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Regional assessment of the effects of land use on water quality: A case study in the Oldman River Basin, Alberta

by

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Dedication

To Sarah, for always making me laugh!
I love you and miss you

Abstract

Protecting and managing Canadian water resources in the face of growing cumulative effects and non-point source pollution from development (industrial, agricultural, and urban), depends on defensible, scientifically founded, watershed assessments. The objectives of this research were to broadly characterize the spatial and temporal patterns in water quality (total phosphorus and total nitrogen concentration, export and yield) across a land use disturbance gradient (forest, agriculture, urban) to elucidate pressures on water quality from specific landscape regions within the three headwater sub-basins of the Oldman River basin. While the water quality in the Oldman basin, remains fairly pristine, important spatial differences in nutrient production were evident between the upstream (predominantly forested) and the downstream (mixed agricultural/forested) reaches within the sub-basins. Using the pressure state response model as a framework to link landscapes to observed water quality, it was also found that phosphorus contamination may be an issue in the headwaters.

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Chapter 1: Introduction

Increased pollution and water withdrawals from intensive land use practices and rapidly growing urban populations are placing a significant strain on Canada's water resources. To manage water within Alberta, the provincial government has adopted the "Water for Life: Alberta's Strategy for Sustainability" that focuses on a watershed approach to water management planning and that promotes the management of water and land issues collectively (Alberta Environment, 2003). This provincial strategy acknowledges that water resources must be managed within the capacity of individual watersheds, knowledge of water quality and supply are required for effective management, water quality must be preserved while pursuing economic and community development, and best management practices will be used to maintain adaptive watershed management (Alberta Environment, 2003).

In the "Water for Life Strategy," the government acknowledges that water resources need to be managed at the watershed scale. Managing water resources at this scale is exceedingly difficult due to the cumulative effects on water quality from a range of land use practices (agricultural, oil and gas, forestry). Additionally, the variation in both the physiographic characteristics that govern runoff combined with the heterogeneity of land uses throughout a basin often preclude identifying simple cause and effect relationships between land use practices and water quality. Due to the rapid conversion of forested land to agricultural, urban and industrial development, there is a need to understand the relationships between land use practices and water quality and quantity within the physiographic setting of Alberta. This information is needed so that water quality and quantity can be incorporated into and managed in long term landscape level plans.

Non-Point Source Pollution: Agriculture, Urban, and Forested Landscapes

Non-point source pollution is one of the greatest challenges facing North American water managers. Unlike point source pollution from industrial or sewage treatment plants, non-point source pollution emanates from many diffuse sources. The U.S. Environmental Protection Agency has identified non-point source pollution as the primary reason that approximately 40% of American water bodies do not meet regulatory guidelines (USEPA, 1996). The three non-point source landscapes that have received the most attention are forested (harvested) landscapes, agricultural landscapes and urban landscapes. Agriculture has long been considered the leading non-point source contributor to water quality impairment (Carpenter *et al.,* 1998). The application of both nitrogen and phosphorus fertilizers and manure to agricultural lands combined with disturbed soils and reduced vegetation contribute to the large nutrient loads from these landscapes (Carpenter *et al.,* 1998 and Beaulac and Reckhow, 1982). While agricultural practices have received most of the attention in the literature, the recent rapid growth in urban populations has shifted the attention of regulators to impacts of urban landscapes on water quality. As land is converted from agricultural or forested systems to urban landscapes, soils with moderate to high infiltration capacity are replaced with impermeable surfaces that generate high rates of runoff and are not capable of recycling or removing nutrients (Coulter *et al.*, 2004 and Carle *et al.,* 2005) leading to rapid and efficient transport of nutrients to nearby waterways when it rains. Compared to agricultural and urban landscapes, nutrient loads from harvested forested landscapes are quite low (Beaulac and Reckhow, 1982). While the loss of forest cover reduces the recycling and uptake of nutrients (Brett *et al.,* 2005) and increases the possibility of soil erosion, these landscapes do not typically receive additional nutrient inputs from fertilizers or anthropogenic sources which greatly reduces the amount of nutrients that they supply to nearby river systems.

Two nutrients of key concern when examining the impacts of non-point source pollution on water quality are nitrogen and phosphorus. Excessive loading of these nutrients cause eutrophication of rivers and lakes which increase the growth of algae and aquatic weeds which cause oxygen shortages as they senesce (Carpenter *et al.,* 1998). Eutrophication, in turn, is linked to habitat loss, loss of aquatic biodiversity and interferes with the use of waterways for drinking, recreation and agricultural and industrial needs (Carpenter *et al.,* 1998). To further explain the interactions between basin and land use characteristics and water quality, many studies have sampled both the dissolved and the particulate fractions of both total nitrogen and total phosphorus (Hill, 1981; Coulter et al, 2004; Ahearn *et al.,* 2005). By breaking total nutrient concentrations into dissolved and particulate form, further insights into the nutrient processes influencing these contaminants may be drawn.

To address non-point source pollution, most research in forested, agricultural or urban environments has typically approached the problem using one of three dominant landscape based approaches. The first approach involves water quality sampling along a longitudinal disturbance gradient from the upstream to the downstream reaches of a basin (Bolstad and Swank, 1997; Brett *et al.,* 2005). This approach is very effective as a broad “coarse filter” approach to assess regional water quality as it highlights areas on the landscapes that may be contributing the majority of the nutrients to the system. In the second approach, entire basins are selected based on the composition of land uses within their boundaries and are then categorized into broad land use classes that represent the dominant land use within their boundaries. Contaminant production from these basins is then compared to identify and rank non-point source impacts from a range of land uses. In the third approach, one or two large basins are typically sub-divided into sub-catchments and the physiographic and land use characteristics of these sub-catchments are examined to identify the relationships between stream water chemistry and the landscape characteristics. Once this classification has been performed, multiple linear regression models are developed to link the landscape to the observed water quality. While the site specific information obtained from these basin studies cannot be generalized to other areas, it is needed to develop effective integrated land and water management plans.

Furthermore, many studies assessing the impacts of non-point source pollution focus exclusively on the concentration of key nutrient contaminants as opposed to overall nutrient production and export from varying landscapes. While this method is much cheaper, many have questioned the efficacy of using concentration data alone and have suggested that discharge weighted loadings or export are required to the link landscapes to observed water quality (Hill, 1981; Ahearn *et al.*, 2005; Castillo *et al*., 2000). When comparing hydrologically linked sub-basins, concentration data can only be regressed against the total upstream land use (Ahearn et al., 2005). As loading is based on mass, loadings calculated along a disturbance gradient (hydrologically linked sub-basins) can be successively subtracted from one another to determine the effects of the local landscape variables (rather than total upstream landscape variables) on the observed water quality (Ahearn *et al.,* 2005). Thus, in studies where hydrologically linked sub basins are being used to examine the nutrient additions from differing land use practices on water quality, loadings allow the researchers to distinguish nutrient production between individual sub-basins.

To translate observed water quality data into information regarding the state of the environment several frameworks have been developed to address the linkages between land use practices and water quality. One such framework is the Pressure State Response model framework. This framework is very useful in understanding the pressures (human activities) that cause changes in the environmental state and the actions required by all sectors to mitigate the impacts of these environmental changes (Waheed *et al.,* 2009). One of the main benefits of these frameworks is that all sectors including government, private sector and individual stakeholders (farmers, small industry etc.) can participate in the management actions (Waheed *et al.*, 2009).

The pressure state response model has been used by many researchers to examine the impacts of non-point source landscapes on water quality. In this model, the *pressure* is the land use practice(s) occurring on the landscape (agriculture, forestry, urban), the *state* of the environment is the reported water quality and the *response* is the management actions and political decisions undertaken to target the areas of concern (Hardy and Pinter, 1995). This model is useful for decision makers and was chosen for this study as it does not focus on the fine scale biophysical processes which regulate the interactions between land use and water quality, but instead clearly links human activities occurring on the landscape to environmental degradation (Hodge, 1997). A similar framework was used by Laureano and Navar (2002) to assess the water quality in the Rio San Juan watershed in north-eastern Mexico. By comparing water quality samples to water quality standards (Mexican standard for drinking water and World Health Organization standard for drinking water) it was determined that 18.7% of all samples exceeded the proposed standards. Based on these findings, it was proposed that water quality pollution continues to be a problem in the basin and that integrated multi-sectorial approaches are required to address the current issues (Laureano and Navar, 2002).

While the impact of broadly differing categories of land use on water quality has been studied extensively in North America, the present study is the first to examine the relationships between land use and water quality in the headwaters of the Oldman River Basin. The Oldman River Basin is one of Alberta's most water stressed river basins from a water supply and demand perspective (Bladon *et al.*, 2008) and although many studies have addressed the linkages between agricultural and urban development and water quality throughout the lower reaches of the basin, little is known about these relationships in the headwaters. Additionally, because the headwaters terminate in the Oldman Reservoir, an understanding of the landscapes impacting nutrient production throughout the headwaters is essential if the eutrophication risks to the Reservoir are to be recognized.

Research Outline/Objectives

The overall objectives of this research were to broadly characterise the spatial and temporal patterns in water quality within the three headwaters sub-basins of the Oldman River basin. A related objective was to explore the relationships between water quality and land use classes within the three headwater sub-basins.

The objective of Chapter 2 was to broadly characterise the spatial patterns in water quality (total phosphorus and total nitrogen concentration, export and yield) across a land use disturbance gradient (forest, agriculture, urban) to elucidate pressures on water quality from specific regions within the three headwater sub-basins (Oldman, Castle and Crowsnest) of the Oldman River Basin. A related objective was to explore the temporal patterns in water quality across the three major hydrologic flow periods of the area (baseflow, spring freshet and stormflow) to examine the relationship between streamflow and nutrient concentration, discharge weighted nutrient export, and discharge/land-area weighted nutrient yield.

The broad objectives of Chapter 3 were to evaluate the relationships between river water quality and the dominant categories of land use occurring in the headwaters of the Oldman River Basin. A major objective of the work focused on 1) evaluating the relationships between total nitrogen (TN) and total phosphorus (TP) and differing classes and intensities of land use (agricultural {extensive and intensive} and forestry {extensive and intensive}) in the headwaters (Oldman, Castle and Crowsnest) of the Oldman River Basin. An associated objective was to quantify the changes in water quality (TN and TP) along an urban disturbance gradient situated longitudinally down the Crowsnest River. Lastly, a related objective was to explore the suitability of the pressure state response model as a framework to evaluate non-point source impacts on water quality in Alberta.

In Chapter 4, the results from these two studies are summarized, broader inferences which can be drawn from this work are discussed and future research suggestions are proposed.

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Chapter 2: Regional assessment of source water quality: A case study in the headwaters of the Oldman River Basin

2.1 Introduction

Non-point source pollution is one of the leading causes of water quality degradation around the world (Beaulac and Reckhow, 1982; Carpenter *et al.,* 1998; Tufford *et al.*, 1998). In the U.S., the Environmental Protection Agency (EPA) has attributed non-point source pollution to the impairment of 50% of their lakes and 60% of their river reaches (USEPA, 1996). Compared to point sources, which are localized, can be easily quantified and thus successfully regulated, non-point sources are difficult to rigorously measure and regulate (Beaulac and Reckhow, 1982). However, in the past 2-3 decades, the cumulative effects of non-point source pollution from forested (primarily harvested), agricultural, including a wide range of crop and livestock production (both extensive and intensive livestock operations), and urban landscapes, which may include waste water treatment plants, industrial yards, or golf courses, has received considerable attention in the literature.

Agriculture has long been considered the leading non-point source contributor to water quality impairment, followed by urban and forested landscapes (Carpenter *et al.,* 1998). Non-point source discharges from agricultural lands in the U.S. are estimated to contribute approximately 47% of the total phosphorus and 52% of the total nitrogen loading to surface waters (Environmental Protection Agency (EPA), 1983). Excessive nutrient loads from agricultural landscapes result from the application of nitrogen and phosphorus fertilizers and from the application of manure to crop lands (Carpenter *et al.,* 1998; Beaulac and Reckhow, 1982). As well, the manure management practices of confined feeding operations (CFOs) have a significant impact on the nutrient loads from these landscapes (Carpenter *et al.*, 1998). The recent rapid growth in urban populations has shifted the attention of managers to the impacts of urban landscapes on water quality. These highly modified, impervious landscapes alter the timing and magnitude of runoff events (Beaulac and Reckhow, 1982) and influence important nutrient transport mechanisms by changing the quantity and composition of the suspended sediments entering the stream (Brett *et al.,* 2005). Urban non-point source pollution poses a particular problem for water quality management and regulation because high density residential, commercial, and industrial sectors complicate source identification and loading reduction strategies (Carle *et al.,* 2005). Contrary to the two other landscapes mentioned above, forested landscapes typically do not receive inputs from anthropogenic sources. As such, nutrient loads from harvested forested landscapes are quite low when compared to those from agricultural and urban settings (Beaulac and Reckhow, 1982).

Current approaches to assessing non-point source pollution focus on quantifying the nutrient production from various landscapes (agricultural, forested and urban) (Liu *et al.,* 2000; Ahearn *et al.,* 2005; Brett *et al.,* 2005). This is extremely difficult as the nutrient concentrations and loads emanating from these sources are likely the result of land use inputs and complex biotic and abiotic interactions between the terrestrial environment and the aquatic environment (Sliva and Williams, 2001). Furthermore, nutrient inputs can often be highly variable within and across years due to the timing of specific land use activities (e.g. crop fertilization, irrigation, etc.), and the hydrologic variability (seasonality of runoff, timing of major storms) within an area. Due to the complexity of the issue, simple cause and effect relationships between land use and non-point source pollution are rare.

While some studies focus their attention of the fine scale biophysical processes that govern nutrient dynamics, others have chosen to compare the impacts of differing land use practices at the broader regional scale. Recently, three dominant landscape based approaches have been used to describe the impacts of non-point source pollution on water quality. The first approach involves water quality sampling along a longitudinal disturbance gradient from the upstream to the downstream reaches of a basin (Bolstad and Swank, 1997 and Brett *et al.*, 2005). Bolstad and Swank (1997) used this approach in their study in the Coweeta Creek Basin in North Carolina to assess the incremental nutrient additions of near stream land use activities. In their study basin, the sampling sites in the upper reaches of the watershed were mainly forested while the sampling sites throughout the lower reaches encompassed varying degrees of agricultural and urban land use practices (Bolstad and Swank, 1997). By using this longitudinal approach, it was determined that the lower reaches of the study basin supplied more nutrients to the system than the upper reaches and that nutrient management plans should be developed for those areas (Bolstad and Swank, 1997). As shown by Bolstad and Swank, this longitudinal gradient approach can be effectively used to pinpoint areas within a given basin that are contributing the majority of the nutrients to the river system and can be used to broadly describe the spatial patterns in water quality within a basin.

In the second approach, entire basins are selected based on the composition of land uses within their boundaries. The proportion of each land use category within each basin is used to categorized basins into broad land use classes that reflect the dominant land use practice within basin boundaries (agricultural, forested, urban) (Tufford *et al*., 2003 and Coulter *et al.*, 2004). Contaminant production from these basins is then compared across differing land use categories to identify and rank non-point source impacts from a range of land uses. The third approach combines elements of the two approaches above. In this third approach, one or two large basins are typically sub-divided into sub-catchments and the physiographic and land use characteristics of these sub-catchments are examined to identify the relationships between stream water chemistry and the landscape characteristics. Physiographic features, and land use type and intensity are typically classified using geographical information systems (GIS) with remotely sensed land cover and physiographic data. Once this classification has been performed, multiple linear regression models are developed to link the landscape to the observed water quality. This approach was used by Brett *et al.,* (2005) to quantify the impacts of urban vs. forested land cover on stream nutrient concentrations in the Lake Washington and Lake Sammamish watersheds in Seattle, WA. Using GIS data to classify the physiographic and land cover variables they were able to determine that land cover variables (forest and urban) had the largest influence on stream nutrient concentrations (Brett *et al.,* 2005).

Within each of these three general approaches, studies have either focused on a broader range of water quality parameters (Bolstad and Swank, 1997 and Jarvie *et al.,* 2008), or used a small suite of parameters to broadly characterise their regions (Hill, 1981; Sharpley *et al.,* 1999; Arheimer and Lidén, 2000). While characterizing the water quality using a broad range of water quality parameters supports the use of multivariate approaches to identify groups of contaminants associated with particular land use categories, this approach can be very expensive. Furthermore, the use of fewer (but important) water quality parameters in a regional water quality assessment can be used to highlight “problem areas” on the landscape. Problem areas are those areas on the landscape that are identified as supplying the majority of the nutrients to the system. Once these areas have been located, recommendations for improved management approaches or practices (e.g. nutrient and sediment loading management plans) can be made.

Most of the research on non-point source pollution has also focused exclusively on the concentration of key nutrient contaminants to describe the impacts of varying non-point sources on water quality. However, a number of researchers question the efficacy of using concentration data alone to link landscapes to observed water quality (Hill, 1981; Ahearn *et al.*, 2005; Castillo *et al*., 2000). Ahearn *et al.,* (2005) argued it is impossible to link specific landscapes within a basin to the water quality at the outflow using regression approaches based on contaminant concentrations to establish relationships with upstream land uses. Alternatively, they argued that discharge weighted loading or export (concentration multiplied by discharge) is necessary to link the landscape to the observed water quality. Loading or export is the mass of a contaminant moving downstream and when loading is calculated along a disturbance gradient, loadings at each site can be successively subtracted from one another to determine the effects of the local landscape variables on the observed water quality (Ahearn *et al.*, 2005). While calculating loads does increase the sampling costs associated with water quality research, concentration data alone usually does not have adequate resolution to describe spatial patterns in water quality needed to link non-point source pollution to land use (Ahearn *et al.*, 2005). Establishing linkages between specific areas on the landscape and water quality is needed to develop strategies to effectively manage water quality at a landscape scale.

It has also been recognized by the Environmental Protection Agency in the U.S. that concentration based criteria or guidelines to monitor and regulate water quality may not be adequate to deal with the impacts of non-point source pollution on water quality (Elshorbagy et al., 2005). Thus, the USEPA has shifted the focus of their management from effluent based standards to ambient based water quality standards which focus attention towards a desired level of environmental quality and the efforts necessary to mitigate impairment (Elshorbagy et al., 2005). Through this TMDL approach, which allows managers to limit the level of activity occurring on the landscape within a given basin (Elshorbagy et al., 2005), regulators hope to increase the number of water bodies meeting their desired uses.

This research is focused on the Oldman River Basin which is one of Alberta’s most water stressed river basins from a water supply and demand perspective (Bladon *et al.*, 2008). Throughout the last decade, many studies have related the intensive agricultural practices (large confined feeding operations and row crop cultivation) present in the lower portions of the basin to stream water quality (Canada-Alberta Environmentally Sustainable Agricultural Agreement, (CAESAA) 1998; Greenlee *et al.*, 2000; Little *et al.*, 2003); however, little is generally known about the water quality in the headwater regions of the basin, above the Oldman River Reservoir. The overall objectives of this study were to broadly characterise the spatial patterns in water quality (total phosphorus and total nitrogen concentration, export and yield) across a land use disturbance gradient (forest, agriculture, urban) to elucidate pressures on water quality from specific regions within the three headwater sub-basins (Oldman, Castle and Crowsnest) of the Oldman River Basin. A related objective was to explore the temporal patterns in water quality across the three major hydrologic flow periods of the area (baseflow, spring freshet and stormflow) to examine the relationship between streamflow and nutrient concentration, discharge weighted nutrient export, and discharge/land-area weighted nutrient yield.

2.2 Materials and Methods

2.2.1 Description of Study Region

The study was conducted in three large sub-basins (Oldman, Castle and Crowsnest) that form the headwaters of the Oldman River Basin. Located in south western Alberta, the Oldman basin has a drainage area of 28 200km² and provides water resources for over 200 000 people (Rock and Mayer, 2007). All three headwater sub-basins originate in the Rocky Mountain forest reserve in the extreme south western portion of Alberta and extend eastward through the foothills fescue eco-region to the Oldman River Reservoir which forms the confluence of these three sub-basins.

The forested region forming the upper reaches of all three sub-basins contains alpine, sub-alpine and montane eco-regions (Oldman Watershed Council, 2010). The alpine eco-region occurs above the tree line at the highest elevations within the sub-basins. This area is largely comprised of exposed bedrock, alpine meadows, and shrubs. The sub-alpine eco-region lies below the alpine and is primarily forested with lodgepole pine (*Pinus contorta)*, englemann spruce (*Picea englemannii*), white spruce (*Picea glauca*) and douglas fir (*Pseudotsuga menziesii*). The montane eco-region lies below the sub-alpine eco-region and is characterised by rolling foothills. Lodgepole pine (*Pinus contorta)*, douglas fir (*Pseudotsuga menziesii*) and aspen mixedwood forests cover north and eastern facing slopes while grasslands dominate southerly and westerly areas and lower elevations (Oldman Watershed Council, 2010). The foothills fescue eco-region dominates the lower portions of all three catchments. This eco-region is characterized by a rolling topography dominated by shrubs, aspen (*Populus tremuloides*) and balsom poplar (*Populus balsamifera).*

Soils in the three headwater sub-basins are comprised of two main soil groups. Soils in the upper and middle reaches of the three headwater sub-basins are well to perfectly drained brunisols and gray luvisols with weak horizon development, characteristic of higher elevation northern environments (Rock and Mayer, 2009; Bladon *et al.*, 2008). Soils found throughout the lower reaches of the three sub-basins are brown chernozems (Rock and Mayer, 2009). Surficial geology in all three headwater sub-basins is composed of a thick, continuous till blanket consisting of glacio-lacustrine deposits except for the most western portion of the basins which also include alpine complexes (Rock and Mayer, 2009).

Mean annual precipitation and air temperatures are generally similar among the three sub-basins but vary considerably from the upper elevation headwaters to the lower elevation regions (Table 2-1). The long term mean annual precipitation (1971-2000) in the higher elevation regions along the western portion of the study area ranged from 741-915 mm/yr while precipitation along the lower elevation eastern portion ranged from 439-654 mm/yr. Mean annual precipitation in the Oldman sub-basin was approximately 100-150 mm/yr lower than that of the two southerly sub-basins (Table 2-1). Approximately 60 % of the total annual precipitation within the Oldman and the Castle sub-basins occurred as rainfall, while the Crowsnest sub-basin received 69% as rainfall. Mean annual temperatures were also generally similar among the three sub-basins from 1971-2000 (Table 2-1) with a similar range of mean summer and winter temperatures. Both summer and winter temperatures were approximately 2 ^{o}C cooler in the higher elevation western regions compared to the lower elevation eastern portions of all three sub-basins except in the Oldman basin where mean summer temperatures at the upper elevations were approximately 15 ^{o}C cooler compared with the lower elevations.

The distribution of land uses within the three sub-basins generally follows a similar pattern of change from the headwaters in the western study region to the downstream reaches in the eastern part of the study area. The upper reaches in all sub-basins are predominantly forested with extensive front- and back-country recreational use occurring in all three of the sub-basins. Industrial resource utilization includes both historic and current timber harvesting, low intensity petrochemical development, and extensive historic coal mining development (1900-1960) which occurred primarily in the Crowsnest sub-basin. In the Oldman and the Castle sub-basins, the middle and lower reaches are dominated by agricultural development which consists primarily of extensive grazing but also includes cow/calf operations and some limited cultivation cropping. Crops grown in this region include: cereal crops such as wheat, oats and barley and forage crops such as alfalfa (Oldman Watershed Council, 2010).

Unlike the Oldman and Castle river sub-basins, the middle and lower reaches of the Crowsnest R. run through the municipality of the Crowsnest Pass which consists of five small communities (Coleman, Blairmore, Frank, Bellevue and Hillcrest). The population of the municipality is approximately 5700 people with a population density of 15.4 people per km^2 (Statistics Canada, 2008). Extensive, low density acreage development exists between each of these communities. Tourism and service sector businesses comprise the bulk of the industrial activities in this Municipality which also includes a golf course (Blairemore), septic fields (Hillcrest), regional sewage treatment facilities (Frank), industrial yards (Coleman, Blairmore, Frank, Hillcrest) and old mining facilities distributed within, and between all five communities.

2.2.2 Study Design and Field Sampling

The goal of this study was to examine the broad spatial and temporal patterns in water quality in the three headwater sub-basins (Oldman, Castle and Crowsnest) of the Oldman River Basin to elucidate both the role of natural variability due to climate and development pressures (i.e. land uses) on water quality. Accordingly, the overall study was designed to capture both a) the broad spatial patterns in water quality that reflect the longitudinal gradient in both physiography and land-use from the headwaters downstream to the Oldman Reservoir, and b) the temporal patterns in water quality that reflect the dominant climatic and hydrologic seasons in each of these three sub-basins.

Sampling locations were chosen along the main stems of the three headwater rivers to reflect the spatial variability in water quality produced by differences in the physiographic characteristics (i.e. vegetation, soils, watershed slope and topography) and land use (i.e. forestry, agriculture, urban) patterns from the upper tributaries downstream to the Oldman River Reservoir. A minimum number of samples representing the dominant hydrologic flow periods (baseflow, spring snowmelt freshet and stormflows) were used to describe the broad temporal variability in water quality. In the Oldman sub-basin, four sites along the main stem of the Oldman R. and major tributaries were chosen. Racehorse Creek (OM1) and the Oldman River above Racehorse Creek (OM2) represent the upper tributaries and the Oldman at Maycroft (OM3) and the Oldman at Olin Bridge (OM4) represent the lower reaches of the Oldman sub-basin (Figure 2-1). In the Castle sub-basin, five sites were chosen. Lynx creek (CA1), the Carbondale River above Lynx creek (CA2), and the Castle River at the ranger station (CA3) represent the upper tributaries while the Carbondale at the Adinac road (CA4) and the Castle River at Highway 507 (CA5) represent the lower reaches (Figure 2-1). In the headwaters of the Castle sub-basin, two major forks (Carbondale and Castle Rivers) are represented by sites CA1, CA2, CA3 and CA4. CA1, CA2 and CA3 represent the Carbondale fork which merges with the Castle fork (CA4, Figure 2-1). Three sites along the main stem of the Crowsnest R. were chosen including the Crowsnest River at Star (CR1), the Crowsnest River at Frank (CR2) and the Crowsnest River at Lundbreck (CR3) (Figure 2-1). In the Oldman and the Castle sub-basins, this network of sampling sites represents a gradient from the forested headwaters regions down through the mixed forest/agriculture regions to a dominantly agricultural landscape, encompassing an increasingly larger basin scale (Table 2-2). In the case of the Crowsnest R., the downstream gradient in land cover does not include a clear transition from forest to predominantly agricultural settings as it does in the other two sub-basins. However, the series of communities forming the Municipality of the Crowsnest Pass (Coleman, Blairmore, Frank, Bellevue and Hillcrest) forms a downstream gradient of increasing low density urban influence on water quality.

To describe the broad temporal patterns in water quality that reflect the regional hydro climatic setting and dominant annual hydrologic seasons, water quality sampling was conducted during the spring snowmelt freshet, during mid- to late-summer to capture baseflow conditions and during stormflow conditions. These periods were chosen as they represent the dominant features of the annual single peak hydrographs typical of this area and were categorized using discharge hydrographs of the three sub-basins recorded from the Water Survey of Canada hydrometric gauging stations. The spring snowmelt freshet generally occurs from April through to June and is characterized by high discharges due to melting of the snowpack which contributes a large component to the annual runoff in these rivers. Baseflows reflect a dominance of subsurface contributions to streamflow and begins in late summer during the latter portion of the recession limb of the annual hydrograph and continues through the overwinter periods (in the absence of large rainfall or early winter melt events). Stormflows can occur at any time throughout the year and are defined as higher than normal discharges due to large precipitation events. Because the sampling strategy aimed to balance the description of both spatial and temporal patterns of water quality across these three sub-basins, generally only one or two samples were collected per site for each of these three hydrologic seasons per year. Sampling frequency differed each year and ranged from one sample in 2006 for some sites to five samples per site in 2007 (Table 2-3). However, because the objective of the study was to provide a broad, synoptic description of the spatial and temporal patterns of water quality in the headwaters of the Oldman River Basin, sampling across four years (2005-2008) was considered adequate and representative of the spatial and temporal variability within this study region. Across the four year study period, sample sizes generally range from 4-5 for each site per hydrologic season treatment combination.

2.2.3 Hydrometric and Water Quality Sampling

Instantaneous discharge measurements were taken at the time water samples were collected to calculate flow weighted contaminant export and area-based yields. Flow measurements were conducted at natural control sections selected at each site that had reasonably straight stream alignment and entrenched river banks. Flow measurements at each site were performed using standard area-velocity current metering techniques (10 point measurement) using a Global (FP-201) velocity meter. Discharge during high flow events was estimated from linear relationships developed between hourly discharge recorded at nearby Water Survey of Canada (WSC) hydrometric gauging stations (continuous discharge data) and the instantaneous discharge recorded at my sites from previous sampling events. The date/time of sampling and discharge measurement was recorded for each sample and simultaneous discharge values from the (WSC) stations obtained from the Water Survey of Canada (www.wsc.ec.gc.ca) to enable development of these inter-station discharge relationships.

Manual, depth-integrated grab samples were collected from the middle of the river in acid washed (10% HCl), triple rinsed, high density polyethylene bottles (Bladon *et al.*, 2008). These samples were stored in a refrigerator at 4ºC and transported to the laboratory within four days of collection. Water chemistry analysis was performed by the University of Alberta Biochemical Analytical laboratory in the Department of Biological Sciences as follows. Total nitrogen concentration (TN; unfiltered) was determined by automated cadmium reduction (Method 4500; NO_3^-:F) using a Lachat QuickChem 8500 multichannel flow injection analyzer (Greenberg et al. 1999). Samples were then digested with potassium persulfate ($K_2S_2O_8$) prior to analysis. Total phosphorus concentration (TP; unfiltered) was determined by automated ascorbic acid reduction (Method

4500 – P:F) using a Lachat QuikChem 8500 multi-channel flow injection analyzer (Greenberg *et al.*, 1999). Samples were digested using the persulfate oxidation technique with potassium persulfate ($K_2S_2O_8$) prior to analysis.

Using TN and TP concentration and the discharge measurements calculated for each sampling event, nutrient export (kg/day), and nutrient yield (kg/ha/yr) were calculated. Export for each contaminant was calculated as the product of the concentration (μg/l) and discharge (m^3/s). Specific watershed area weighted contaminant yield expresses total contaminant production per unit land area and was calculated as the difference in total contaminant export between each station and the next upper most station, divided by the difference in watershed area between these two stations. In contrast to simply calculating cumulative watershed contaminant yield at increasing spatial scales, this approach provides information on differential unit area contaminant production in different regions of each sub-basin. For the uppermost headwater stations, contaminant yield was calculated as the total contaminant export divided by watershed area (Bladon *et al.*, 2008).

2.2.4 Statistical Analysis

Given the broad synoptic approach and the small sample size used to describe variability in nutrient production among the three headwater sub-basins, statistical analysis of the data focused on identifying broad trends or patterns evident in spatial and temporal variability of water quality in this study region. Thus, the primary sampling objective was to "capture" the main sources of spatial temporal variability in water quality across the dominant hydrologic seasons acknowledging that statistical power to show differences in water quality parameters among regions may be limited. All data analysis was performed using SAS statistical software (version 9.2, Cary, United States). Total phosphorus and total nitrogen concentration, export and yield data failed to meet Shapiro-Wilk's tests for normality as is typically the case with water quality data (Bladon et al., 2008). Additionally, transformations of these data using log, log(x+1) and square root(x) also failed to meet assumptions for normality. However, non-parametric techniques such as the Kruskal-Wallis test have been recommended for water quality data of this type (Helsel and Hirsch, 2002). A series of single-factor Kruskal-Wallis non-parametric tests were used to test the strength of spatial patterns (differences among sub-basins and variability among sites), and temporal patterns (hydrologic flow period, annual variation) of the total phosphorus and total nitrogen concentration, exports and yields. A Dunn's comparison test was then used to compare the sites within each sub-basin and across hydrologic flow periods and years to identify dominant sources of variation. Dunn's test compares the differences in the sum of ranks between two groups with the expected average difference (based on the number of groups and their size) (Daniel, 1990).

2.3 Results

2.3.1 River discharge

Streamflow in the Oldman, Castle and Crowsnest sub-basins from 2005-2008 was characterized by annual hydrographs dominated by a single peak reflecting the annual snowmelt freshet beginning in early May, peaking in late June, followed by flow recession towards baseflow conditions in late summer (Figure 2-2). On a volume basis, mean total annual discharges (2005-2008) gauged near the confluence with the Oldman Reservoir were 429439 Dam^3/yr in the Oldman R. (WSC station 05AA023, Oldman R. at Waldron's Corner), 489690 Dam^3/yr in the Castle R. (WSC station 05AA022, Castle R. near Beaver Mines), and 167519 Dam^3/yr in the Crowsnest R. (WSC station 05AA008, Crowsnest at Frank) (Table 2-4). Over this four year period (2005-2008), the Castle R. produced the greatest amount of water, 12 % more than the Oldman R. and 66 % more than the Crowsnest R. Annual peak discharges generally reflected the same variability among sub-basins ranging from 62-360 m^3/s in the Oldman R., 63-325 m^3/s in the Castle R., and 22-50 m^3/s in the Crowsnest R. Baseflow conditions in all three catchments ranged from 1 to 3 m^3/s and generally occurred from late July through to March (Figure 2-2). Fall and early winter peakflow events also occurred in all three headwater sub-basins during the study period.

A considerable increase in streamflow from the upstream to the downstream sites existed throughout all three hydrologic flow periods in all three headwater sub-basins (Table 2-5). During baseflow periods, the range in discharge values from the upstream to the downstream sites differed only slightly between the three sub-basins (1.3 m^3/s at OM1 increasing to 12.9 m^3/s at OM4; 1.0 m^3/s at CA1 increasing to 9.73 m^3/s at CA5; and 3.72 m^3/s at CR1 increasing to 6.95 m^3/s at CR3, Table 2-5). During high discharge events, spring freshet and stormflow periods, mean streamflow at the upper sites in all three sub-basins increased by a factor of 4.1 and 12.7 times respectively. Similarly, mean streamflow at the lower sites in all three sub-basins increased by a factor of 3.4 and 12.1 times during spring freshet and stormflow periods respectively. It is also important to note that the Castle fork within the Castle sub-basin supplies more water to system than the Carbondale fork (Table 2-5).

Differences in river discharge generally reflected differences in total annual precipitation among the three sub-basins. Mean annual precipitation (2005-2008) was 581.8, 708.2, and 507.6 mm/yr for the Oldman, Castle, and Crowsnest sub-basins respectively (Table 2-4). For all three sub-basins, 2005 was a generally wet year with both the greatest annual precipitation and greatest total streamflow production. Heavy rains during June 2005 produced high river discharge in all three sub-basins, but particularly in the northern Oldman sub-basin (362 m^3/day). The next three years (2006-2008) were considerably drier with both less annual precipitation and runoff. While 2008 was generally dry, a large rainstorm in late May produced very high discharges in southern sub-basins (particularly in the Castle R., 320 m^3/day) (Figure 2-2).

2.3.2 Spatial Variability of Water Quality

2.3.2.1 Total Phosphorus

Total phosphorus (TP) production was generally similar among the three sub-basins, but showed considerable spatial variability within each sub-basin. The range of TP concentrations from 2005-2008 differed only slightly among the three sub-basins over the study period (3-831 µg/L in the Oldman R., 2-809 µg/L in the Castle R. and 3-522 µg/L in the Crowsnest R., Table 2-6, Figure 2-3). Despite these small differences in range of concentrations, median total phosphorus concentrations, exports and yields were quite similar in the three sub-basins over the four year study period and across the three hydrologic regimes. Median phosphorus concentrations (2005-2008) were 12.8 µg/L, 10.5 µg/L and 15.0 µg/L in the Oldman, Castle, and Crowsnest rivers, respectively (p=0.21, Table 2-6, Figure 2-3). While the mean river discharges recorded during the study period at all of the sampling sites along the Oldman, Castle and Crowsnest rivers were 45.5 m^3/s, 25.5 m^3/s, and 15.5 m^3/s respectively, these moderate differences in streamflow did not produce large differences in the flow weighted TP exports among the three sub-basins (Table 2-6). Median TP exports were 2.0 x 10^{-2} kg/day, 0.8 x 10^{-2} kg/day, and 1.4 x 10^{-2} kg/day in the Oldman, Castle, and Crowsnest rivers (p=0.16, Table 2-6, Figure 2-3). Consistent with these patterns, median TP yields were 2.0 x 10^{-4} kg/ha/yr, 3.0 x 10^{-4} kg/ha/yr, and 3.0 x 10^{-4} kg/ha/yr in these same three sub-basins, respectively (p=0.89, Table 2-6, Figure 2-3).

While TP concentrations were variable within each of the three headwater sub-basins, median TP concentrations across all four study years were similar from the upstream to the downstream sites. Median total phosphorus concentrations (2005-2008) in the Oldman basin ranged from 9.55 µg/L in the headwaters at OM1 increasing to 22.6 µg/L at OM4, the most downstream sampling site (p=0.64, Table 2-7, Figure 2-4). While the coefficient of variation did not change appreciably from upstream to downstream sampling sites (Table 7), the range of TP concentrations increased from 3-262 µg/L at the upper most site, OM1 to 3-821 µg/L at OM4. An increase in both median TP and the range of TP was evident between the two upper sites (OM1 and OM2) and the two downstream sites (OM3 and OM4). A generally similar pattern of weakly increasing median TP concentrations and range of concentrations were evident in both the Castle and Crowsnest sub-basins. In the Castle sub-basin, median TP concentrations ranged from 9.14-11.64 μg/L at the upper sampling sites (CA1, CA2, and CA3) to 16.2-16.36 μg/L at the two downstream sites (p=0.92, for CA4 and CA5). As in the Oldman sub-basin, the range of TP concentrations were generally similar for upper sites in the Castle sub-basin (CA1-CA4; 2-361 μg/L) but increased to 2-809 μg/L at the lower most CA5 site (Table 2-7, Figure 2-4). Similarly, a weak increase in both median TP concentrations and the range of concentrations from 12.64 μg/L and 5-73.6 μg/L at CR1 respectively, to 15.7 μg/L and 7-522 μg/L at CR3, respectively, were observed in the Crowsnest sub-basin (p= 0.51, Table 2-7, Figure 2-4).

While no strong trend was evident in TP concentrations from the upstream to the downstream sites in the three headwater sub-basins, a strongly increasing linear pattern in TP exports was observed between the upstream and the downstream sites along the Oldman and the Castle rivers over the four year study period (Figure 2-5). In the Oldman basin, median total phosphorus exports over the four year study period at the upper sites were 0.6×10^{-2} kg/day at OM1 increasing to 1.9×10^{-2} kg/day at OM2 (Table 2-7, Figure 2-5). The range of values observed at these two upper sites (2005-2008) was $0.02 - 276.0 \times 10^{-2}$ kg/day (Table 2-7). The lower sites in the Oldman basin exported roughly 3.8 times the total phosphorus of the upper sites (p=0.02). Median total phosphorus exports at these lower sites were 3.1×10^{-2} kg/day at OM3 increasing to 6.5×10^{-2} kg/day at OM4 (Figure 2-5). The range of values observed at the lower sites throughout the entire study period was also greater (more variable) than the upper sites at $0.008\text{-}2461 \times 10^{-2}$ kg/day (Table 2-7, Figure 2-5). This increase in variability of exports and the linear increase in median TP exports from upper to lower sites along the Oldman R. reflects the combined increase in TP loading and increase in streamflow from the upstream to the downstream sites (Table 2-7, Figure 2-5). The same general trend in TP exports was observed in the Castle sub-basin with the upstream sites exporting less TP than the lower sites, though the gradient was not as strong as in the Oldman sub-basin. Median TP exports observed at the upper sites in the Castle basin over the four year study period were 0.4 x 10^{-2} kg/day at CA1, 0.7 x 10^{-2} kg/day at CA2 and 2.1 x 10^{-2} kg/day at CA3 and the range of exports and coefficient of variation also generally increased in the downstream direction (Table 2-7, Figure 2-5). The lower sites within the Castle basin, exported roughly 2.7 times more TP as the upper sites (p=0.15). Median TP export values observed at these lower sites were 1.6 x 10^{-2} kg/day at CA4 increasing to 4.3 x 10^{-2} kg/day at CA5 (Table 2-7, Figure 2-5). While a similar linear trend of increasing downstream TP export existed in the Crowsnest basin, the gradient from the upstream and the downstream sites was very weak. Median TP exports were 0.7 x 10^{-2} kg/day, 1.6 x 10^{-2} kg/day, and 2.7 x 10^{-2} kg/day at CR1, CR2 and CR3 respectively (p=0.42, Table 2-7, Figure 2-5). As with the other sub-basins, an increase in variability of downstream exports was observed.

A stronger pattern of increasing TP yield from upstream to downstream regions was observed in all three headwater sub-basins. Median total phosphorus yields (2005-2008) from the upper sites in the Oldman basin were 0.08 x 10^{-3} kg/ha/yr at OM2 and 0.1 x 10^{-3} kg/ha/yr at OM1 (Table 2-7, Figure 2-6) while TP yields in the lower reaches (OM3 and OM4) were approximately 5.3 times greater (p=0.01, Figure 2-6). Median TP yield from these lower reaches (2005-2008) were 0.35 x 10^{-3} kg/ha/yr at OM3 increasing to 0.61 x 10^{-3} kg/ha/yr at OM4 (Table 2-7). This discrete change between the upper and the lower sites of the Oldman basin clearly indicates that the landscape in the lower portion of the basin was contributing more total phosphorus to the river on a unit area basis than the landscape in the upper portion of the basin. This same discrete increase in TP yield between upstream and downstream regions was also evident in the Castle sub-basin (Figure 2-6). Median TP yield (2005-2008) in the upper sites (CA1, CA2, and CA3) ranged from 0.15-0.21 x 10^{-3} kg/ha/yr compared to 1.6-10.0 x 10^{-3} kg/ha/yr at the lower sites (CA4 and CA5). In the Castle sub-basin, this corresponded to a 7.3 fold increase in TP yield for lower reaches compared to the headwaters region ($p<0.01$). Unlike the discrete change in TP yield evident in both the Oldman and Castle sub-basins, only a very weak, gradual gradient of increasing TP yield was observed from upstream to downstream regions in the Crowsnest sub-basin ($p=0.76$, Table 2-7, Figure 2-6).

2.3.2.2 Total Nitrogen

Consistent with results for TP, considerable variability in total nitrogen (TN) was observed within the three headwater sub-basins, however, median TN concentrations varied significantly among the three headwater basins. Median TN concentrations (2005-2008) were 134 µg/L, 166 µg/L, and 251 µg/L in the Oldman, Castle, and Crowsnest sub-basins, respectively ($p=0.007$, Table 2-8, Figure 2-7). However, despite differences in TN concentrations and mean discharge across the study period (45.5 m^3/s , 25.5 m^3/s, and 15.5 m^3/s in the Oldman, Castle, and Crowsnest, respectively) median flow weighted TN exports (2005-2008) were not strongly variable among sub-basins ($p=0.10$). Median TN exports were 0.33, 0.16, and 0.28 kg/day in the Oldman, Castle, and Crowsnest sub-basins, respectively (Figure 2-7). No difference in median TN yield was evident among the three headwater sub-basins ($p=0.66$, Table 2-8, Figure 2-7).

Within each of the sub-basins, TN concentrations (2005-2008) showed similar, weak patterns of variability from headwaters to downstream sites as observed for TP. In the Oldman sub-basin, a weak (non significant) increase in median TN concentrations was evident from the upper headwaters site (OM1, 145 µg/L) downstream to the lower (OM4) site (195 µg/L) ($p=0.71$, Table 2-9, Figure 2-8). However, in the Castle sub-basin, median TN concentrations at the upper most sites were greater than those at the lower sites. Median TN concentrations (2005-2008) ranged from 117–299 µg/L at the upper most sampling sites (CA1, CA2 and CA3) to 98–138 µg/L at the two downstream sites (CA4 and CA5) ($p=0.39$, Table 2-9, Figure 2-8). Lastly, no consistent pattern in TN concentrations was evident from the upstream to the downstream sites along the Crowsnest R. ($p=0.51$, Table 2-9, Figure 2-8). While the uppermost site (CR1) had the lowest median TN concentrations (220 µg/L) over the study period, the mid-reach site (CR2, Crowsnest at Frank) had greater TN concentrations than the lower (CR 3) site (262 and 247 µg/L, respectively, Figure 2-8). Consistent with the pattern of spatial variability observed for TP, variability in TN (range and coefficient of variation) was generally greater at the most downstream sites.

As with TP, the combination of weakly increasing trends in TN concentration combined with greater downstream river discharge resulted in strong spatial patterns of increasing TN export from the uppermost headwaters to the downstream reaches in all three sub-basins over the study period. In the Oldman sub-basin, median TN exports at the upper sites were 8.0 x 10^{-2} kg/day at OM1 increasing to 31.0 x 10^{-2} kg/day at OM2 (Table 2-9). The lower sites in the basin, exported roughly 3.7 times the amount of TN as the upper sites (p=0.03) with median TN export of 48.0 x 10^{-2} and 93.0 x 10^{-2} kg/day at OM3 and OM4, respectively (Figure 2-9). This same linear increase in TN exports was evident in the Castle sub-basin. Median TN exports (2005-2008) at the upper sites in the Castle sub-basin were 10.0 x 10^{-2} kg/day at CA1, 11.0 x 10^{-2} kg/day at CA2 and 19.0 x 10^{-2} kg/day at CA3, while 30.0 x 10^{-2} and 54 x 10^{-2} kg/day were observed at CA4 and CA5, respectively (Table 2-9, Figure 2-9). This corresponds to a 2.2 fold increase in exports at these lower sites (p=0.08). Similarly, a weak trend in TN exports was evident in the Crowsnest basin; Median TN exports increased from 11.0 x 10^{-2} kg/day at CR1, to 42.0 x 10^{-2} and 47.0 x 10^{-2} kg/day at CR2 and CR3 respectively (p= 0.29, Table 2-9, Figure 2-9).

In comparison with phosphorus yields, a more abrupt increase in TN yield was observed from the upper to the lower sites in the three headwater sub-basins. In the Oldman sub-basin, median TN yields from the upper two sites ranged from 12.0 x 10^{-4} to 13.0 x 10^{-4} kg/ha/yr at OM1 and OM2 respectively, while the downstream OM3 (54.0 x 10^{-4} kg/ha/yr) and OM4 (88.0 x 10^{-4} kg/ha/yr) sites produced 5.6 times more TN (p=0.01, Table 2-9, Figure 2-10). This same pattern was observed in the Castle sub-basin with the downstream sites (CA4 and CA5) producing 5.3 times greater TN than the upper (CA1, CA2, and CA3) sites (p<0.01, Figure 2-10). Lastly, while the Crowsnest sub-basin showed this same general pattern from upper to lower sites (25.0×10^{-4}, 68.0×10^{-4}, and 61.0×10^{-4} kg/ha/yr for CR1, CR2 and CR3 respectively, Figure 2-10), this downstream pattern of TN production was not significant (p=0.77).

2.3.3 Temporal Variability in Water Quality

2.3.3.1 Flow Periods

Nutrient (TP and TN) concentrations, exports and yields were highly variable among the three hydrologic flow periods (baseflow, spring freshet, stormflow) over the study period in all three sub-basins (Figures 2-11 and 2-12). This variability was driven by strong variability in streamflow among these dominant hydrologic flow periods (Table 2-10). Discharge in the Oldman sub-basin was most strongly variable with mean Q ranging from 6.8, 29.2, and 109.3 m^3/s during baseflow, spring freshet, and stormflow periods, respectively (Table 2-5). Flow variability among hydrologic periods was intermediate in the Castle sub-basin, and least variable in the Crowsnest sub-basin.

Total phosphorus concentration, export and yield in the Oldman basin were highly variable among dominant flow periods with the greatest concentrations, flow weighted export and yield occurring during snowmelt freshet and stormflow conditions (Figure 2-11). Similarly, a strong increase in variability of TP concentrations, exports and yields was evident with increasing streamflow from baseflow to spring freshet and stormflows in all 3 sub-basins (Table 2-10, Figure 2-11). Strong variability in TP concentration among flow periods was evident with median TP concentrations during periodic stormflows 11.4 times greater than those observed during baseflow periods (p<0.01). The combination of both increased TP concentrations and river discharge during higher flow periods (melt freshet and stormflows) resulted in 191- and 206-fold greater median TP export and yield compared to baseflows (p<0.01 for both TP export and yield, Table 2-10). The same general trends in TP concentrations, exports and yields between hydrologic flow periods existed in the Castle and Crowsnest sub-basins.

In the Castle sub-basin, median TP concentration, export and yield was 12.9, 164.6, and 170.5 times greater (respectively) during stormflow periods than during non-event baseflows ($p<0.01$ for all three TP parameters; Table 2-10, Figure 2-11). Similarly, while slightly less variability in discharge among flow periods was evident in the Crowsnest river compared to the Oldman and Castle sub-basins, the pattern of variability in median TP concentration among flow periods was similar to the other sub-basins ($p<0.01$, Table 2-10). This resulted in 39.9 and 37.4 fold greater median TP export and yield (respectively) with higher discharges during the melt freshet and stormflows compared to those observed during baseflow periods ($p<0.01$ for both TP parameters; Table2-10, Figure 2-11).

Similarly, TN concentration, export and yield were also highly variable among dominant flow periods with the greatest concentrations, flow weighted export and yield occurring during stormflow conditions in all three sub-basins (Figure 2-12). A strong increase in variability of TN concentrations, exports and yields was also evident with increasing streamflow from baseflow to spring freshet and stormflows in all three sub-basins (Table 2-11, Figure 2-12). In the Oldman sub-basin, strong variability in TN concentration among flow periods was evident with median TN concentrations during periodic stormflows 12.9 times greater than those observed during baseflow periods ($p<0.01$). The combination of both increased TN concentrations and river discharge in the Oldman sub-basin during higher flow periods (particularly stormflows) resulted in a 192- and 242-fold greater median TN export and yield compared to baseflow conditions ($p<0.01$ for both TN export and yield, Table 2-10). The same general temporal patterns among hydrologic flow periods for TN concentrations, exports and yields existed in the Castle and Crowsnest sub-basins. In the Castle sub-basin, median TN concentration, export and yield was 12.2, 266.0, and 169.9 times greater (respectively) during stormflow periods than during non-event baseflows ($p<0.01$ for all three TN parameters; Table 2-11, Figure 2-12). Similarly, while slightly less variability in discharge among flow periods was evident in the Crowsnest sub-basin compared to the Oldman and Castle sub-basins, the pattern of variability in median TN concentration among flow periods was similar to the other sub-basins ($p<0.01$, Table 2-11). This resulted in 37.5 and 34.6 fold greater median TN export and yield (respectively) during the melt freshet and stormflows compared to those observed during baseflow periods ($p<0.01$ for both TN parameters; Table 2-11, Figure 2-12).

2.3.3.2 Annual Variability

Overall annual nutrient production also varied during the four year study period (2005-2008) in the three headwater sub-basins. This variability was driven by the inter-annual variability in precipitation observed throughout the study. Precipitation was highest in 2005 (852.8mm, 1041.6mm and 712.0mm in the Oldman, Castle and Crowsnest sub-basins respectively), followed by three generally drier years in all three sub-basins (Table 2-4).

A general pattern of increasing total phosphorus concentration, export, and yield with increasing annual discharge was observed in the Castle and the Crowsnest sub-basins (Table 2-12). Concentrations were highest in 2005 (22.3 µg/L and 33.0 µg/L in the Castle and Crowsnest basins respectively), the wettest year of the study, and lowest during 2007 (8.0 µg/L and 10.0 µg/L in the Castle and Crowsnest basins respectively, Table 2-12, Figure 2-13), the driest year of the study. Total phosphorus exports and yields in the Castle and Crowsnest sub-basins were also the highest in 2005 and the lowest in 2007 (Table 2-12, Figure 2-13). This same pattern was not observed in the Oldman basin throughout the four year study period due to the occurrence of a large storm event in May of 2008. While 2005 was the overall wettest year of the study, in the Oldman basin, total phosphorus concentrations, exports and yields were highest in 2008 (93.8 µg/L, 47.5×10^{-2} kg/day and 55.0×10^{-4} kg/ha/yr, Figure 2-13). This reflects the importance of sampling intra-annual variability.

Similarly, the Castle and the Crowsnest basins experienced the same general pattern of increasing total nitrogen concentration, export, and yield with increasing annual discharge. Concentrations of total nitrogen were highest in 2005 (375.2 µg/L and 601.5 µg/L in the Castle and Crowsnest basins respectively,

Figure 2-14) and lowest in the Castle basin during 2007 (83.0 µg/L) and lowest in the Crowsnest basin during 2008 (147.0 µg/L, Table 2-13). Again the pattern was different in the Oldman basin. While 2005 was the wettest year and did produce the largest total nitrogen concentrations, exports and yields (558.8 µg/L, 78.3 x 10^{-2} kg/day and 100.0 x 10^{-3} kg/ha/yr, respectively), 2008, the driest year throughout the basin produced considerable total nitrogen concentrations, exports and yields (136.5 µg/L, 45.8 x 10^{-2} kg/day, and 5.0 x 10^{-3} kg/ha/yr, respectively, Figure 2-14). Again, this is likely due to the occurrence of a large storm event during the spring of 2008.

2.4 Discussion

Over the four year study period, considerable spatial variability in total phosphorus and total nitrogen concentration, export and yield was observed in the three headwaters sub-basins of the Oldman River Basin. While there were no major differences in TP and TN concentrations, export and yield among the three headwater sub-basins, in the Oldman and the Castle sub-basins, important spatial differences in nutrient production were evident between the upstream (predominantly forested) and the downstream (mixed agricultural/forested) reaches. These differences between the upstream and the downstream reaches were not as distinct in the Crowsnest sub-basin largely because there is no clear transition between a forested and an agricultural landscape in this basin. These broad spatial findings are essential to future land and water management in the headwaters of the Oldman Basin as they identify regions on the landscape that contribute the greatest amount of nutrients (both TP and TN) to the system. This identification enables the development of site specific management strategies to address these water quality problems.

The link between land use (forest, agriculture and urban) and water quality degradation is well established in the literature (de la Crétaz and Barten, 2007). Undisturbed forested landscapes have been shown to contribute relatively low concentrations of phosphorus and nitrogen to nearby streams (Ahearn *et al.*, 2005;

Beaulac and Reckhow, 1982; Herlihy *et al.,* 1998). Conversely, many studies have shown a positive correlation between agricultural and urban land use with stream phosphorus and nitrogen concentrations (Hill, 1981; Beaulac and Reckhow, 1982; Omernik, 1976; Jordan *et al.,* 1997). Results from this study indicate that over the four year study period, no significant trends in median total phosphorus and total nitrogen concentrations were evident from the upstream sites to the downstream sites in the Oldman, Castle, and Crowsnest sub-basins. The lack of an increase in both total phosphorus and total nitrogen concentrations downstream was unexpected because of the changing land use patterns that exist within the three sub-basins. In all three headwater sub-basins, the upper reaches are predominantly forested. In the Oldman and the Castle basins, the lower reaches are dominated by a mixed agricultural setting which consists primarily of extensive grazing, but also includes some small cow-calf operations and limited cultivation. The middle and lower reaches of the Crowsnest basin flow along an urban disturbance gradient through the Municipality of the Crowsnest Pass.

While the absence of a clear downstream trend in total phosphorus and total nitrogen concentrations was unexpected, it is consistent with the results of several others working in mixed land use basins in other regions. Tufford *et al.,* (1998) and Jarvie *et al.* (2008) found that within a basin composed of both forestry and agricultural activities, median concentrations of total phosphorus did not show a clear downstream trend. While clear regional differences in climate and physiography often exist among studies of this type, land use activities in the study area examined by Tufford *et al.,* (1998) in South Carolina were similar to those examined in my study and included forest, agriculture (row crops and pasture) and urban, with the forested areas typically occurring at the upper ends of the basins and the agricultural and urban areas occurring at the lower ends of the basins. Throughout the basins examined in their study, median total phosphorus concentrations ranged from approximately 62.5 µg/L at the upper sites to approximately 65.0 µg/L at the downstream sites (Tufford *et al.,* 1998). Median total phosphorus values throughout the three sub-basins in my study ranged from

10.6 μg/L at the upper sites to 16.7 μg/L at the lower sites, much lower than those reported by Tufford *et al.,* (1998). While the magnitude of TP concentrations would be expected to differ among these widely separated regions, Tufford *et al.,* (1998) observed only a 4% increase in TP between upstream forested regions and downstream areas dominated by agriculture, whereas I observed a 58% increase in TP concentration along similar gradients in the Oldman River Basin.

Similarly, consistent with my results for TP, other researchers have observed weak downstream trends in total nitrogen concentrations from upstream to downstream regions that span a range of lower intensity to higher intensity land uses. In a study conducted on a series of watersheds ranging from native grasslands to row crops (wheat, cotton, oats) in Woodward OK, Sharpley *et al.,* (1987) found total nitrogen concentration did not increase appreciably downstream (5260μg/L at the upper sites to 5280μg/L at the lower sites). While the values reported in their study are much higher than those reported in the present study (186.5μg/L at the upper sites to 184.2μg/L at the lower sites) due to the large amount of nitrogen fertilizer being applied to the fields in their study; the relative trend from upstream to downstream was very similar in both studies.

Conversely, many other studies have observed an increase in TP and TN concentrations along disturbance gradients (forested to agricultural or urban landscapes) (Little *et al.*, 2003; Ahearn *et al.*, 2005; Zampella, 1994; Castillo *et al.*, 2000). The lack of a large increase in both total phosphorus and total nitrogen concentrations within the Oldman and the Castle sub-basins likely reflects the extensive nature of the agricultural practices within these two basins. Many studies that have reported increases in concentrations have examined agricultural landscapes in which large cow-calf operations and cultivation dominate the landscape. While these practices are present within my study region, the percentage of land area occupied by these intensive practices was very small in comparison to previous studies. In the Crowsnest sub-basin, the lack of a large increase in downstream TP and TN concentration is likely due to the small size and low population density of the communities and situated along the river.

The differences in physiographic setting, land use characteristics, and climatic regimes between Alberta, South Carolina and Oklahoma are partially responsible for the differences observed in absolute TP and TN concentrations (Sharpley *et al.,* 1987; Tufford *et al.,* 1998). However, the comparison of TP and TN concentrations in the present study to those observed by others in similar land use settings confirms that water quality in the headwaters of the Oldman R. Basin (Oldman, Castle, and Crowsnest Rivers) remains fairly pristine when compared to areas with a high population density and higher proportions of intensively managed (agricultural, forested etc.) areas.

While I did not observe a large change in total phosphorus and total nitrogen concentrations between the upper and the lower sites in all three headwater sub-basins, a linearly increasing trend in exports was observed in all three sub-basins. This suggests nutrient loading was evident along the main stem of all three headwater rivers. For concentrations to remain constant with increasing discharge, the rate of nutrient loading must equal the rate of increasing river discharge. In the present study, the downstream increase in both discharge and nutrient additions resulted in a two fold increase in exports of both nutrients at the lower sites in comparison to the upper sites. The purpose of this study was not to explore the biogeochemical processes which govern nutrient dynamics; however, it is important to note that loading in all three sub-basins may be greater than observed due to the removal of contaminants (TP and TN) through instream nutrient processing. Despite regional differences in nutrient concentrations and river discharges, these results are consistent with similar studies exploring upstream/downstream gradients in nutrient exports (Beaulac and Rechow 1982 and Jordan *et al.,* 1997).

Increased nutrient additions from the downstream reaches in the Oldman and the Castle sub-basins were also evident when examining total phosphorus and total nitrogen yields. The distinct jump between the upper and the lower sites along these two headwater rivers combined with the fact that nutrient yield reflects a land area based expression of nutrient loading, strongly supports the inference that the lower reaches of these rivers likely supply the bulk of the nutrients to the Oldman Reservoir. This inference is also consistent with findings of other research. Ahearn *et al.,* (2005) and Castillo *et al*., (2000) also found that by including differential yields into their analysis, the lowlands could be identified as the key sources of nutrients to the system. Unlike the Oldman and Castle sub-basins, yields along the Crowsnest River increased linearly and reflected the incremental additions of nutrients from the five communities located longitudinally downstream

This study clearly indicates that production of TP and TN in the three headwater sub-basins was greatest during spring freshet and stormflow events. This is expected as discharge during these periods are much higher than average discharges. Additionally, increased sediment inputs from bank erosion and stream bed scouring, increase the amount of nutrients in the water column, Furthermore, the connectivity between the surrounding landscape and the stream is enhanced, thus increasing the amount of sediment associated nutrients available to enter the stream (Wilson *et al.*, 1990). While these major discharge events have significant impacts on the water quality and quantity in a basin, many studies do not include the range of hydrologic seasons in their sampling design (Johnson *et al.*, 1997; Liu *et al.*, 2000; Tufford *et al.*, 2003). Johnson *et al.*, (1997) collected samples only during the falling limb of the hydrograph and during baseflow periods, while Tufford *et al.*, (2003) and Liu *et al.*, (2000) chose to capture only baseflow conditions in their study, and specifically did not sample during or immediately after rainfall events. Using these methods, they were unable to link variation in nutrient concentrations to land use categories in their study. Furthermore, because much of the nutrient production occurs during higher flow periods, by excluding these discharge events these studies likely miss key information (sediment loads, extreme nutrient concentrations etc.) needed to link non-point source research to the design of effective BMP's (nutrient and sediment management).

Results of this study strongly support the idea that water quality assessments that consider only contaminant concentration may not provide a robust description of non-point source pollution. Others have also suggested that it is necessary to include both concentration and discharge information in regional water quality analyses to link the landscape with the observed patterns in water quality (Hill 1981). However, this issue is not universally acknowledged and remains a topic of debate in the literature. Both Johnson (1997) and Osborne and Wiley (1988) argued that contaminant concentration should be used in regional water quality studies because ecosystem health is more easily and directly linked to contaminant concentrations (in Ahearn *et al.*, 2005). However, while many studies of this kind default to broad or vague statements supported by other researchers concerning the sufficiency of contaminant concentration data for regional water quality assessments, few researchers are able to link observed patterns of water quality to specific problem regions on the landscape.

While Johnson *et al.,* (1997) were able to identify broad associations between non-point source nutrient pollution and land-use characteristics within study basins, they were not able to identify specific problem areas or "hot spots" on the landscape that supply the largest amount of nutrients to the river system. Because the broad link between various land-use activities and water quality degradation from phosphorus and nitrogen is very well established in the literature (Hill, 1981; Bolstad and Swank, 1997; Beaulac and Reckhow, 1982; Osborne and Wiley, 1988), contemporary research and regional water quality assessments must accomplish more than simply re-affirming these links within a given region. Because discharge weighted nutrient export and yield provides much more spatial resolution than contaminant concentration alone, regional water quality assessments should focus on identifying problem areas on the landscape to enable development of management strategies to address non-point source pollution. The additional inferences made possible by integrating contaminant concentrations with river discharge information justify the higher level of effort and cost.

The U.S. Environmental Protection Agency has recognized that concentration based criteria have not succeeded in protecting the nations waterways (Boyd, 2001). While the American Clean Water Act (1972) supported considerable progress in assessing and controlling point source contamination, the majority of water quality degradation of that nation's waterways stems from non-point sources (Brown *et al.*, 1993). While discharge weighted contaminant loading (TMDL; total maximum daily loads) were initially proposed as a solution to identifying degraded waterways in the 1972 Clean Water Act, TMDLs have only recently received higher attention. The U.S. EPA has recognized that TMDLs provide the mechanism for the integrated management of point and non-point sources and aid in the development of more stringent water quality controls in situations where technology based controls are not adequate to achieve state water quality standards (USEPA, 1991).

Individual states are now required to prioritize impaired waters based on use and severity of impairment and must establish TMDLs that recognize the contributing contaminants, identify the source of these contaminants and establish load reductions for these contaminants (Boyd, 2001). By calculating loadings throughout a watershed, "hot spots" (areas on the landscape which are supplying the greatest amount of contaminants) can be identified and the appropriate TMDLs can be established. While TMDLs are a necessary step in watershed and non-point source water quality management, there are significant implementation challenges. Although the scientific knowledge exists to develop the analytical tools required to implement this program, the development of the models required to link the landscape factors to the contaminant loads and to the processes influencing these loads (contaminant transport, in-stream processing etc.) require site specific information (Boyd, 2001). Similarly, the costs associated with collecting concentration and discharge data are considerable (Boyd, 2001). While some agencies have argued that the benefits of contaminant loading based approaches to regional water quality assessment do not justify the higher costs (NRC, 2001), the present study confirms this information can be obtained with a modest budget. Additionally, the present study confirms that nutrient loadings can be used to effectively identify "hot spots" on the landscape.

2.4.1 Conclusions

Results from this study show that concentration based water quality criteria alone are likely insufficient to identify regions on the landscape that contribute significantly to non-point source water quality degradation. Analyses focused on discharge weighted nutrient export and area weighted nutrient yield allowed for clear identification of high TP and TN production in the lower portion of the Oldman and Castle sub-basins, while discrete changes in nutrient production were less clear in the Crowsnest sub-basin. Higher flows characteristic of snowmelt periods and periodic stormflow events contributed the vast majority of nutrient inputs into all three headwaters rivers. While flow weighted water quality assessments add costs to regional water quality studies, the additional insights produced by this approach are likely to significantly outweigh the costs of implementing a full scale water quality monitoring program.

Tables and Figures

Table 2.1 Mean annual precipitation (mm) and mean summer / winter temperature (°C) in the upper and lower elevations of the Oldman, Castle and Crowsnest sub-basins.

Sub-basin	Mean Annual Precipitation (mm)	Mean Summer and Winter Air Temperature (°C)
Oldman R.		
Upper	740.7	(-2.1) - 1.0
Lower	493.8	(-5.2) -16.9
Castle R.		
Upper	906.5	(-3.4) - 9.18
Lower	654.4	(-1.1) - 10.3
Crowsnest R.		
Upper	915.0	(-9.6) - 13.1
Lower	576.5	(-7.8) - 14.5

Table 2-2 Physical catchment characteristics of the twelve headwater sites in the Oldman, Castle and Crowsnest sub-basins.

Oldman R.	Dominant Land Classification	Area (km^2)	Elevation (m) (mean/range)	Channel Slope (%)	Mean Discharge (m^3/s)[1]
Racehorse Creek (OM1)	Forested	896.3	1854.4 / (1444-2636)	2.3	10.8
Oldman Above Racehorse (OM2)	Forested	220.1	1936.1 / (1402-3065)	1.5	37.2
Oldman at Maycroft (OM3)	Forested/Foothills	1441.2	1849.3 / (1258-3065)	1.2	60.4
Oldman at Olin Bridge (OM4)	Agriculture	1826.6	1762.2 / (1206-3065)	1.1	74
Castle R.					
Lynx Creek (CA1)	Forested	105.1	1745.7 / (1366-2645)	2.1	4.4
Carbondale above Lynx Creek (CA2)	Forested	150.3	1744.6 / (1365-2586)	2.7	9.6
Castle at Ranger Station (CA3)	Forested/Agriculture	372.5	1819.8 / (1340-2592)	1.2	36.5
Carbondale below Adinack (CA4)	Forested/Foothills	291.7	1719.9 / (1336-2645)	2	13.1
Castle at Highway 507 (CA5)	Agriculture	819.3	1709.36 / (1204-2645)	0.9	63.1
Crowsnest R.					
Crowsnest at Star (CR1)	Forested	158.5	1728.3 / (1314-2721)	3.3	9.5
Crowsnest at Frank (CR2)	Forested/Urban	382.4	1704.7 / (1236-2732)	2.3	16.7
Crowsnest at Lundbreck (CR3)	Forested/Urban	661.7	1621.9 / (1184-2732)	1.5	20.2

[1] Discharge measured manually

Table 2-3 Sampling frequency within the Oldman, Castle and Crowsnest sub-basins over the four year study period (2005-2008).

	2005			2006			2007			2008				
Oldman R.	Baseflow	Freshet	Stormflow	Baseflow	Freshet	Stormflow	Baseflow	Freshet	Stormflow	Baseflow	Freshet	Stormflow	N	Average per year
OM1	1	1	2	1	1	0	2	2	1	1	1	1	14	3.5
OM2	1	1	2	0	1	0	2	2	1	1	1	1	13	3.25
OM3	1	1	2	0	1	0	2	2	1	1	1	1	13	3.25
OM4	1	1	2	1	1	0	2	2	1	1	1	1	14	3.5
Castle R.														
CA1	1	1	2	1	1	0	2	2	1	1	1	1	14	3.5
CA2	1	1	2	1	1	0	2	2	1	1	1	1	14	3.5
CA3	1	1	2	1	1	0	2	2	1	1	1	1	14	3.5
CA4	1	1	2	0	1	0	2	2	1	1	1	1	13	3.25
CA5	1	1	2	1	1	0	2	2	1	1	1	1	14	3.5
Crowsnest R.														
CR1	1	1	2	1	1	0	2	2	1	1	1	1	14	3.5
CR2	1	1	2	0	1	0	2	2	1	1	1	1	13	3.25
CR3	1	1	2	1	1	0	2	2	1	1	1	1	14	3.5

Table 2-4 Total annual discharge (Reservoir^3/yr), range in mean daily discharge (Reservoir^3/day), and total annual precipitation (mm) in the Oldman, Castle and Crowsnest sub-basins over the four year study period (2005-2008).

Oldman	Total Discharge (Q) (Dam^3/yr)	Range in mean daily Q (Dam^3/day)	Annual Precipitation (mm)
2005	695834	(2.6-362.0)	852.8
2006	334159	(2.0-87.9)	568.3
2007	324285	(2.0-62.1)	493.6
2008	363480	(1.6-168.0)	412.5
Average	**429440**		**582**
Castle			
2005	580267	(2.3-150.0)	1041.6
2006	475990	(2.4-111.0)	669.9
2007	409129	(2.2-76.2)	502.6
2008	493376	(1.4-320)	618.8
Average	**489691**		**708**
Crowsnest			
2005	216347	(1.4-47.3)	712
2006	158171	(1.4-22.4)	538.2
2007	164275	(1.3-24.9)	367.8
2008	131284	(1.0-50.7)	412.5
Average	**167519**		**508**

Table 2-5 Mean streamflow (Q, m^3/s) at sample sites within the three headwaters sub-basins from 2005-2008 during baseflow, spring freshet and stormflow conditions.

Oldman R.	Q Baseflow (m^3/s)	Q Spring Freshet (m^3/s)	Q Stormflow (m^3/s)
Racehorse Creek (OM1)	1.3	8.3	25.7
Oldman Above Racehorse (OM2)	5.6	23.0	86.6
Oldman at Maycroft (OM3)	7.5	37.3	142.2
Oldman at Olin Bridge (OM4)	12.9	48.0	182.8
Average	**6.8**	**29.2**	**109.3**
Castle R.			
Lynx Creek (CA1)	1.0	4.1	8.9
Carbondale above Lynx Creek (CA2)	1.6	8.8	20.6
Castle at Ranger Station (CA3)	6.3	31.6	80.4
Carbondale below Adinack (CA4)	1.5	11.5	26.6
Castle at Highway 507 (CA5)	9.7	42.5	155.7
Average	**4**	**19.7**	**58.4**
Crowsnest R.			
Crowsnest at Star (CR1)	3.7	7.6	19.3
Crowsnest at Frank (CR2)	3.9	13.2	33.8
Crowsnest at Lundbreck (CR3)	6.9	15.7	42.4
Average	**4.8**	**12.2**	**31.8**

Table 2-6 Total phosphorus concentration (μg/L), export (kg/day) and yield (kg/ha/yr) in the Oldman, Castle and Crowsnest sub-basins across all sampling sites over the four years study period (2005-2008).

	TP Concentrations (μg/L)			TP Exports (kg/day x 10^{-2})			TP Yields (kg/ha/yr x 10^{-4})		
	Median	Range	CV	Median	Range	CV	Median	Range	CV
Oldman R.	12.8	3.0-831.0	2.26	2.0	(0.008-2460)	3.34	2.0	(0.01-2300)	3.40
Castle R.	10.5	2.0-809.0	2.42	0.8	(0.006-2390)	5.85	3.0	(0.01-5600)	5.29
Crowsnest R.	15.0	3.0-522.0	2.08	1.4	(0.047-220)	3.02	3.0	(0.1-3000)	2.90

Table 2-7 Total phosphorus concentration (µg/L), export (kg/day) and yield (kg/ha/yr) at sites in theOldman, Castle and Crowsnest sub-basins over the four year study period (2005-2008).

	TP Concentrations (µg/L)			TP Exports (kg/day x 10^{-2})			TP Yields (kg/ha/yr x 10-^{3})		
Oldman R.	Median	Range	CV	Median	Range	CV	Median	Range	CV
Racehorse Creek (OM1)	9.5	(3-262.0)	1.95	0.6	(0.019 - 9.0)	2.53	0.10	(0.001 - 10)	2.53
Oldman Above Racehorse (OM2)	12.0	(3-338.0)	2.12	1.9	(0.067 - 2760)	2.42	0.08	(0.001 - 10)	2.42
Oldman at Maycroft (OM3)	14.6	(3-831.0)	1.99	3.1	(0.093 - 1940)	2.52	0.35	(0.01 - 210)	2.52
Oldman at Olin Bridge (OM4)	22.6	(2-821.0)	1.95	6.5	(0.008 - 2461	2.52	0.61	(0.01 - 230)	2.52
Castle R.									
Lynx Creek (CA1)	11.6	(2.0-332.0)	1.86	0.4	(0.009 - 52)	2.88	0.15	(0.001 - 20)	2.88
Carbondale above Lynx Creek (CA2)	10.9	(3.0-309.0)	2.03	0.7	(0.006 - 120)	3.12	0.18	(0.001 - 30)	3.12
Castle at Ranger Station (CA3)	9.1	(2.0-216.0)	2.05	2.1	(0.030 - 310)	3.09	0.21	(0.01 - 30)	3.09
Carbondale below Adinack (CA4)	16.4	(3.0-361.0)	2.04	1.6	(0.016 - 170)	3.01	1.60	(0.02 - 170)	3.01
Castle at Highway 507 (CA5)	16.2	(2.0-809.0)	2.61	4.3	(0.040 - 2390)	3.38	10.0	(0.01 - 560)	3.38
Crowsnest R.									
Crowsnest at Star (CR1)	12.6	(5.0-73.60)	0.97	0.7	(0.047 - 18)	1.69	0.17	(0.01 - 4.0)	1.69
Crowsnest at Frank (CR2)	14.5	(3.0-502.00)	1.99	1.6	(0.050 - 220)	2.63	0.26	(0.01 - 36)	2.63
Crowsnest at Lundbreck (CR3)	15.7	(7.0-522.00)	1.93	2.7	(0.2 - 290)	2.55	0.36	(0.03 - 0 37)	2.55

*CV - Coefficient of Variation

Table 2-8 Total nitrogen concentration (µg/L), export (kg/day) and yield (kg/ha/yr) in the Oldman, Castle and Crowsnest sub-basins across all sampling sites and over the four years study period (2005-2008).

	TN Concentrations (µg/L)			TN Exports (kg/day x 10^{-2})			TN Yields (kg/ha/yr x 10^{-4})		
	Median	Range	CV	Median	Range	CV	Median	Range	CV
Oldman R.	134.0	(3.5-995.5)	1.04	33.0	(0.017 - 2940)	2.44	28.0	(0.01 - 2700)	2.55
Castle R.	165.8	(3.5-1073.1)	1.06	16.0	(0.021 - 670)	2.14	39.0	(0.05 - 1600)	1.93
Crowsnest R.	251.0	(71-989.0)	0.77	28.0	(0.9 - 540)	1.71	48.0	(2.2 - 700)	1.55

Table 2-9 Total nitrogen concentration (µg/L), export (kg/day) and yield (kg/ha/yr) at sites in the Oldman, Castle and Crowsnest sub-basins over the four year study period (2005-2008).

	TN Concentrations (µg/L)			TN Exports (kg/day x 10^{-2})			TN Yields (kg/ha/yr x 10^{-4})		
Oldman R.	Median	Range	CV	Median	Range	CV	Median	Range	CV
Racehorse Creek (OM1)	145.0	(3.5-818.4)	1.14	8.0	(0.017 - 260)	2.04	12.0	(0.01 - 430)	2.04
Oldman Above Racehorse (OM2)	166.0	(19.0-899.1)	1.10	31.0	(0.4 - 1270)	2.20	13.0	(0.2 - 510)	2.20
Oldman at Maycroft (OM3)	165.5	(21.0-995.5)	1.13	48.0	(0.6 - 2110)	2.03	54.0	(0.7 - 2370)	2.03
Oldman at Olin Bridge (OM4)	194.8	(19.0-979.7)	0.90	93.0	(0.8 - 2940)	2.09	88.0	(0.8 - 2780)	2.09
Castle R.									
Lynx Creek (CA1)	299.0	(7.0-1073.1)	0.96	10.0	(0.1 - 52)	1.19	34.0	(0.7 - 180)	1.19
Carbondale above Lynx Creek (CA2)	117.0	(3.5-924.7)	1.20	11.0	(0.02 - 69)	1.19	27.0	(0.05 - 160)	1.19
Castle at Ranger Station (CA3)	172.0	(22.0-746.9)	0.95	19.0	(0.1 - 104)	1.16	29.0	(0.1 - 210)	1.16
Carbondale below Adinack (CA4)	97.7	(7.0-345.4)	0.09	30.0	(0.01 - 218)	1.29	190.0	(1.2 - 1050)	1.29
Castle at Highway 507 (CA5)	138.0	(7.0-576.1)	0.94	54.0	(0.1 - 668)	1.53	127.0	(0.3 - 1570)	1.53
Crowsnest R.									
Crowsnest at Star (CR1)	220.0	(72.0-845.2)	0.77	11.0	(0.9 - 183)	1.52	25.0	(2.2 - 420)	1.52
Crowsnest at Frank (CR2)	262.0	(103.0-768.0)	0.64	42.0	(2.4 - 338)	1.42	68.0	(4.1 - 550)	1.42
Crowsnest at Lundbreck (CR3)	247.0	(71.0-989.0)	0.85	47.0	(2.6 - 542)	1.56	61.0	(3.4 - 700)	1.56

*CV - Coefficient of Variation

Table 2-10 Total phosphorus concentration (µg/L), export (kg/day) and yield (kg/ha/yr) during baseflow, spring freshet and stormflow conditions in the Oldman, Castle and Crowsnest sub-basins over the four year study period (2005-2008).

	TP Concentrations (µg/L)			TP Exports (kg/day x 10^{-3})			TP Yields (kg/ha/yr x 10^{-2})		
Oldman R.	Median	Range	CV	Median	Range	CV	Median	Range	CV
Baseflow	6.1	(2.0-12.9)	0.54	1.9	(0.19 - 32)	1.69	2.0	(0.0002-0.03)	1.68
Spring Freshet	14.3	(7.0-182.0)	1.49	29.6	(1.9 - 1158)	2.11	27.0	(0.003-109)	2.16
Stormfow	69.6	(18.0-831.0)	1.26	366.4	(8.5 - 24611)	1.75	410.0	(0.014-23.3)	1.78
Castle R.									
Baseflow	4.0	(2.0-10.5)	0.48	0.7	(0.06 - 7)	1.30	2.0	(0.0001-2.0)	1.10
Spring Freshet	13.7	(5.0-54.0)	0.90	16.1	(1.3 - 169)	1.26	41.0	(0.004-56)	1.39
Stormfow	51.7	(16.0-809.0)	1.38	120.2	(7.2 - 23919)	1.38	340.0	(0.023-562.9)	2.86
Crowsnest R.									
Baseflow	7.0	(3.0-22.5)	0.57	2.3	(0.47 - 27)	1.5	5.0	(0.001-35)	1.21
Spring Freshet	16.0	(5.8-93.9)	0.93	16.4	(4.3 - 177)	1.25	26.0	(0.009-29)	1.23
Stormfow	51.6	(15.0-522.0)	1.35	92.6	(14.9 - 2864)	1.64	190.0	(0.034-374)	1.56

Table 2-11 Total nitrogen concentration (µg/L), export (kg/day) and yield (kg/ha/yr) during baseflow, spring freshet and stormflow conditions in the Oldman, Castle and Crowsnest sub-basins over the four year study period (2005-2008).

	TN Concentrations (µg/L)			TN Exports (kg/day x 10^{-2})			TN Yields (kg/ha/yr x 10^{-4})		
Oldman R.	Median	Range	CV	Median	Range	CV	Median	Range	CV
Baseflow	38.0	(3.5-541.0)	1.40	1.6	(0.02 - 90.4)	2.28	1.0	(0.02 - 86)	2.39
Spring Freshet	155.0	(43.0-532.0)	0.67	32.6	(1.18 - 256.2)	1.23	22.0	(2.0 - 243)	1.27
Stormfow	475.0	(149.0-995.5)	0.62	307.1	(16.4 - 2936.9)	1.32	290.0	(20.0 - 2782)	1.40
Castle R.									
Baseflow	26.5	(3.5-369.0)	1.30	0.3	(0.02 - 13.8)	1.88	1.0	(0.1 - 46)	1.88
Spring Freshet	122.0	(7.0-924.7)	0.97	16.9	(0.12 - 91.6)	0.91	43.0	(0.4 - 584)	1.30
Stormfow	322.1	(103.0-1073.1)	0.73	73.7	(11.7 - 668.2)	1.31	170.0	(29 - 1573)	1.16
Crowsnest R.									
Baseflow	103.0	(71.0-262.0)	0.52	3.1	(0.97 - 19.9)	1.02	5.0	(2.0 - 26.0)	0.91
Spring Freshet	230.0	(121.0-872.9)	0.60	27.8	(9.5 - 99.9)	0.74	60.0	(13.0 - 131)	0.62
Stormfow	645.1	(247.0-948.0)	0.50	115.8	(32.3 - 542.6)	0.96	166.0	(82 - 709)	0.82

Table 2-12 Total phosphorus concentration (µg/L), export (kg/day) and yield (kg/ha/yr) from 2005 to 2008 in the Oldman, Castle and Crowsnest sub-basins across the three hydrologic flow regimes (baseflow, spring freshet and stormflow).

	TP Concentration (µg/L)			TP Exports (kg/day x 10^{-2})			TP Yields (kg/ha/yr x 10^{-4})		
Oldman R.	Median	Range	CV	Median	Range	CV	Median	Range	CV
2005	15.6	(6.5-831.0)	2.15	4.0	(0.10 - 2461)	2.60	3.0	(0.2 - 2330)	2.61
2006	12.2	(10.9-14.0)	0.09	2.4	(0.29 - 4.2)	0.68	2.0	(0.5 - 4.0)	0.71
2007	7.5	(2.0-60.0)	1.04	10.7	(0.02 - 33.6)	1.72	1.0	(0.1 - 32.0)	1.75
2008	93.8	(5.93-710.0)	1.28	47.5	(0.03 - 1225)	1.79	55.0	(0.1 - 1161)	1.84
Castle R.									
2005	22.3	(3.0-146.3)	1.10	2.4	(0.053 - 149.5)	2.49	8.0	(0.2 - 352)	2.18
2006	10.5	(3.4-16.4)	0.43	0.7	(0.18 - 2.9)	0.94	2.0	(0.6 - 16)	1.60
2007	8.0	(2.0-72.0)	1.16	0.2	(0.006 - 21.0)	1.80	1.0	(0.1 - 56)	1.79
2008	8.7	(4.0-809.0)	1.70	2.5	(0.016 - 2391.9)	3.09	6.0	(0.1 - 5629)	2.79
Crowsnest R.									
2005	33.0	(7.0-223.7)	1.16	3.5	(0.23 - 106.3)	1.98	5.0	(0.7 - 139)	1.79
2006	14.5	(8.0-28.4)	0.46	1.6	(0.39 - 4.1)	0.77	3.0	(0.9 - 5.0)	0.59
2007	10.0	(5.0-93.0)	1.12	0.7	(0.05 - 17.7)	1.50	1.0	(0.1 - 29)	1.45
2008	11.4	(5.8-522.0)	1.71	0.6	(0.16 - 286.4)	1.90	1.0	(0.3 - 374)	1.83

Table 2-13 Total nitrogen concentration (µg/L), export (kg/day) and yield (kg/ha/yr) from 2005 to 2008 in the Oldman, Castle and Crowsnest sub-basins across the three hydrologic flow regimes (baseflow, spring freshet and stormflow).

	TN Concentration (µg/L)			TN Exports (kg/day x 10^{-2})			TN Yields (kg/ha/yr x 10^{-4})		
Oldman R.	Median	Range	CV	Median	Range	CV	Median	Range	CV
2005	558.8	(188.1-995.5)	0.57	78.3	(3.4 - 2936.9)	1.60	10.0	(0.6 - 278)	1.70
2006	199.8	(145.0-532.0)	0.67	40.5	(7.5 - 178.5)	1.14	3.0	(1.2 - 17)	1.20
2007	62.5	(19.0-182.0)	0.67	10.0	(0.1 - 113.3)	1.37	1.0	(0.02 - 11)	1.42
2008	136.5	(3.5-376.0)	0.80	45.8	(0.02 - 643.9)	1.40	5.0	(0.001 - 61)	1.46
Castle R.									
2005	375.2	(97.7-1073.1)	0.57	52.3	(3.3 - 588.9)	1.50	14.0	(0.59 - 138)	1.34
2006	253.5	(203.0-311.0)	0.18	20.2	(9.8 - 67.0)	0.87	6.0	(3.4 - 20)	0.87
2007	83.0	(7.0-324.0)	0.98	2.2	(0.026 - 92.2)	1.60	1.0	(0.01 - 23)	1.64
2008	100.0	(3.5-229.0)	0.66	20.7	(0.021 - 668.2)	2.10	7.0	(0.01 - 157)	1.97
Crowsnest R.									
2005	601.5	(218.4-948.0)	0.48	72.9	(8.2 - 450.3)	1.15	13.0	(1.9 - 59)	1.04
2006	375.0	(323.0-400.0)	0.11	41.6	(26.18 - 46.8)	0.28	6.0	(6.0 - 7.0)	0.06
2007	194.0	(91.0-322.0)	0.41	10.2	(0.97 - 63.1)	1.01	2.0	(0.22 - 10)	0.95
2008	147.0	(71.0-989.0)	1.12	11.7	(2.20 - 542.6)	1.80	3.0	(0.43 - 71)	1.69

Figure 2-1 Map of the study area showing streamflow gauging stations, sub-basins (from north to south – Oldman, Crowsnest and Castle), and sampling sites (Oldman: west to east – Racehorse Creek (OM1), Oldman River above Racehorse (OM2) Creek, Oldman at Maycroft (OM3) and Oldman at Olin bridge (OM4); Crowsnest: west to east – Crowsnest at Star (CR1), Crowsnest at Frank (CR2), and Crowsnest at Lundbreck (CR3); Castle: west to east – Lynx Creek (CA1), Carbondale above Lynx Creek (CA2), Carbondale at the Adinac (CA4), Castle River at Ranger Station (CA3), Castle River at highway 507 (CA5)).

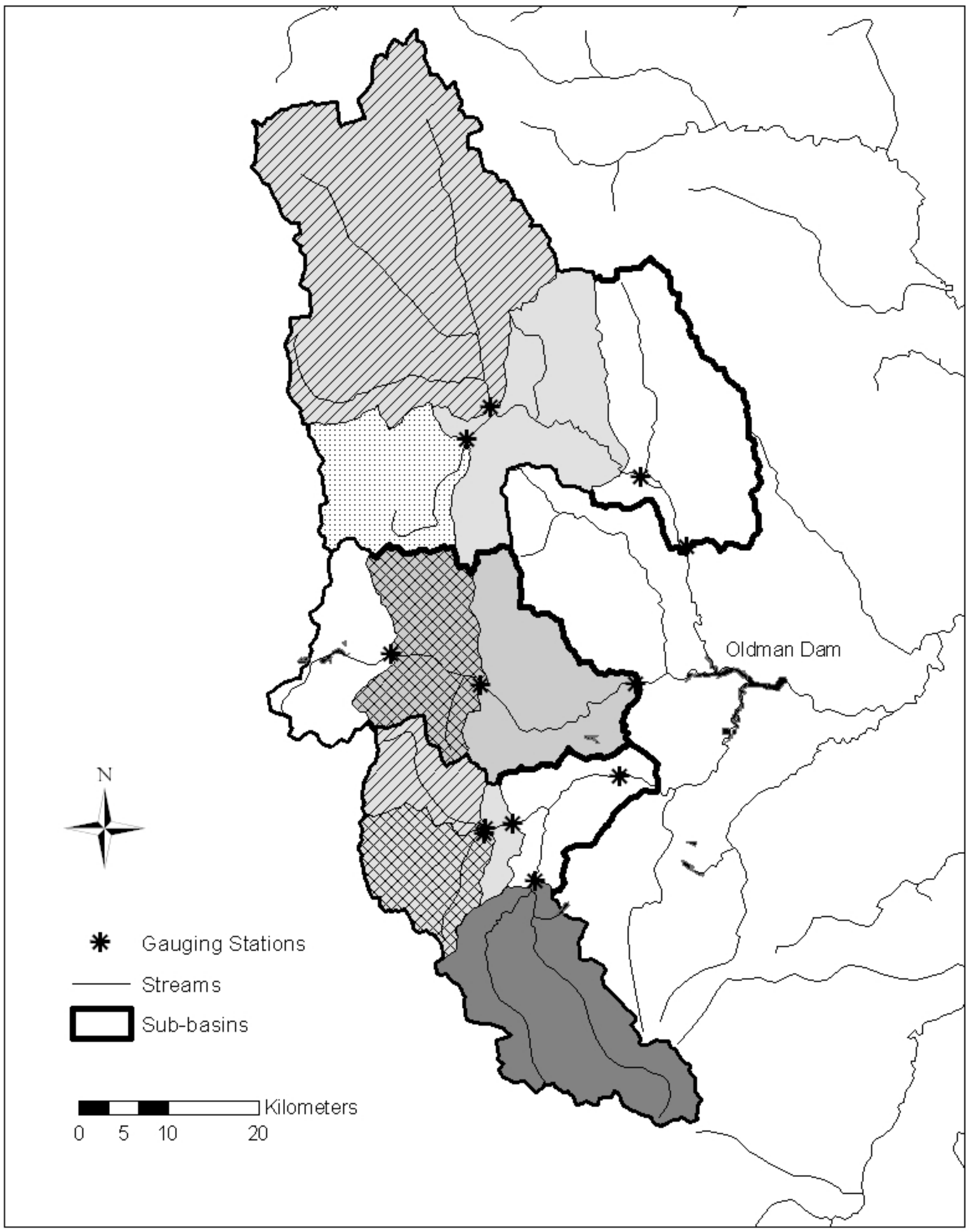


Figure 2-2 Mean daily discharge (m^3/s) for the Oldman River near Waldron's corner, the Castle River near highway 507 and the Crowsnest River at Frank from 2005-2008.

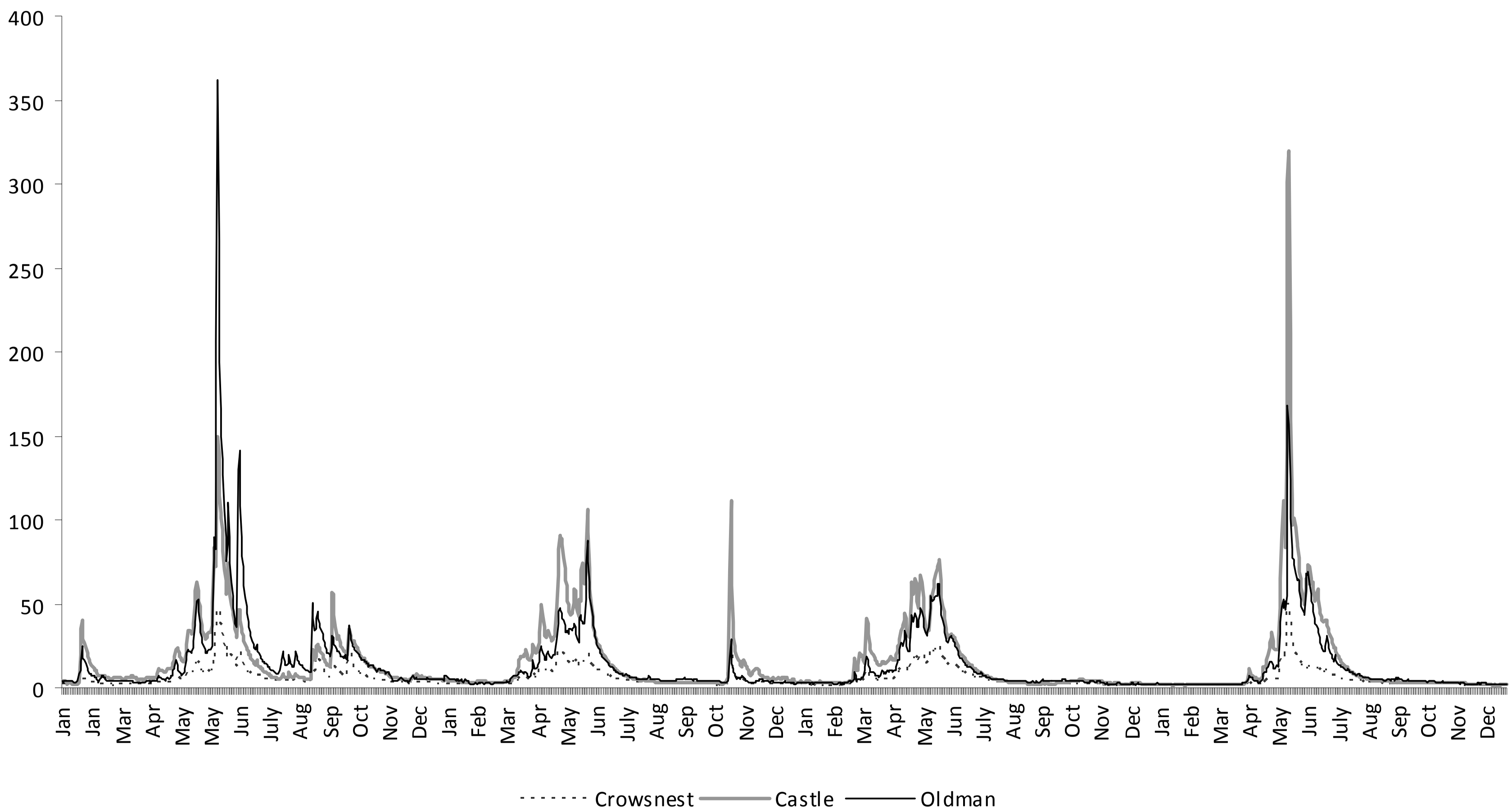


Figure 2-3 Total phosphorus concentration (µg/L), export (kg/day) and yield (kg/ha/yr) in the Oldman, Castle and Crowsnest sub-basins. The box-plots indicate the range of values (5th and 95th percentile), the arithmetic mean (dotted line), the median (solid line), the outer limits of the boxes are the 25th and 75th percentiles and the small dots are the outliers.

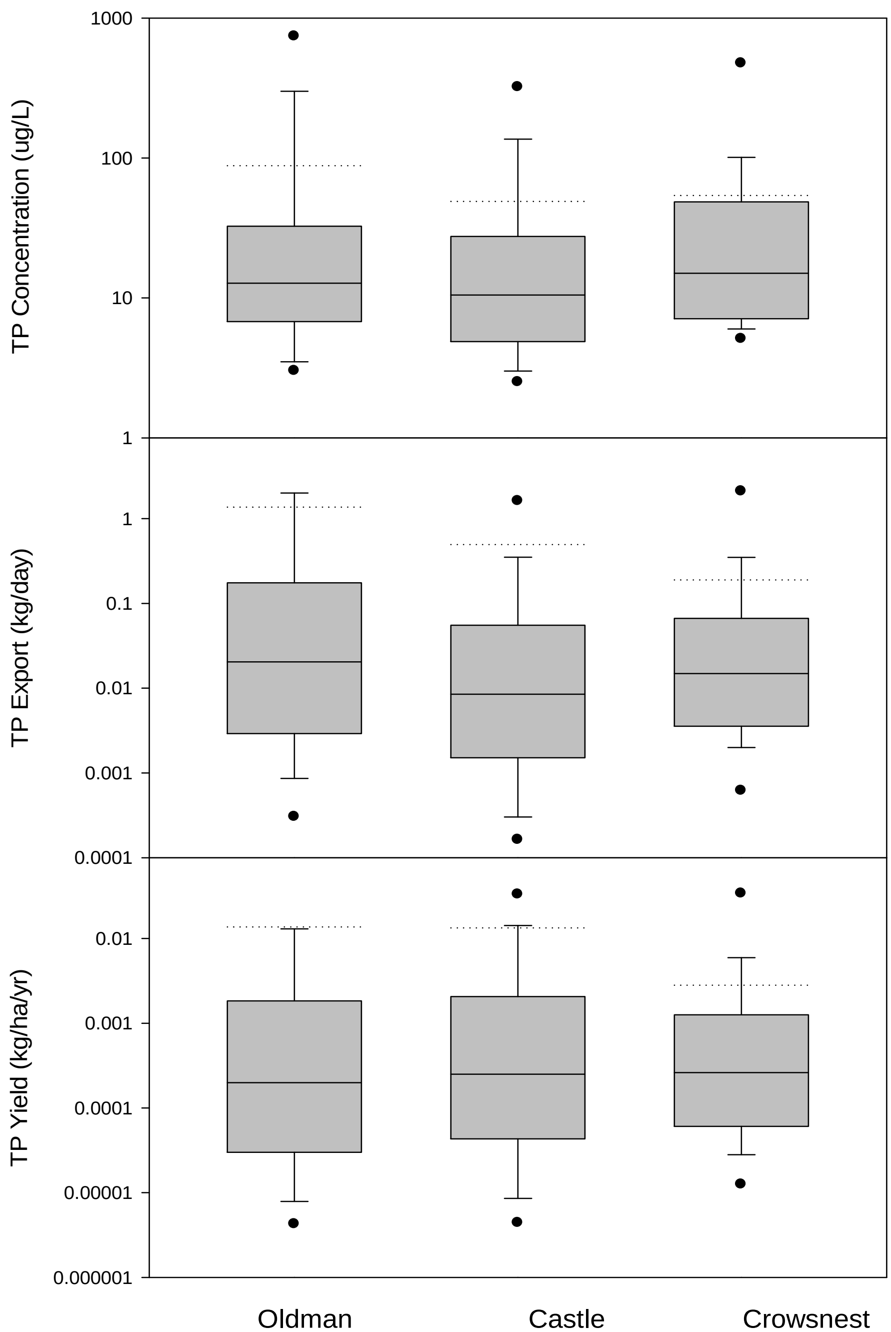


Figure 2-4 Total phosphorus concentration (μg/L) in the Oldman, Castle and Crowsnest sub-basins over the four year study period (2005-2008).

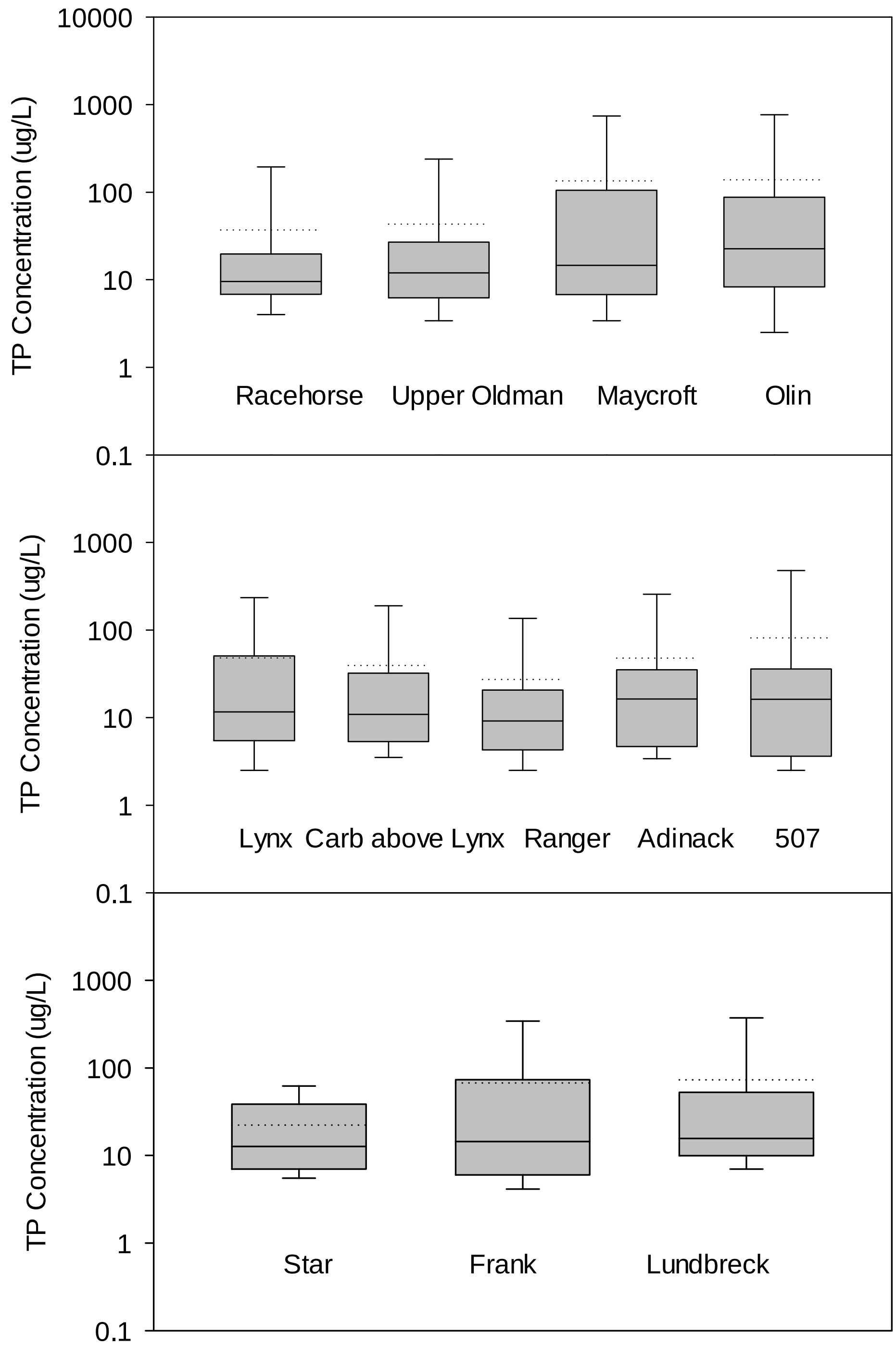


Figure 2-5 Total phosphorus export (kg/day) in the Oldman, Castle and Crowsnest sub-basins over the four year study period (2005-2008).

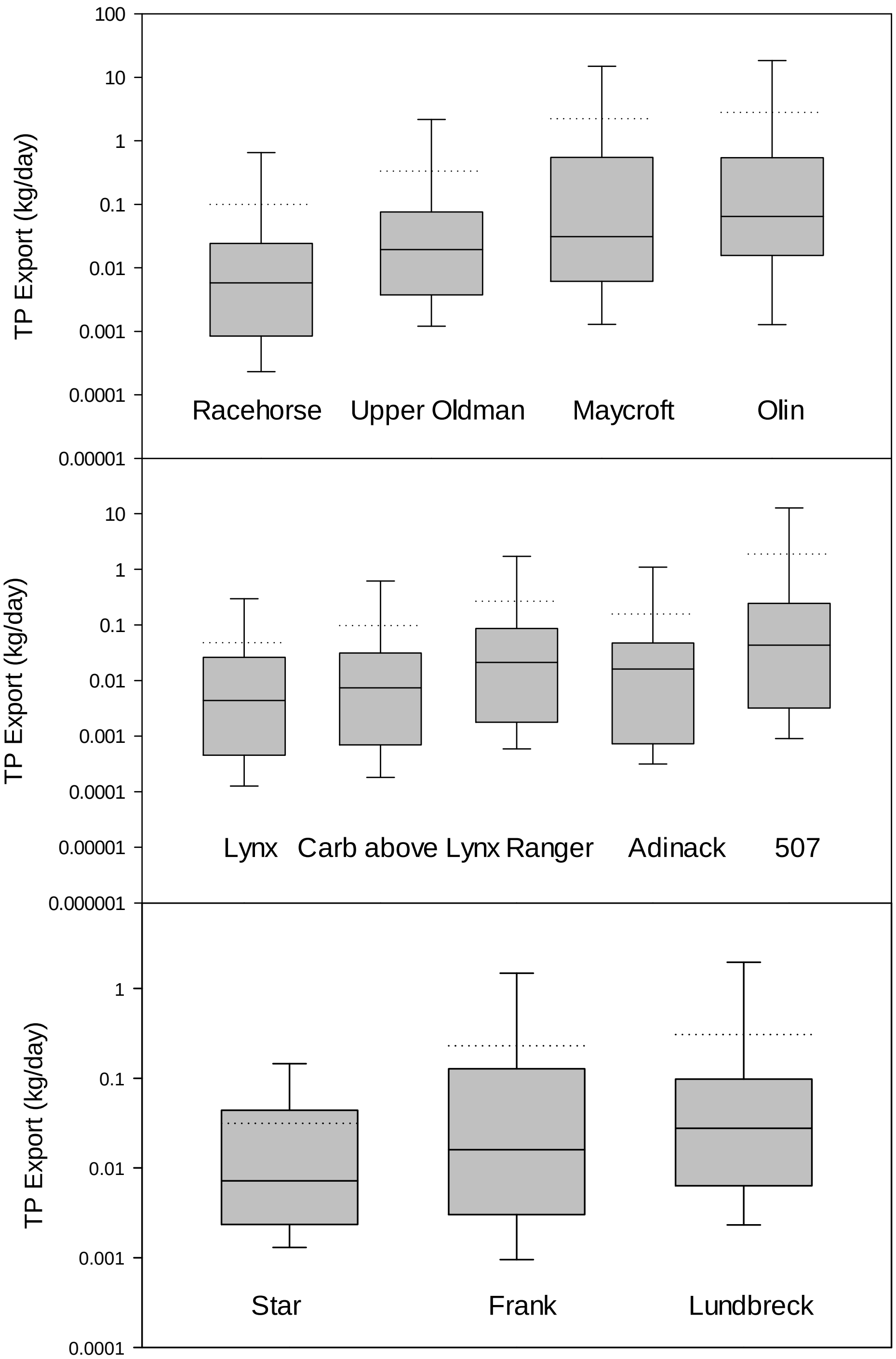


Figure 2-6 Total phosphorus yield (kg/ha/yr) from the Oldman, Castle and Crowsnest sub-basins over the four year study period (2005-2008).

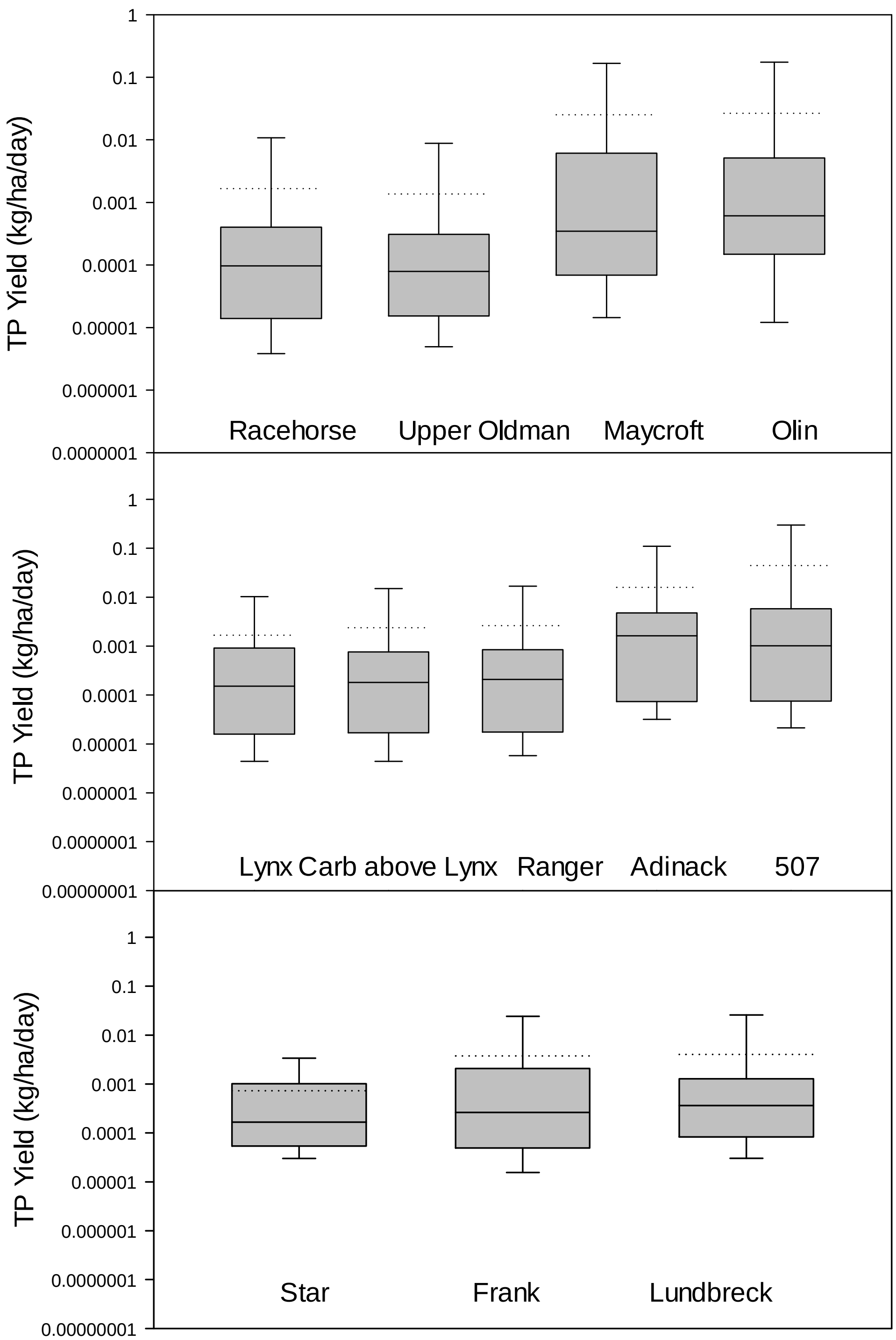


Figure 2-7 Total nitrogen concentration (µg/L), export (kg/day) and yield (kg/ha/yr) in the Oldman, Castle and Crowsnest sub-basins.

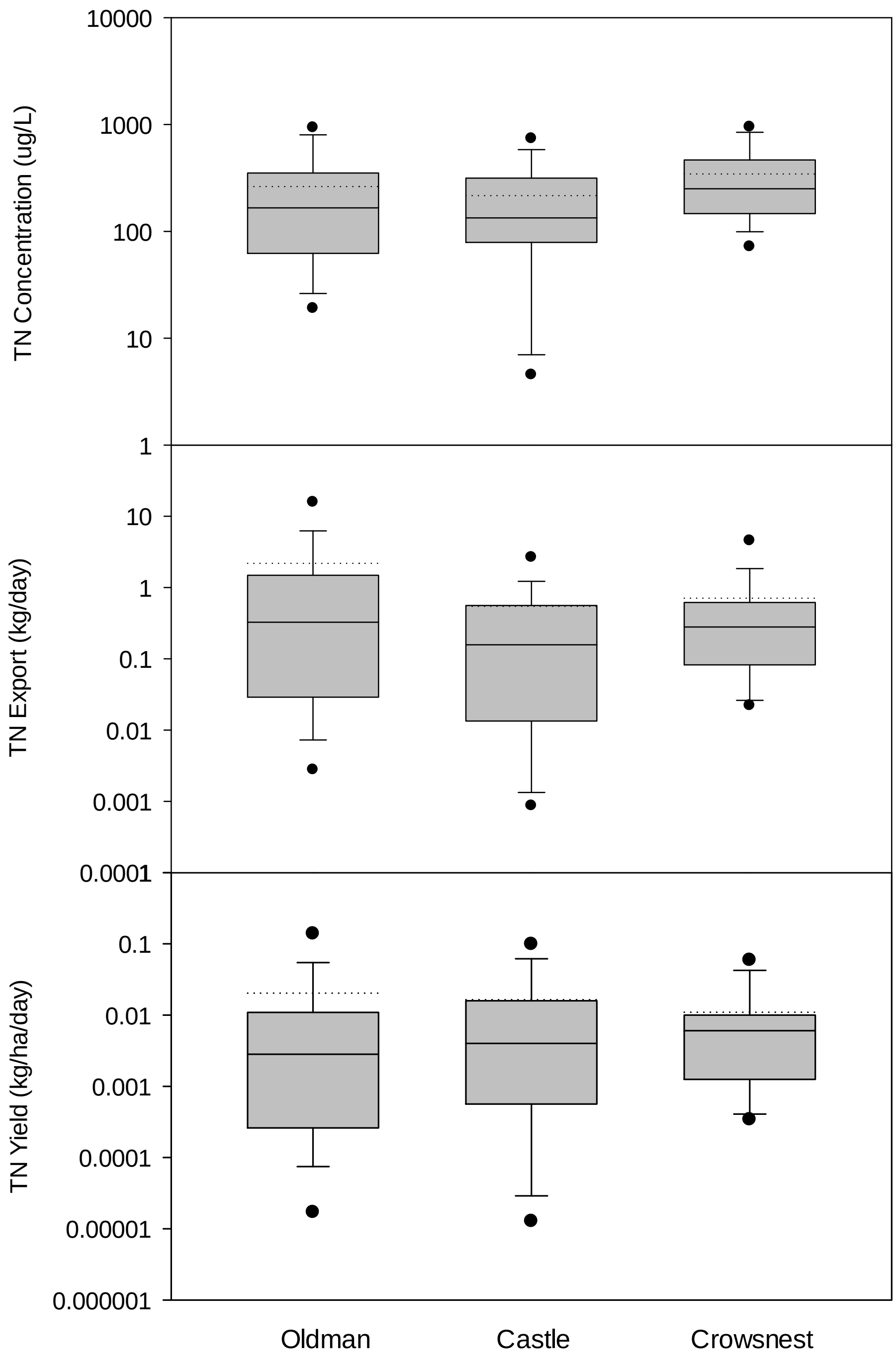


Figure 2-8 Total nitrogen concentration (µg/L) in the Oldman, Castle and Crowsnest sub-basins over the four year study period (2005-2008).

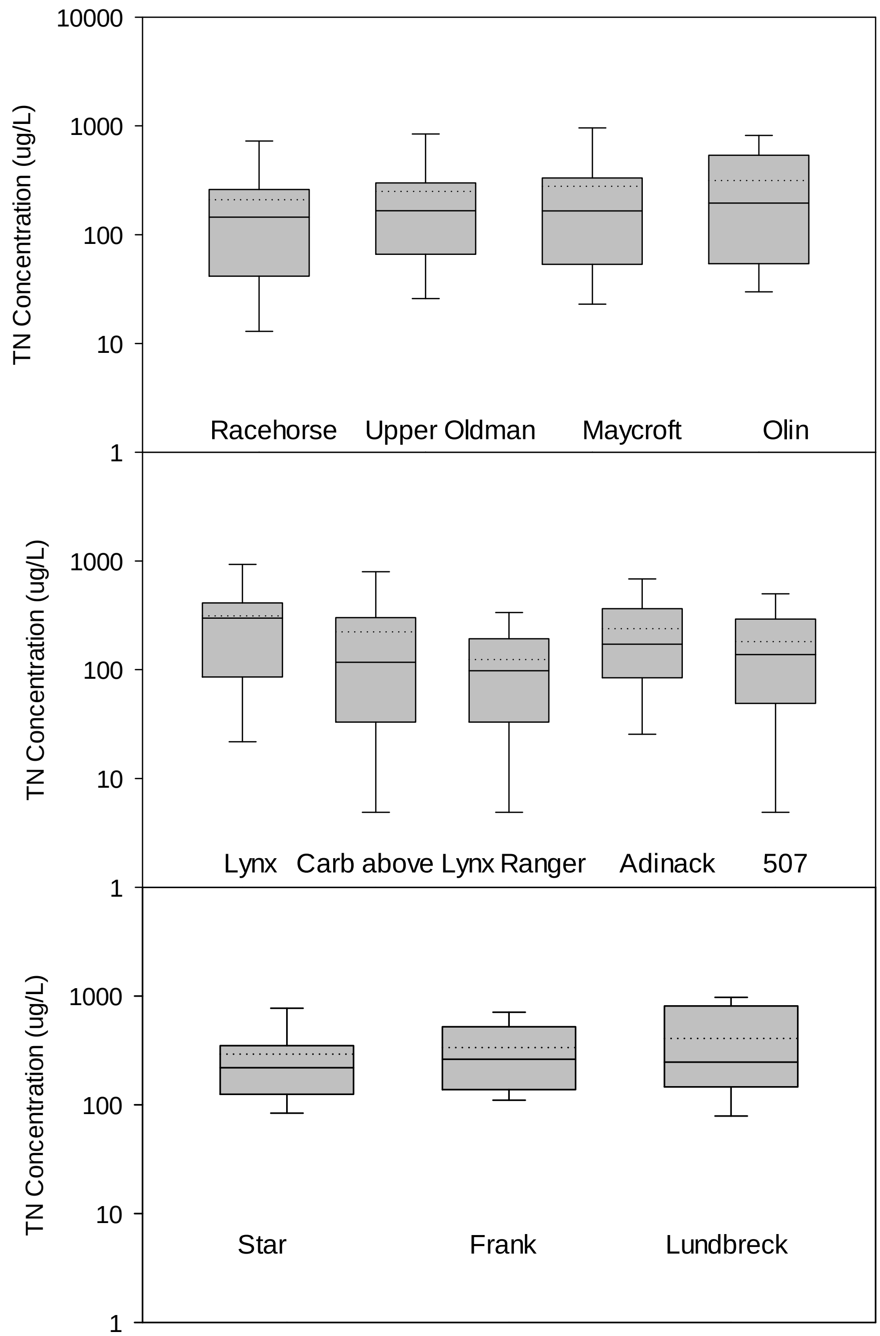


Figure 2-9 Total nitrogen export (kg/day) from the Oldman, Castle and Crowsnest sub-basins over the four year study period (2005-2008).

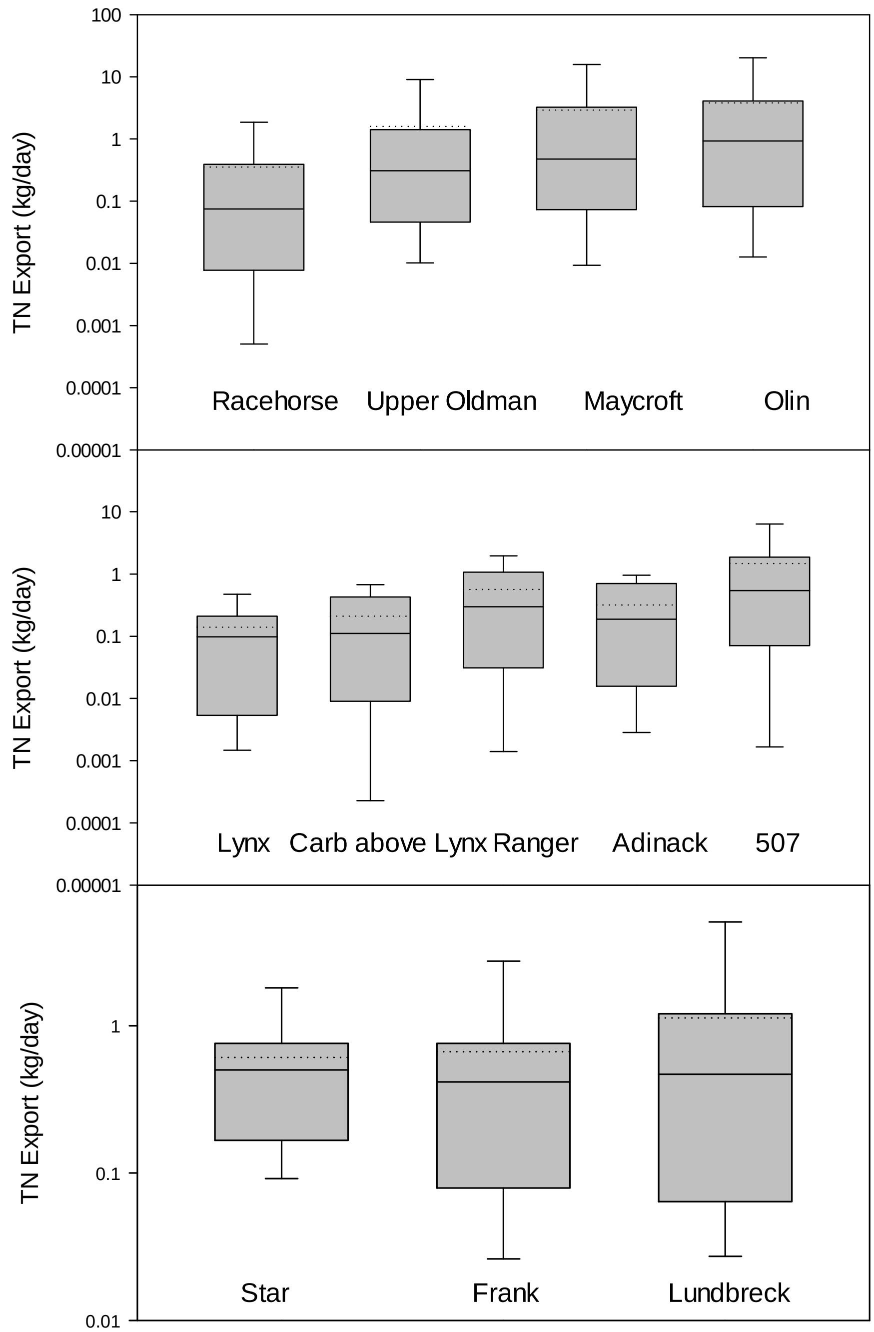


Figure 2-10 Total nitrogen yield (kg/ha/yr) in the Oldman, Castle and Crowsnest sub-basins over the four year study period (2005-2008).

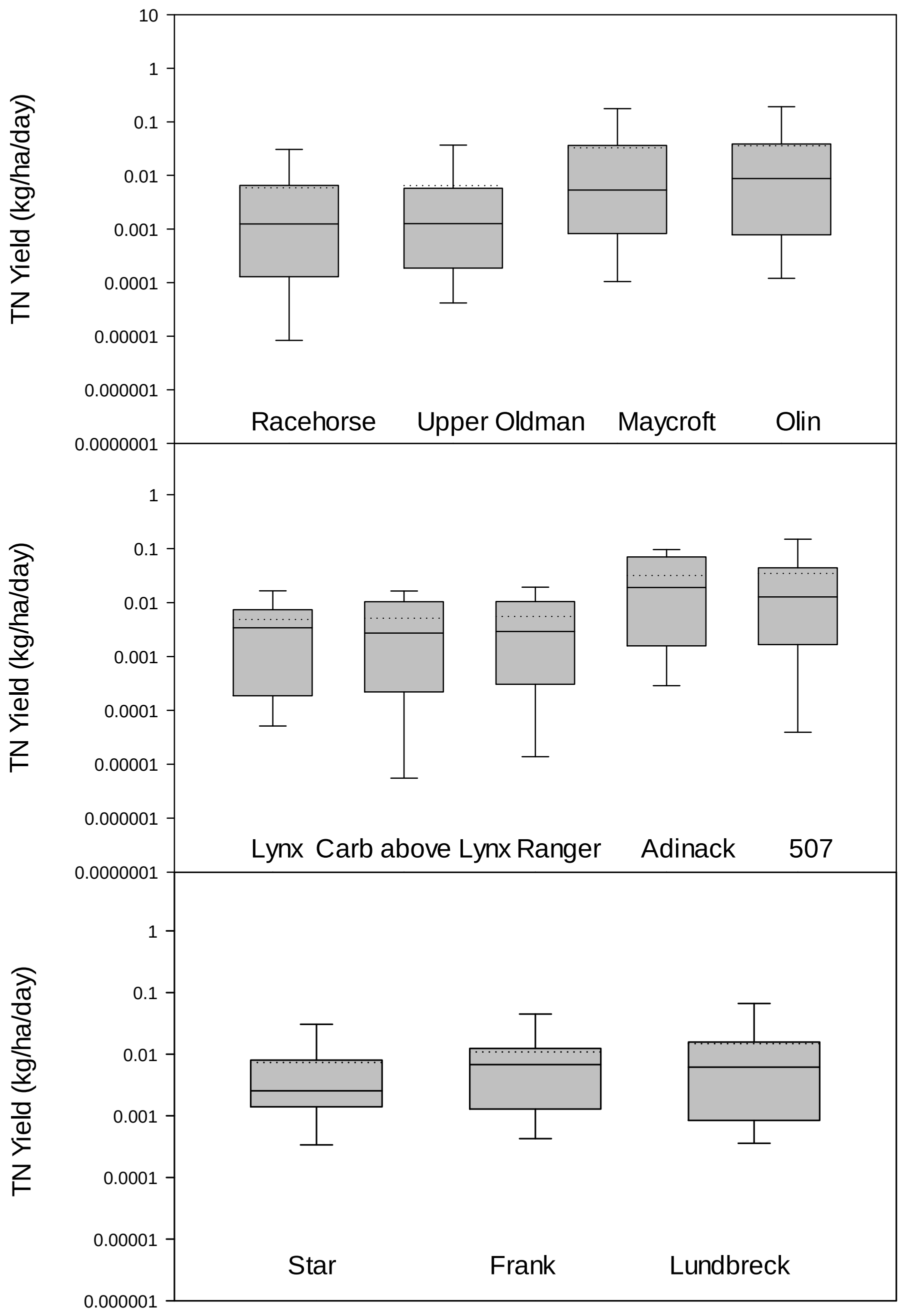


Figure 2-11 Total phosphorus concentration (µg/L), export (kg/day) and yield (kg/ha/yr) in the Oldman, Castle and Crowsnest sub-basins by hydrologic flow period (baseflow, snowmelt freshet and stormflow) over the four year study period (2005-2008).

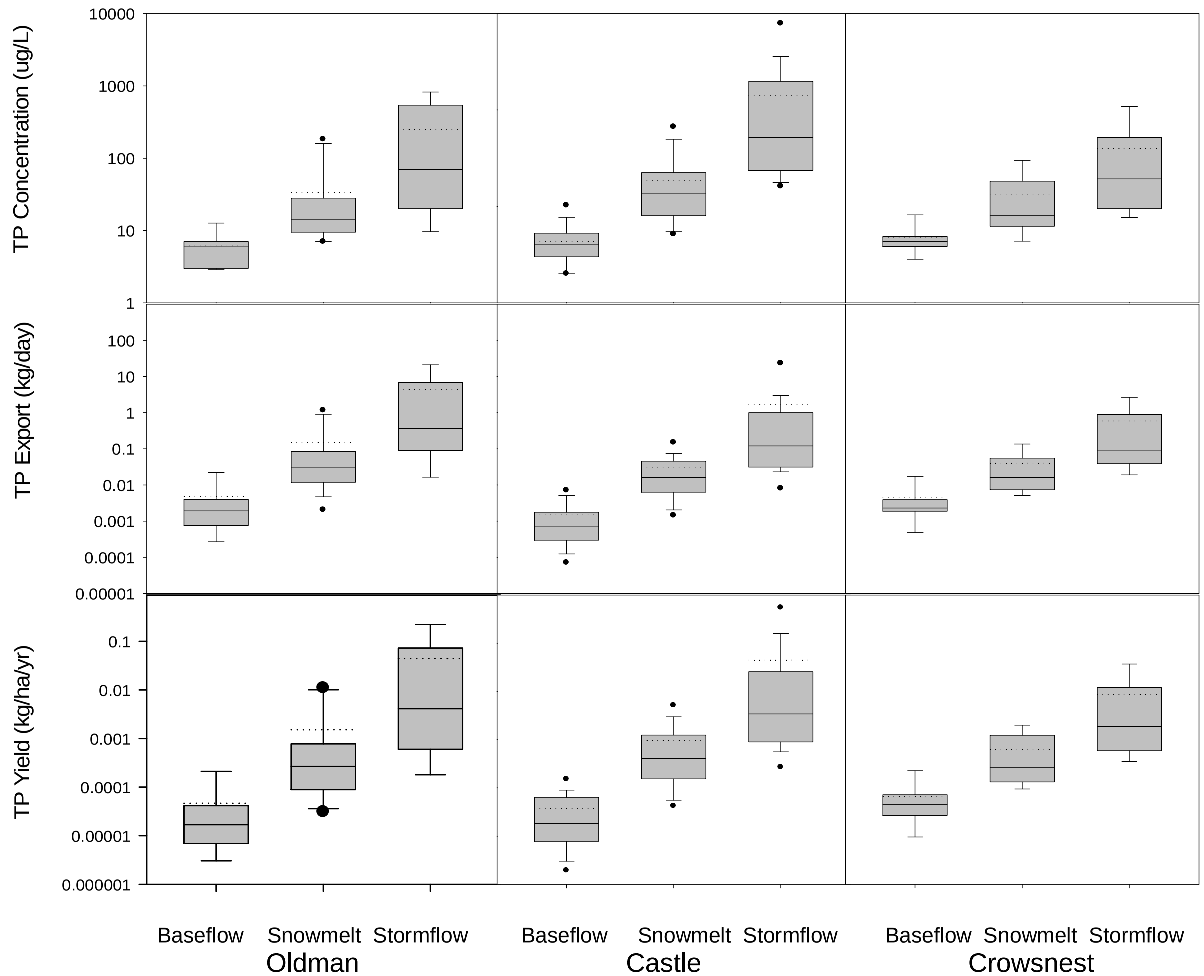


Figure 2-12 Total nitrogen concentration (µg/L), export (kg/day) and yield (kg/ha/yr) in the Oldman, Castle and Crowsnest sub-basins by hydrologic flow period (baseflow, snowmelt freshet and stormflow) over the four year study period (2005-2008).

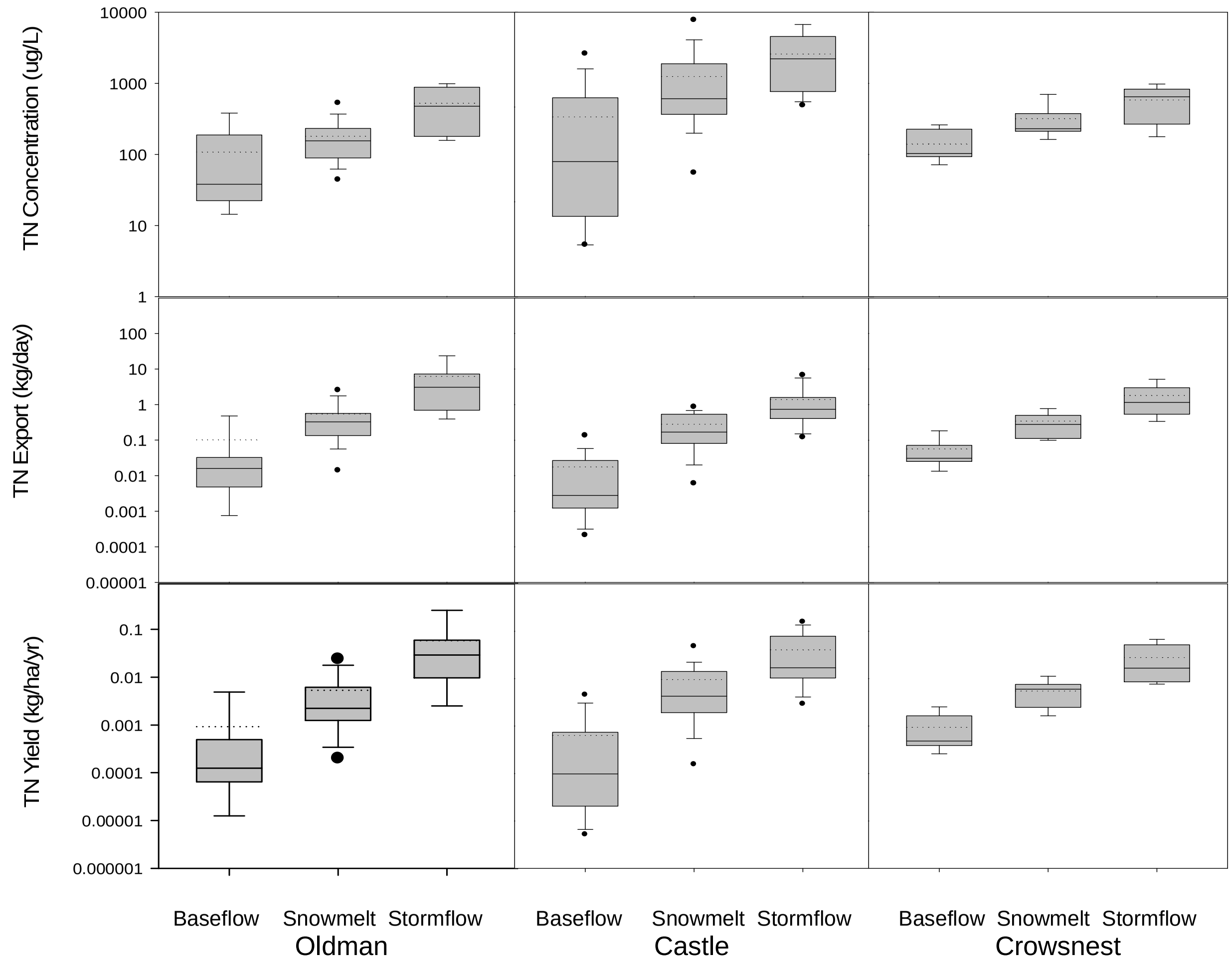


Figure 2-13 Total phosphorus concentration (μg/L), export (kg/day) and yield (kg/ha/yr) in the Oldman, Castle and Crowsnest sub-basins by year (2005-2008) over the study period.

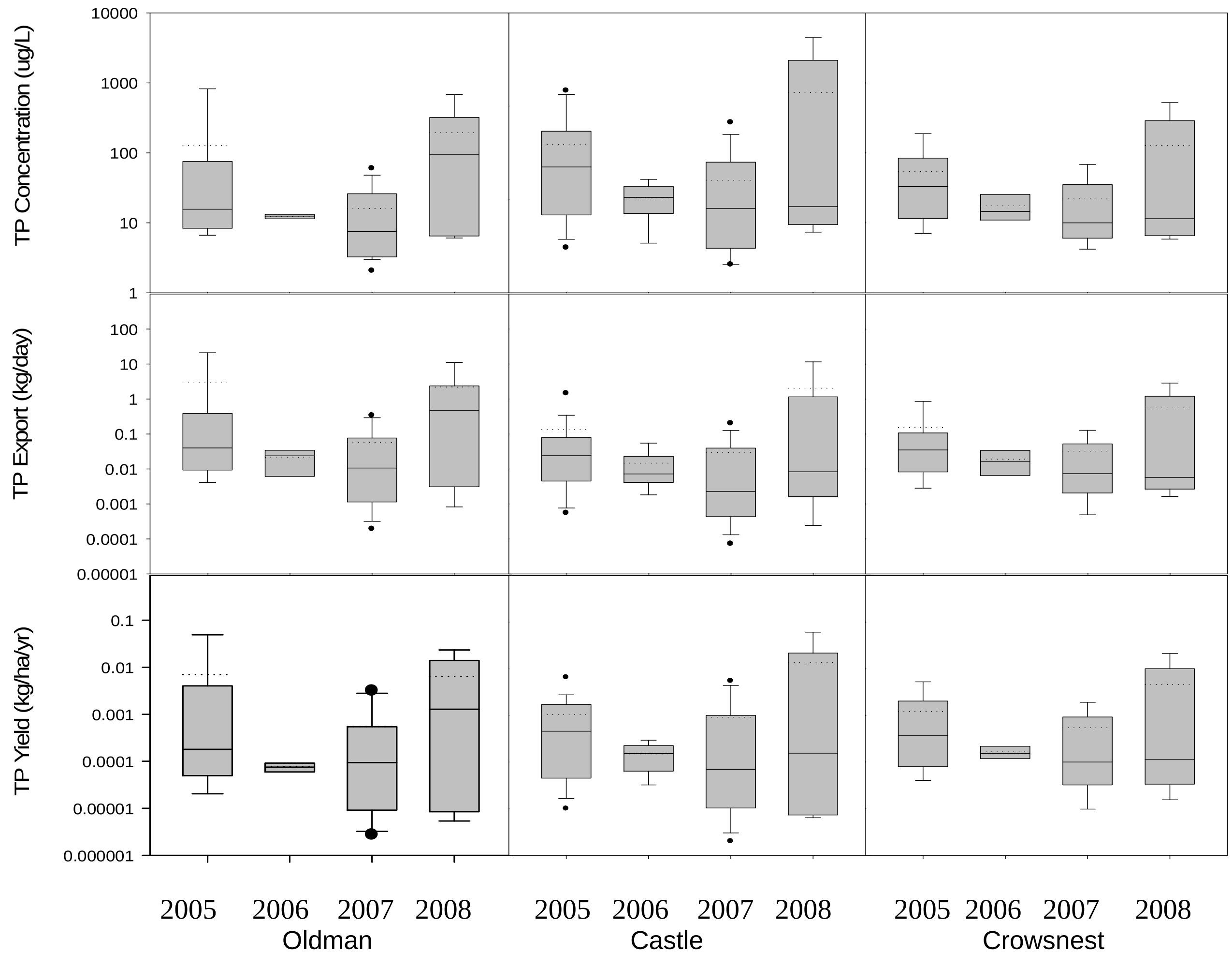
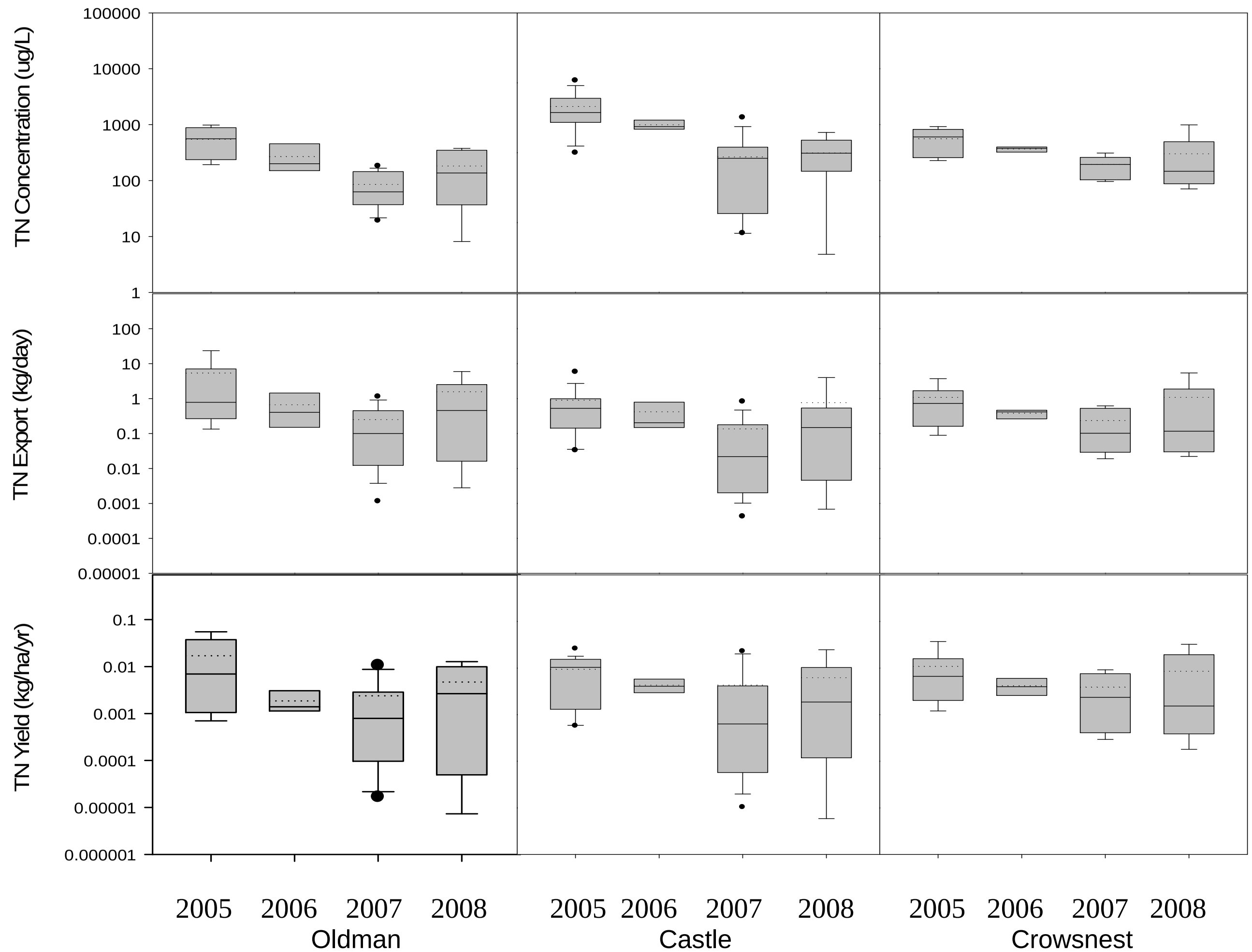


Figure 2-14 Total nitrogen concentration (μg/L), export (kg/day) and yield (kg/ha/yr) in the Oldman, Castle and Crowsnest sub-basins by year (2005-2008) over the study period.



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Chapter 3: Impacts of agricultural, forested and urban watersheds on water quality in the headwaters of the Oldman River Basin

3.1 Introduction

Eutrophication of surface waters through excessive inputs of nitrogen and phosphorus is a global problem (Carpenter *et al.*, 1998; Arheimer and Liden, 2000). As a result of both point and non-point source pollution, many major rivers systems world-wide are no longer suitable for fisheries, recreation or drinking water supply (Carpenter *et al.*, 1998). While point source pollution continues to represent a significant threat to many rivers, identifying major sources of non-point source contamination to waterways has been a major watershed management focus over the past 3-4 decades in many regions (Carpenter *et al.*, 1998). In particular, nutrient inputs from a range of different landscape categories (i.e., agricultural, urban, and forested) have received significant research focus in an attempt to explore relationships between land use and nutrient production. Much of this research attention has focused on forested landscapes undergoing harvesting activities, agricultural landscapes including extensive and intensive agricultural production, and urban landscapes. By changing the watershed characteristics that influence runoff dynamics, and the biogeochemical processes on the landscape, each of these three landscape categories can contribute varying amounts of nutrients to river systems, and thus have a major impact on water quality in many parts of the world.

Agricultural and urban landscapes are the major non-point source contributors of nitrogen and phosphorus to surface waters (Omernik, 1976; Osborne and Wiley, 1988; Carpenter *et al.*, 1998). In a comprehensive review of the literature, Beaulac and Reckhow (1982) concluded that nutrient yields (nitrogen and phosphorus production on a unit-area basis) from agricultural and urban settings are significantly higher than those from more undisturbed forested settings. In agricultural settings, the application of nutrient fertilizers and manure produced from large confined feeding operations can often exceed the crop nutrient requirements, leading to significant nutrient production from these landscapes (Carpenter *et al.,* 1998; Little *et al.,* 2003). The timing of the application of fertilizers and manure also has a major additional effect on the nutrient production from these landscapes (Ahearn *et al.,* 2005). If fertilizers or manure are spread at a time when crop requirements for nutrients are low such as during dormant periods or on frozen ground or during wet periods when nutrient transport (runoff) to streams is most efficient, nutrient loss can be high.

The heterogeneity and complexity of developed urban landscapes (roads, residential and industrial sites) present additional challenges in quantifying nutrient fluxes from these landscapes (Groffman *et al.,* 2004; Carle *et al.,* 2005). As land is converted from agricultural or forested systems to urban landscapes, soils with moderate to high infiltration capacity are replaced with impermeable surfaces that generate high rates of runoff and are not capable of recycling or removing nutrients (Coulter *et al.,* 2004; Carle *et al.,* 2005); this leads to rapid and efficient transport of nutrients and a range of other contaminants to nearby waterways during precipitation events. Additionally, the use of lawn fertilizers by golf courses and households, the application of salt to roadways, the erosion of soils from construction sites and the inputs from unsewered developments contribute to the nutrient production from these landscapes.

Undisturbed forested landscapes usually produce the highest water quality, however, after forest disturbance from harvesting, the ability of the landscape to capture nutrients and sediments before they enter the stream channel is decreased and the potential for soil erosion increases. Forested landscapes that have undergone harvesting can also become significant sources of nutrients and sediment to nearby waterways (Bormann and Likens, 1968). Similarly, the construction of roads and cutlines create linear disturbances where the soil becomes compacted and the potential for the rerouting of water and nutrients increases (Swank *et al.,* 2001). Grayson *et al.,* (1993), found that 50–90 tonnes of sediment per hectare of road surface per year reached small streams in their

Australian catchments. Approximately two-thirds of the stream sediment observed was suspended while one third was coarse material (Grayson *et al.,* 1993). As much of the phosphorus entering forested streams is bound to sediment (Sharpley, 1980), increases in sediment production greatly influence the amount of phosphorus entering nearby waterways.

While impacts of these land uses are well documented, quantifying the nutrient production from non-point sources within large river systems is extremely difficult due to the variation in physiographic conditions (climate, watershed characteristics governing runoff dynamics), the heterogeneity of different categories of land uses typically present at larger spatial scales and the biogeochemical processes which regulate nutrient dynamics. By focusing on smaller watersheds with contrasting land uses, the effects of land cover and land use practices that are confounded at the larger basin scale can be resolved (Liu *et al.,* 2000). For example, Coulter *et al.*, (2004) used this approach in Kentucky to examine the differences in nutrient production among an agricultural, a mixed (agricultural-urban), and an urban basin. Using geographical information systems (GIS) to delineate and characterise the land cover within their basins, Coulter *et al.,* (2004) were able to compare the water quality at the outflows of the three basins and use this information to draw inferences on the differing impacts of land use practices on water quality at the larger basin scale. Although this approach focuses on specific areas within a larger basin, the inferences gained at this smaller scale can be used to develop management strategies for the entire basin.

While the comparative impact of broadly differing categories of land use on water quality has been studied extensively in North America, the extent of these landscapes continues to increase while the composition of land use within basins is becoming more heterogeneous. This has increased the difficulty of managing non-point source pollution of water supplies in many regions and thus historical approaches have typically been qualitative assessments of how relative water quality varies across larger river basins. Such assessments often describe water quality within a basin as “good”, “fair” or “poor”, but typically do not link local water quality to any particular land use or basin attribute. To efficiently and effectively manage pollution in these areas, many agencies are now turning their attention to water quality assessment approaches that address the linkages between land use practices and water quality. While several frameworks for such assessments have been developed over the past 10-20 years, the pressure state response model framework (Hardy and Pinter, 1995) is particularly well suited to the difficult problem of non-point source pollution management as it links the pressure (i.e. land use practice(s) such as agriculture, forestry, urban development), to the state of the environment (water quality). Once this link has been made, potential responses or management actions and political decisions can be undertaken to target the areas of concern (Hardy and Pinter, 1995).

This framework has been used as a “coarse filter” to describe the state of water quality within a basin to identify the key land use practices effecting water quality and to support the development of management strategies to address these impacts. Several studies using similar frameworks have used this approach to compare measured nutrient concentrations to targets or guidelines defined by the regulatory agencies in their area (e.g., Canadian Council of the Ministers of the Environment (CCME) or the Environmental Protection Agency (EPA) water quality guidelines) (Laureano and Navar, 2002; Bressler at el., 2009). If the measured contaminant concentration values exceed those predetermined guidelines, this indicates that land use activities have impacted or caused a shift in the state of the environment. Once this link between land use and water quality has been established, managers can initiate actions to improve water quality by targeting the source of the contaminant. These actions may involve government, the private sector or individual stakeholders and may include workshops, best management practices (BMPs) or protective legislation (Bowen and Riley, 2003). A similar framework was used by Laureano and Navar (2002) to assess the water quality in the Rio San Juan watershed in north-eastern Mexico. By comparing water quality to water quality standards (Mexican standard for drinking water and World Health Organization standard for drinking water) it was determined that

18.7% of all samples exceeded the regulatory standards. Based on these findings, it was concluded that water quality pollution continues to be a problem in the basin and that integrated multi-sectorial approaches are required to address the current issues (Laureano and Navar, 2002).

The PSR model was chosen for this study as it does not focus on the fine scale biophysical processes which regulate the interactions between land use and water quality, but instead clearly links human activities occurring on the landscape to environmental degradation (Hodge, 1997), thus simplifying the very confounded issue of assessing regional water quality. Detailed knowledge of fine-scale biophysical processes often does not identify suitable management actions to remediate water quality at a regional scale. The identification of a problem associated with a particular land use is often enough to serve as a starting point leading to remediation. While this approach has been criticized for being overly simple and narrow in scope, it is very useful as a management tool because it directs attention on the factors influencing environmental systems and the associated consequences (environmental and regulatory) (Hodge, 1997) .

Unfortunately, studies examining the comparative pressures exerted on river water quality from a range of land uses representative of conditions in Alberta are limited. Furthermore, while several studies have addressed comparative land use impacts in the lower reaches of larger river basins with comparatively high intensities of different land uses, few have explored this issue in basins spanning a range of land use intensities (low to high). In southern Alberta where both land use pressures and water supply shortages are increasing, this type of information is critically needed to support integrated land use planning and management as part of the South Saskatchewan Regional Plan mandated by the Alberta Land Use Framework. The present study focused on the headwaters of the Oldman River basin that supplies water to support a large agricultural sector in addition to providing municipal water supplies for many towns and cities located throughout southwestern Alberta. The broad objectives of this study were to evaluate the relationships between river water quality and the dominant categories of land use occurring in the headwaters of the Oldman River Basin. The objectives of the work focused on 1) evaluating the relationships between total nitrogen (TN) and total phosphorus (TP) and differing classes and intensities of land use (agricultural {extensive and intensive} and forestry {extensive and intensive}) in the headwaters (Oldman, Castle and Crowsnest) of the Oldman River Basin. An associated objective was to quantify the changes in water quality (TN and TP) along an urban disturbance gradient situated longitudinally down the Crowsnest River. Lastly, a related objective was to explore the suitability of the pressure state response model as a framework to evaluate non-point source impacts on water quality in Alberta.

3.2 Materials and Methods

3.2.1 Description of Study Area

This study was conducted in six forested catchments, seven agricultural catchments and seven urban catchments all located within the three headwater basins (Oldman, Crowsnest and Castle) of the Oldman River Basin located in southwestern Alberta (Figure 3-1). This watershed extends from the Rocky Mountain forest reserve in the extreme south western portion of Alberta eastward through to the foothills fescue eco-region and then to the Oldman River Reservoir.

The six forested catchments chosen were situated within the upper elevations of the Oldman River Basin where alpine, sub-alpine and montane eco-regions dominate (Oldman Watershed Council, 2010). The alpine eco-region occurs above the tree line at the highest elevations within the catchments. This area is largely comprised of exposed bedrock, alpine meadows, and shrubs. The sub-alpine eco-region lies below the alpine and is primarily forested with lodgepole pine (*Pinus contorta)*, Engelmann spruce (*Picea engelmannii*), white spruce (*Picea glauca*) and Douglas-fir (*Pseudotsuga menziesii*). The montane eco-region lies below the sub-alpine eco-region and is characterised by rolling foothills. Lodgepole pine, Douglas-fir and aspen (*Populus tremuloides*) mixedwood forests cover north and eastern facing slopes, while grasslands dominate southerly and westerly areas and lower elevations (Oldman Watershed Council, 2010).

The seven agricultural catchments were situated within the foothills fescue eco-region, which dominates the lower regions of the Oldman Basin. This eco-region is characterized by a rolling topography dominated by shrubs, aspen and balsam poplar (*Populus balsamifera).* The seven urban catchments were located along the Crowsnest River which originates in the Rocky Mountain forest reserve (alpine, sub-alpine and montane eco-regions), runs through the Municipality of the Crowsnest Pass, through the foothills fescue eco-region and terminates at the Oldman River Reservoir.

Soils in the forested catchments and the upper ends of the agricultural and urban catchments are well to perfectly drained brunisols and gray luvisols with weak horizon development, characteristic of higher elevation northern environments (Rock and Mayer, 2009; Bladon *et al.,* 2008). Soils in the lower ends of the agricultural and urban catchments are brown chernozems (Rock and Mayer, 2009). Surficial geology in the Oldman River Basin is composed of a thick, continuous till blanket consisting of glacio-lacustrine deposits except for the most western portion of the basins which also include alpine complexes (Rock and Mayer, 2009).

Mean annual precipitation and air temperatures varied between the forested catchments located throughout the higher elevation western portions of the Basin and the agricultural and urban catchments located throughout the lower elevations of the Basin. The long term mean annual precipitation (1971-2000) at the higher elevation western regions within the Oldman Basin ranged from 741-915 mm/yr while precipitation along the lower elevation eastern portion ranged from 439-654 mm/yr. Temperatures during summer and winter months were approximately 2 ºC cooler in the higher elevation western regions compared to the lower elevation eastern portions in the Castle and Crowsnest sub-basins, while the temperatures at the higher elevation sites in the Oldman basin were approximately 15 ºC cooler compared with the lower elevations.

3.2.2 Study Design and Field Sampling

To capture the representative land use classes within the headwaters, the study design was to sample one extensively and one intensively managed agricultural catchment and one extensively and one intensively managed forested catchment within each of three headwater sub-basins (Oldman, Castle and Crowsnest) of the Oldman River Basin (Table 3-1, Figure 3-1). These catchments were chosen based on satellite imagery provided by Google Earth, prior knowledge of the area and personal communications with Alberta Environment staff. As agricultural catchments in this region predominantly exhibit a gradient in land use intensity, where grazing practices dominate the upper reaches of the catchments (i.e., extensive) and small cow-calf operations and cultivation (i.e., intensive) dominate the lower reaches of the catchments, a nested approach was adopted with extensive agricultural sampling locations located at the upper end of the catchment and intensive sampling locations located at the lower end of the sample catchment (Table 3-1, Figure 3-1). It was not possible to locate a suitable agricultural catchment within the Oldman sub-basin; therefore two were selected in the Castle sub-basin. Additionally, three sites were chosen along Cow Creek in the Crowsnest sub-basin, one extensively and two intensively managed agricultural catchments to capture the influence of a feedlot located along the creek. Overall, seven agricultural catchments were chosen, Beaver Mines creek (top and bottom) and Gladstone creek (top and bottom) located in the Castle sub-basin and Cow Creek (top, below feed lot and bottom) located within the Crowsnest sub-basin (Table 3-1, Figure 3-1).

Six forested catchments were also chosen with two catchments (one intensively and one extensively managed) occurring in each headwater sub-basin (Table 3-1, Figure 3-1). Within the forested region, historic and current timber harvesting, low intensity petrochemical development and both intensive and extensive recreational activities occur. Intensively managed forestry catchments were those characterized by large expanses of harvesting and linear disturbances, while extensively managed forestry catchments are those characterized by little harvesting and linear disturbance. In the Oldman sub-basin, Pasque creek was chosen as the intensively managed catchment, while Cache creek was chosen as the extensively managed catchment. In the Castle sub-basin, Whitney creek was chosen as the intensively managed catchment while Syncline creek was chosen as the extensively managed catchment and in the Crowsnest sub-basin Allison creek was chosen as the intensively managed catchment while McGilvray creek was chosen as the extensively managed catchment (Table 3-1).

To evaluate the spatial patterns in water quality along an urban disturbance gradient, a disturbance gradient characterized by increasing low density land use intensity (percent developed) was set up by placing sampling locations downstream of each of the five small communities from west to east along the Crowsnest River throughout the Municipality of the Crowsnest Pass (Table 3-1, Figure 3-1). This Municipality was suitable for this type of analysis as five small communities (Coleman, Blairmore, Frank, Bellvue and Hillcrest) are situated longitudinally from the upper reaches of the basin through to the lower reaches. The population of the municipality is approximately 5700 people with a population density of 15.4 people per km^2 (Statistics Canada, 2008). Between each of these communities, low density acreages dominate the landscape. Tourism and service sector businesses comprise the bulk of the industrial activities in this Municipality which also include a golf course (Blairemore), septic fields (Hillcrest), regional sewage treatment facilities (Frank), industrial yards (Coleman, Blairmore, Frank, Hillcrest) and old mining facilities distributed within, and between all five communities. The seven sampling sites located along the River were: Crowsnest R. below lake (above all urban disturbance) (CA1), Crowsnest R. below Coleman (CA2), Crowsnest R. below Blairmore (CA3), Crowsnest R. below Frank (CA4), Crowsnest R. above Septic Fields (CA5), Crowsnest R. below Septic Fields (CA6) and Crowsnest R. at Lundbreck (CA7). Sites CA5 and CA6 were chosen to evaluate the impacts of the Hillcrest septic fields.

To describe the broad temporal patterns in water quality reflective of the regional climate and dominant hydrologic regime, water quality sampling was conducted during the rising limb of the spring snowmelt freshet, during the recession limb of the spring snowmelt freshet and during baseflow conditions. These periods represent the dominant features of the single peak hydrographs typical of this area and were roughly categorized using discharge hydrographs from the Water Survey of Canada hydrometric gauging stations. Generally, the spring melt freshet occurs from April through to June and is characterized by high discharges due to melting of the snowpack. Baseflows reflect a dominance of subsurface contributions to streamflow and begin in late summer during the latter portion of the recession limb of the annual hydrograph. In the Crowsnest River and some of the larger forested streams baseflow continues through the overwinter periods (in the absence of large rainfall or early winter melt events). Conversely, the agricultural streams and some of the smaller forested streams are predominantly frozen during the winter months.

The differences in elevation and vegetation between the forested and the agricultural and urban sites were also associated with a difference in snowmelt timing. Consequently, actual sampling dates varied to reflect the differences in the timing of the dominant hydrological seasons within and across land use categories. Three water samples were collected for analysis during each hydrological flow period at each one of the twenty sampling locations to broadly evaluate and compare the differences in water quality among the land use classes and among the dominant hydrologic flow regimes. This sampling occurred over two years. Additionally, a large storm occurred in May of 2008, thus one storm sample was taken at each site during this period.

3.2.3 Hydrometric and Water Quality Sampling

Discharge measurements were taken at natural control sections (reasonably straight stream alignment and entrenched river banks) at each site.

These instantaneous discharge measurements were taken at the time water samples were collected to calculate flow weighted contaminant export and area-based yields. Flow measurements at each site were performed using standard area-velocity current metering techniques (10 point measurement) using a Global (FP-201) velocity meter. Staff gauges were installed at each control section and were read immediately after discharge measurements were taken to develop a stage discharge relationship to be used when it was not possible to safely current meter. When discharge along the Crowsnest River could not be measured, it was estimated from linear relationships developed between hourly discharge recorded at nearby Water Survey of Canada (WSC) hydrometric gauging stations (continuous discharge data) and the instantaneous discharge recorded at the uppermost site (CA1) along the Crowsnest River. The date/time of sampling and discharge measurement was recorded for each sample and simultaneous discharge values from the (WSC) stations were obtained from the Water Survey of Canada (www.wsc.ec.gc.ca) to enable development of these inter-station discharge relationships.

Manual, depth-integrated grab samples were collected from the middle of the river in acid washed (10% HCl), triple rinsed, high density polyethylene bottles, refrigerated at 4ºC and transported to the laboratory within four days of collection (Bladon *et al.*, 2008). Water chemistry analysis was performed by the University of Alberta Biochemical Analytical laboratory in the Department of Biological Sciences as follows. Total nitrogen concentrations (TN; unfiltered) and total dissolved nitrogen concentrations (TDN; 0.45 µm filter) were determined by automated cadmium reduction (Method 4500; NO_3^-:F) using a Lachat QuickChem 8500 multichannel flow injection analyzer (Greenberg *et al.*, 1999). Samples were then digested with potassium persulfate ($K_2S_2O_8$) prior to analysis. Total phosphorus (TP; unfiltered) and total dissolved phosphorus (TDP; 0.45 µm filter) were determined by automated ascorbic acid reduction (Method 4500 – P:F) using a Lachat QuikChem 8500 multi-channel flow injection analyzer (Greenberg *et al.*, 1999). TP and TDP samples were digested using the persulfate oxidation technique with potassium persulfate ($K_2S_2O_8$) prior to analysis. Particulate nitrogen and phosphorus concentrations were determined by subtracting total dissolved nitrogen and phosphorus concentrations from total nitrogen and phosphorus concentrations.

Using TN and TP concentrations and the discharge measurements calculated for each sampling event, total nutrient export (kg/day), and total nutrient yield (kg/ha/yr) were calculated. Export for each contaminant was calculated as the product of the concentration (µg/l) and discharge (m^3/s). Specific watershed area weighted contaminant yield reflects the contaminant production per unit land area and was calculated by dividing the contaminant export (kg/day) by watershed area above each sampling point. In the agricultural catchments, yields from the bottom sites were calculate using the area between the two stations to reflect the difference in contaminant production between the extensive and the intensive agricultural catchments.

3.2.4 Statistical Analysis

To evaluate and compare the differences in nutrient production among the agricultural and the forested catchments and among the sites situated longitudinally down the Crowsnest River, the statistical analysis focused on identifying differences among the land use categories. All data analysis was performed using SAS statistical software (version 9.2, Cary, United States). Median values of total nitrogen (TN), total dissolved nitrogen (TDN), total phosphorus (TP) and total dissolved phosphorus (TDP) concentration, export and yield data failed to meet Shapiro-Wilk's tests for normality despite the attempts to transform the data using log, log(x+1) and square root(x). However, non-parametric techniques such as the Kruskal-Wallis test have been recommended for water quality data of this type (Helsel and Hirsch, 2002). A series of single-factor Kruskal-Wallis non-parametric tests were used to test for differences in nutrient concentration, export and yield among the agricultural (intensive and extensive) and the forested (intensive and extensive) catchments, for differences in nutrient concentration, export and yield among the urban sites located along the Crowsnest River, and for temporal patterns (hydrologic flow period) in total phosphorus and total nitrogen concentration, exports and yields within all three land use classes.

3.2.5 Pressure State Response Model Framework

The pressure state response model framework was used to assess the impacts of land use practices (agricultural, forested and urban) on water quality (TN and TP). In this study, the pressures are the land use activities occurring throughout each basin which may be adversely influencing water quality. The state of the environment (water quality) will then be related to the land use practices within the basins by evaluating the number of times the measured concentrations (TN and TP) exceed threshold values set out by the CCME (Canadian Council of Ministers of the Environment) and proposed by NAESI (National Agri-Environmental Standards Initiative). NAESI is a program developed by Environment Canada and Agriculture and Agri-Food Canada which focused on the development of non-regulatory environmental performance standards to protect surface waters from excessive nutrients inputs (Chambers *et al*., 2009). For total nitrogen and total phosphorus concentrations, the guidelines proposed by the CCME for the protection of aquatic health were used as ecosystem health and eutrophication risks to the Oldman Reservoir were the focus of this evaluation (Table 3-2; CCME, 1999). The response variable of the pressure state response model framework was not addressed in this study. The overall objectives were to evaluate the relationships between water quality and the dominant land use classes present in the headwaters of the Oldman Basin. Proposing effective response mechanisms (best management practices, legislation etc.) to mitigate the changes in the state of the environment (water quality) was beyond the scope of this study.

3.3 Results

3.3.1 River Discharges

Streamflow patterns in the agricultural (intensively and extensively managed) and forested (intensively and extensively managed) catchments were characterised by annual hydrographs dominated by a single peak reflecting the annual snowmelt freshet. In the agricultural catchments, the snowmelt freshet started in late April, peaked during late May to early June and receded to baseflow conditions by the end of July. In the forested catchments, the snowmelt freshet started later (mid-May), peaked during late-June and receded to baseflow conditions by the end of July. Peak discharges varied across the four landscape classes and generally occurred one month earlier in the agricultural catchments.

In the agricultural catchments, there was a considerable increase in streamflow from the extensively managed areas downstream to the intensively managed areas. This difference in streamflow was highest during the rising limb of the hydrograph when discharges from the intensively managed sites were approximately 1.9 times higher than those at the extensively managed sites. Similarly, during baseflow periods and recession limb periods, discharges from the intensive sites were approximately 1.3 and 1.2 times greater than at the extensive sites (Table 3-3). Discharge was greatest in the forested catchments, with measured streamflow values being 1.8 and 2.2 times higher in the extensively and intensively managed forested catchments than streamflow in the extensively managed agricultural catchments (Table 3-3). These differences in river discharge and timing of spring melt generally reflect the physiographic and climatic differences between the landscape classes. The agricultural catchments are primarily grasslands with some cropland located at lower elevations throughout the Oldman Basin while the forested catchments are largely covered by vegetation and are located at higher elevations.

Along the Crowsnest River a linearly increasing trend in streamflow from the uppermost site at CA1 through to the lowest site at CA7 was observed.

Average streamflow measured throughout the River ranged from 3.2 m^3/s at CA1 to 8.7 m^3/s at CA7 (Table 3-4). This downstream increase in streamflow reflects the incremental additions of water from the surrounding landscape and was observed during all three hydrologic periods.

3.3.2 Agricultural vs. Forested Catchments

3.3.2.1 Nitrogen

Median total nitrogen concentration showed a generally decreasing trend along a gradient of land use intensity from an intensively managed landscape (agriculture) to more extensively managed landscape (forestry). Median total nitrogen concentrations were highest in the intensively and extensively managed agricultural catchments (222.0 µg/L and 185 µg/L, respectively) while median TN concentrations were considerably lower ($p<0.01$) but generally similar among the two forested catchments (135.5 µg/L and 134.0 µg/L in the extensively and intensively managed forested catchments respectively, Table 3-5, Figure 3-2). The coefficient of variation was generally similar among the four groups; however, the range of TN values observed in both the extensively and intensively managed agricultural catchments (37.0 – 377.0 µg/L and 42.0 – 458.0 µg/L, respectively) was much higher than that observed throughout the forested catchments (21.0-235.0 µg/L and 7.0 – 283.0 µg/L in the extensively and intensively managed catchments respectively). Within the agricultural catchments, median TN concentrations were 1.2 times higher in the intensively vs. the extensively managed catchments while the intensively and extensively managed forestry catchments had similar TN concentrations.

While median total nitrogen concentration values were highest in both of the agricultural catchments, median total nitrogen export was highest in the forested catchments ($p= 0.15$, Table 3-5, Figure 3-2). Overall, the forested catchments exported roughly 2.2 times more TN than the agricultural catchments. Furthermore, within the forested catchments, TN exports were roughly 1.6 times higher in the extensively managed catchments vs. the intensively managed catchments. Conversely, within the agricultural catchments, TN exports were roughly 2.2 times higher in the intensively managed catchments vs. the extensively managed catchments. This variability in TN exports reflects the differences in streamflow among the four groups (Table 3-5). Differences in TN yields were less apparent among the four landscape classes. Median total nitrogen yields were highest in the intensively managed agricultural catchments and the extensively managed forested catchments (1.0×10^{-3} kg/ha/yr and 0.6×10^{-3} kg/ha/ yr respectively) decreasing to 0.6×10^{-3} kg/ha/yr and 0.2×10^{-3} kg/ha/yr in the intensively managed forestry and extensively managed agricultural catchments respectively ($p=0.05$, Table 3-5, Figure 3-2). Within the agricultural catchments, TN yields were 5 times higher from the intensively managed catchments vs. the extensively managed catchments while TN yields from the extensively managed forestry catchments were 1.5 times higher than those from the intensively managed catchments.

Among the four landscape classes, total dissolved nitrogen (TDN) concentrations showed similar trends as total nitrogen concentrations (Table 3-6, Figure 3-3). The highest median TDN concentrations were observed in the agricultural catchments (179.0 µg/L and 212.0 µg/L, in the extensively and intensively managed catchments respectively) while the forestry catchments had the lowest median TDN concentrations (116.5 µg/L and 135.0, in the extensively and intensively managed catchments respectively, $p < 0.01$, Table 3-6, Figure 3-3). Similar trends between total nitrogen and total dissolved nitrogen were observed as the majority of the nitrogen was transported in the dissolved form in all four landscape classes (Figure 3-4). Approximately 94 % of TN was in the dissolved form in both the extensively and intensively managed agricultural catchments, while in the extensively and intensively managed forested catchments, approximately 95 % of the total nitrogen was in the dissolved form.

3.3.2.2 Phosphorus

Among the four landscape classes, median total phosphorus concentrations showed a similar pattern to total nitrogen concentrations with values increasing as landscape intensity increased (Table 3-7, Figure 3-5). Median total phosphorus concentrations were highest in the intensively and extensively managed agricultural catchments (15.0 µg/L and 12.0 µg/L, respectively), decreasing to 4.0 µg/L and 6.0 µg/L in the extensively and intensively managed forested catchments respectively ($p<0.01$, Table 3-7, Figure 3-5). Contrary to observations for total nitrogen concentrations, the variability in total phosphorus concentrations were different for each landscape class with the largest variability in concentrations occurring in the intensively managed agricultural and extensively managed forested catchments (1.0 – 163.0 µg/L and 1.0 – 134.0 µg/L, respectively; Table 3-7). Within the agricultural catchments, TP concentrations were roughly 1.3 times higher at the intensively managed sites, while concentrations in the intensively managed forestry catchments were 1.5 times those in the extensively managed catchments.

Contrary to the patterns observed for median total phosphorus concentrations, total phosphorus exports were highest in the intensively managed forested catchments. While both of the agricultural catchments had the highest concentrations, median phosphorus exports were highest in the intensively managed forested catchments (0.24×10^{-3} kg/day) followed by the intensively managed agricultural catchments (0.20×10^{-3} kg/day; $p=0.33$, Table 3-7, Figure 3-5). The lowest median total phosphorus export values were noted in the extensively managed forestry and the extensively managed agricultural catchments (0.19×10^{-3} kg/day and 0.12×10^{-3} kg/day, respectively). This pattern reflects the influence of streamflow on total phosphorus export. Additionally, within the agricultural and forested catchments, TP export was 1.7 and 1.3 times higher from the intensively managed catchments, respectively. In contrast, total phosphorus yields showed a different pattern (Figure 3-5); Median total phosphorus yields were highest in the intensively managed agricultural catchments (1.0×10^{-4} kg/ha/yr) while a linearly decreasing pattern in yields was observed from the extensively managed forestry to the intensively managed forestry to the extensively managed agricultural catchments (0.34 x 10^{-4} kg/ha/yr, 0.21 x 10^{-4} kg/ha/yr and 0.14 x 10^{-4} kg/ha/yr respectively; p=0.23, Table 3-7). Within the agricultural catchments, TP yields were 7 times higher in the intensively vs. the extensively managed catchments while TP yields from the extensively managed forestry catchment were 1.6 times those from the intensively managed forested catchment.

Contrary to the values observed for total dissolved nitrogen, median total dissolved phosphorus concentrations, were considerably lower than total phosphorus concentrations. Median TDP concentrations were highest in the two agricultural landscape classes (5.0 µg/L and 4.0 µg/L in the extensively and intensively managed classes respectively), followed by a slight decrease in the two forestry classes (2.0 µg/L and 3.0 µg/L in the extensively and intensively managed classes, respectively) (p=0.08, Table 3-8, Figure 3-6). These differing patterns show that while most of the nitrogen was transported in the dissolved form, much of the phosphorus in all four of the landscape classes was transported in the particulate form (Figure 3-7). In the extensively and intensively managed agricultural catchments approximately 40 % and 17 % of TP was transported in the dissolved form, respectively, while in the extensively and intensively managed forested catchments approximately 28 % and 42 % of the TP was transported in the dissolved form. respectively.

3.3.2.3 Seasonal Trends in Agricultural and Forested Catchments

Median total nitrogen and total phosphorus concentration, export and yield were highly variable among the three hydrologic flow seasons (baseflow, rising limb and recession limb) in both catchment types. These differences reflect the considerable variability in streamflow among the three hydrologic periods and among the four landscape classes. In the agricultural and forested catchments, discharge was highest during the recession limb of the hydrograph with considerably lower flows occurring during baseflow conditions (Table 3-9). Overall, discharge was the most variable in the agricultural catchments and least variable in the forested catchments. In the extensively managed agricultural catchment, discharges ranged from 0.07 m^3/s, 0.37 m^3/s, and to 0.64 m^3/s during baseflow, rising limb and recession limb periods respectively (Table 3-9).

Median total nitrogen concentrations, exports and yields in both the extensively and intensively managed agricultural catchments were highly variable among the three flow periods with the highest concentrations, exports and yields occurring during the rising limb of the hydrograph (Figure 3-8). The increase in both concentrations and river discharges during the rising limb, resulted in a 14.7 to 16.7-fold greater median TN export and yield compared to baseflows (Table 3-9). The same general trends in TN concentrations were observed in the extensively and intensively managed forestry catchments, with the highest concentrations occurring during the rising limb of the hydrograph. Alternatively, median TN exports and yields in the extensively and intensively managed forestry catchments were highest during the recession limb of the hydrograph (14.7 and 13.3 – fold greater than median TN baseflow exports and yields; Figure 3-9). These differences in TN exports and yields between the agricultural and forestry catchments reflect differences in the melt timing between the catchments.

Similarly, in both the agricultural and forested catchments, total phosphorus concentrations, export and yield were highly variable among the three hydrologic flow periods (Figures 3-10 and 3-11). In all four landscape classes, median TP concentrations were highest during the rising limb of the hydrograph and lowest during baseflow conditions. In the intensively managed agricultural and forestry catchments, median TP export and yield were considerably higher than those reported during the recession limb of the hydrograph. In the agricultural catchment this resulted in median TP exports and yields being 3.9 and 1.9 times higher than during the recession limb of the hydrograph (Table 3-10). In the forested catchments, median TP exports and yields were 2.4 and 2.9 times greater than those reported during the recession limb of the hydrograph (Table 3-10). Alternatively, TP exports and yields were similar between the rising and the recession limbs in the extensively managed agricultural and forested catchments.

3.3.3 Urban Catchments

3.3.3.1 Nitrogen

Along the Crowsnest River, the pattern in total nitrogen concentrations generally reflected the incremental additions of nutrients from the five communities situated along the River (Figure 3-12). From sites CA1 to CA3, the areas on the landscape that contain the largest proportion of the population, a linearly increasing trend in median total nitrogen was observed (104 µg/L, to 135 µg/L, to 205 µg/L, respectively). After this initial increase, median total nitrogen concentrations from sites CA4 through to CA7 remained fairly consistent (Table 3-11, Figure 3-12), while the range of total nitrogen concentrations and the coefficient of variation generally increased downstream (Table 3-10).

While median total nitrogen concentrations generally remained consistent downstream of Blairmore (CA3), total nitrogen exports showed a linearly increasing pattern from CA1 (2.1×10^{-2} kg/day) through to CA6 (8.4×10^{-2} kg/day) ($p<0.01$, Table 3-11, Figure 3-12). Downstream of CA6, however, there was a large increase in export at CA7 (17.7×10^{-2} kg/day). This linearly increasing pattern reflects the pattern of increasing streamflow observed throughout the Crowsnest River. However, this pattern was not observed when examining total nitrogen yields along the Crowsnest River. The sites which produced the highest total nitrogen were CA1 and CA7 (9.7×10^{-4} kg/ha/yr and 9.8×10^{-4} kg/ha/yr, respectively), approximately 1.4 times more than the amount of nitrogen at the other sites, while the middle reach sites (CA2 through CA6), all showed very similar total nitrogen yields ($p=0.29$, Table 3-11, Figure 3-12).

Patterns observed for total dissolved nitrogen concentrations along the Crowsnest River were very similar to those of total nitrogen as most of the nitrogen was transported in the dissolved form (Figure 3-13). From site CA1 through to site CA3, a linearly increasing trend existed (91 µg/L, 126 µg/L, and 194 µg/L respectively), concentrations then levelled off and remained fairly consistent from site CA4 through to CA7 ($p<0.01$, Table 3-12). This is consistent with what was found in the agricultural and the forested catchments. Total dissolved nitrogen made up approximately 90 % of the nitrogen in the samples taken along the Crowsnest River (Figure 3-14).

3.3.3.2 Phosphorus

Median total phosphorus concentrations along the Crowsnest River generally reflected the same pattern as was observed for total nitrogen concentrations (Table 3-13, Figure 3-15). Initially, there was an increase in TP concentrations from CA1 through to CA4. After CA4, there was a slight decrease in concentrations at CA5. However, concentrations then gradually increased again to CA6 through to CA7 ($p=<0.01$, Table 3-13, Figure 3-15). Similar to TN concentrations, the range and the coefficient of variation for total phosphorus concentrations increased downstream (Table 3-13).

Patterns in total phosphorus export along the Crowsnest River paralleled those of total phosphorus concentrations, reflecting the influence of increasing concentrations and streamflows. Median total phosphorus exports initially increased from 1.2×10^{-3} kg/day at CA1 to 9.7×10^{-3} kg/day at CA4, decreasing to 8.2×10^{-3} kg/day at CA5 and increasing to 10.1×10^{-3} kg/day at CA7 ($p<0.01$, Table 3-13, Figure 3-15). A similar pattern existed for total phosphorus yields along the Crowsnest River. Initially, yields increased from CA1 through to CA4 and then decreased slightly at CA5 ($p=0.92$, Table 3-13, Figure 3-15). After CA5 however, there was not a steady increase in yields, instead, yields initially increased at CA6 and then decreased again at CA7 (Figure 3-15).

Unlike total dissolved nitrogen concentrations, the trend in total dissolved phosphorus concentrations was very different than that observed for concentrations of total phosphorus. Initially, median concentrations of total dissolved phosphorus along the Crowsnest River were very low (1.0 µg/L, 2.0 µg/L, and 1.0 µg/L at CA1, CA2 and CA3 respectively, $p<0.01$, Table 3-14, Figure 3-16). At CA4, there was a large increase in median total dissolved phosphorus concentrations (7.0 µg/L). Further downstream, concentrations of

TDP decreased and remained consistent throughout the remainder of the sampling sites. Total dissolved phosphorus made up approximately 79 % of the phosphorus in the samples taken along the Crowsnest River (Figure 3-17). This proportion is considerably larger than the proportion observed in the agricultural and forested catchments.

3.3.3.3 Seasonal Trends in Urban Catchments

Similar to the trends observed in the agricultural and forested catchments, sites along the Crowsnest River showed considerable variability in median total nitrogen and phosphorus concentrations, export and yield among the three hydrologic flow periods (rising limb, recession limb and baseflow). These differences also reflect the variability in streamflow among the flow periods and among the sites along the River. The variability in discharge among the three hydrologic periods was fairly consistent from the upper to the lower sites along the Crowsnest River (Table 3-4). Measured discharges along the River were highest during the recession limb of the hydrograph (5.4 – 11.4 m^3/s from CA1 through to CA7) and comparable during the rising limb of the hydrograph and baseflow conditions (Table 3-4). These large differences in streamflow among the three hydrologic periods may be a result of sampling over two years.

Trends in total nitrogen concentrations, export and yield along the Crowsnest River were very different among the three hydrologic flow periods. Median total nitrogen concentrations were highest and increased linearly downstream during the rising limb of the hydrograph at sites CA2 through to CA7 (172.0 μg/L – 291.0 μg/L). In contrast, median total nitrogen exports increased linearly downstream as well, but were highest at all sites during the recession limb of the hydrograph (Table 3-15, Figure 3-18). This was expected as measured discharges from the upper to the lower sites were highest during the recession limb. Trends in median total nitrogen yields among the hydrologic periods were quite different than those observed for concentrations and exports. At each site, yields were highest during the recession limb of the hydrograph. However, as opposed to what was observed for concentrations and exports, a linear downstream increasing pattern was not present. Instead, CA1 showed the highest TN yields (25.0 x 10^{-4} kg/ha/yr) while CA7 showed the lowest yields (9.8 x 10^{-4} kg/ha/yr) (Table 3-15, Figure 3-18).

Along the Crowsnest River, total phosphorus concentration, export and yield also showed considerable variability between the three hydrologic flow periods. As observed with TN concentrations, TP concentrations were highest at each site during the rising limb of the hydrograph (Table 3-16, Figure 3-19). The downstream trend in TP concentrations, however, was quite different. Initially, TP concentrations were quite low (Table 3-16), generally increasing from CA1 to site CA4 and then gradually declining until site CA7. Median TP exports were also generally higher during the rising limb of the hydrograph and generally increased linearly downstream during all three hydrologic flow periods, similar to TN exports (Table 3-16, Figure 3-19). Trends in median TP yields among the three hydrologic flow periods were also quite different than those observed for TP concentrations and exports. Generally, TP yields were highest during the rising limb of the hydrograph. While TP yields were highest during the rising limb, they remained fairly consistent during all three flow periods from site CA1 through to site CA6 (Table 3-16, Figure 3-19).

3.3.4 Pressure State Response Model

In the intensively managed agricultural catchments, CCME and NAESI guidelines for total nitrogen were exceeded 5% of the time (2 out of 40 samples) throughout the sampling period. This number decreased to 3% of the time (1 out of 40 samples) in the extensively managed agricultural catchments for both targets (Table 3-17). In the intensively and extensively managed forestry catchments, total nitrogen guidelines (CCME and NAESI) were not exceeded during any sampling event while throughout the urban basin one sample exceeded the NAESI guidelines. All of the exceedances for total nitrogen occurred during stormflow conditions.

The number of exceedances was much higher for total phosphorus concentrations. In the intensively managed agricultural catchments, CCME guidelines were exceeded roughly 30% of the time (12 out of 40) while in the extensively managed agricultural catchments, CCME guidelines were exceeded roughly 19% of the time (6 out of 31) (Table 3-17). The NAESI guidelines were not exceeded as often in the agricultural catchments (6% of the time in the extensively managed catchments and 13% of the time in the intensively managed catchments) (Table 3-17). In the forested catchments, CCME guidelines were exceeded 10% and 16% of the time in the extensively and intensively managed catchments respectively, while the NAESI guidelines were exceeded once out of 30 samples in both the extensively and intensively managed catchments. At sites along the Crowsnest River, CCME guidelines for total phosphorus were exceeded 21% of the time and NAESI guidelines were exceeded 10% of the time. While all of the storm samples exceeded the targets proposed by the CCME and NAESI, numerous samples during the rising limb and recession limb of the hydrograph also exceeded the guidelines for total phosphorus.

3.4 Discussion

Considerable variability in nutrient concentration (total nitrogen, total dissolved nitrogen, total phosphorus and total dissolved phosphorus) was observed between the agricultural and the forested catchments and among the extensive and intensive catchments within both the agricultural and the forested land use classes. While differences between total nitrogen and total phosphorus exports and yields among the two landscape classes were not as strong, important differences in nutrient production were still evident. These results support the hypothesis that watersheds containing similar land use activities (agricultural, forested) will exhibit similar nutrient production (McMahon and Harned, 1998). Along the urban disturbance gradient throughout the Crowsnest River, the generally increasing pattern in median total nitrogen and total phosphorus concentration, export and yield reflect the incremental additions of these nutrients from the five small communities situated longitudinally down the River. Based on the differences in nutrient production between land use classes, it is proposed that at the sub-watershed scale, land use information can be used to help explain the variability in nutrient production in the headwaters of the Oldman River basin.

Excessive inputs of nitrogen and phosphorus to surface waters from non-point source land uses (agricultural, urban, forestry) has been well documented (Beaulac and Reckhow, 1982; Carpenter *et al*., 1998; Coulter *et al.*, 2004). In a comprehensive review of the literature discussing the impacts of varying land uses on water quality, Beaulac and Reckhow (1982) found that agricultural catchments (mixed {cultivated and grazing}, non-cultivated and cultivated) export more nitrogen than urban or forested catchments. Conversely, they found that urban catchments export more phosphorus than agricultural (excluding cultivation) and forested catchments (Beaulac and Reckhow, 1982). While it is recognized that physiographic and climatic variables greatly influence water quality, it is important to note that similar patterns in nutrient production were observed in the present study.

Cumulative additions resulting in an increase in total nitrogen concentration, export and yield between the extensive and the intensive agricultural catchments were expected due to the location of each catchment (intensive catchments located downstream of extensive) and the nature of the land use within each category. Median total nitrogen concentration in the intensive catchments was 1.2 times higher than in the extensive catchments, while total nitrogen yield from the intensive catchments was 5 times higher than from the extensive catchments. These results are similar to those observed by Sharpley *et al.*, (1987), who observed that with cultivation of native grasslands, TN concentration increased in agricultural lands in the Southern Plains of the U.S.. While the concentration values reported in their study (5260 µg/L in the largely extensive watersheds and 5300 µg/L in the more intensive watersheds) are much larger than those reported in the present study (185 µg/L in the extensive sites and

222 µg/L in the intensive agricultural sites), the same general pattern between extensive and intensive agricultural land use was observed. Additionally, I observed an 80% increase in nutrient production (total nitrogen yields) from the extensive to the intensive sites, while they observed a 77% increase in nutrient production.

Contrary to the differences noted above, median total nitrogen concentration was similar between the extensive and the intensive forestry catchments. Ahtiainen and Huttunen (1999) also observed similar patterns between extensive forestry and intensive forestry catchments in a study conducted in eastern Finland. Conversely, nutrient production (total nitrogen) from the extensive forested catchments was 1.5 times higher than the intensive catchments. This decrease is consistent with the findings of Vuorenmaa *et al*., (2002) who studied nutrient production throughout forested catchments in Finland. While their nutrient yields were substantially larger than the ones recorded in this study, they reported a 10% increase in nutrient production between their extensive and intensive sites, while an increase of 33 % was observed in the present study.

A generally increasing trend in median total phosphorus concentration was observed from the forested to the agricultural catchments. This is consistent with other researchers who have observed an increase in TP concentration and loading due to the conversion of grazing land or forests to cultivated land or livestock retention areas. In the Southern Plains of the U.S., Sharpley *et al*. (1987) observed a major increase in TP concentration and loading between native grasslands and cultivated land. They observed concentrations ranging from 670 µg/L to 1670 µg/L in extensive and intensive agricultural sites, respectively (Sharpley, *et al*., 1987). While absolute concentrations are likely to vary between the southern U.S. and southern Alberta, it is important to note that phosphorus production increased by roughly 85 % between the extensive and the intensive regions in both studies. Alternatively, phosphorus production in the extensive forested catchments was higher than in the intensive forested catchments. While this was unexpected, it is likely due to similar concentrations between the two land use classes and the size differences between the extensive and the intensive forested catchments.

While the agricultural catchments consistently had higher concentrations of total nitrogen and total phosphorus than the forested catchments, it is important to note that area-based yields among the agricultural and forested catchments were similar. These findings are essential to the management of the headwaters of the Oldman Basin as eutrophication of the Oldman Reservoir becomes an increasingly important issue. While the agricultural catchments had the highest nutrient concentrations, discharges from these catchments were quite low. Conversely, concentrations were lower in the forested catchments; however these catchments supplied more nutrients to the receiving waters due to higher discharge values. This suggests that both agricultural and forested landscapes should be considered when developing a eutrophication management plan for the headwaters.

Along the urban disturbance gradient situated longitudinally down the Crowsnest River, median total nitrogen concentration increased up to Crowsnest at Blairmore (CA3) and then generally levelled off. This peak in nitrogen concentration after CA3 is likely a reflection of the urban inputs from the community of Blairmore, the largest community within the Crowsnest Pass. These results are consistent with the results of others working in an urban environment (McMahon and Harned, 1998; Brett *et al*., 2005). Similarly, a generally increasing trend in total phosphorus concentration was observed along the Crowsnest River; however, peak concentration occurred after Crowsnest at Frank (CA4). This is likely due to the presence of a Waste Water Treatment facility in Frank. Brett *et al.*, (2005) and Zampella (1994) also observed an increasing trend in total phosphorus concentration among watersheds with varying proportions of urban disturbance. In the study by Brett *et al*., (2005) in the Puget Sound area in Washington State, watersheds with varying degrees of human disturbance and forests were chosen to highlight the influence of increasing urban cover on water quality. Throughout the basins examined in their study, total phosphorus concentrations ranged from 36.5 µg/L (20% urban) to

80.0 µg/L (87% urban) (Brett *et al*., 2005). Median total phosphorus concentrations throughout the Crowsnest River ranged from 6 µg/L at CA1 to 18 µg/L at CA4. It is expected that the concentrations observed by Brett *et al.,* (2005) would be larger than those observed in this study as the proportion of land covered by urban development is much larger in their region and is largely comprised of commercial, industrial and high density residential development. It is important to note, however that similar patterns exist between these two regions.

In the headwaters of the Oldman Basin, intensively managed agricultural landscapes had the highest median total nitrogen concentration, followed by urban and forested landscapes, while urban landscapes (CA4, below the waste water treatment plant (WWTP) at Frank) had the highest median total phosphorus concentration followed by agricultural and forested landscapes. This is consistent with previous studies that have examined the influence of agricultural, forested and urban landscapes on total nitrogen and total phosphorus concentrations (e.g., Beaulac and Reckhow, 1982; Coulter *et al*., 2004; Ahearn *et al*., 2005). Higher nitrogen concentrations in the agricultural catchments are likely a result of fertilizer and manure application and proximity of disturbance to the stream. In the majority of the agricultural catchments studied, livestock was not kept out of streams and cultivation occurred right up to the banks of the river. Elevated phosphorus concentrations in the urban landscape may be a result of erosion from construction sites, the excess application of lawn fertilizers or the inputs of waste water from treatment facilities. In a similar study conducted throughout a disturbed basin in the Albemarle-Pamlico region in North Carolina and Virginia, McMahon and Harned (1998) also found that median total phosphorus concentrations were highest in urban catchments, followed by agricultural and forested catchments (1900 µg/L and 360 µg/L and 50 µg/L, respectively).

While physiographic and climatic differences between study regions may explain some of the differences in absolute nutrient concentration values, it is important to note that variation in TP and TN concentration, export and yield may also arise from differences in characterization of land use classes. In the present study, agricultural catchments are largely dominated by less intensive practices (grazing, small cow-calf operations, limited cultivation). Alternatively, similar studies examining the effects of agricultural practices on water quality have focused on areas where large confined feeding operations are present and where cultivation dominates the landscape (Johnson *et al*., 1997; Castillo *et al*., 2000; Little *et al*., 2003). It is important to be aware of these differences if meaningful comparisons are to be made across studies.

Although considerable research has focused on the comparative effects of non-point source pollution on water quality of from a range of differing land uses (agricultural, urban, forest), effective management of nutrient loading to aquatic systems across large landscapes is difficult because of difficulties in identifying regions with the greatest impact and difficulties in identifying the water quality parameter of greatest concern. One tool that may prove very useful in the assessment and management of non-point source pollution is the Pressure State Response model framework. Results from this study indicate that total nitrogen exceedances (both CCME and NEASI guidelines) are very infrequent in all of the land use classes with most of the exceedances occurring during storm events. Based on these results and the guidelines used, it appears that nitrogen contamination may not be a threat in the headwaters of the Oldman River Basin. Conversely, CCME total phosphorus drinking water quality guidelines were exceeded on average 25% of the time in the agricultural catchments, 13% of the time in the forested catchments and 21% of the time in the urban catchments, while NAESI guidelines were exceeded on average 10%, 3% and 10% of the time in the agricultural, forested and urban catchments, respectively. These results highlight the fact that phosphorus contamination may be an issue in the headwaters of the Oldman River basin. Consequently, eutrophication management strategies proposed for the headwaters of the Oldman River Basin should focus on best management practices that reduce the amount of phosphorus reaching nearby surface waters. Some of these practices may include nutrient management strategies (appropriate timing and amount of fertilizer and manure application, adequate manure storage facilities, etc) and erosion and runoff strategies (shelterbelts, conservation tillage practices etc.) (Hilliard and Reedyk, 2000).

The CCME and NAESI guidelines used as threshold values in this study were concentration guidelines. It has been argued that concentration based criteria alone may not adequately link the landscape to the observed water quality (Hill, 1981). The U.S. Environmental Protection Agency has also recognized that concentration based criteria may not adequately protect their waterways and have implemented the use of total maximum daily loads (TMDLs), and discharge weighted contaminant loading (Boyd, 2001). TMDLs are specific to individual waterways and must be designed to identify contributing contaminants and identify the source of these contaminants (Boyd, 2001). Had TMDLs been previously proposed for this area, they would have been used as the threshold values in this study.

While the nutrient concentration and yield data from this study allowed for the broad spatial description of the water quality throughout the headwaters of the Oldman Basin, relating water quality to the CCME and NAESI guidelines clearly showed that phosphorus contamination may be an issue in the headwaters. Using regulatory guidelines as management thresholds or benchmarks (CCME and NAESI guidelines), use of this framework in the present study supported the linking of specific pressures to problems with specific water quality parameters. This, in turn, supports the development of actions to mitigate future environmental degradation. Essentially, this approach translates regional water quality “data” into “information” on the state of the environment in a particular watershed (Ward *et al.*, 1986). Additionally, the information obtained from this research, can be used as a baseline by which managers can assess the results of their future water management decisions (BMP’s).

3.4.1 Conclusions

While the analysis of the nutrient production (TN and TP) from the agricultural and the forested catchments did not show a considerable difference between the two land use classes, concentration data and an examination of the number of times that water quality exceeded CCME and NAESI guidelines indicated that the agricultural catchments could benefit from management actions. Similarly, results indicate that along the Crowsnest River, water quality (TN) deteriorates after Blairmore, the largest community in the Crowsest Pass, and again after the waste water treatment facility in Frank (TP). The pressure state response model also indicated that in the headwaters of the Oldman Basin, phosphorus contamination is more an issue than nitrogen contamination. It is important to note that similar areas of concern were highlighted using both the area weighted yield technique and the pressure state response framework. Having said this, guidelines used were based on concentration criteria, had they been loading guidelines, they may have highlighted different areas of concern.

Tables and Figures

Table 3-1 Physical catchment characteristics of the agricultural (extensive and intensive), forested (extensive and intensive) and urban catchments

				Elevation (m)		
Sub-Basin	**Land use Class**	**Location**	**Area (km²)**	**mean**	**min**	**max**
Castle	Agriculture (Extensive)	Top of Beaver Mines Creek	28	1535	1358	2166
Castle	Agriculture (Intensive)	Bottom of Beaver Mines Creek	37	1416	1248	1697
Castle	Agriculture (Extensive)	Top of Gladstone Creek	32	1716	1372	2443
Castle	Agriculture (Intensive)	Bottom of Gladstone Creek	4	1405	1347	1525
Crowsnest	Agriculture (Extensive)	Top of Cow Creek	39	1584	1353	2475
Crowsnest	Agriculture (Intensive)	Cow Creek below Feedlot	6	1361	1274	1525
Crowsnest	Agriculture (Intensive)	Bottom of Cow Creek	47	1332	1188	1677
Castle	Forestry (Extensive)	Syncline Creek	15	1762	1449	2504
Castle	Forestry (Intensive)	Whitney Creek	20	1783	1453	2477
Crowsnest	Forestry (Extensive)	McGillvray Creek	27	1868	1476	2732
Crowsnest	Forestry (Intensive)	Allison Creek	41	1816	1430	2721
Oldman	Forestry (Extensive)	Cache Creek	24	2157	1740	2920
Oldman	Forestry (Intensive)	Pasque Creek	23	2073	1786	2465
Crowsnest	Urban	Crownest below Lake (CA1)	80	1796	1329	2649
Crowsnest	Urban	Crowsnest below Coleman (CA2)	250	1569	1272	2593
Crowsnest	Urban	Crowsnest below Blairmore (CA3)	379	1661	1246	2610
Crowsnest	Urban	Crowsnest below Frank (CA4)	382	1750	1236	2472
Crowsnest	Urban	Crowsnest above Septic Fields (CA5)	455	1403	1233	2143
Crowsnest	Urban	Crowsnest below Septic Fields (CA6)	461	1534	1233	1999
Crowsnest	Urban	Crowsnest at Lundbreck (CA7)	662	1449	1184	2287

Table 3-2 Canadian Council of Ministers of the Environment (CCME) and the National Agri-Environmental Standards Initiative (NAESI) guidelines for total nitrogen and total phosphorus.

	CCME Guidelines (µg/L)	NAESI Guidelines (µg/L)
TN	1000[1]	940
TP	30[1]	87

[1]CCME guideline for the protection of aquatic health

Table 3-3 Mean streamflow (Q, m^3/s) in the agricultural (extensive and intensive) and forested (extensive and intensive) catchments during the rising limb of the hydrograph, the recession limb of the hydrograph, and baseflow conditions.

Land use Class	Q Rising Limb (m^3/s)	Q Recession Limb (m^3/s)	Q Baseflow (m^3/s)	Average Q (m^3/s)
Extensive Agriculture	0.37	0.64	0.07	**0.36**
Intensive Agriculture	0.70	0.78	0.09	**0.52**
Extensive Forestry	0.62	1.12	0.17	**0.65**
Intensive Forestry	0.90	1.06	0.30	**0.78**

Table 3-4 Mean streamflow (Q, m^3/s) at sites along the Crowsnest River during the rising limb of the hydrograph, the recession limb of the hydrograph, and baseflow conditions.

Site	Q Rising Limb (m^3/s)	Q Recession Limb (m^3/s)	Q Baseflow (m^3/s)	Average Q (m^3/s)
Crowsnest below Lake (CA1)	1.82	5.44	2.37	**3.21**
Crowsnest below Coleman (CA2)	2.85	6.96	3.07	**4.30**
Crowsnest below Blairmore (CA3)	3.76	9.07	3.94	**5.59**
Crowsnest below Frank (CA4)	4.08	9.22	3.26	**5.52**
Crowsnest above Septic (CA5)	4.17	9.09	4.52	**5.93**
Crowsnest below Septic (CA6)	4.77	10.80	5.10	**6.91**
Crowsnest at Lundbreck CA7)	10.00	11.35	4.74	**8.70**

Table 3-5 Total nitrogen concentration (µg/L), export (kg/day) and yield (kg/ha/yr) in the agricultural (extensive and intensive) and forestry (extensive and intensive) catchments across the three hydrologic periods (rising limb, recession limb, baseflow).

	TN Concentrations (µg/L)			TN Exports (kg/day x 10^{-3})			TN Yields (kg/ha/day x 10^{-3})		
Land use Class	Median	Range	CV	Median	Range	CV	Median	Range	CV
Extensive Agriculture	185.0	(37.0 - 377.0)	0.53	1.7	(0.06 - 41.0)	1.77	0.20	(0.01 - 4.6)	1.73
Intensive Agriculture	222.0	(42.0 - 458.0)	0.51	3.7	(0.40 - 49.0)	1.28	1.00	(0.10 - 45.0)	2.00
Extensive Forestry	135.5	(21.0 - 235.0)	0.49	7.1	(0.20 - 36.0)	0.99	0.90	(0.03 - 8.5)	1.19
Intensive Forestry	134.0	(7.0 - 283.0)	0.56	4.5	(0.20 - 27.0)	1.02	0.60	(0.03 - 4.9)	1.24

Table 3-6 Total dissolved nitrogen concentration (µg/L) in the agricultural (extensive and intensive) and forestry (extensive and intensive) catchments across the three hydrologic periods (rising limb, recession limb, baseflow).

	TDN Concentrations		
Land use Class	Median	Range	CV
Extensive Agriculture	179.0	(21.0 - 377.0)	0.55
Intensive Agriculture	212.0	(22.0 - 410.0)	0.50
Extensive Forestry	116.5	(4.0-227.0)	0.53
Intensive Forestry	135.0	(7.0 - 279.0)	0.59

Table 3-7 Total phosphorus concentration (µg/L), export (kg/day) and yield (kg/ha/yr) in the agricultural (extensive and intensive) and forestry (extensive and intensive) catchments across the three hydrologic periods (rising limb, recession limb, baseflow).

	TP Concentrations (µg/L)			TP Exports (kg/day x 10^{-3})			TP Yields (kg/ha/day x 10^{-4})		
Land use Class	Median	Range	CV	Median	Range	CV	Median	Range	CV
Extensive Agriculture	12.0	(1.0 - 80.0)	1.03	0.12	(0.07 - 20.0)	3.03	0.14	(0.04 - 23.0)	3.06
Intensive Agriculture	15.0	(1.0-163.0)	1.22	0.20	(0.02 - 11.0)	1.86	1.00	(0.04 - 100.0)	2.86
Extensive Forestry	4.0	(1.0 - 134.0)	2.62	0.19	(0.01 - 6.2)	2.17	0.34	(0.01 - 8.0)	1.91
Intensive Forestry	6.0	(1.0 - 38.0)	0.92	0.24	(0.01 - 4.8)	1.60	0.21	(0.02 - 9.0)	2.00

Table 3-8 Total dissolved phosphorus concentration (µg/L) in the agricultural (extensive and intensive) and forestry (extensive and intensive) catchments across the three hydrologic periods (rising limb, recession limb, baseflow).

	TDP Concentrations		
Land use Class	Median	Range	CV
Extensive Agriculture	5.0	(1.0 - 22.0)	0.83
Intensive Agriculture	4.0	(1.0 - 9.0)	0.62
Extensive Forestry	2.0	(1.0 - 8.0)	0.73
Intensive Forestry	3.0	(1.0 - 22.0)	1.10

Table 3-9 Total nitrogen concentration (µg/L), export (kg/day) and yield (kg/ha/yr) during the rising limb of the hydrograph, the recession limb of the hydrograph and baseflow conditions in the agricultural (extensive and intensive) and forested (extensive and intensive) catchments.

	TN Concentrations (µg/L)			TN Exports (kg/day x 10^{-3})			TN Yields (kg/ha/yr x 10^{-4})		
Extensive Agriculture	Median	Range	CV	Median	Range	CV	Median	Range	CV
Baseflow	99.0	(37.0 - 185.0)	0.53	0.04	(0.06 - 0.6)	0.51	0.50	(0.08 - 0.64)	0.49
Rising Limb	257.0	(215.0 - 377.0)	0.19	4.70	(0.90 - 32.1)	1.22	6.00	(1.0 - 36.0)	1.11
Recession Limb	158.0	(40.0 - 289.0)	0.47	3.10	(0.30 - 40.8)	1.59	3.00	(0.39 - 46.0)	1.63
Intensive Agriculture									
Baseflow	175.0	(42.0 - 320.0)	0.33	0.08	(0.70 - 2.1)	0.57	1.00	(0.59 - 4.0)	0.80
Rising Limb	294.0	(129.0 - 458.0)	0.50	12.9	(1.10 - 33.4)	0.74	19.0	(1.0 - 84.0)	1.03
Recession Limb	225.0	(46.0 - 413.0)	0.56	9.60	(1.60 - 49.7)	1.14	10.0	(1.0 - 68.0)	1.17
Extensive Forestry									
Baseflow	66.5	(36.0 - 144.0)	0.53	1.50	(0.20 - 7.1)	1.10	2.00	(0.30 - 16.0)	1.11
Rising Limb	170.0	(62.0 - 235.0)	0.28	10.70	(0.40 - 35.9)	0.83	16.0	(0.55 - 84.0)	1.13
Recession Limb	121.0	(21.0 - 161.0)	0.5	14.90	(0.50 - 22.4)	0.72	22.0	(1.0 - 53.0)	0.18
Intensive Forestry									
Baseflow	57.0	(17.0 - 193.0)	0.79	0.04	(0.20 - 6.6)	1.33	0.70	(0.31 - 6.0)	1.16
Rising Limb	177.0	(7.0 - 283.0)	0.47	7.00	(0.20 - 26.6)	0.98	8.00	(0.42 - 49.0)	1.03
Recession Limb	132.0	(71.0 - 210.0)	0.35	13.0	(2.0 - 24.4)	0.61	14.0	(3.0 - 45.0)	0.88

Table 3-10 Total phosphorus concentration (μg/L), export (kg/day) and yield (kg/ha/yr) during the rising limb of the hydrograph, the recession limb of the hydrograph and baseflow conditions in the agricultural (extensive and intensive) and forested (extensive and intensive) catchments.

	TP Concentrations (μg/L)			TP Exports (kg/day x 10^{-4})			TP Yields (kg/ha/yr x 10^{-4})		
Extensive Agriculture	Median	Range	CV	Median	Range	CV	Median	Range	CV
Baseflow	5.0	(1.0 - 12.0)	0.60	0.26	(0.47 - 2.0)	0.50	0.02	(0.004 - 0.04)	0.60
Rising Limb	21.0	(2.0 - 35.9)	0.57	1.60	(1.0 - 88.0)	1.84	0.29	(0.06 - 4.2)	1.62
Recession Limb	14.0	(3.0 - 45.0)	0.75	2.10	(1.7 - 110.0)	2.49	0.27	(0.03 - 13.0)	2.53
Intensive Agriculture									
Baseflow	13.0	(1.0 - 23.0)	0.56	0.61	(0.003 - 3.5)	0.63	0.06	(0.06 - 0.37)	0.92
Rising Limb	28.0	(4.0 - 163.0)	1.13	11.0	(0.48 - 7.2)	1.25	1.68	(0.08 - 6.8)	1.01
Recession Limb	15.0	(2.0 - 66.0)	0.84	2.90	(0.24 - 110.0)	1.83	0.91	(0.14 - 11.0)	1.59
Extensive Forestry									
Baseflow	1.5	(1.0 - 5.0)	0.70	0.35	(0.11 - 1.1)	0.77	0.06	(0.02 - 0.17)	0.80
Rising Limb	6.0	(2.0 - 134.0)	2.08	3.10	(0.26 - 61.0)	1.68	0.47	(0.03 - 8.3)	1.47
Recession Limb	4.0	1.07 - 14.0)	0.77	3.70	(0.99 - 6.7)	0.53	0.51	(0.23 - 1.0)	0.49
Intensive Forestry									
Baseflow	5.0	(1.0 - 7.0)	0.35	0.47	(0.13 - 1.4)	0.78	0.08	(0.04 - 0.12)	0.50
Rising Limb	19.0	(2.0 - 38.0)	0.72	12.0	(0.37 - 24.0)	0.84	1.59	(0.05 - 3.9)	0.93
Recession Limb	9.0	(1.0 - 26.0)	0.79	5.00	(0.78 - 48.0)	1.44	0.54	(0.14 - 8.8)	1.63

Table 3-11 Total nitrogen concentration (µg/L), export (kg/day) and yield (kg/ha/yr) at the seven sites along the Crowsnest River across the three hydrologic periods (rising limb, recession limb, baseflow).

	TN Concentrations (µg/L)			TN Exports (kg/day x 10^{-2})			TN Yields (kg/ha/day x 10^{-4})		
	Median	Range	CV	Median	Range	CV	Median	Range	CV
Crowsnest below Lake (CA1)	104.0	(84.0 - 139.0)	0.24	2.10	(0.9 - 5.6)	0.69	9.70	(4.2 - 32.0)	0.69
Crowsnest below Coleman (CA2)	135.0	(105.0 - 214.0)	0.28	4.70	(2.1 - 11.0)	0.62	6.80	(3.1 - 17.0)	0.62
Crowsnest below Blairmore (CA3)	205.0	(144.0 - 261.0)	0.23	7.30	(5.0 - 16.0)	0.48	7.10	(4.9 - 16.0)	0.48
Crowsnest below Frank (CA4)	191.0	(139.0 - 367.0)	0.35	8.40	(4.4 - 21.0)	0.60	6.90	(3.6 - 18.0)	0.60
Crowsnest above Septic (CA5)	189.0	(26.0 - 400.0)	0.52	9.70	(4.0 - 19.0)	0.60	7.80	(1.2 - 16.0)	0.60
Crowsnest below Septic (CA6)	202.0	(116.0 - 280.0)	0.27	8.40	(7.2 - 23.0)	0.52	6.70	(5.1 - 19.0)	0.52
Crowsnest at Lundbreck (CA7)	163.0	(71.0 - 478.0)	0.64	17.7	(3.2 - 29.0)	0.69	9.80	(1.8 - 17.0)	0.69

Table 3-12 Total dissolved nitrogen concentration (µg/L) at the seven sites along the Crowsnest River across the three hydrologic periods (rising limb, recession limb, baseflow).

	TDN Concentrations (µg/L)		
	Median	Range	CV
Crowsnest below Lake (CA1)	91.0	(61.0 - 122.0)	0.20
Crowsnest below Coleman (CA2)	126.0	(71.0 - 210.0)	0.34
Crowsnest below Blairmore (CA3)	194.0	(126.0 - 260.0)	0.22
Crowsnest below Frank (CA4)	173.0	(151.0 - 348.0)	0.31
Crowsnest above Septic (CA5)	163.0	(12.0 - 361.0)	0.54
Crowsnest below Septic (CA6)	169.0	(54.0 - 265.0)	0.36
Crowsnest at Lundbreck (CA7)	143.0	(73.0 - 397.0)	0.59

Table 3-13 Total phosphorus concentration (µg/L), export (kg/day) and yield (kg/ha/yr) at the seven sites along the Crowsnest River across the three hydrologic periods (rising limb, recession limb, baseflow).

	TP Concentrations (µg/L)			TP Exports (kg/day x 10^{-3})			TP Yields (kg/ha/day x 10^{-5})		
	Median	Range	CV	Median	Range	CV	Median	Range	CV
Crowsnest below Lake (CA1)	6.0	(4.0 - 9.0)	0.23	1.20	(0.34 - 3.9)	0.66	5.50	(1.6 - 18.0)	0.67
Crowsnest below Coleman (CA2)	8.3	(6.0 - 37.0)	0.80	3.90	(0.69 - 14.0)	0.89	5.70	(1.0 - 20.0)	0.90
Crowsnest below Blairmore (CA3)	10.4	(5.0 - 43.0)	0.89	7.00	(1.5 - 13.0)	0.66	6.70	(1.5 - 13.0)	0.66
Crowsnest below Frank (CA4)	18.0	(13.0 - 50.0)	0.63	9.70	(3.8 - 13.0)	0.41	8.00	(3.1 - 11.0)	0.41
Crowsnest above Septic (CA5)	14.0	(5.0 - 47.0)	0.73	8.20	(3.0 - 14.0)	0.49	6.60	(2.6 - 12.0)	0.50
Crowsnest below Septic (CA6)	16.0	(8.0 - 47.0)	0.61	9.40	(3.1 - 20.0)	0.50	7.40	(2.4 - 17.0)	0.50
Crowsnest at Lundbreck (CA7)	16.0	(5.0 - 101.0)	1.22	10.1	(1.9 - 33.0)	1.42	5.60	(1.0 - 19.0)	1.43

Table 3-14 Total dissolved phosphorus concentration (µg/L) at the seven sites along the Crowsnest River across the three hydrologic periods (rising limb, recession limb, baseflow).

	TDP Concentrations (µg/L)		
	Median	Range	CV
Crowsnest below Lake (CA1)	1.0	(1.0 - 3.0)	0.47
Crowsnest below Coleman (CA2)	2.0	(1.0 - 4.0)	0.67
Crowsnest below Blairmore (CA3)	1.0	(1.0 - 6.0)	0.97
Crowsnest below Frank (CA4)	7.0	(1.0 - 14.0)	0.66
Crowsnest above Septic (CA5)	3.0	(1.0 - 13.0)	0.83
Crowsnest below Septic (CA6)	3.0	(1.0 - 10.0)	0.68
Crowsnest at Lundbreck (CA7)	2.0	(1.0 - 8.0)	0.80

Table 3-15 Total nitrogen concentration (µg/L), export (kg/day) and yield (kg/ha/yr) during the rising limb of the hydrograph, the recession limb of the hydrograph and baseflow conditions at the seven sites along the Crowsnest River.

	TN Concentrations (µg/L)			TN Exports (kg/day x 0.01)			TN Yields (kg/ha/yr x 0.0001)		
Crowsnest below Lake	Median	Range	CV	Median	Range	CV	Median	Range	CV
Baseflow	88.0	(84.0 - 111.0)	0.15	1.90	(1.6 - 2.1)	0.14	9.00	(7.4 - 9.7)	0.14
Rising Limb	102.0	(95.0 - 162.0)	0.31	1.20	(0.93 - 2.8)	0.63	5.40	(4.4 - 13.0)	0.63
Recession Limb	139.0	(104.0 - 139.0)	0.16	5.60	(4.7 - 6.9)	0.19	2.50	(21.0 - 31.0)	0.19
Crowsnest below Coleman									
Baseflow	114.0	(109.0 - 177.0)	0.28	2.90	(2.7 - 5.0)	0.35	4.30	(3.9 - 7.3)	0.35
Rising Limb	172.0	(135.0 - 213.0)	0.22	4.70	(2.1 - 4.9)	0.40	6.90	(3.0 - 7.2)	0.40
Recession Limb	128.0	(105.0 - 214.0)	0.39	10.0	(4.2 - 12.0)	0.45	15.0	(6.2 - 17.0)	0.45
Crowsnest below Blairmore									
Baseflow	164.0	(144.0 - 205.0)	0.18	5.60	(5.1 - 6.5)	0.12	5.30	(4.9 - 6.2)	0.12
Rising Limb	258.0	(152.0 - 261.0)	0.28	7.30	(5.1 - 7.6)	0.21	7.10	(4.8 - 7.3)	0.21
Recession Limb	210.0	(150.0 - 214.0)	0.19	14.0	(12.0 - 17.0)	0.16	14.0	(11.0 - 16.0)	0.16
Crowsnest below Frank									
Baseflow	170.0	(139.0 - 210.0)	0.21	4.60	(4.4 - 5.0)	0.07	3.80	(3.6 - 4.1)	0.07
Rising Limb	294.0	(191.0 - 367.0)	0.31	10.0	(6.1 - 11.0)	0.28	8.20	(5.4 - 8.9)	0.28
Recession Limb	178.0	(139.0 - 228.0)	0.25	15.0	(8.42 - 22.0)	0.45	12.0	(6.9 - 18.0)	0.45
Crowsnest above Septic									
Baseflow	166.0	(113.0 - 232.0)	0.35	5.80	(4.1 - 11.0)	0.50	4.70	(3.3 - 8.5)	0.50
Rising Limb	279.0	(179.0 - 400.0)	0.39	9.70	(6.8 - 12.0)	0.26	7.80	(5.4 - 9.4)	0.26
Recession Limb	189.0	(26.0 - 221.0)	0.72	16.0	(1.6 - 19.0)	0.77	13.0	(1.3 - 16.0)	0.77
Crowsnest below Septic									
Baseflow	202.0	(128.0 - 209.0)	0.25	8.10	(6.5 - 8.4)	0.14	6.50	(5.1 - 6.7)	0.14
Rising Limb	265.0	(183.0 - 280.0)	0.22	9.70	(7.2 - 11.0)	0.22	7.70	(5.7 - 8.9)	0.22
Recession Limb	182.0	(116.0 - 221.0)	0.31	18.0	(7.9 - 23.0)	0.48	14.0	(6.3 - 19.0)	0.48
Crowsnest at Lundbreck									
Baseflow	108.0	(71.0 - 139.0)	0.32	4.10	(3.2 - 5.4)	0.26	2.20	(1.7 - 3.0)	0.26
Rising Limb	291.0	(169.0 - 478.0)	0.50	19.0	(19.0 - 30.0)	0.26	11.0	(11.0 - 17.0)	0.26
Recession Limb	163.0	(122.0 - 219.0)	0.33	18.0	(6.5 - 28.0	0.61	9.80	(3.6 - 15.0)	0.61

Table 3-16 Total phosphorus concentration (µg/L), export (kg/day) and yield (kg/ha/yr) during the rising limb of the hydrograph, the recession limb of the hydrograph and baseflow conditions at the seven sites along the Crowsnest River.

	TP Concentrations (µg/L)			TP Exports (kg/day x 0.001)			TP Yields (kg/ha/yr x 0.00001)		
Crowsnest below Lake	Median	Range	CV	Median	Range	CV	Median	Range	CV
Baseflow	5.0	(4.0 - 6.0)	0.20	1.1	(0.77 - 1.2)	0.22	4.9	(3.5 - 5.5)	0.22
Rising Limb	7.0	(6.0 - 9.0)	0.21	1.0	(0.35 - 2.1)	0.76	4.7	(1.5 - 9.5)	0.76
Recession Limb	6.0	(5.3 - 6.0)	0.07	2.2	(2.0 - 4.0)	0.40	9.8	(9.2 - 18.0)	0.40
Crowsnest below Coleman									
Baseflow	6.0	(6.0 - 6.0)	0.00	1.6	(1.4 - 1.7)	0.09	2.4	(2.1 - 2.5)	0.09
Rising Limb	25.0	(7.0 - 37.0)	0.66	9.1	(0.69 - 10.0)	0.78	13.0	(1.0 - 14.0)	0.78
Recession Limb	11.0	(8.3 - 15.0)	0.30	4.5	(3.9 - 14.0)	0.75	6.5	(5.7 - 20.0)	0.75
Crowsnest below Blairmore									
Baseflow	5.0	(5.0 - 6.0)	0.11	1.6	(1.6 - 2.3)	0.23	1.5	(1.5 - 2.2)	0.23
Rising Limb	39.0	(20.0 - 43.0)	0.36	9.9	(8.4 - 11.0)	0.13	9.6	(8.1 - 11.0)	0.13
Recession Limb	10.4	(8.0 - 12.0)	0.20	7.0	(4.5 - 13.0)	0.55	6.7	(4.3 - 13.0)	0.55
Crowsnest below Frank									
Baseflow	18.0	(13.0 - 18.0)	0.18	4.7	(3.8 - 4.8)	0.13	3.9	(3.1 - 4.0)	0.13
Rising Limb	44.0	(23.0 - 50.0)	0.36	12.0	(10.0 - 13.0)	0.11	9.8	(8.6 - 11.0)	0.11
Recession Limb	15.0	(8.73 - 16.0)	0.29	9.7	(8.4 - 12.0)	0.19	7.9	(6.8 - 10.0)	0.19
Crowsnest above Septic									
Baseflow	14.0	(9.0 - 14.0)	0.23	4.9	(3.2 - 6.4)	0.33	3.9	(2.6 - 5.2)	0.33
Rising Limb	39.0	(20.0 - 47.0)	0.39	11.0	(10.0 - 11.0)	0.03	9.2	(8.7 - 9.2)	0.03
Recession Limb	11.5	(5.0 - 14.0)	0.46	8.2	(3.0 - 14.0)	0.67	6.6	(2.4 - 12.0)	0.67
Crowsnest below Septic									
Baseflow	14.0	(8.0 - 22.0)	0.48	5.9	(3.1 - 11.0)	0.61	4.7	(2.5 - 8.9)	0.61
Rising Limb	27.0	(23.0 - 47.0)	0.40	13.0	(9.4 - 14.0)	0.20	10.0	(7.4 - 11.0)	0.20
Recession Limb	13.0	(8.9 - 16.0)	0.28	8.9	(7.2 - 21.0)	0.60	7.1	(5.7 - 17.0)	0.60
Crowsnest at Lundbreck									
Baseflow	5.0	(5.0 - 7.0)	0.2	1.9	(1.9 - 3.2)	0.32	1.1	(1.0 - 1.8)	0.32
Rising Limb	29.0	(25.0 - 101.0)	0.83	34.0	(10.0 - 100.0)	0.99	19.0	(5.6 - 57.0)	0.99
Recession Limb	16.0	(10.0 - 22.0)	0.38	20.0	(5.8 - 24.0)	0.57	11.0	(3.2 - 13.0)	0.57

Table 3-17 Number and proportion of samples that exceeded the Canadian Council of Ministers of the Environment (CCME) and the National Agri-Environmental Standards Initiative (NAESI) guidelines for total nitrogen and total phosphorus concentration (µg/L) in the agricultural (extensive and intensive), forested (extensive and intensive) and urban catchments.

	# and Proportion of N Exceedances		# and Proportion P Exceedances	
Land use Class	CCME Guidelines (1000µg/L)	NAESI Guidelines (940 µg/L)	CCME Guidelines (10ug/L)	NAESI Guidelines (87ug/L)
Extensive Agricultural	1 (3%)	1 (3%)	6 (19%)	2 (6%)
Intensive Agricultural	2 (5%)	2 (5%)	12 (30%)	5 (13%)
Extensive Forested	0	0	3 (10%)	1 (3%)
Intensive Forested	0	0	5 (16%)	1 (3%)
Urban (all sites)	0	1 (1%)	15 (21%)	7 (10%)

Figure 3-1 Map of the study area showing streamflow gauging stations, and research watersheds (Agricultural: from north to south – Cow creek, Beaver Mines Creek, and Gladstone Creek; Forested: from north to south – Pasque Creek, Cache Creek, Allison Creek, McGilvray Creek, Whitney Creek and Syncline Creek; Urban – from west to east - Crowsnest below lake (CA1), Crowsnest below Coleman (CA2), Crowsnest below Blairmore (CA3), Crowsnest below Frank (CA4), Crowsnest above Septic Fields (CA5), Crowsnest below Septic Fields (CA6) and Crowsnest at Lundbreck (CA7)).

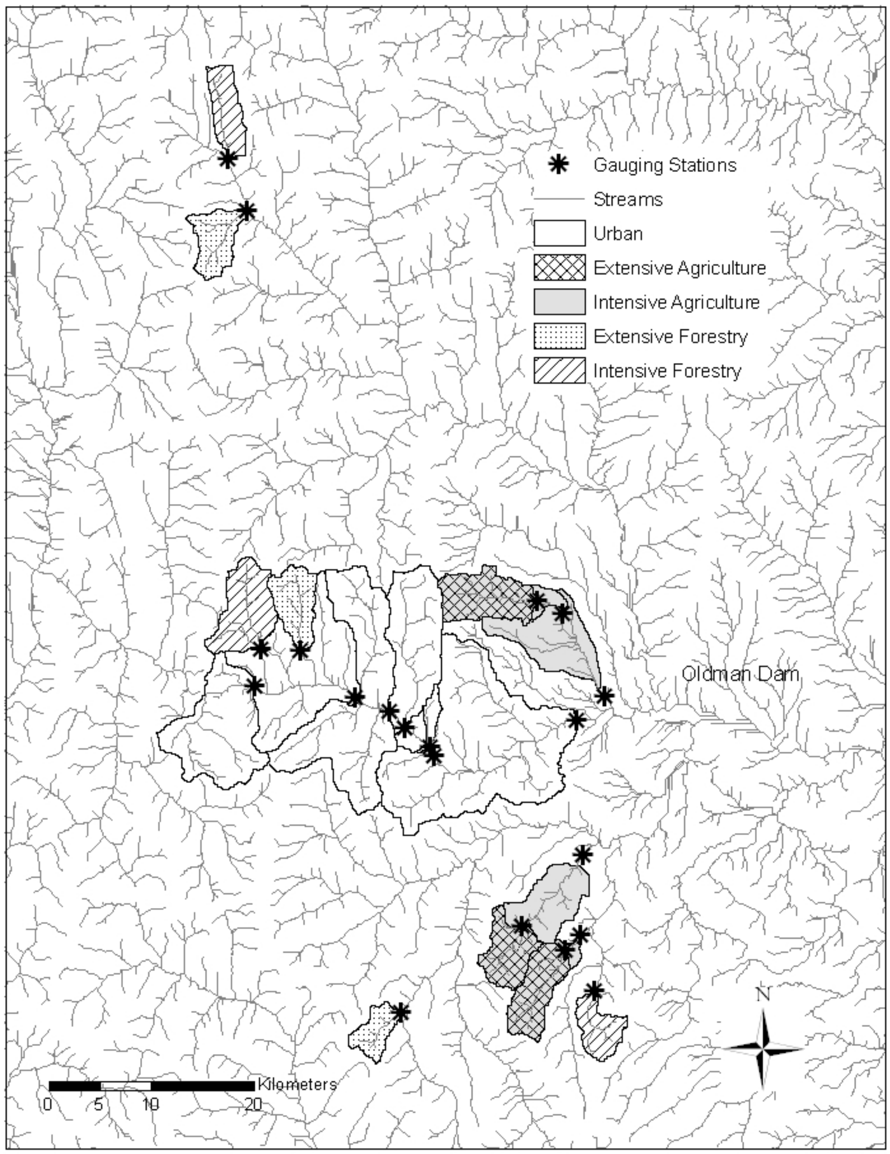


Figure 3-2 Total nitrogen concentration (µg/L), export (kg/day) and yield (kg/ha/yr) in the agricultural (extensive and intensive) and forested (extensive and intensive) catchments. The box-plots indicate the range of values (5th and 95th percentile), the arithmetic mean (dotted line), the median (solid line), and the outer limits of the boxes are the 25th and 75th percentiles.

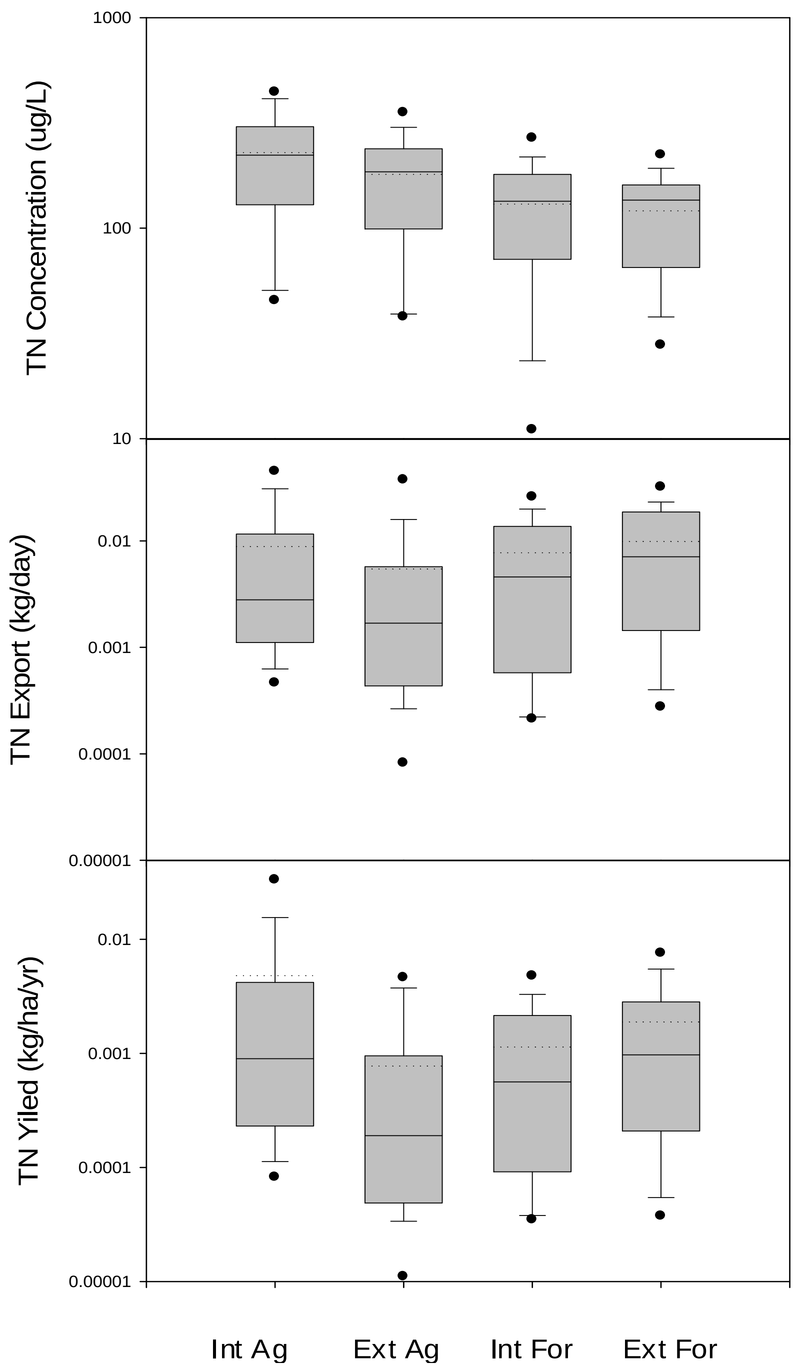


Figure 3-3 Total dissolved nitrogen concentration (µg/L) in the agricultural (extensive and intensive) and forested (extensive and intensive) catchments.

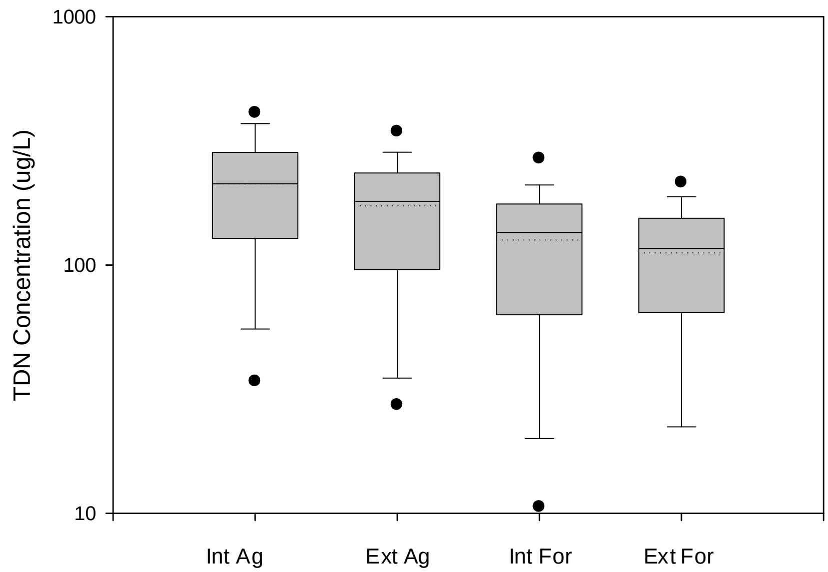


Figure 3-4 Proportion of total nitrogen in the dissolved form in the agricultural (extensive and intensive) and forestry (extensive and intensive) catchments.

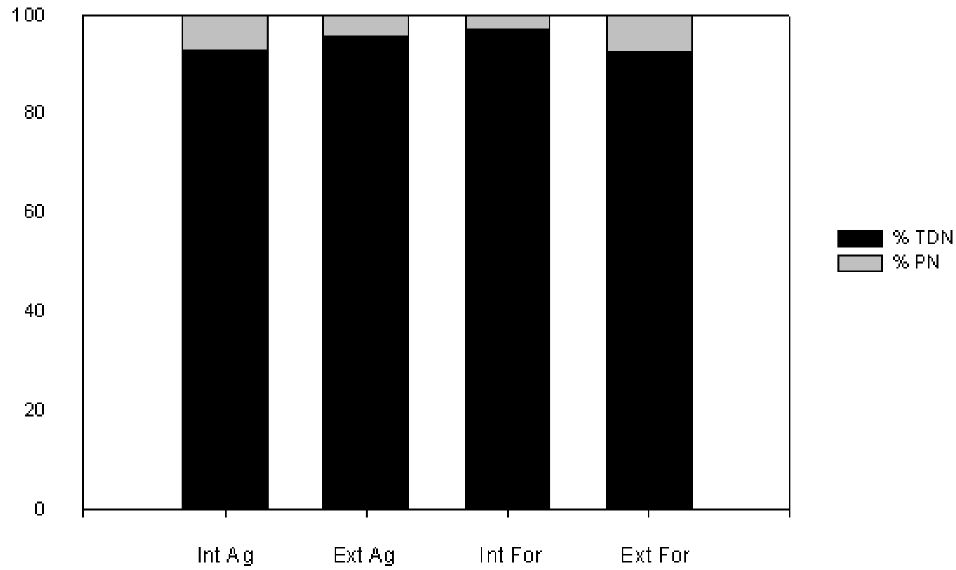


Figure 3-5 Total phosphorus concentration (μg/L), export (kg/day) and yield (kg/ha/yr) in the agricultural (extensive and intensive) and forested (extensive and intensive) catchments.

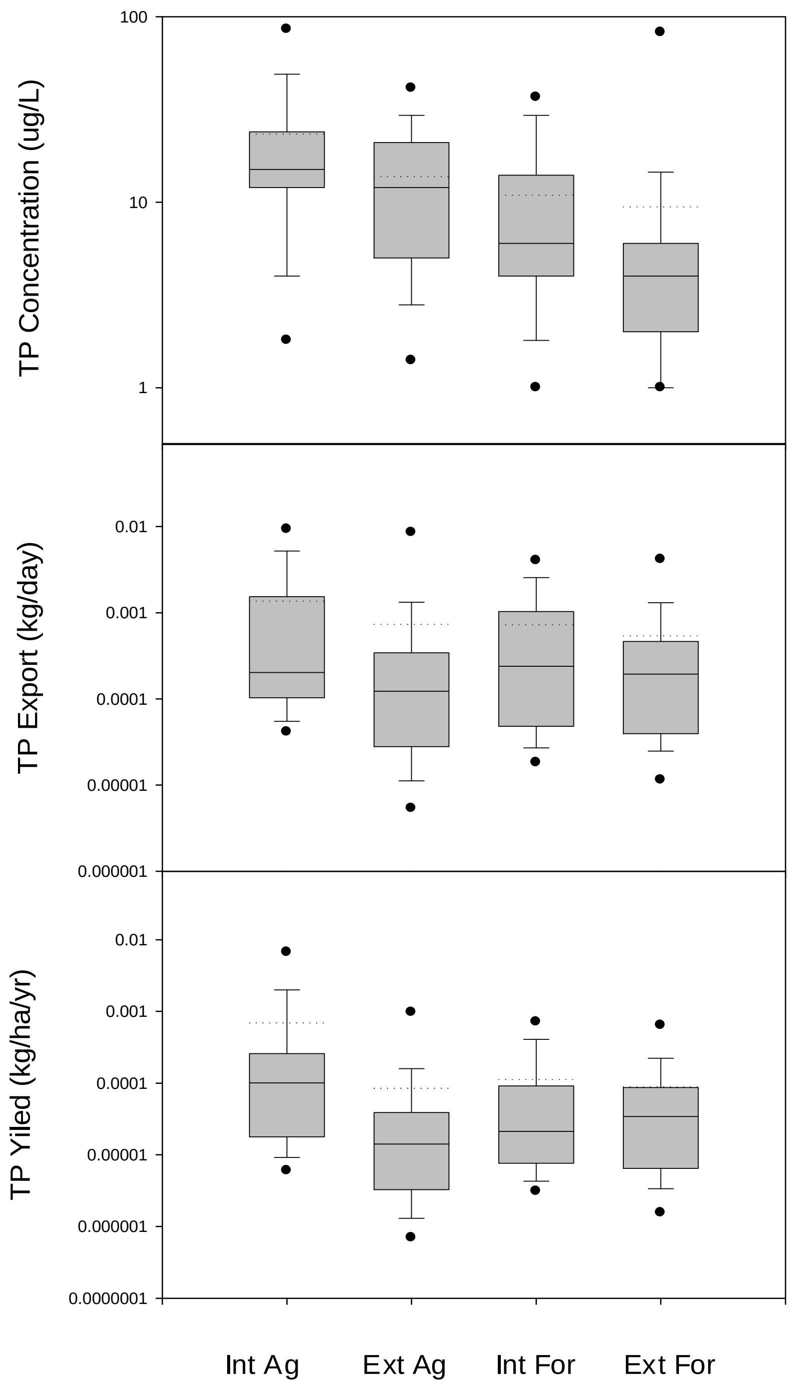


Figure 3-6 Total dissolved phosphorus concentration (µg/L) in the agricultural (extensive and intensive) and forested (extensive and intensive) catchments.

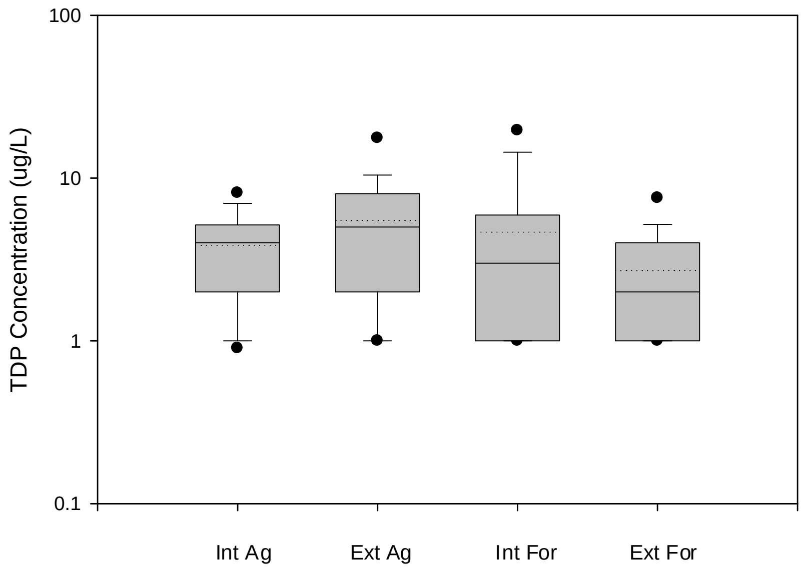


Figure 3-7 Proportion of total phosphorus in the dissolved form in the agricultural (extensive and intensive) and forested (extensive and intensive) catchments.

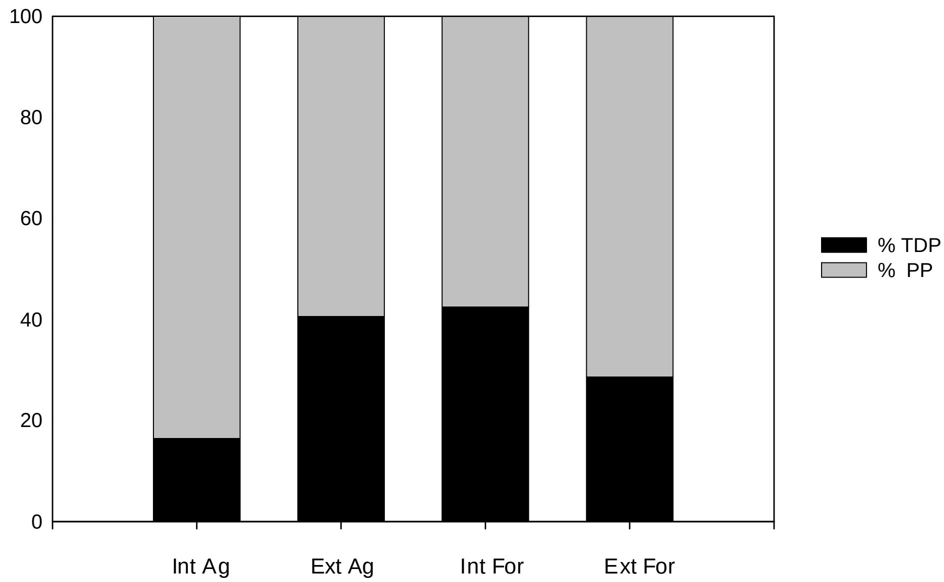


Figure 3-8 Total nitrogen concentration (µg/L), export (kg/day), and yield (kg//ha/yr) in the extensive and intensive agricultural catchments by hydrologic flow period (rising limb of hydrograph, recession limb of hydrograph and baseflow).

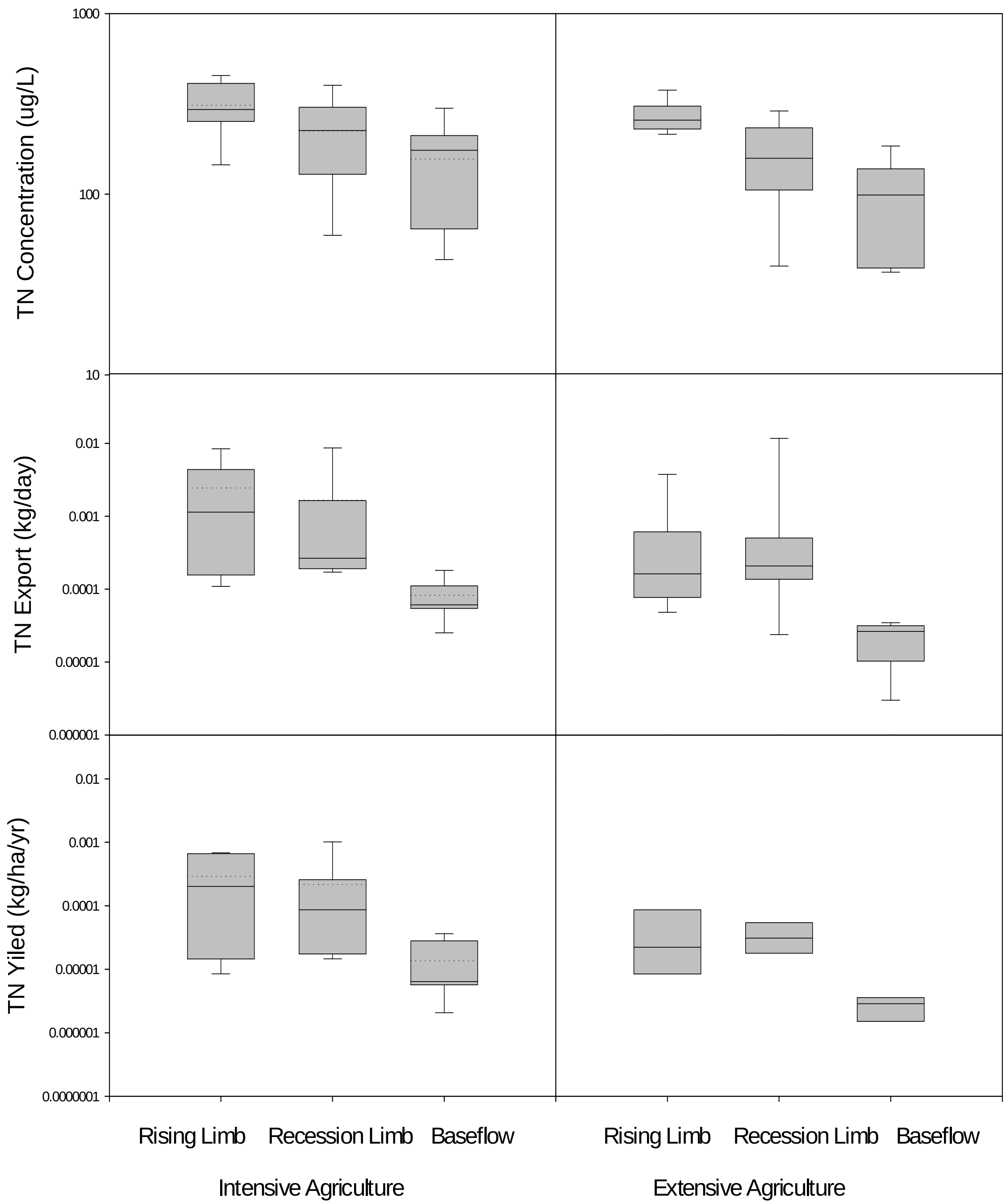


Figure 3-9 Total phosphorus concentration (µg/L), export (kg/day), and yield (kg//ha/yr) in the extensive and intensive agricultural catchments by hydrologic flow period (rising limb of hydrograph, recession limb of hydrograph and baseflow).

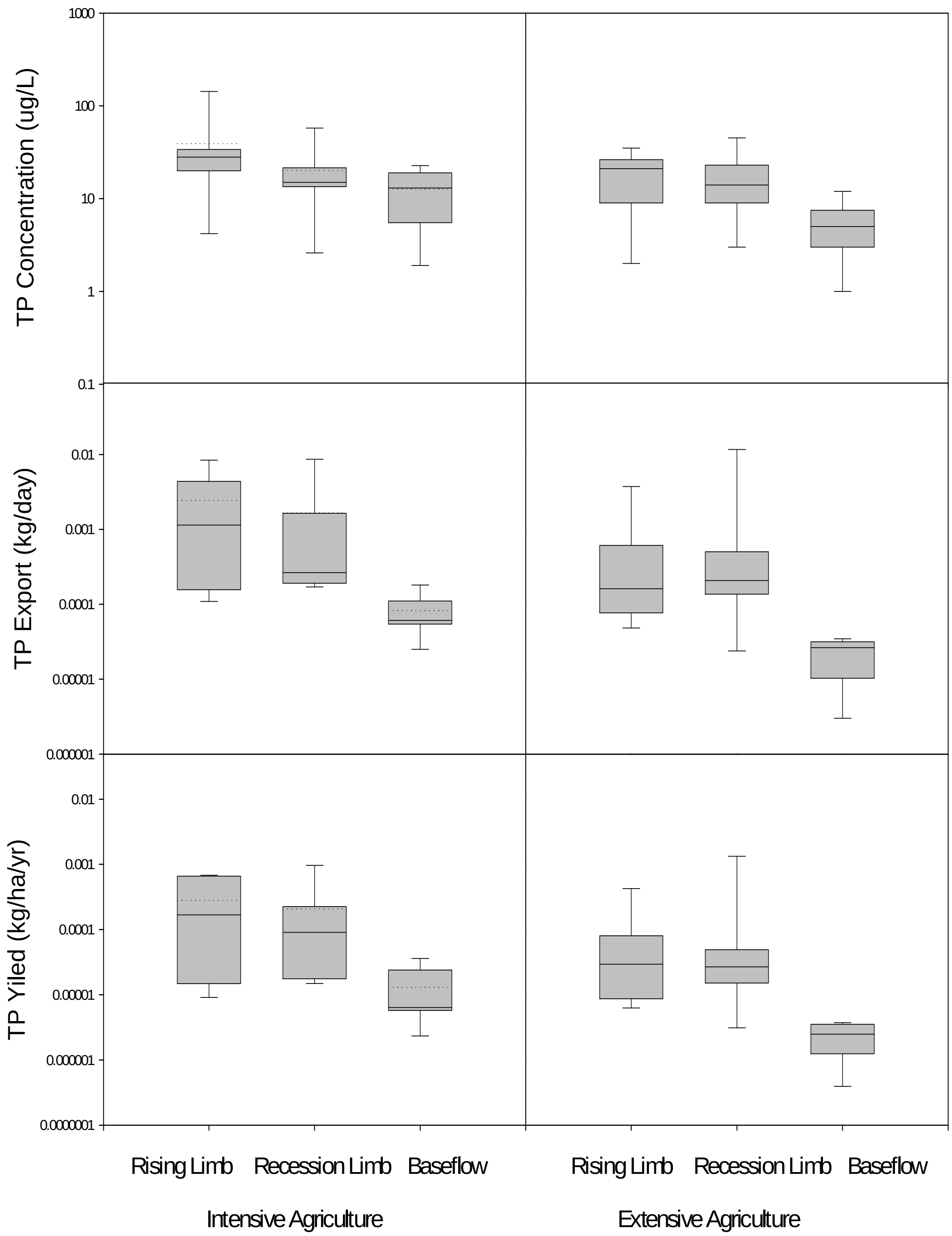


Figure 3-10 Total nitrogen concentration (µg/L), export (kg/day), and yield (kg//ha/yr) in the extensive and intensive forested catchments by hydrologic flow period (rising limb of hydrograph, recession limb of hydrograph and baseflow).

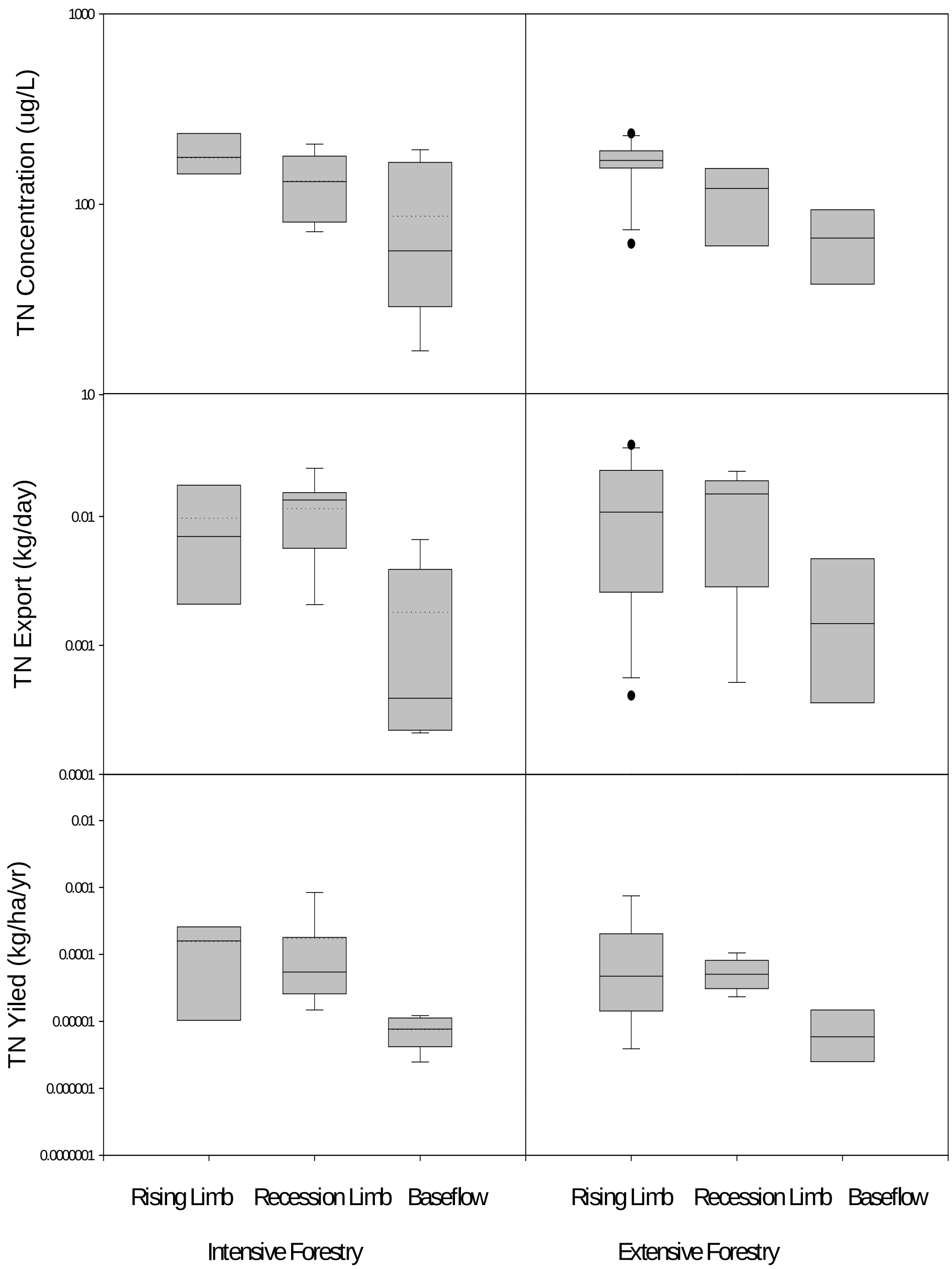


Figure 3-11 Total phosphorus concentration (µg/L), export (kg/day), and yield (kg//ha/yr) in the extensive and intensive forested catchments by hydrologic flow period (rising limb of hydrograph, recession limb of hydrograph and baseflow).

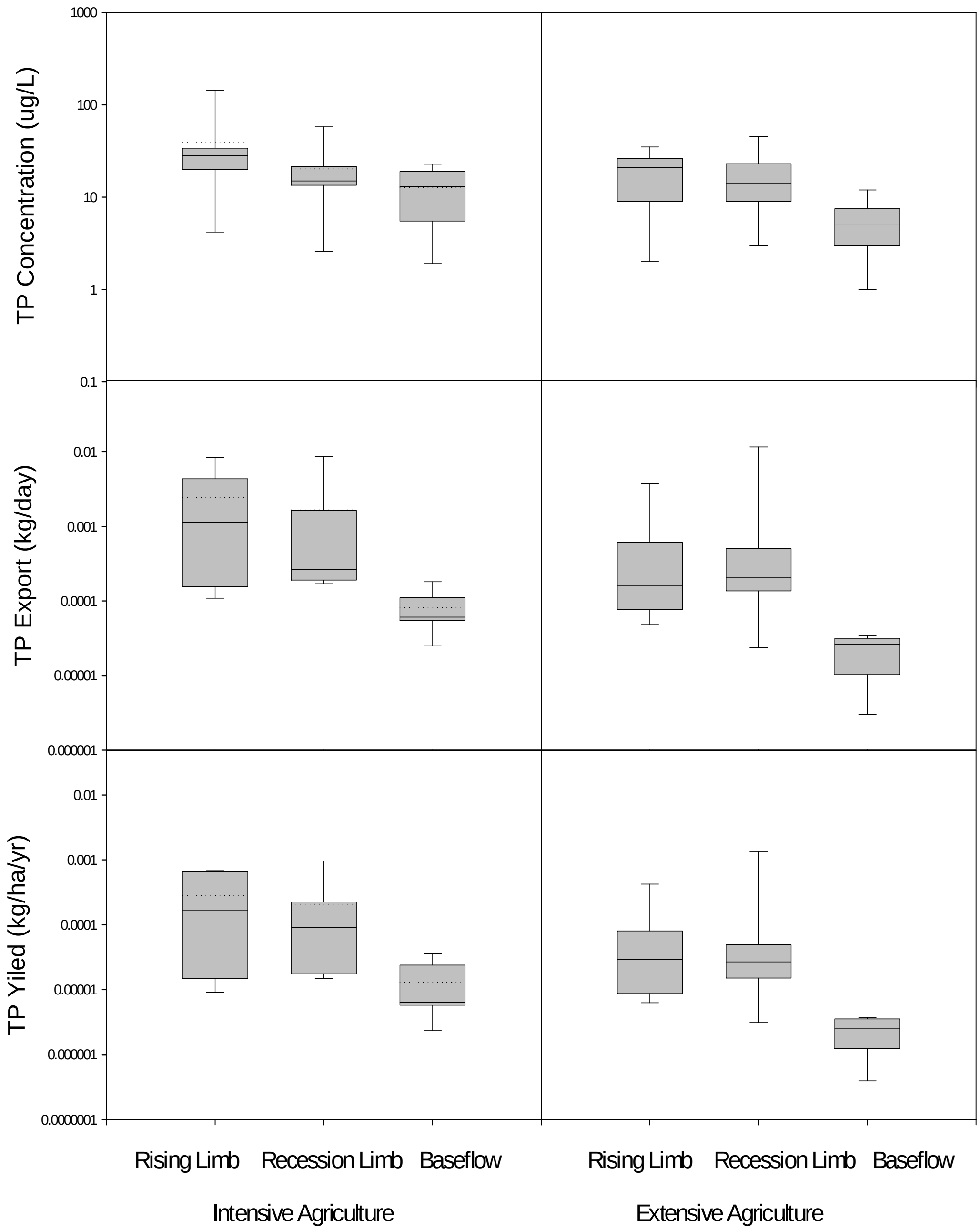


Figure 3-12 Total nitrogen concentration (µg/L), export (kg/day), and yield (kg/ha/yr) at the seven sites along the Crowsnest River.

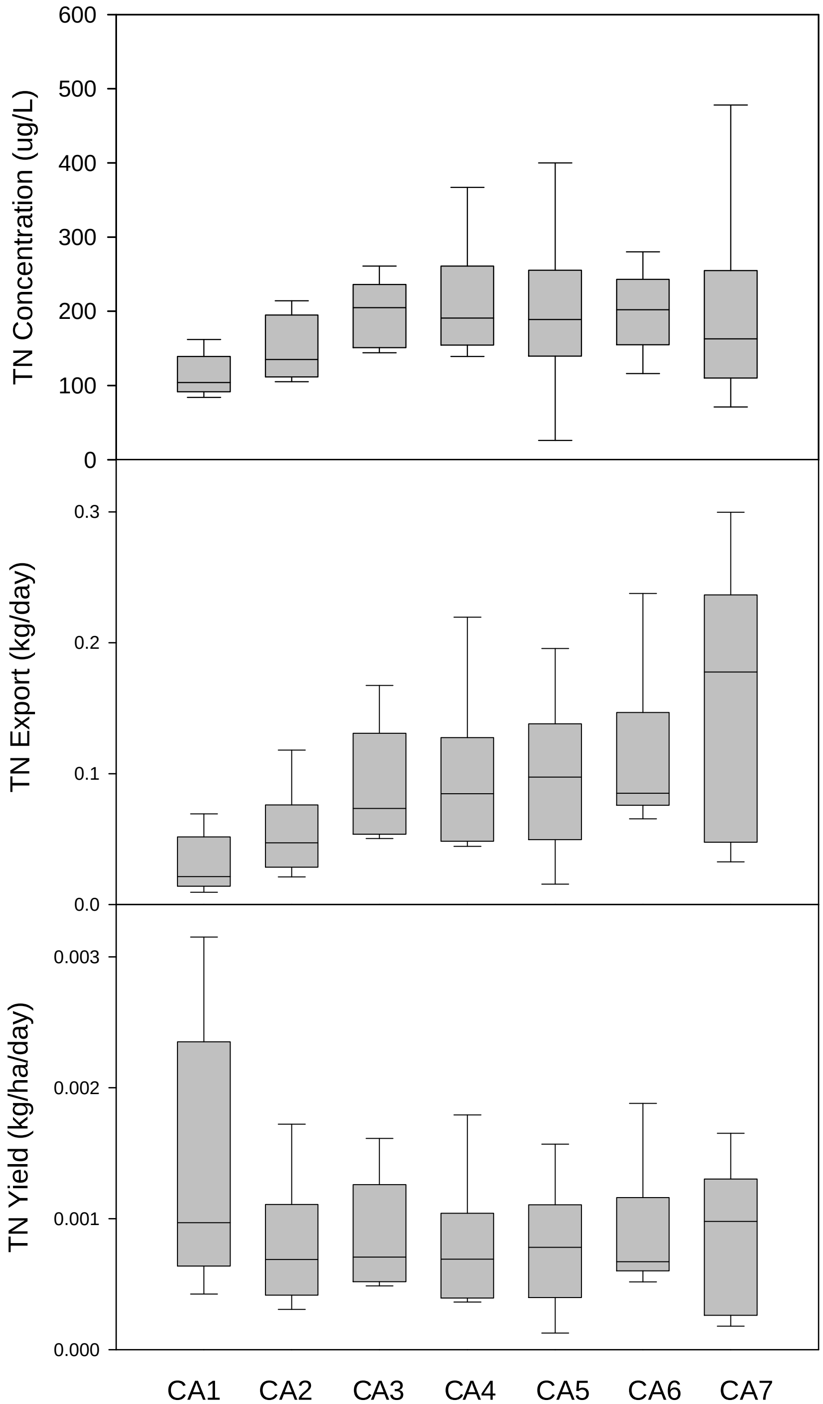


Figure 3-13 Total dissolved nitrogen concentration (µg/L) at the seven sites along the Crowsnest River.

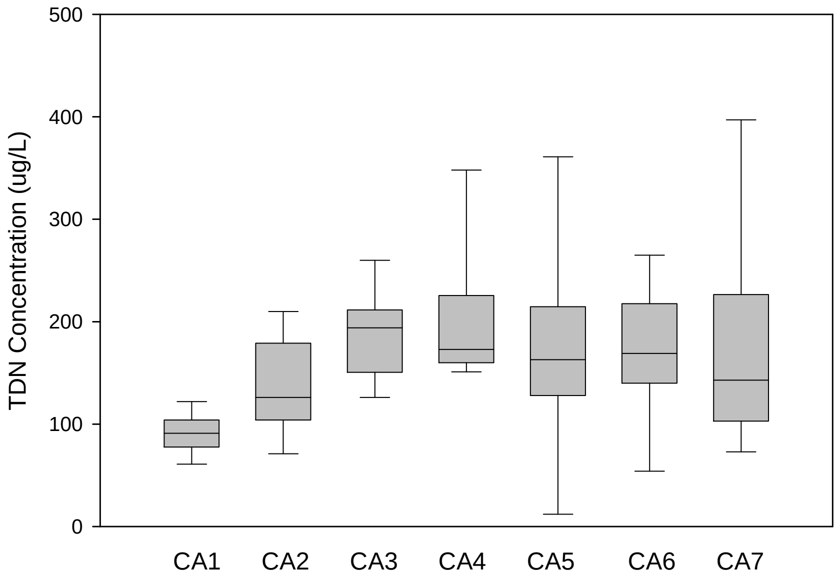


Figure 3-14 Proportion of total nitrogen in the dissolved form at the seven sites along the Crowsnest River.

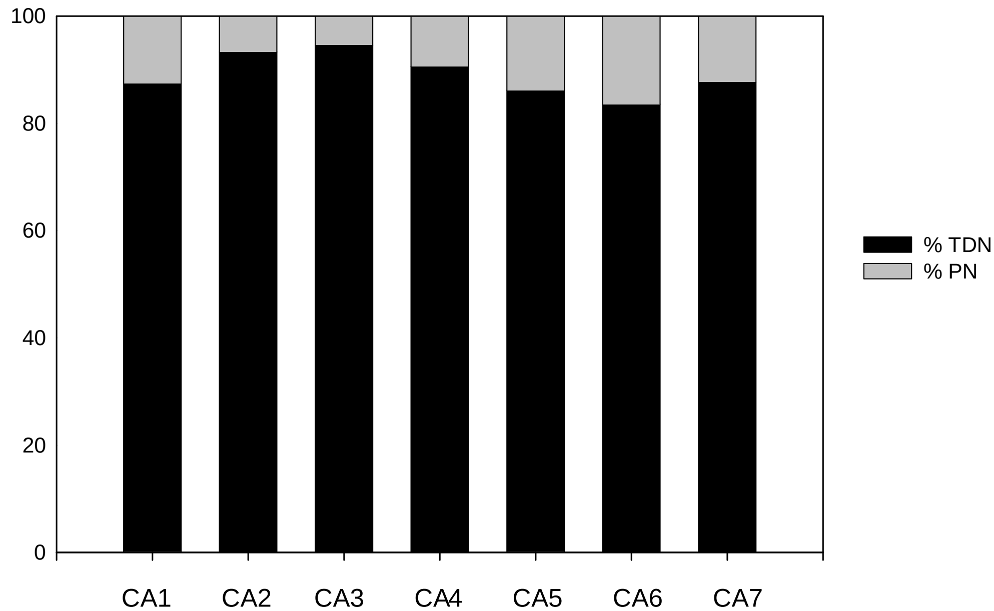


Figure 3-15 Total phosphorus concentration (µg/L), export (kg/day), and yield (kg/ha/yr) at the seven sites along the Crowsnest River.

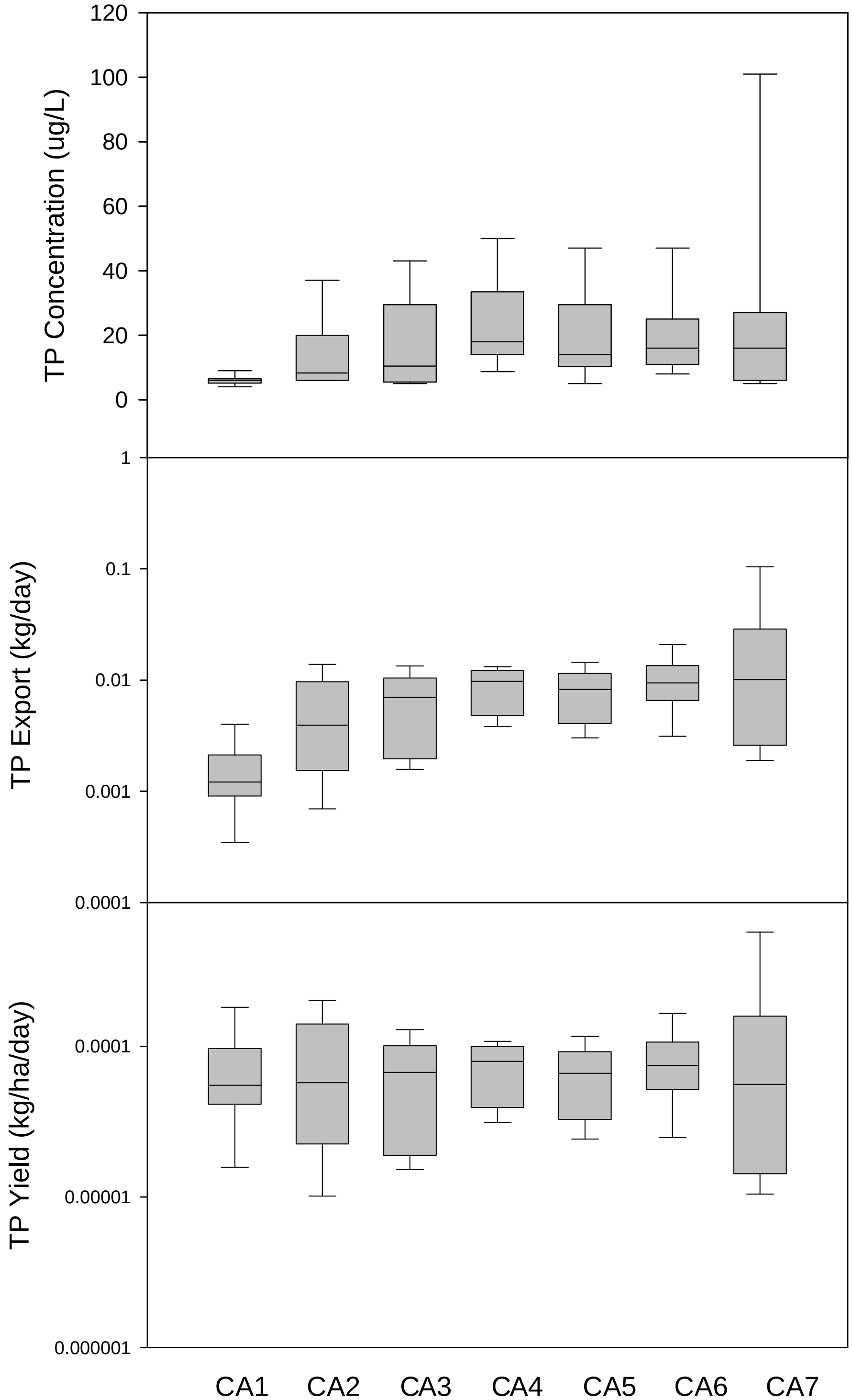


Figure 3-16 Total dissolved phosphorus concentration (µg/L) at the seven sites along the Crowsnest River.

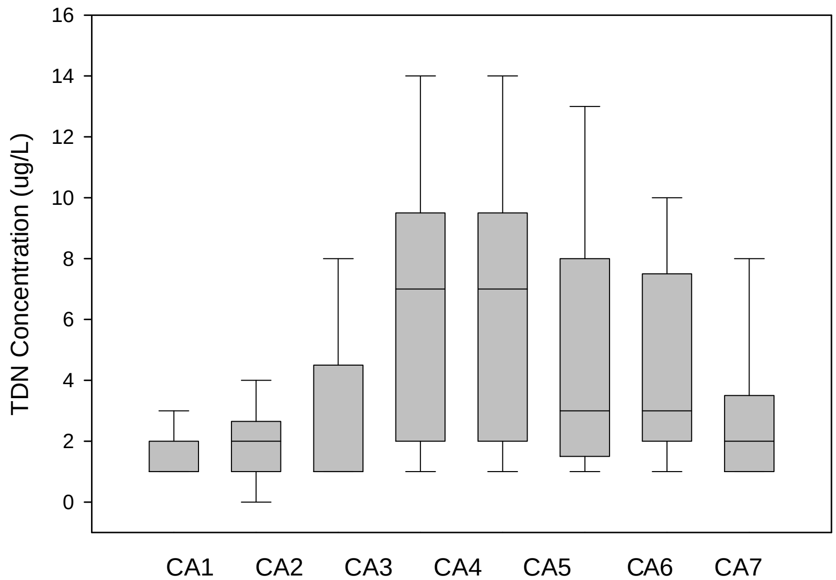


Figure 3-17 Proportion of total phosphorus in the dissolved form at the seven sites along the Crowsnest River.

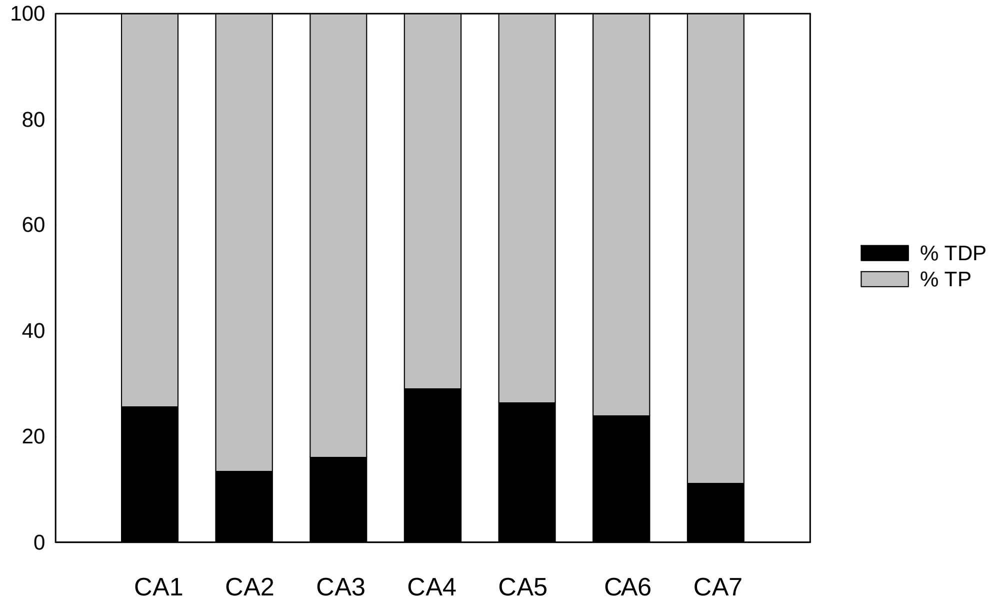


Figure 3-18 Total nitrogen concentration (µg/L), export (kg/day), and yield (kg//ha/yr) at the seven sites along the Crowsnest River by hydrologic flow period (rising limb of hydrograph, recession limb of hydrograph and baseflow).

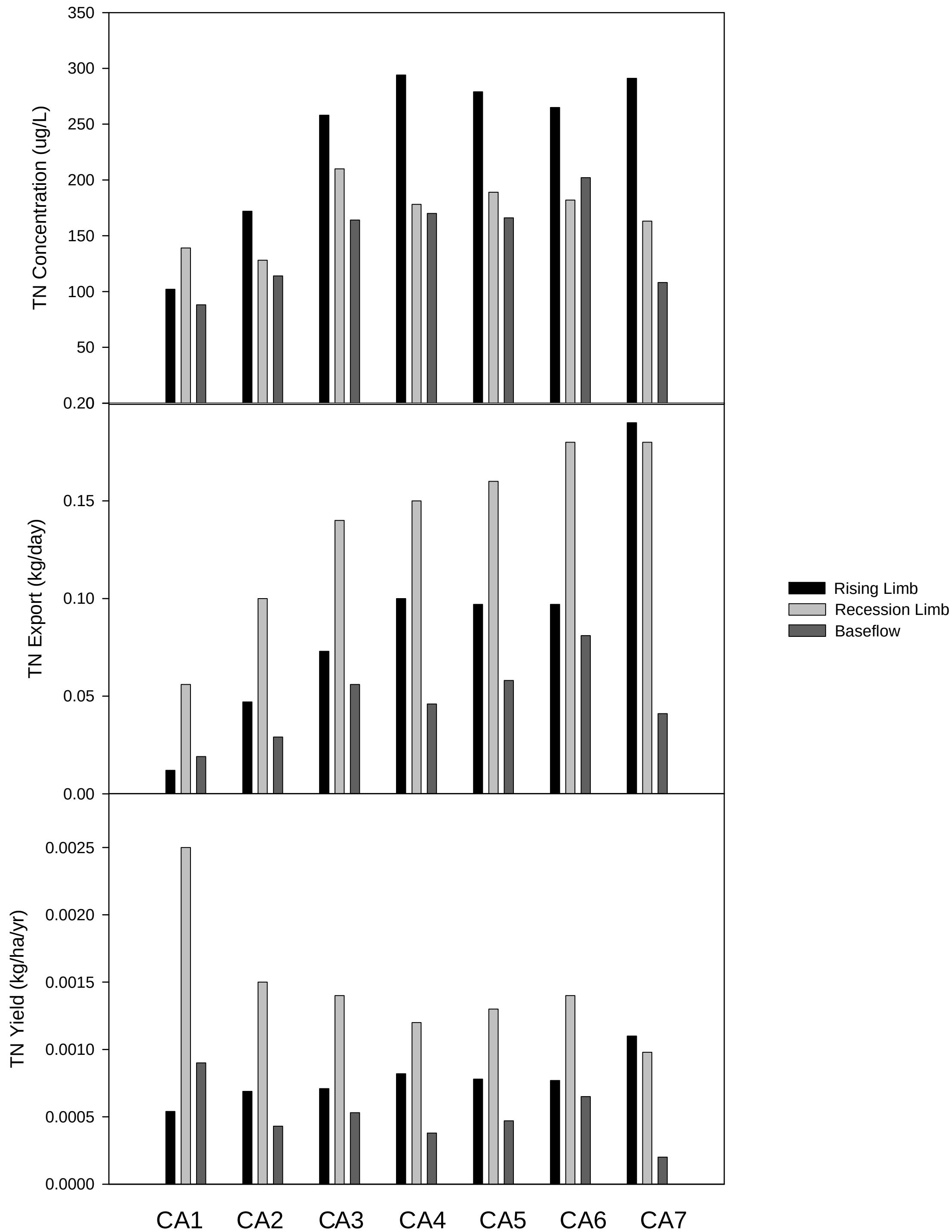
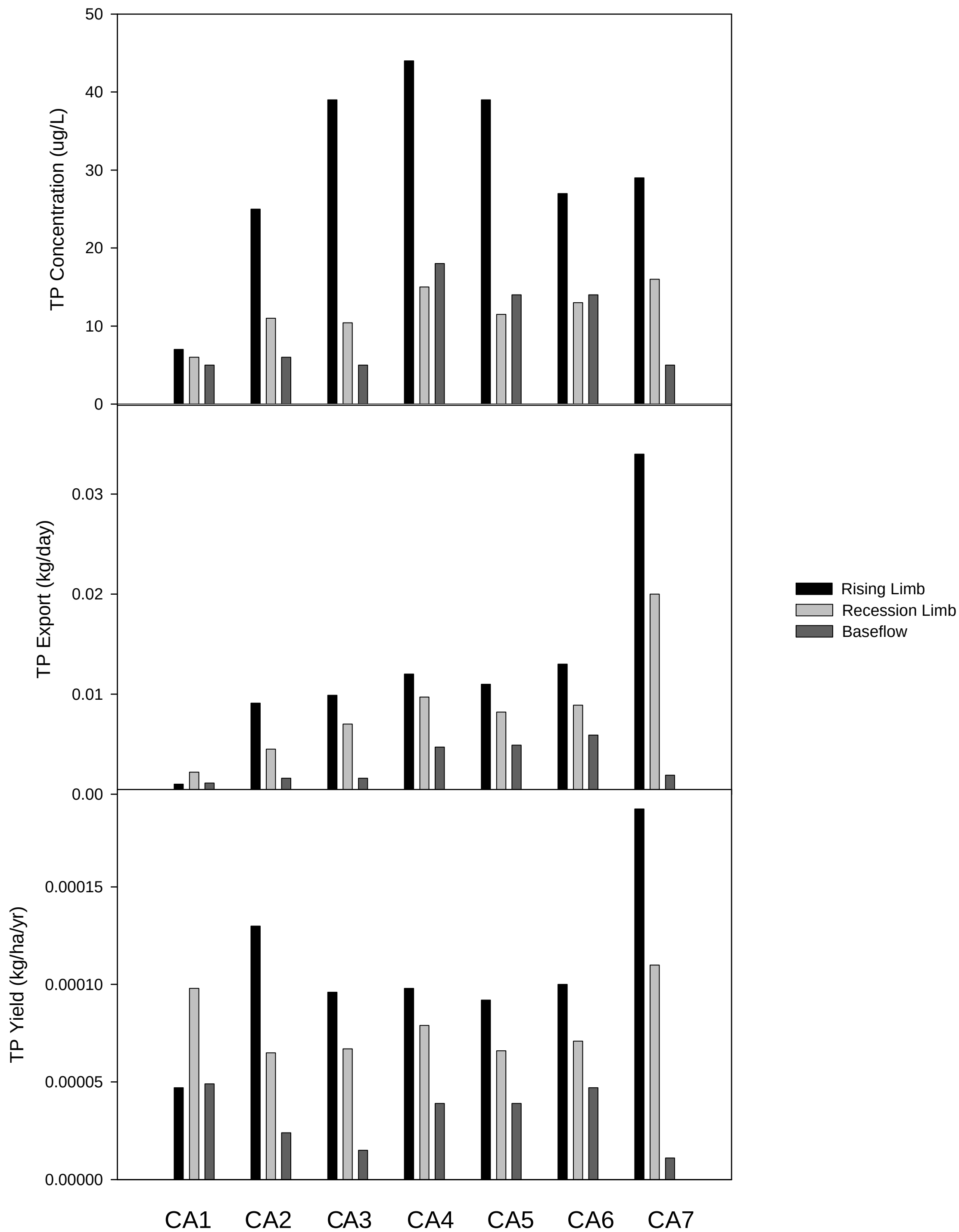


Figure 3-19 Total phosphorus concentration (µg/L), export (kg/day), and yield (kg//ha/yr) at the seven sites along the Crowsnest River by hydrologic flow period (rising limb of hydrograph, recession limb of hydrograph and baseflow).



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Chapter 4 Synthesis

The overall objective of this research was to examine the spatial and temporal patterns in water quality within the three headwater sub-basins (Oldman, Castle and Crowsnest) of the Oldman River Basin to examine the relationships between land use and water quality. The first study (Chapter 2) broadly characterised the spatial and temporal patterns in water quality (total phosphorus and total nitrogen concentration, export and yield) across a land use disturbance gradient (forest, agriculture, urban) to elucidate pressures on water quality from specific regions within the three headwater sub-basins. The results from chapter 2 clearly illustrate that important spatial differences in nutrient production were evident between the upstream (predominantly forested) and the downstream (mixed agricultural/forested) reaches in the Oldman and the Castle sub-basins. Conversely, a distinct pattern was not observed in the Crowsnest sub-basin largely because a clear transition between a forested and an agricultural landscape is not present. Although no changes in total phosphorus and total nitrogen concentrations were observed between the upper and the lower reaches in all three headwater sub-basins, a linearly increasing trend in exports and a distinct jump in differential nutrient yields strongly support the inference that the lower reaches of these rivers are supplying the bulk of the nutrients to the Oldman Reservoir.

The distinct jump in nutrient production between the upper and the lower reaches of the Oldman and the Castle sub-basin reflects the change from a predominantly forested landscape to a mixed agricultural/forested landscape. This pattern is consistent with what others have found when examining the impacts of non-point source land use practices on water quality (Omernik, 1976; Osborne and Wiley, 1988; Carpenter *et al.*, 1998); however, absolute nutrient concentrations and export observed in this study were much lower than those observed in different regions of North America. These results confirm that water quality in the headwaters of the Oldman R. Basin remains fairly pristine.

Results from chapter 2 also support the idea that water quality assessments that consider only contaminant concentration may not provide a robust description of non-point source pollution. In my study, key information would have been missed had I relied solely on concentration data to describe the patterns in water quality. By including nutrient export and differential yield into the analysis, I was able to locate “hot spots” on the landscape that supply the largest amount of nutrients to the river system. These results support policy decisions proposed by the U.S. Environmental Protection Agency to develop and implement total maximum daily loads (TMDLs) to assess and control non-point source contamination. In Canada, the TMDL approach has not yet been adopted (Elshorbagy et al. 2005); however, Elshorbagy *et al.*, (2005) found that similar management strategies for the improvement of impaired water bodies are being devised. While it is recognized that the implementation of TMDLs requires considerable information regarding the physiographic and land use characteristics of an area, results from chapter 2 highlight the importance of developing nutrient loading guidelines to mitigate the impacts of non-point source pollutants on water quality.

In the second study (Chapter 3) the first objective was to evaluate the relationships between stream water quality (total nitrogen and total phosphorus) and land use classes (agricultural {extensive and intensive} and forestry {extensive and intensive}) in the headwaters (Oldman, Castle and Crowsnest) of the Oldman River Basin. Results indicated considerable variability in nutrient concentration (total nitrogen, total dissolved nitrogen, total phosphorus and total dissolved phosphorus) and production between the agricultural and the forested catchments. These relationships are also consistent with what others have found when examining the differences in nutrient production between agricultural and forested landscapes (Beaulac and Reckhow, 1982; Carpenter *et al*., 1998; Coulter *et al.*, 2004). While TP and TN concentration differences were expected between the intensive and extensive agricultural and forested catchments, it was interesting to note that exports and yields (TP and TN) were generally similar among all four landscape categories. These results suggest that these four landscapes are likely supplying similar amounts of nutrients to the receiving waters. Thus, management strategies designed to reduce the risk of eutrophication in the Oldman Reservoir should focus on all of these landscapes. These results also support the findings from chapter 2 that support the idea that nutrient exports and yields be included when designing management strategies to assess non-point source pollution.

A second objective in chapter 3 was to evaluate the changes in water quality (TN and TP) along an urban disturbance gradient situated longitudinally down the Crowsnest River. Median total nitrogen concentration increased until Crowsnest at Blairmore (CA3) and then generally levelled off while a generally increasing trend in total phosphorus concentration was observed until the Crowsnest at Frank (CA4). These two locations along the River reflect the inputs from the largest community within the Crowsnest Pass and the point source inputs from the waste water treatment facility in Frank.

A further objective was to use the pressure state response model as a framework to evaluate the number of times water quality samples exceeded CCME and NAESI guidelines for total phosphorus and total nitrogen. Results indicate that total nitrogen exceedances (both CCME and NEASI guidelines) were very infrequent in all of the land use classes with most of the exceedances occurring during storm events. These results suggest that nitrogen contamination may not presently represent a major threat in the headwaters of the Oldman River Basin. Conversely, CCME total phosphorus drinking water quality guidelines were exceeded on average 25 % of the time in the agricultural catchments, 13 % of the time in the forested catchments and 20 % of the time in the urban catchments, while NAESI guidelines were exceeded on average 10%, 3% and 10% of the time in the agricultural, forested and urban catchments, respectively. These results highlight the fact that phosphorus contamination may be an issue in the headwaters of the Oldman River basin. By crossing a clearly defined threshold value (CCME and NAESI guidelines), the PSR framework proposes that a relationship has been established between pressure (land use) and state (water quality). Having identified the agricultural and the urban areas as the primary landscapes influencing water quality, actions to mitigate future environmental degradation can now be implemented.

The guidelines used as threshold values for the PSR model were nutrient concentration values. This research, suggests that nutrient loading guidelines may serve as more valuable thresholds for use in PSR based approaches to address non-point source pollution. Had these guidelines been available at the time of this research, they would have been used in the present analysis.

Future Research

While this research was the first to broadly characterise the water quality in the headwaters of the Oldman River Basin, it also generated more questions surrounding the relationships between the physiographic and land use characteristics and water quality in the headwaters and the overall management of non-point source pollution in a Canadian context. While the future research questions are presented in the context of the Oldman Basin, these questions are applicable across many regions in Canada.

1. Evaluation of relationship between physiographic and land use characteristics and water quality in the headwaters of the Oldman River Basin. Because the objective of this work was to broadly characterise the water quality within the headwaters of the Oldman Basin, the inferences based on these results are somewhat limited. Future research should include more spatial and temporal resolution. This will require an increase in sampling frequency. This information is essential for a more complete understanding of factors effecting water quality in the headwaters of the Oldman Basin.

2. Evaluate the eutrophication risk in the Oldman Reservoir.

Future research in the headwaters of the Oldman River Basin should address the risk of eutrophication in the Oldman Reservoir. The results from this thesis suggest that phosphorus may be a contaminant of concern in the headwaters. As eutrophication is caused by the excessive inputs of nitrogen or phosphorus to surface waters (Carpenter *et al.*, 1998), future studies should monitor the Oldman Reservoir for signs of eutrophication.

3. Development of nutrient loading guidelines for water bodies in Canada. Future research should focus on developing nutrient loading guidelines for water bodies in Canada. Research should focus on modelling frameworks to help develop TMDLs for different water bodies and technical and practical strategies to implement these guidelines at the provincial and the federal level. While one of the major barriers to the development and implementation of these guidelines is the availability of discharge data, results from this thesis confirm the additional inferences made possible by integrating contaminant concentrations with river discharge information justify the higher level of effort and cost.

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