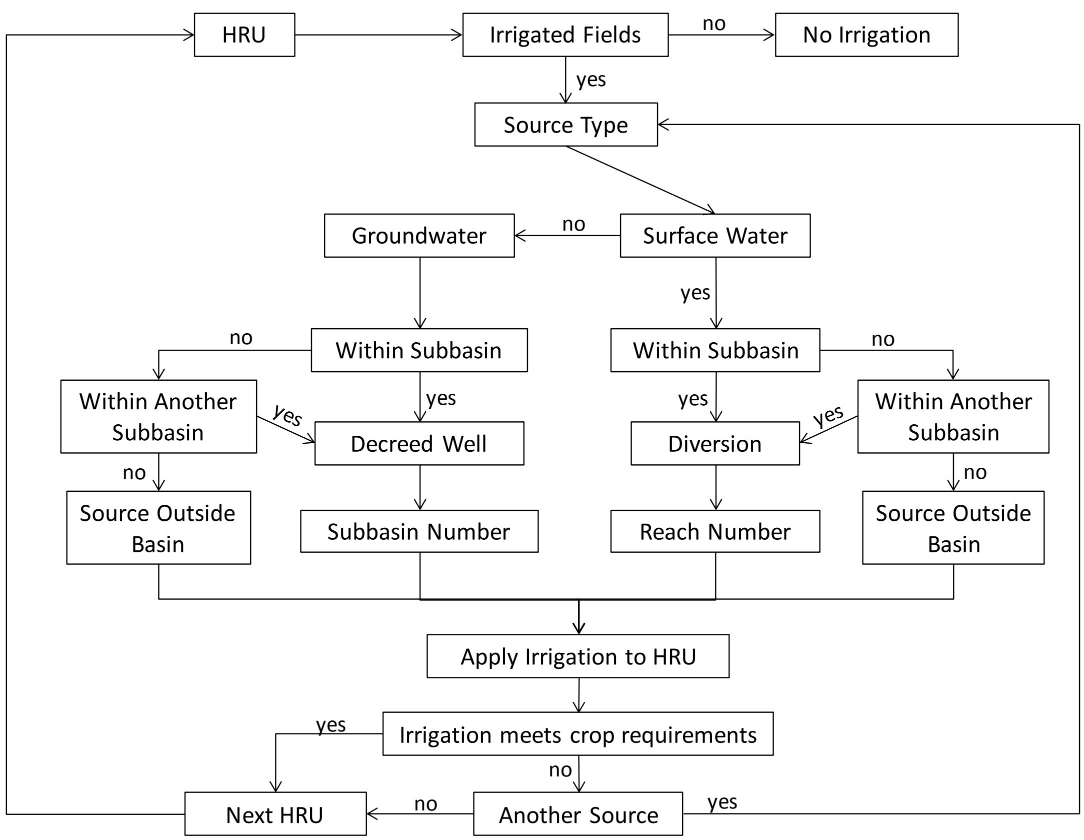


Figure 3.11: Decision tree describing the overall concept of applying irrigation to HRUs.

3.6.3 Applying Manure from Animal Feeding Operations

One objective in creating this model was to capture the anthropogenic impacts of animal feeding operations (AFOs, confined and unconfined) within Boxelder Creek basin. Information required for applying manure as fertilizer in SWAT includes the amount of manure applied, the type of manure applied, and the timing of the operation (month and day). Data for the 2 beef cattle feedlots and three dairy operations in the watershed were obtained from the CDPHE (Scott, personal communication, 2011). The CDPHE data included facility name and location, content type (AFO or CAFO), registered capacity, maximum capacity, and species and classification of each animal (beef, milk cow, etc.). Equations and state and national average statistics from Kellogg et al., (2000) were also used to determine the necessary model input parameters. The first step in determining the amount of manure produced by each facility per year was to calculate the annual average number of animals. The number of animals per animal unit, the degree of confinement, and the nutrient content of animal manure vary among livestock types and by maturity of the animal (Kellogg et al., 2000). Therefore, the following equations from Kellogg et al. (2000) were used for each type of animal operation. Equations 3.1 and 3.2 show methods used for calculating the number of animal units for each animal operation. According to Kellogg et al. (2000), an animal unit (AU) is the basic building block for estimating manure and manure nutrient production on animal feeding operations. An animal unit "represents 1,000 pounds of live animal weight and serves as the common unit for aggregating over different types of livestock." (Kellogg et al., 2000) Animal units are based on percent weight of 1,000 pounds and amount of time spent at each type of facility. According to CDPHE, the study basin only contains dairy and beef-feedlot operations. Upon further investigation, two of the dairies were not actual milking dairies, but dairy heifer feeding and breeding operations. These facilities receive heifers around four to five months of age from local dairies, care for them until breeding age, and return them as bred springers. No equation was give that seemed to adequately describe this type of facility. Therefore, Equation 3.2 was used for both types of dairy operations (milk cow and heifer). However, other parameters, such as tons of manure per animal unit per year (Table 3.2), were provided for these dairy heifer operations in Kellogg et al. (2000) and were incorporated into calculations that will be described in this section.

Equation 3.1

$$Fattened\ cattle\ animal\ unit\ (AU) = \frac{\left(\frac{fattened\ cattle}{2.5}\right)}{1.14}$$

Equation 3.2

$$Dairy\ AU = \frac{milk\ cow\ inventory}{0.74}$$

The amounts of recoverable manure and manure nutrients were estimated using parameters provided in Table 3.2 and Equation 3.3 (Kellogg et al., 2000). Recoverable manure was calculated using animal units for confined livestock (from Equations 3.1 and 3.2), estimates for tons of manure per animal unit per year, and a factor of manure recoverability. Manure nutrients were then computed by multiplying the amount of manure produced per year, in tons, by the pounds of nutrients per ton of manure after nutrient losses during collection, transfer, storage, and treatment (Kellogg et al., 2000).

Table 3.2: Parameters used to calculate the quantity of manure and manure nutrients for three livestock categories.

Livestock category	Tons of manure per animal unit per year as excreted	Pounds of nitrogen per ton of manure After losses	Pounds of phosphorus per ton of manure After losses	Combined confinement and recoverability factor
Fattened cattle	10.59	4.39	2.86	0.85
Milk cows	15.24	4.30	1.65	0.80
Dairy heifers	12.05	1.82	1.10	0.80

Equation 3.3

$$Recoverable\ manure\ nutrients\ (lbs) = (tons\ manure\ per\ AU) \times (confined\ AU) \times (recoverability\ factor) \times (nutrients\ per\ ton\ of\ manure\ after\ losses)$$

The quantities of manure nutrients (N and P) were used to approximate the area of manure application surrounding each AFO and CAFO. Regional average N and P application rates were provided by Ribaudo et al. (2003). An average N application rate of 154 lbs/acre and an average P application rate of 42.6 lbs/acre were used in conjunction with the recoverable manure nutrients calculated for each AFO and CAFO (Equation 3.3) to calculate the manure land application radius surrounding each animal facility. Average N and P application rates used in this study agreed with values utilized in previous research on manure application (Powell et al., 2005; Vellidis et al., 1996). Results from these calculations are included in Table 3.3.

Table 3.3: AFO/CAFO capacity (number and AU) and manure land application radius and rate.

Facility Type	Registered Capacity	Confined Animal Units (AU)	Acres of Manure Application	Manure applied (tons/ac)
Fattened cattle AFO	150	53	32	15
Dairy CAFO, milk cows	2,250	1,665	786	26
Dairy CAFO, heifers	7,000	5,180	1,289	39
Fattened cattle CAFO	18,000	6,316	3,817	15
Dairy CAFO, heifers	2,200	1,628	405	39

Figure 3.12a shows all of the irrigated fields and AFO/CAFOs in the Boxelder Creek basin, and Figure 3.12b shows the irrigated fields and grassland where AFO/CAFO manure was applied. The northern-most CAFO was dairy heifer operation. While this CAFO was not surrounded by irrigated cropland, it was surrounded by grassland/pasture that could be used for grazing and manure application, which is why these HRUs appear

in Figure 3.12b and not Figure 3.12a. Manure application rates, in tons/acre, for each type of CAFO were then calculated by dividing recoverable manure (tons) by the area of manure application (acres).

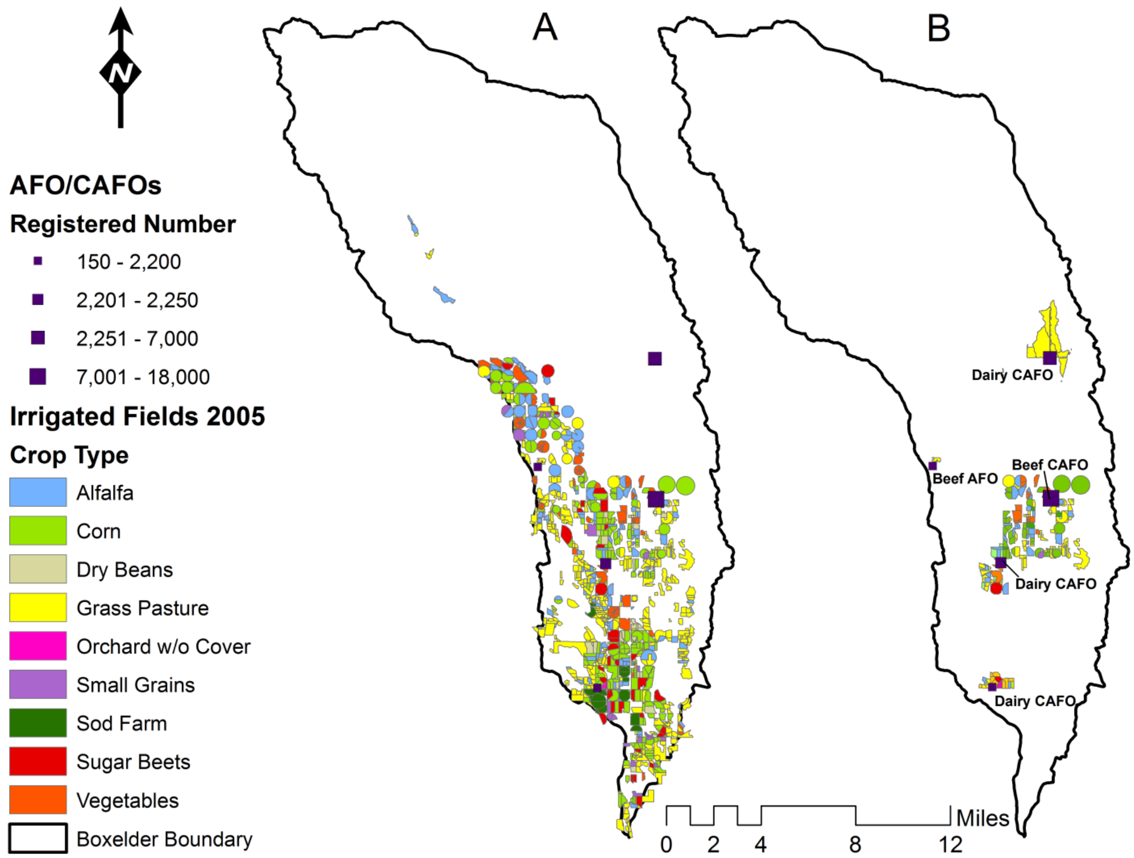


Figure 3.12: (A) Irrigated fields and AFOs/CAFOs within Boxelder Creek basin (B) Irrigated-field and grassland HRUs surrounding AFOs/CAFOs where manure was applied.

Once the quantity of manure was determined, manure type had to be input into the SWAT model. Since three manure application rates were determined for the study basin, three manure types were required. Manure types available in SWAT include "Dairy-Fresh Manure" and "Beef-Fresh Manure", but SWAT does not define any specific type for dairy heifers. Therefore, the "Veal-Fresh Manure" type was selected to define the manure application rate from the two dairy heifer operations in the basin. Veal is typically a by-product of the dairy industry, and usually comes from male calves of dairy cattle breeds. While this does not describe the actual operations, it was assumed that this classification would yield adequate results for this study.

Bauder et al. (2011) recommends splitting manure applications to improve uptake efficiency and yield return. For Colorado soils, including those located in the study basin, it is recommended to apply one-third of the manure at or prior to planting and the balance before the critical growth stage for that crop (Bauder et al., 2011). Planting and harvesting dates described in section 3.6.2 were used to determine the timing of manure fertilization (USDA, 2008; USDA, 2009; USDA, 2010a; USDA, 2010b). Planting dates for continuous corn and continuous soybeans occurred on May 20th, and the crops were both harvested on November 10th (USDA, 2008; USDA, 2009). Therefore, manure application for these two crops occurred in mid-May and mid-August. Winter wheat was planted around October 10th, and harvesting was simulated to begin in July (USDA, 2010a). Manure for winter wheat was applied early in October and mid-April. Continuous pasture and alfalfa were planted August 10th and harvested May 15th, July 10th, and September 15th (USDA, 2010b). Manure was applied to pasture and alfalfa fields in early August and early May. However, in order to construct a more accurate model, nitrogen credits should have been applied to fields containing alfalfa and soybeans since legumes naturally fix nitrogen to the soil (Bauder et al., 2011). This was not done for this model, but should be considered in future water quality simulations in Boxelder Creek basin. In addition to giving N credits for legumes, additional steps could have been taken to construct a more accurate model. For example, Bauder et al. (2011)

and Kellogg et al. (2000) suggest calculating manure application rates based on crop type, yield, and assimilative capacity, which could be done in the future for each HRU within the AFO/CAFO manure application radii. Nutrient management criteria for each crop contained within the study basin are described by multiple Colorado State University Extension factsheets (Brummer and Davis, 2009; Davis and Westfall, 2009a, 2009b, 2009c; Davis and Brick. 2009; Davis et al., 2009; Swift, 2009).

3.7 Results and Discussion

The objective of this study was to determine if a simplified model of the Boxelder Creek basin is adequate to capture the heterogeneity of the watershed. Figure 3.13 displays the simulated and observed stream flows in the study basin outlets over the study period, and Figure 3.14 presents the same results with log-normal values to show the between data sets more clearly. The model inputs described in previous sections resulted in unsatisfactory stream flow simulations.

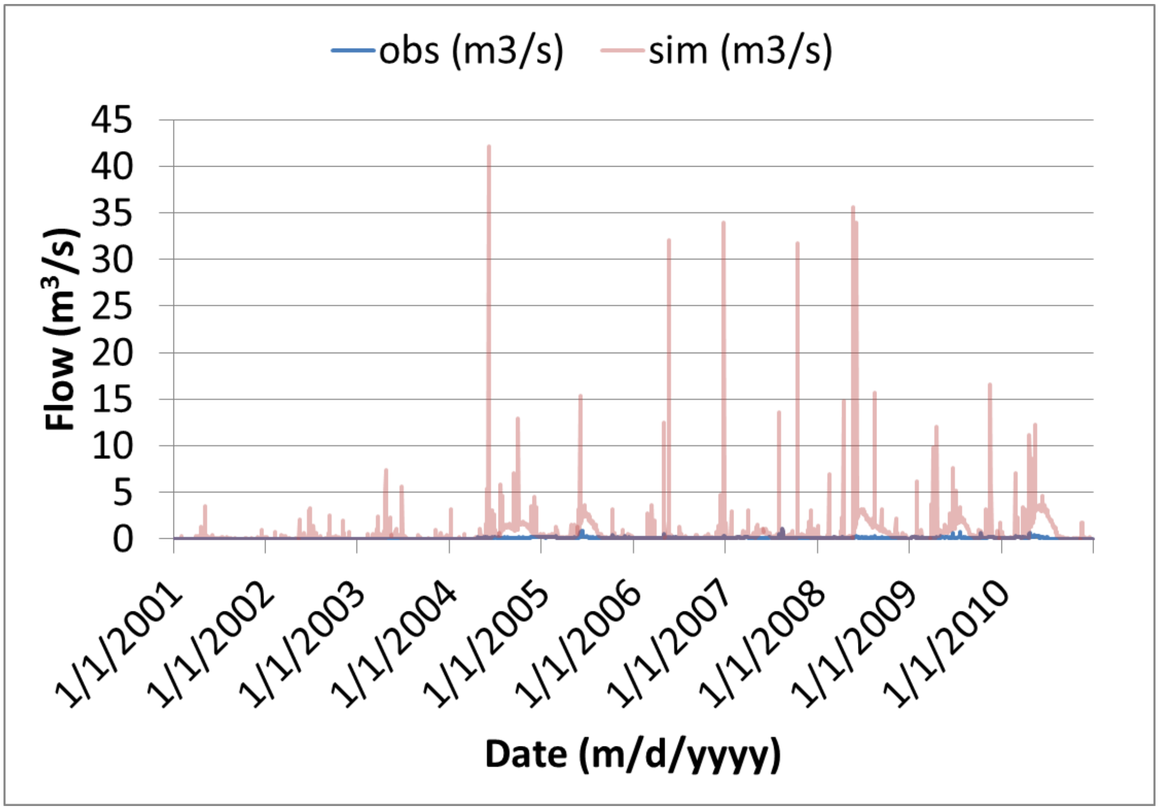


Figure 3.13: A time series comparing SWAT stream flow simulations with observed stream flows at the study watershed outlet.

While the results of this study are not favorable, Figure 3.1 suggests that stream flow can be modeled in the Cache La Poudre River watershed with satisfactory results. Several factors in *this* study could have contributed to the inaccurate stream flow values simulated by the model. First (and perhaps most importantly), irrigation canals were eliminated from the watershed, and "natural" streamlines were delineated in ArcSWAT using the DEM.

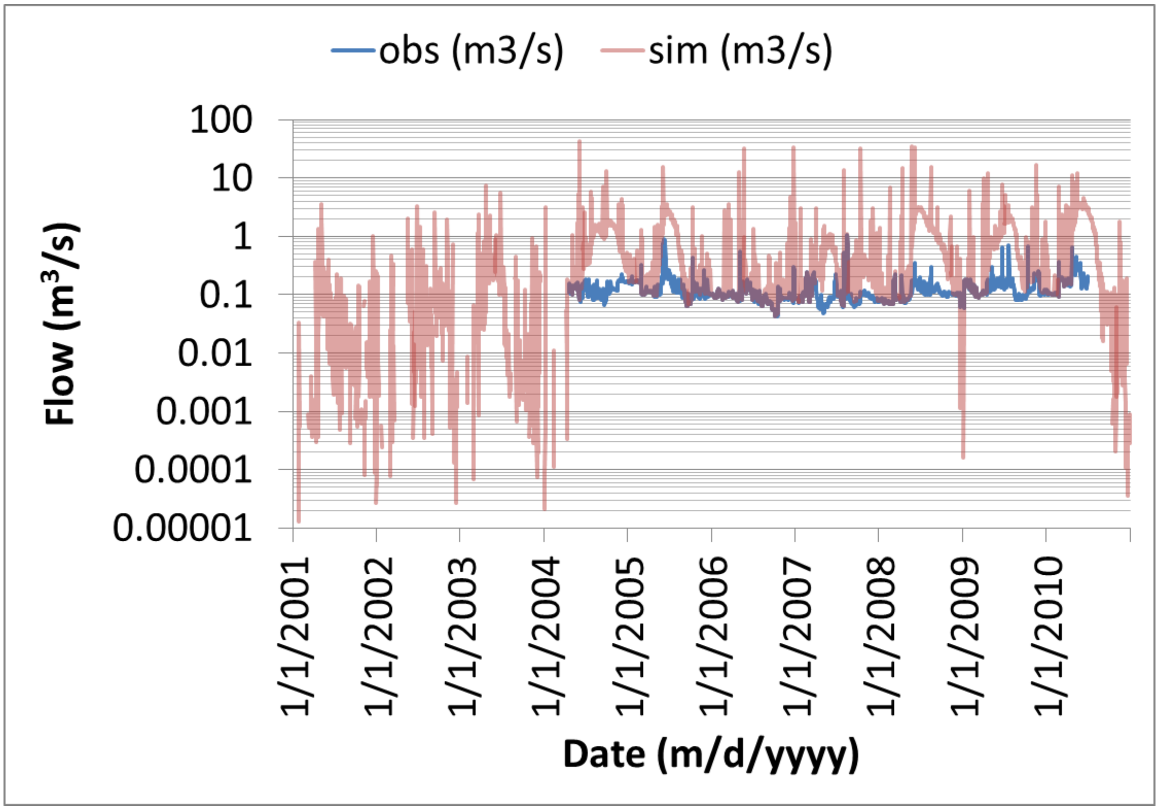


Figure 3.14: A log-normal time series comparing SWAT stream flow simulations with observed stream flows at the study watershed outlet.

The hydrology of the study basin has been vastly altered by agricultural irrigation activities. Figure 3.15 shows what happens to the basin when irrigation ditches are removed. Without irrigation, the lower portion of the watershed has no natural stream network except for the main stem of Boxelder Creek. In SWAT, simulation of the hydrology of a watershed can be separated into two divisions: the land phase and the water, or routing, phase (Neitsch et al., 2005). The land phase controls the amount of water, sediment, and nutrient loadings to the main channel in each subbasin (Neitsch et al., 2005). The water phase can be defined as the movement of water, sediments, and nutrients through the channel network of the watershed to the outlet (Neitsch et al., 2005). Water balance and the hydrologic cycle are the driving forces behind everything that happens in the watershed. The model incorporates precipitation, initial soil water content, snow melt, reservoir seepage, and irrigation as inputs and surface runoff, evapotranspiration, percolation, and plant uptake as outputs during the land phase. After the loadings of water, sediment, and nutrients are determined by SWAT, stream flow is routed through the channel using a variable storage coefficient method developed by Williams (1969) or the Muskingum routing method (Neisch et al., 2005). Main inputs into the Boxelder Creek system include precipitation and irrigation, which could explain the simulated flow values shown in Figures 3.13 and 3.14. However, as described in Section 3.5 and Figure 3.13, irrigation ditches can have a major impact on the water balance and routing throughout the watershed and especially along the main stem of Boxelder Creek. While simulated values reflect a natural system with no impoundments or augmentations; the observed values reflect the true watershed that is highly regulated with minimal seasonal variation.

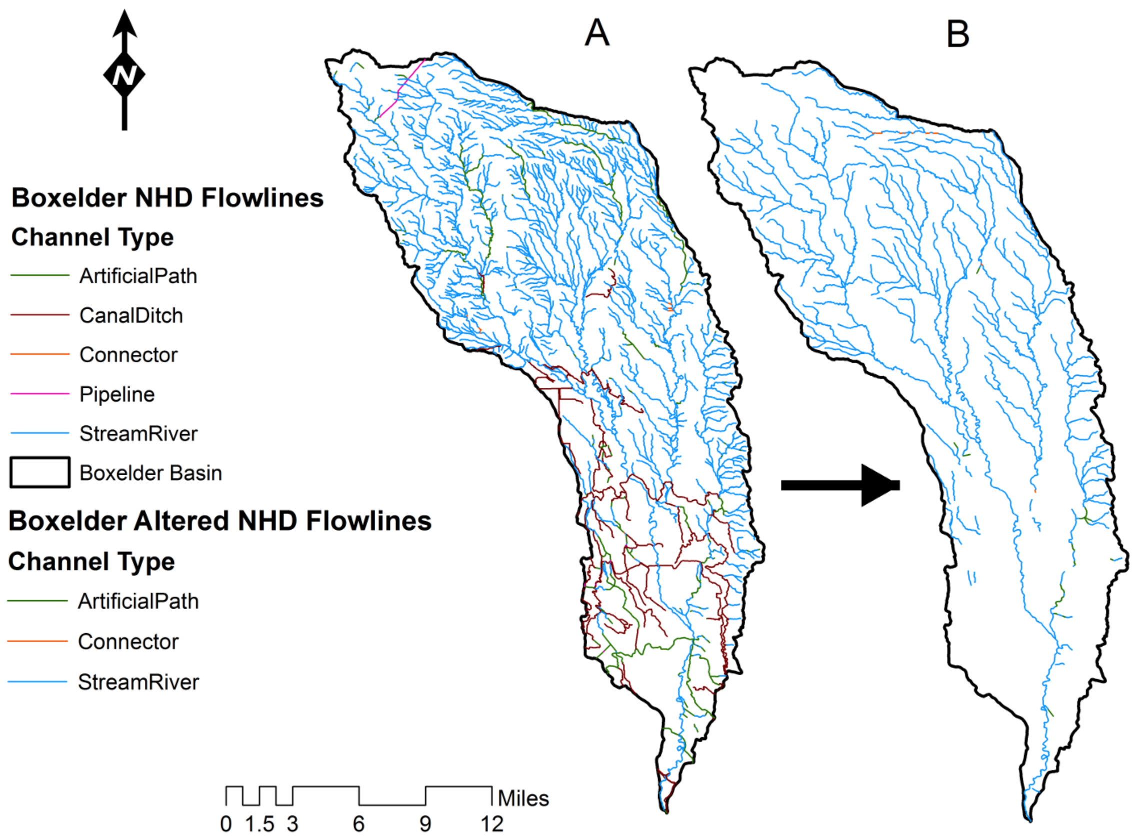


Figure 3.15: (A) NHD Plus flowlines with irrigation ditches and artificial paths and (B) Altered NHD Plus flowlines, where irrigation ditches, some artificial paths, nonexistent streams, and one pipeline have been removed.

Along with the elimination of canals, another issue that may reduce the accuracy of this model involves the method used for irrigation. As previously described, auto-irrigation was used in this study, which applies water until the soil reaches field capacity. Irrigated fields in the Boxelder Creek basin use one of two methods of irrigation: sprinkler irrigation or flood irrigation. Applying water to field capacity does not accurately represent flood irrigation because flood irrigation can sometimes supply water that exceeds the field capacity of the soil. Another limitation of this study was a lack of historic stream flow data. It typically requires at least ten years of historic data to obtain good simulations for stream flow. Only six years of daily data were available for Boxelder Creek at the time of this study.

Although the approach used in this study of Boxelder Creek Basin did not adequately simulate stream flow, the model did perform much better when simulating total phosphorus (TP) concentrations (in ppm). Figure 3.16 shows the observed and simulated TP values generated by the SWAT model. While a longer time period was simulated, this figure only shows the values simulated for the period of observation (see Chapter 2). As with stream flow data, minimal nutrient data is available for Boxelder Creek. However, although only six observed data points were available for running this model, it appears that the model performed much better when simulating nutrients. It appears that the method used for applying manure from CAFOs could be viable for simulating the impacts of animal feeding operations in agricultural areas. However, as previously stated in Section 3.6.3, improvements could also be made when calculating the amount of manure to land apply which could produce more satisfactory simulated values for TP.

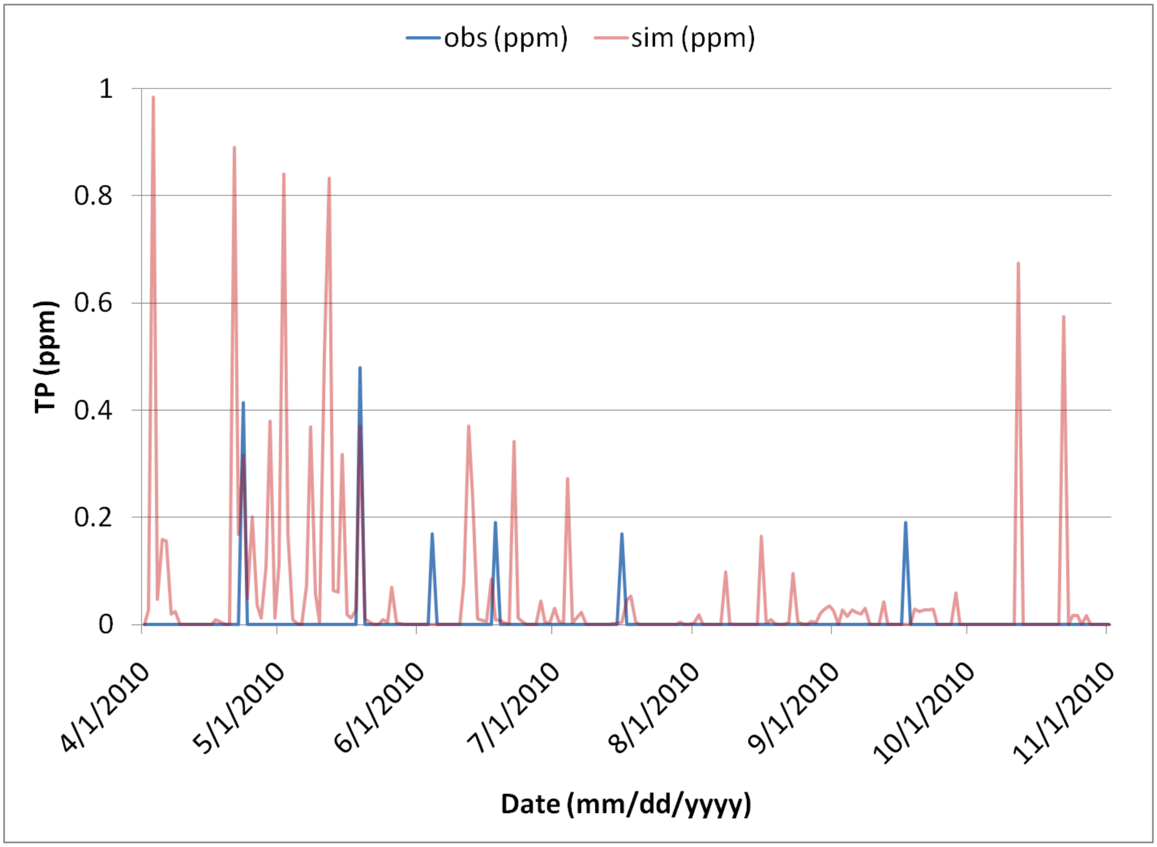


Figure 3.16: A time series comparing SWAT TP simulations with observed TP at the study watershed outlet.

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CHAPTER 4: CONCLUSIONS

The results of this study suggest that the impacts of CAFOs and WWTPs on phosphorus concentrations throughout a watershed can differ significantly under varying hydrologic conditions. During a precipitation event, CAFO capacity, with help from geospatial factors, appeared to be the most important factor for determining phosphorus concentrations in the Poudre River. The significantly higher phosphorus concentrations during the rainfall event and the importance of total distance as a geospatial variable support the assumption that irrigation ditches are important transport mechanisms for phosphorus in arid regions where natural tributaries are rare. In the absence of irrigation ditches, CAFOs would not have as great an impact on surface water quality without a mechanism for the transport of nutrients and other contaminants. Irrigation ditches provide this mechanism and should be analyzed and managed more closely as regional, state, and local agencies prepare to develop and implement phosphorus regulations and standards.

In the absence of rainfall, irrigation, and during low river flow conditions, WWTPs have a greater impact on phosphorus concentrations. Additionally, as regulations and standards require monitoring programs to be put into place, it is important to be aware of hydrologic conditions when obtaining phosphorus data on a continual basis because precipitation events coupled with irrigation practices and low flows may increase phosphorus concentrations above required levels. This study also shows the importance of location when choosing sampling sites. Geospatial variables such as the intensity of anthropogenic activities (CAFO, WWTP) and surface flow distances are key in representing the fate and transport of immobile compounds. Geospatial analysis presents an opportunity for selecting sampling sites with maximum information content. The methods used could also contribute to more effective placement of pollution control strategies in watersheds.

Results varied when analyzing only river samples as opposed to samples collected throughout the entire watershed. This could be due to the aggregation of CAFO geospatial factors, the exclusion of WWTP stream distance without inverse distance weighting, and/or dry irrigation ditches during in February that prevented obtaining a complete dataset for the watershed. Despite their differences, both methods produced valuable results. At the watershed-scale, quantifying anthropogenic and geospatial factors was adequate for predicting phosphorus concentrations throughout the watershed for most sampling dates. This method also gave more detailed insight regarding specific factors that impact phosphorus occurrence and transport, such as irrigation ditches. Sampling across the watershed in the river, irrigation ditches and streams allows for a better understanding of the distribution of phosphorus. On the other hand, minimal input variables were needed to predict phosphorus concentrations with very high coefficients of determination when using only the river samples.

In order to gain a better understanding of water and nutrient interactions in mixed-landuse watersheds, a thorough investigation of Boxelder Creek basin was executed. The objectives were to gain an understanding of the geospatial heterogeneity and hydrologic complexity of the watershed using available data, aerial photography, and ground truthing and to develop a model that could accurately simulate the hydrology and nutrient routing in the watershed. Modeling the system using a simplified method for irrigation produced simulated results that were inconsistent with observed flow measurements. These results seem to indicate that irrigation ditches play a vital role in the hydrologic cycle of a basin. Previous studies indicate that watersheds in the study region can be accurately modeled; and although stream flow was not adequately simulated, the model did perform better when estimating total phosphorus concentrations. Therefore, future studies attempting to model basins containing irrigation ditches, like Boxelder Creek basin, should incorporate methods for representing the channels and their various interactions with the natural system. Routing irrigation canals through the watershed, along with irrigation and manure application methods described in this study, should improve the feasibility of modeling the heterogeneity of mixed landuse watersheds.

APPENDIX A – SUPPLEMENTARY TABLES

Table A.1. Total number of animals, design flow of WWTPs, and distance upstream from Poudre River confluence for each sampling location

Station No.	Location	Upstream AFOs (No. of animals)	Upstream WWTPs (million gal day^{-1})	Upstream distance from Poudre River confluence (km)
1	USGS - NORTH FORK CACHE LA POUDRE RIVER AT LIVERMORE, CO	0	0.05	126.1
2	South Fork Poudre River upstream	0	0	127.8
3	South Fork Poudre River in canyon	0	0	109.5
4	North Fork Poudre River	0	0.05	108.9
5	Mouth of Poudre River downstream from Picnic Rock	0	0.05	102.9
6	Buckeye Lateral @ Rd 80 and Rd 17	0	0	111.7
7	Stream @ Route 70 below Grant Farms ("Cultivated" location)	0	0	106.2
8	Irrigation Ditch @ Route 70, West of Route 15 Intersection	0	0	101.1
9	Irrigation Ditch @ CR 1 and CR 15	0	0	94.7
10	Poudre River @ Overland	0	0.05	91.3
11	Larimer County Canal No. 2 @ Route 21C	0	0.05	94.3
12	Coal Creek @ Route 70, near Horton Feedlot	7000	0	98.9
13	Indian Creek @ Route 3	25,000	0	106.6
14	Boxelder Creek @ CR 58 and Inspiration Rd.	27,250	0.45	82.2
15	USGS - CACHE LA POUDRE RIVER AT FORT COLLINS, CO	0	0.05	83.3
16	Irrigation Ditch @ Mtn Vista Dr. & CR 9 E	2200	0	79.5
17	Larimer County Canal No. 2 @ J F Kennedy Pkwy	0	0.05	68.1
18	Poudre River @ Prospect Rd	0	0.05	77.7
19	Poudre River, Upstream DWRF	0	0.05	76.1
20	DWRF Effluent	0	14.35	65.3
21	Canal Upstream of DWRF Effluent	0	0.05	65.4
22	Boxelder Creek Upstream of Boxelder WWTP	29,450	0.45	74.3
23	USGS - CACHE LA POUDRE RIV AB BOXELDER CRK NR TIMNATH, CO	0	0.05	74.9
24	Poudre River Near Archery Range	29,450	2	73.5
25	CR 14 @ Boulder Rd (Along E. Mulberry St.)	29,450	0.5	70.7
26	Muskrat Ditch Near Development	0	0.05	59.5
27	Route 13/901 North of Timnath	29,450	0.5	64.5
28	County HWY 13 N	30,350	0.45	78.1
29	Irrigation Ditch @ HWY 254	30,350	0.45	73.3
30	Poudre downstream of Fossil Creek Reservoir	35,250	26.3	53
31	Drainage Ditch @ CR 13	32,550	1.95	48
32	Poudre River @ CR 17/7th St., Windsor	35,250	26.3	43.7
33	Cowan Lateral @ Rd. 64	25,000	0	97.1
34	Irrigation Ditch @ CR 21	107,550	0.5	56.1
35	Larimer & Weld Canal @ Rd 23 and Rd 76	109,550	0.5	49.2
36	Irrigation Ditch @ Stagecoach Rd., S. of Severance	107,550	0.66	38.6
37	Poudre River @ Route 27/83rd Ave. Greeley	113,350	27.96	28.8
38	Irrigation Dicth @ CR 27	109,750	0.66	35.2
39	Irrigation Dicth @ Rd 31 and Coalbank Rd.	109,550	0.5	35.4
40	Rd. 74, Eaton	167,050	0.84	21.8
41	Irrigation Ditch @ CR 33 & HWY 392	128,800	23.46	26.6
42	Irrigation Ditch @ O St. Greeley	128,800	23.46	18.1
43	Poudre River @ Route 35	192,100	27.96	15.9
44	Poudre River @ 11th Ave Greeley	192,100	27.96	11.7
45	Sand Creek @ Route 43	186,300	23.8	11.7
46	Poudre River @ 5th St. Greeley	192,100	28.3	9.3
47	Irrigation Ditch @ 1st Ave. Greeley	113,350	27.96	10.3
48	Ogilvy Ditch near Poudre River Confluence, along Rd. 80	192,100	43	2.1

Table A.2. Multiple linear regression analysis for all 48 Poudre River watershed samples

No.	4/23-24/2010 Regression Variables						R^2
	CAFO Cap	**WWTP Cap**	**CAFO OL Dist.**	**CAFO Canal Dist.**	**CAFO Stream Dist.**	**WWTP Stream Dist.**	**values**
1	D[a]						0.34
2	D			D			0.41
3	D	D		D			0.43
4	D	D		D		D	0.59
5	D	D	D	D	D	D	0.60

No.	5/19/2010 Regression Variables						R^2
	CAFO Cap	**WWTP Cap**	**CAFO OL Dist.**	**CAFO Canal Dist.**	**CAFO Stream Dist.**	**WWTP Stream Dist.**	**values**
1						D	0.34
2	C[b]		IDW[c]			D	0.58
3	C		IDW		D	D	0.66
4	C	D	IDW		D	D	0.67
5	C	D	IDW	D	D	D	0.72

No.	6/4/2010 Regression Variables						R^2
	CAFO Cap	**WWTP Cap**	**CAFO OL Dist.**	**CAFO Canal Dist.**	**CAFO Stream Dist.**	**WWTP Stream Dist.**	**values**
1						D	0.69
2		D				D	0.78
3		D			D	D	0.82
4	C	D		IDW	D	D	0.84
5	C	D	D	IDW	D	D	0.84

No.	6/18/2010 Regression Variables						R^2
	CAFO Cap	**WWTP Cap**	**CAFO OL Dist.**	**CAFO Canal Dist.**	**CAFO Stream Dist.**	**WWTP Stream Dist.**	**values**
1	C		IDW				0.12
2	C		IDW	D			0.29
3	C		IDW	D	D		0.31
4	C	C	IDW	D	D	IDW	0.59

No.	7/16/2010 Regression Variables						R^2
	CAFO Cap	**WWTP Cap**	**CAFO OL Dist.**	**CAFO Canal Dist.**	**CAFO Stream Dist.**	**WWTP Stream Dist.**	**values**
1	C	C				IDW	0.33
2	C	C		IDW		IDW	0.35
3	C	C	D	IDW		IDW	0.38
4	C	C	D	IDW	D	IDW	0.65

No.	9/17/2010 Regression Variables						R^2
	CAFO Cap	**WWTP Cap**	**CAFO OL Dist.**	**CAFO Canal Dist.**	**CAFO Stream Dist.**	**WWTP Stream Dist.**	**values**
1	C						0.85
2	C	C				IDW	0.90
3	C	C	D			IDW	0.93
4	C	C	D		D	IDW	0.94
5	C	C	D	D	D	IDW	0.95

No.	2/22-23/2011 Regression Variables						R^2
	CAFO Cap	**WWTP Cap**	**CAFO OL Dist.**	**CAFO Canal Dist.**	**CAFO Stream Dist.**	**WWTP Stream Dist.**	**values**
1				D			0.08
2		C		D			0.11
3		C		D	D		0.26
4		C		D	D	D	0.28
5	C	C	IDW	D	D	D	0.30

Table A.3. Multiple linear regression analysis results for Poudre River samples

No.	4/23/2010 Regression Variables				R^2
	CAFO Capacity	WWTP Capacity	CAFO Total Distance	WWTP Total Distance	values
1	D[a]				0.42
2	D		D		0.69
3	D	D	D		0.99
No.	5/19/2010 Regression Variables				R^2
	CAFO Capacity	WWTP Capacity	CAFO Total Distance	WWTP Total Distance	values
1	D				0.70
2	D	D			0.98
No.	6/4/2010 Regression Variables				R^2
	CAFO Capacity	WWTP Capacity	CAFO Total Distance	WWTP Total Distance	values
1	D				0.61
2	D	D			0.96
No.	6/18/2010 Regression Variables				R^2
	CAFO Capacity	WWTP Capacity	CAFO Total Distance	WWTP Total Distance	values
1	D				0.82
2	D	D			0.89
3	D	D	D		0.95
No.	7/16/2010 Regression Variables				R^2
	CAFO Capacity	WWTP Capacity	CAFO Total Distance	WWTP Total Distance	values
1	D				0.03
2	D	D			0.93
No.	9/17/2010 Regression Variables				R^2
	CAFO Capacity	WWTP Capacity	CAFO Total Distance	WWTP Total Distance	values
1	D				0.32
2	D	D			0.73
No.	2/22/2011 Regression Variables				R^2
	CAFO Capacity	WWTP Capacity	CAFO Total Distance	WWTP Total Distance	values
1		C		IDW	0.59
2	C	C	IDW	IDW	0.66

[a]D = variable input directly (or separately) into the regression equation

[b]C = capacity is used in regression equation by is inverse distance weighted

[c]IDW = variable is used to inverse distance weight capacity in regression equation

APPENDIX B – SUPPLEMENTARY FIGURES

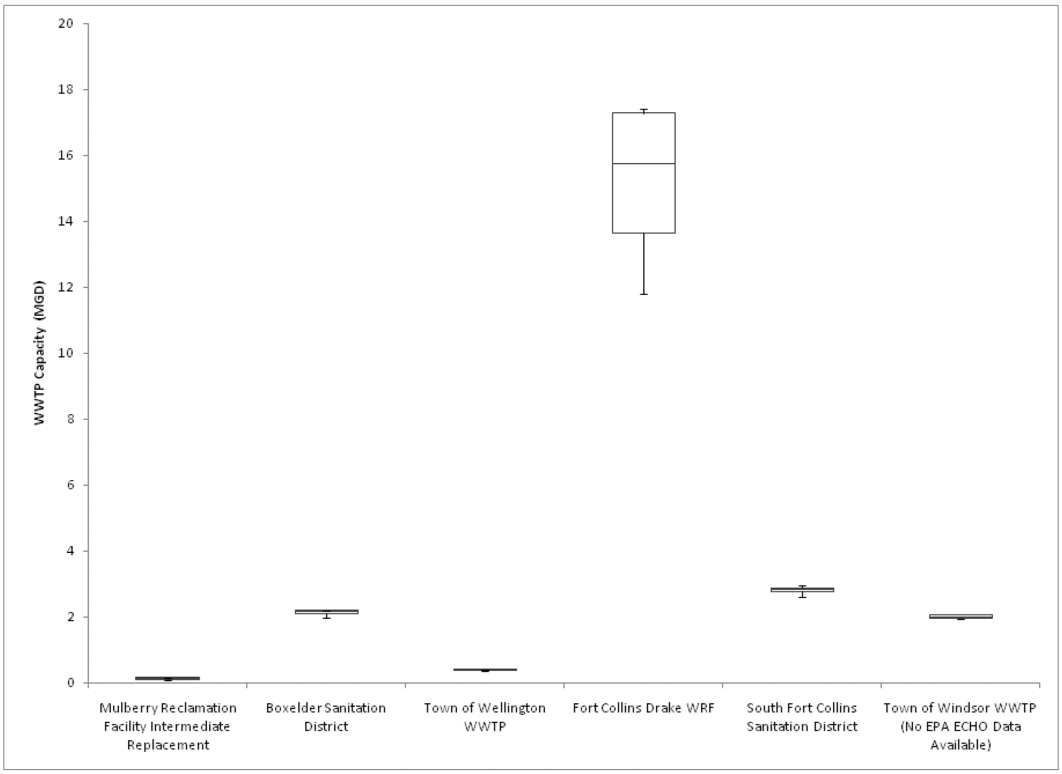

Figure A.1: The variability in the monthly averages of WWTP gross effluent in the study region.