Livestock on Waterways

A Literature Review

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Introduction

Alberta's rangelands are a diverse landscape containing a mosaic of forests, shrublands, and grasslands which support complex plant communities and a diversity of wildlife (ACIMS [Alberta Conservation Information Management System], formerly ANHIC). Alberta's rangelands support many important ecological goods and services, including valuable water resources, which originate at the headwaters where high-elevation streams are born from meltwater and eventually become large prairie river systems as they cross east over the foothills and prairies.

Since the early 1900s, people have recognized water as a limited resource. They have highlighted the importance of water, both environmentally and economically, through processes such as the formation of the Rocky Mountains Forest Reserves in 1910:

> There has also been set apart by order in council a reservation of the eastern slope of the Rocky Mountains in the province of Alberta, comprising an area of approximately 3,000,000 acres. This reservation is one of the most important in the whole of the western provinces, as it is a timbered area lying alongside of a prairie country hundreds of miles in extent which is almost devoid of trees, and, moreover, it forms the watershed for the river systems which water the great plains to the east where the water supply is practically the only limit to the development that may be attained. (Annual Report of the Department of the Interior for the fiscal year ending March 31, 1910. Printed by order of parliament Ottawa 1910).

The importance of this landscape as the source for water resources in the prairies has been repeatedly recognized in Alberta's historical land use policy development, through the creation of The Eastern Rockies Forest Conservation Board (1948), and the Policy for Resource Management of the Eastern Slopes (1977; revised in 1984).

Most recently, through the Water for Life Strategy (2007) and the Land-Use Framework (2008), Albertans have reiterated the importance of water. Initiatives such as Water for Life have begun to quantify water as a limited resource, and highlight the importance of water both environmentally and economically.

Water for Life's action plan identifies three main goals:

- safe and secure drinking water
- healthy aquatic ecosystems
- reliable water supplies for a sustainable economy.

The Land-Use Framework is a provincial land use policy that guides the development of seven regional plans, whose goals are to balance economic development with the environmental and social values of Albertans. The South Saskatchewan Regional Plan contains much of the Eastern Slopes, and during public discussion throughout this region, water was consistently listed as a top concern. Other concerns included establishing parameters for water quality and quantity, as well as an aim for the highest and best uses for this limited resource. Clearly, water quality and quantity are of great interest to Albertans, with close attention being given to the Eastern Slopes as the headwaters region.

Livestock grazing is one of many overlapping land uses throughout the province. In general, grazing occurring throughout Alberta's public lands is considered extensive as opposed to intensive, where livestock are contained in very large distribution units or fields at low densities. Livestock management focuses on even distribution of animals to promote a more uniform utilization of forage resources.

Alberta Environment and Parks (AEP) administers public land grazing dispositions, and monitors and records grazing practices to ensure that they are ecologically sustainable and meet legislative and regulatory requirements. Specific to the waterways, riparian health has become a key tool for monitoring the ecological health and function of riparian areas. AEP has adopted and incorporated the monitoring processes created by the Alberta Riparian Habitat Management Society (Cows and Fish) into their grazing disposition management strategy. The primary goal is to ensure that riparian areas maintain key ecological functions. These functions include:

- trapping and storing sediments
- building banks and shores
- storing water and energy
- recharging aquifers
- filtering and buffering water
- reducing flood energy
- maintaining biodiversity
- creating primary productivity

By definition, extensive grazing management is characterized by low livestock densities, though preferential selection by cattle does occur in easily accessible areas that provide highly palatable forage and water resources. Riparian areas provide such features and livestock will tend to congregate in them.

Under the extensive grazing systems implemented on public lands there is often unrestricted access to riparian areas, streams and springs within pastures. This access may result in possible contamination of water sources directly (i.e., during a drinking event), or indirectly from upland areas, (i.e., transportation of contaminants via runoff or seepage). This leads to the question of how much waterway contamination is attributable to cattle in extensive grazing situations, as even in areas with good riparian health it is expected that some fecal material may directly or indirectly make its way into water sources.

There is abundant published research on livestock and water quality, but the majority is focused on intensive agriculture situations. This literature review focuses on the potential impacts of extensive grazing on water quality, and explores commonalities and differences between other agricultural and land use practices.

This document is organised into four sections for the sake of clarity:

- **Section 1** contains a brief examination of the management and behavioural factors influencing the location of manure deposition, and the physical processes involved in the transport of fecal material.
- **Section 2** examines literature pertaining to the contamination of surface water with fecal micro-organisms.
- **Section 3** examines water contamination with fecal nutrients.
- **Section 4** contains a discussion of the risk that extensive grazing activities occurring public lands in Southern Alberta are expected to pose to surface water quality.

Section 1: Location of Manure Deposition and Transport Mechanisms

1.1 Contamination Risk by Hydrologic Position

The term "water quality" refers to the concentration of contaminants — including sediment, micro-organisms, and nutrients — as measured by standardized water sampling methods at a point or points along the length of a watercourse. By this definition, whether they are microbial, nutrient or sediment, for livestock-derived contaminants to be identified as a surface water contaminant, the following must have occurred:

1. Fecal contaminants must be transported from the upland area, through the riparian zone, to the stream.
2. Fecal contaminants must then be carried downstream to the sampling point.

The primary mechanisms that lead to contamination include hydrologic position of contaminants, and transport processes.

Hydrologic connectivity is dependent on runoff generated by an area, and the likelihood that runoff will reach a watercourse. The amount of runoff generated depends on soil permeability, and the likelihood that runoff will reach surface water depends on:

- the distance between runoff accumulation and surface water,
- the amount of vegetative ground cover, and
- soil permeability to water (Naeth et al., 1991a; Naeth et al., 1991b; Butler, 2004).

Manure deposition may occur on saturated soils in the riparian zone adjacent to the stream, or in drier upland areas (Collins and Rutherford, 2004). Saturated riparian soils are considered primary source areas of runoff and contaminants because they are connected to water sources at all times through groundwater and aboveground flow. Unsaturated soils are said to be secondary source areas, because they are only connected to water sources during periods of high precipitation, and under normal conditions do not contribute runoff or contaminants. The extent of primary source areas expands during periods of high precipitation and contracts during dry periods (Walling, 1983). The third flow path position defined in hydrologic connectivity is direct deposition.

The importance of each flow path as a source of surface water contamination depends on the properties of the contaminant in question. Subsurface flow is only a significant path for water-soluble contaminants because, in most soils, structure acts to filter particulate contaminants in the top few inches of the soil profile (Rosen, 2000; Newman et al., 2003). All types of contaminants, both particulate and water soluble in nature, may be transported to surface water in overland runoff.

1.2 Transport from Uplands

Fecal material deposited on land must be carried from the deposition site to surface water to affect water quality. Particulate contaminants and micro-organisms are transported in a series of pulses occurring from large precipitation and stream flow events. The first pulse washes contaminants from land into the stream, from where they settle onto the streambed. Subsequent pulses re-suspend contaminants, and carry them further downstream (Verhoff et al., 1982).

Soil permeability is the most important factor affecting contaminant transport during runoff events (Larsen and George, 1995). Impermeable soils generate high runoff volumes and show higher rates of contaminant transport compared to more permeable soils (Robbins, 1979). A rainfall simulation experiment examining bacterial transport in runoff in two different soil types found transport of fecal bacteria to be approximately six times larger over an impermeable soil than over a permeable soil (Larsen et al., 1994).

Since frozen soils are impermeable, waste deposited on frozen soils poses a considerable risk to surface water quality during snowmelt. Plants and soil microbes are dormant when soils are frozen, so uptake processes that retain nutrients during the growing season are not active and there is a high risk of contaminant loading during the winter and early spring (Hoffmann et al., 2009). Contaminant transport in meltwater runoff may be substantial in areas subject to frost due to these factors. In Alberta, the bulk of nutrient losses from grasslands is observed during spring snowmelt (Palliser Environmental Services Ltd. and Alberta Agriculture and Rural Development, 2008). Another study conducted in Nebraska examined the quality of surface runoff generated by snowmelt and rain. It was found that concentrations of total nitrogen (TN) and total phosphorus (TP) increase by 1.6 times during snowmelt runoff when compared to concentrations observed during rainfall runoff (Doran et al., 1981).

Ground cover is another important factor determining runoff transport of contaminants. Vegetative ground cover reduces surface runoff volume and contaminant transport by reducing the velocity of overland flow, allowing for increased infiltration and settling of suspended contaminants (Doran et al., 1981; Mosley et al., 1999). Many researchers have proposed threshold levels of ground cover above which no significant transport of sediment or contaminants will occur. A threshold of approximately 70-75 per cent ground cover is suggested to effectively limit runoff and contaminant transport. However, the threshold cover for a given site depends on soils and topography. For instance, researchers in Utah have proposed that a threshold of 50 per cent ground cover will be effective in semi-arid environments, while sites with steep slopes require up to 85 per cent ground cover to effectively limit transport of contaminants (Butler, 2004).

Species composition of vegetative cover affects contaminant filtration, with herbaceous grass species providing more effective filtration properties than woody species (Jacobs et al., 2007). Perennial grass species are also beneficial to ground water quality due to dense root systems which serve as filters to remove water-soluble nutrients from leaching into groundwater (Hubbard et al., 2004).

Filtration of surface runoff by vegetative cover is size selective. Large sediment and contaminant particles are more completely filtered out of overland flow than fine textured particles. This results in an upper limit to contaminant filtration — some contaminants may simply be too small to be trapped (Jacobs et al., 2007). Free microbial cells and clay or silt particles carrying adsorbed nutrients may be too fine to be filtered out of overland flow by vegetation, and are transported in surface water as a solute (Butler, 2004).

Distance between manure deposits and surface water also affects contamination. Risk of contamination decreases as distance between a fecal deposit and surface water increases (Buckhouse and Gifford, 1976; Larsen et al., 1994). In areas with high densities of manure deposition, water-soluble nutrients may leach into groundwater in significant quantities (Peterjohn and Correll, 1984; Schilling and Jacobson, 2008).

Many contaminants are not subject to transport by leaching. Under most circumstances, only a small proportion of contaminants from manure deposited on land can be expected to reach surface water. Factors such as slope and vegetative cover can impact the amount of contaminant transport.

1.3 Transport from Deposition in Riparian Zones

Primary source areas include saturated soils in riparian and wetland areas, extending outwards from the stream where the water table is close to the soil surface. Saturated areas typically result in more transport of contaminants when compared to drier upland soils, as less precipitation is required to initiate runoff and they are located closer to water sources (Collins and Rutherford, 2004. Vegetation in these areas is a critical component to filtering contaminants.

Riparian areas and riparian vegetation are influential in preserving overall surface water quality, they act as a buffer between land use and surface water (Peterjohn and Correll, 1984; Lowrance and Sheridan, 2005). Some studies directly attribute improved riparian health to improved surface water quality (Miller et al., 2010a).

Riparian and wetland vegetation has been found to be a more efficient filter of contaminants than upland vegetation as cover tends to be denser than in upland vegetation, and better able to filter overland flow (Butler, 2004). Riparian vegetation decreases velocity of runoff flow, providing the opportunity for sediment and large organic particles to settle, promoting higher levels of nutrient uptake and groundwater recharge (McIver, 2004; Agouridis et al., 2005).

Filtration by riparian or upland vegetation is not always a permanent solution, and contaminants that have settled in vegetated buffers may be re-suspended, given sufficiently large runoff events (Mosley et al., 1999). Riparian areas are low slope areas that tend to accumulate contaminates by nature of their topography, and if these contaminants are not up taken by plants there is a risk of stream contamination following precipitation events. The risk posed by deposited contaminants is reduced over time as nutrients are taken up by plants and fecal organisms are killed by exposure to UV light.

1.4 Direct Instream Deposition

Direct deposition in the stream allows contaminants to bypass processes that limit contaminant transport on land, resulting in 100 per cent of contaminants entering surface water. Many authors associate the most severe water quality impacts observed in grazed areas with direct instream deposition (Larsen et al., 1994; Sheffield et al., 1997; Mosley et al., 1999; Hubbs, 2002).

1.5 Downstream Transport

Contaminant transport depends on flow rate and particle size. Contaminants are deposited on, or scoured from, the streambed depending on streamflow velocity. When flows are elevated, streambeds are scoured and sediment input into the water column. When flows are low, sediment and particulate contaminants settle out of the water column, depositing on the streambed (Verhoff et al., 1982). While many contaminants may be transported during regular base flow conditions, the majority of contaminant transport occurs during storms when flows are elevated (Verhoff et al., 1982).

Contaminants that reach the stream through surface runoff are considered to be the product of one precipitation event. In subsequent precipitation events, they are re-suspended from the streambed, and carried downstream as long as the velocity of streamflow remains sufficiently high (Verhoff et al., 1982). Fine-textured particulate contaminants, such as fine clays and individual microbial cells, may also behave as water-soluble contaminants once they reach the water column, as they settle so slowly that deposition on the streambed is unlikely even under low flow rates (Graf, 1971; Sherer et al., 1988).

Streambed sediments often contain considerable amounts of nutrients and microbial contaminants, and act as mid- to long-term contaminant reservoirs (Giskie et al., 1988; Sherer et al., 1988; Bagshaw, 2002). Literature on the subject has proposed that the majority of contaminants observed in the water column during high-flow events were present in streambed sediments prior to the onset of high-flow conditions (Verhoff et al., 1982; Sherer et al., 1988; Collins and Rutherford, 2004).

1.6 Manure Deposition and Cattle Behaviour

The factor that most strongly influences grazing impact on water quality is the location of manure deposition and accumulation relative to a body of water.

The location of manure deposition depends on cattle behaviour and management factors. In extensive grazing operations manure accumulation is not uniform across grazed areas (Larsen et al., 1994), but is concentrated in areas where cattle congregate, resulting in disproportionately high manure accumulation in these areas. These areas include water sources and riparian areas, shade, salt licks and supplemental feed supplies (Newman et al, 2003; Tate et al, 2003; Lenehan et al., 2005). Manure accumulation also depends on slope, with rapid decreases in buildup once slope exceeds 10 per cent.

Cattle activity in streams is most frequent during the summer and declines in the fall. Researchers in California found cattle spent 11.2 min/animal/day in the stream in the summer, compared to 2.6 min/animal/day in the fall. Manure deposition in the stream is proportional to the amount of time spent in the stream, with 0.41 defecations/animal/day observed during the summer and 0.17 defecations/animal/day observed in the winter and spring (UCCE Rangeland Watershed Fact Sheet No. 25).

A New Zealand study found 8.3 per cent of defecations to occur in the stream, and 6.3 per cent within the riparian area (Bagshaw, 2002). Fecal loading of riparian areas is also seasonal, with higher accumulation rates observed during dry periods, when cattle are drawn to higher quality forage found in moist riparian areas (Tate et al., 2003). GPS collar studies conducted in southwestern Alberta also report that livestock spend a disproportionately high amount of time in or near streams, so elevated manure accumulation is expected within the riparian area (DeMaere and Alexander personal communication, 2011).

Strategic placement of alternative watering sources may decrease stream utilization, resulting in lower contaminant loading.

Virginia studies have noted that installation of an offstream watering trough (OSW) decreased stream utilization by cattle by 85 per cent (Mosley et al., 1999), and that if given a choice between drinking from an OSW or a stream, cattle preferred to drink from the OSW 92 per cent of the time. Along with the reduction in time spent in the stream, the study noted after the OSW was installed there was:

- 90 per cent reduction in sediment concentrations,
- 54 per cent reduction in total nitrogen (TN) concentrations,
- 81 per cent reduction in total phosphorus (TP) concentrations,
- 51 per cent reduction in fecal coliform concentrations,
- 77 per cent reduction in fecal *Streptococcus* concentrations, and
- 77 per cent reduction in streambank loss due to sloughing (Sheffield et al., 1997).

These findings are supported by a study conducted in British Columbia that also observed a strong preference for drinking from an OSW over streams, with 80-92 per cent of cattle drinking events occurring at an OSW. The study did note that cattle utilization of the riparian area is not only for watering, but also for forage and shade resources, crossing points and grooming sites. The addition of scratching locations in conjunction with OSWs was the most effective approach to reduce overall utilization of the riparian area (Veira and Liggins, 2002).

1.7 Grazing Impacts on Transport Processes

If cattle are present in high numbers and/or densities the risk of contamination increases. High intensity grazing activities decrease soil permeability and vegetative ground cover, thereby increasing runoff volume and flow velocity. In heavily stocked confined grazing operations, stock trample and compact soils, and vegetation changes may also occur, where fibrous rooted perennial plants are replaced by shallow rooted annual species, or tap rooted shrubs or forbs (Platts, 1981). As soil compaction increases and favorable ground cover diminishes, water infiltration is decreased and surface runoff volumes increase (Platts, 1981; Butler, 2004).

Ground cover decreases runoff volume transport of contaminants by providing resistance to overland flow and allowing contaminants to settle (Walling, 1983). Areas of bare ground pose the greatest risk of contaminant runoff into surface water, and demonstrate increased leaching of water-soluble contaminants into ground water (Rosen, 2000). Generally, once ground cover reaches 70-75 per cent cover or less it is not considered to provide adequate protection for surface water as patches of bare ground begin to connect and runoff is able to flow relatively unimpeded (Butler, 2004).

Section 2: Nutrient Contamination

2.1 Water Quality Guidelines for Nutrients

Alberta guidelines for the protection of freshwater aquatic life specify that Total Nitrogen (TN), Total Phosphorus (TP) and Total Suspended Solids (TSS) should not exceed concentrations of 1.0mg/L, 0.05mg/L and 10mg/L respectively (Alberta Environment, 1999).

2.2 Grazing and Potential Nutrient Contamination of Surface Water

Livestock waste contains nitrogen and phosphorus compounds which may enter waterways through various transport processes and present a nutrient contamination concern. Nutrient contamination may lead to eutrophication which alters the productivity and structure of aquatic ecosystems.

Nutrient levels in surface water are reported to be less sensitive than fecal bacterial concentrations to the presence of grazing animals (Robbins, 1979). Many studies examining the relationship between extensive grazing activities and surface water quality have found little or no increase in nutrient concentrations associated with cattle presence (Doran et al., 1981; Gary et al., 1983; Larsen and George, 1995; Miller et al., 2010a).

Even under intensive stocking rates it is difficult to predict the risk cattle pose to surface water quality based solely on stocking rates alone. In many cases, the contribution of extensive grazing activities to surface water nutrient loading may be so small as to be confounded with background nutrient sources within a watershed (Robbins, 1979).

Feeding supplemental forage (hay, grain, etc.) does not commonly occur in extensive grazing systems, specifically on public land. Therefore, in extensive settings, grazing does not add nutrients to the system, but may alter the rate of nutrient cycling or result in a minor loss of nutrients from the site through transport processes.

Manure-derived nutrients become pollutants only once the nutrients available in manure exceed the nutrient requirements of surrounding vegetation, or where nutrients are mobilized at a time of the year when they cannot be taken up by plants (Hubbard et al., 2004; Hoffmann et al., 2009).

2.3 Nutrients of Concern to Surface Water Quality

Nitrogen and phosphorus inputs have implications on surface water quality as they contribute to eutrophication of surface waters, particularly oligotrophic streams (streams with low nutrient contents), in which phosphorus or nitrogen availability limit primary productivity (Mosley et al., 1999; Hoffmann et al., 2009). This is problematic in aquatic ecosystems because where nitrogen or phosphorus concentrations increase, primary productivity rapidly increases, and biomass accumulates, dies, and decomposes. The rapid uptake of oxygen through decomposition processes can leave aquatic ecosystems severely depleted in oxygen, leading to aquatic organism mortality (Hoffmann et al., 2009).

Nutrient contaminants may be transported by surface water in several forms, which can be broadly classified as either organic or inorganic.

Nitrogen is present in numerous distinct forms due to the complexity of the nitrogen cycle, which involves movement of nitrogen between inorganic minerals, organic materials and the atmosphere (Bock and Wagner, 2006).

Rates of nitrogen loading and export in surface water are reported at various levels, ranging from total nitrogen (TN) to measurements of specific nitrogen containing compounds. Total nitrogen is the broadest measurement of nitrogen content, and is the sum of inorganic and organic nitrogen fractions present in a sample. The inorganic fraction contains compounds such as nitrites (NO2-N), nitrates (NO3-N), and ammonia (NH3-N). Ammonia can occur in the environment in the form of ammonia (NH3-N), or the ammonium ion (NH4-N), and the form it takes is dependent on ambient temperature and pH conditions, with ammonium favoured at a higher pH (Mapfumo et al., 2002). Organic nitrogen (ON) is contained in organic material of biological origin.

There is less diversity in phosphorus compounds that are commonly reported in the literature. As with nitrogen, the lowest level of resolution at which phosphorus levels are reported is total phosphorus (TP), which is the sum of the inorganic and organic phosphorus fractions in a sample. The inorganic phosphorus fraction is frequently referred to in the literature as water extractable phosphorus (WEP), or dissolved reactive phosphorus (DRP). Lower diversity in phosphorus compounds in the environment relative to nitrogen reflects the relative simplicity of the phosphorus cycle - which is dominated by inorganic reactions and lacks an atmospheric component - compared to the nitrogen cycle (Freifelder et al., 1998).

Both nitrogen and phosphorus compounds can be transported by sediments and soil particles (Sheffield et al., 1997). Nitrogen and phosphorus cycle between organic and inorganic forms in the environment. Organic forms of nutrient contaminants are particulate in nature, and vary in size and texture. Inorganic forms are taken up by plants and soil microbes and incorporated into organic compounds. When these organisms die or lose tissue, such as leaves or needles, these dead tissues are referred to as coarse particulate organic material (CPOM) (MacDonald and Coe, 2007).

2.4 Sources of Nutrients

Nutrients may enter watersheds and threaten surface water quality by several different routes. The magnitude and importance of these nutrient sources differs according to land use, as well as site-specific factors, including hydrology and biological activity.

In many watersheds, atmospheric deposition of nutrients may be a significant source of TN and TP. Nutrients may be deposited in several forms, at rates that may vary widely from one area to another (Peterjohn and Correll, 1984; Lowrance and Sheridan, 2005). TN deposition from the atmosphere is reported to range from 5.6–10 kg/ha/year across the continental United States

(Robbins, 1979; Peterjohn and Correll, 1984; Freifelder et al., 1998). In grazed areas, the bulk of TN deposited is reported to be in an organic form, and nitrate or ammonia deposition is less common (Jacobs et al., 2007).

Atmospheric deposition of TP is less significant than for TN, particularly in cropped areas where application of phosphorus fertilizers represents the major input (Peterjohn and Correll, 1984; Smith and Alexander, 2000).

Undisturbed and extensively managed landscapes generally have lower rates of nutrient export than cultivated land (Robbins, 1979; Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008):

- TN and TP export reported from undisturbed forested lands across the United States was estimated to range from 3–13 kg/ha/year and 0.03–0.9 kg/ha/year, respectively.
- From undisturbed grasslands across the United States, TN and TP export was estimated to be 0.65 kg/ha/year and 0.76 kg/ha/year, respectively (Robbins, 1979).

In areas of crop agriculture, TN and TP inputs from fertilizers may be considerable and provide significant contributions to TN and TP loading to surface water:

- Averaged across the United States, fertilizers are estimated to contribute 22 per cent and 17 per cent of TN and TP export in surface water, respectively (Smith and Alexander, 2000).
- At smaller spatial scales, studies have estimated fertilization to account for addition of from 0.1–105kg/ha/year of TN, and 0.06- 20 kg/ha/year of TP (Robbins, 1979; Peterjohn and Correll, 1984).
- Runoff concentrations of TN and TP were found to be similar from cropland fertilized with manure, with export in runoff of 4–13 kg/ha/year and 0.8–2.9 kg/ha/year, respectively (Robbins, 1979).

The inorganic fraction of nutrient loading to surface water tends to increase with agricultural intensity; areas with low agricultural intensity tend to contain a much larger fraction of organic nutrients (Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008). The organic nutrient fraction is also much larger than the inorganic fraction in undisturbed streams (Kaushal et al., 2006).

Areas of human settlement may also contribute considerable amounts of TN and TP to surface waters:

- In the United States, it is estimated that TN and TP loading of urban drainage may account for export between 7–9 kg/ha/year and 1.1–5.6 kg/ha/year, respectively (Robbins, 1979).
- A water quality monitoring study conducted in southern Alberta sampled water upstream and downstream of the city of Lethbridge, and found both average TN and TP concentrations to be higher downstream than upstream. Average TN and TP concentrations downstream of Lethbridge were higher by 0.14 mg/L and 0.032 mg/L, respectively (Hebben, 2007).

- A study conducted in Colorado found that in developed watersheds, between 19 and 23 per cent of TN export was derived from residential septic systems (Kaushal et al., 2006).

Nutrient loading and export due to grazing activities are discussed in detail in Section 2.8 Downstream Transport of Nutrients.

2.5 Nutrient Persistence on Land

The risk of surface water contamination with a given nutrient is based on the persistence of each form in the environment, and the efficiency with which it is transported.

Different forms of nutrients have differing degrees of persistence on land and in water. The question of persistence is further complicated by the fact that nutrients may be converted to other forms by nutrient cycling processes.

Nutrient cycling processes are composed of two phases:

1. uptake processes which incorporate inorganic nutrients into complex organic molecules; and,
2. decomposition processes in which nutrients are mineralized during the breakdown of complex organic molecules (Bock and Wagner, 2006).

Nutrient export from a watershed is explained in one of three scenarios (Freifelder et al., 1998):

1. In watersheds accumulating biomass, nutrients will be taken up by growing plants, and nutrient output will be less than input.
2. In watersheds maintaining a stable level of biomass, nutrients will pass through the watershed in roughly equal amounts to those that entered it.
3. In disturbed watersheds, decaying biomass will contribute nutrients, and nutrient output will exceed input.

Disturbance affects watershed nutrient dynamics by altering nutrient cycles, changing the rate at which reactions occur, and reorganizing biological communities (Jacobs et al., 2007). Nutrients can be stored for long periods of time in stable forms by some types of vegetative matter and organic components of soils.

Areas of long term nutrient storage are referred to as sinks. Sinks are often capable of storing large amounts of nutrients, but will eventually become saturated. When a sink becomes saturated, the capacity a watershed has to take up and store nutrients decreases, resulting in increased nutrient output (Freifelder et al., 1998; Kaushal et al., 2006). Nutrients stored in biological sinks can be released back into the watershed by decomposition and disturbance (Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008).

Uptake of nutrients by plants and soil microbes is strongly influenced by seasonal factors. Nutrient uptake is greatest during the growing season, while during periods of dormancy and decay plants may become a net source of nutrients (Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008; Hoffmann et al., 2009). In arid and semi-arid environments uptake of nutrients may be almost entirely based on the presence or absence of water, with uptake confined to periods shortly after precipitation events (Jacobs et al., 2007). In environments subject to freezing temperatures, frost may cause plant cells to burst, exposing nutrients within plant tissues to meltwater (Hoffmann et al., 2009).

2.5.1 Nitrogen Compounds in Manure

Much of the TN contained in manure and urine is not immediately available to the watershed, as it is contained in relatively immobile organic materials and must first be mineralized before becoming available for uptake by plants or extraction from wastes by water (Freifelder et al., 1998).

Ammonia nitrogen (NH3-N, NH4-N) is fairly short lived in the environment. Ammonia may be present in manure or urine at the time of waste deposition, or produced by the breakdown of urea to form ammonium (Freifelder et al., 1998).

Where conditions are favourable, ammonia in manure and urine deposits is rapidly lost to the atmosphere through volatilization (Butler, 2004; Bock and Wagner, 2006; Miller et al., 2010b). Volatilization is favoured where ambient conditions are warm and dry and it is estimated that 60–80 per cent of TN excreted in urine, and 80 per cent of TN excreted in manure, is lost to the atmosphere by ammonia volatilization in intensive livestock management settings (Freifelder et al., 1998, Mosley et al., 1999). However, volatilization appears to be much less significant in extensive settings, and may account for only 2–12 per cent of TN contained in wastes produced under extensive conditions (Freifelder et al., 1998).

Ammonia levels in animal wastes are strongly dependent on the length of time that has passed since the wastes were deposited. A study conducted in Arkansas found runoff ammonia concentrations reduced by 95 per cent one day after wastes were deposited, and by more than 99 per cent after two weeks.

Butler (2004) conducted rainfall simulation experiments in North Carolina on pasture and wetland plots amended with dairy cattle manure and urine. Results showed ammonia to be present in runoff in significant quantities only during precipitation events that occurred immediately after application of fresh wastes. Significant quantities of ammonia were not present in runoff from the same wastes one month later. Free ammonia is water soluble but may be removed from soil water by binding to clay particles in soils (Bock and Wagner, 2006).

Nitrate (NO3-N) compounds are more stable in the environment than ammonia (Butler, 2004). Nitrate may be present in manure at time of deposition, or may be produced by decomposition. Nitrification converts nitrogen contained in organic compounds or ammonia into nitrates (Butler, 2004; Bock and Wagner, 2006). In oxygen-rich environments, nitrate is the end product of the breakdown of organic nitrogen. The rate at which organic nitrogen is mineralized to yield nitrate is dependent on soil microbe activity, and may occur at a higher rate in soils with high moisture availability (Bock and Wagner, 2006).

A study conducted in North Carolina found that nitrate concentrations on upland plots were not significantly higher one month after manure application when compared to runoff nitrate concentrations observed immediately after application. In wetland plots adjacent to surface water the same study found nitrate concentrations to be higher one month after manure application when compared to those observed immediately after application. It was proposed by the author that the elevated nitrate concentrations in wetland plots one month after manure application were due to mineralization of organic nitrogen or ammonia. Mineralization rates of nitrogen may be higher in riparian or wetland soils because of increased soil moisture availability compared to upland soils (Butler, 2004).

A study conducted in Virginia also noted significant decreases in ammonia levels and organic nitrogen in runoff from a grazed pasture, which coincided with a significant increase in nitrate levels (Sheffield et al., 1997). The decay of legumes has been identified as a particularly significant source of nitrate loading to runoff or leaching water (Agouridis et al., 2005).

Nitrogen export from land primarily occurs by subsurface flow. In a riparian forest in Maryland nitrogen export by surface runoff and subsurface flow accounted for 25 per cent and 75 per cent of total nitrogen export respectively (Peterjohn and Correll, 1984). This is due to the fact that nitrate is highly soluble in water, and is not easily bound to soil particles (Hubbard et al., 2004; Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008). The importance of subsurface transport of nitrogen is also dependent on soil permeability, where soils with low infiltration capacities show increased overland transport of nitrogen.

In most cases, the factors governing uptake and retention of nitrogen and phosphorus by plants are similar enough in nature that they will be considered together in section 2.5.3 Organic Nutrients.

2.5.2 Phosphorus Compounds

Phosphorus appears in fewer forms than nitrogen on land and in surface water, and is often summarized in the literature by measurements of total phosphorus (TP).

Inorganic phosphorus may be water soluble or insoluble, depending on form. Many phosphate salts are water insoluble, while other forms of phosphate are freely water soluble and may be reported in the literature as DRP, SRP, TDP, etc. (Hoffmann et al., 2009). The water-soluble phosphorus component of fresh cattle manure has been reported to range from 55–85 per cent of total phosphorus (Butler, 2004).

In addition to inorganic phosphorus present in waste at time of deposition, additional inorganic phosphorus may be made available by mineralization of organic materials present in manure (Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008). In most soils, inorganic phosphorus is fairly short lived, as it may be immobilized by binding to soil minerals or taken up by phototrophic organisms such as bacteria, fungi, and plants. Inorganic forms of phosphorus may be bound to soil and sediment particles, as well as to humic compounds in soil organic matter (Hoffmann et al., 2009). In soils with calcareous parent materials, binding to soil minerals may represent a long-term, stable phosphorus sink.

A study conducted in Arkansas examined manure-derived dissolved reactive phosphorus (DRP) loading of runoff. Concentrations were found to decrease with subsequent rainfall simulations. One day after manure was applied, DRP concentrations in runoff were found to be 15.3 per cent of those from fresh manure and two weeks later runoff contained only 4.7 per cent of the initial DRP concentration (Butler, 2004).

Rainfall simulations conducted in Alberta found that immediately after manure application, less than 3 per cent of total phosphorus contained in manure was loaded to surface runoff. One year after manure application less than one per cent of total phosphorus contained in manure was loaded to runoff and the authors estimated that phosphorus contained in manure took from 6–12 months to equilibrate with soil phosphorus levels (Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008).

A rainfall simulation study conducted in North Carolina examined phosphorus export in surface runoff from plots amended with dairy manure with simulated grazing at a rate of approximately 16.8 Animal Unit Month (AUM)[1]/ha. It found that DRP export from manure in surface runoff was significantly higher from plots to which manure had been applied than from those with no manure application. DRP export one month after manure application was not significantly different from DRP export from fresh manure (Butler, 2004). The same study also examined total phosphorus export, and found that for plots with 45 per cent or higher ground cover, total phosphorus export was low even with manure application. Conversely, plots with no ground cover showed increased TP export during simulations with fresh manure application, but total phosphorus export did not exceed background (pre-manure application) levels during simulations which did not include the addition of fresh manure (Butler, 2004). It is also worth noting that the stocking rate simulated in Butler's study is intensive and represents much higher stock density and manure accumulation than would be observed in extensive settings.

In acidic soils, phosphates bind tightly with iron and aluminum oxides, and in basic soils phosphates bound to calcium will precipitate out of the soil solution. In both cases, these processes may retain phosphorus in soils in a stable form, until such time that the soil characteristics change enough to cause reverse reactions to occur. Reverse reactions result in release of precipitated phosphorus compounds available to the watershed in mobile forms (Hoffmann et al., 2009). However, phosphorus adsorbed to soil particles may also be mobilized in particulate form if soils are eroded by weathering or runoff (Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008; Hoffmann et al., 2009).

Given that phosphorus retention depends substantially on binding to soil minerals, soils may become saturated once the amount of phosphorus in the soil exceeds the number of mineral binding sites available (Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008; Hoffmann et al., 2009). The point at which soil phosphorus binding sites become saturated is the soil phosphorus content threshold, and soils will not be expected to lose phosphorus to runoff or leaching water until the threshold is exceeded (Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008).

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[1] An Animal Unit Month is defined as the amount of forage (food) needed by an "animal unit" (AU) grazing for one month. The quantity of forage needed is based on the cow's metabolic weight, and the animal unit is defined as one mature 1,000 pound cow with or without calf at foot.

The amount of phosphorus that can be retained by adsorption to soil particles depends on several factors in addition to soil pH, including soil texture, soil moisture, and the availability of oxygen. Phosphorus retention is higher in coarse-textured soils than in fine-textured soils because fine-textured sediments are more easily mobilized in runoff than coarse-textured sediments (Hoffmann et al., 2009). Soil moisture and oxygen content are related, in that saturated soils contain less oxygen than unsaturated soils. The formation of iron and aluminum oxides is more favourable in unsaturated aerobic soils, which have higher phosphorus retention capacities than comparable saturated anaerobic soils. When a dry soil becomes saturated, and if phosphorus binding minerals become water soluble under anaerobic conditions, the soil may change from being a sink to a source of phosphorus in the watershed (Jacobs et al., 2007; Hoffmann et al., 2009).

Soils in Alberta tend to be phosphorus deficient, and have unsaturated phosphorus binding capacity (Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008), so surface flow is expected to be the dominant flow path for phosphorus export to surface water.

2.5.3 Biological Uptake of Organic Nutrients

Inorganic forms of nitrogen and phosphorus may be temporarily retained by uptake and incorporation into organic molecules in the tissues of plants and soil microbes (Bock and Wagner, 2006; Hoffmann et al., 2009). The amount of time nutrients can be stably sequestered in organic material is largely dependent on biological activity of the site, which in turn depends on seasonal environmental factors such as temperature, sunlight, and moisture availability (Jacobs et al., 2007). Nitrogen and phosphorus are available for biological uptake in the forms of ammonium, nitrate, and phosphate (Bock and Wagner, 2006; Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008).

Biological uptake and storage of nutrients in biomass occurs only during the growing season. A study conducted in France applied bovine urine to vegetated plots at different times of the year, and monitored nitrogen levels in soil water to find that 0.7 per cent of the nitrogen applied was recovered in the spring, with 7.7 per cent and 17 per cent of applied nitrogen recovered in the summer and the fall, respectively (Butler, 2004). If the period in which inorganic nutrients are available in runoff or soil water does not coincide with active plant growth, export of inorganic nitrogen and phosphorus may be considerable (Jacobs et al., 2007). Conversely, if inorganic nutrients are present in surface runoff or soil water during periods of plant growth, very little nutrient contamination of surface water is expected where sites are well vegetated.

A study conducted in Kentucky compared the nitrate concentration of runoff from forage plots clipped to various heights, reasoning that plants recovering from clipping should have higher growth rates than unclipped plants and therefore increased nitrate uptake. The runoff nitrate concentration from plots containing the shortest clipped forages was less than half that of runoff from unclipped forages (Butler, 2004). Community composition and successional state of a site effects the rate of uptake of inorganic nutrients. Sites recovering from disturbance will have a higher rate of nutrient accumulation than sites in later successional stages which may have reached equilibrium between nutrient uptake and loss rates (Freifelder et al., 1998; Mulholland, 2004).

2.6 Nutrient Transport on Land

There are two flow paths that manure-derived nutrients may take to reach surface water. Water-soluble contaminants may be carried in surface runoff or in subsurface flow, whereas insoluble particulate contaminants can only be transported by surface runoff.

There are forms of nitrogen and phosphorus that can be transported by either flow path, including nitrate, ammonia, and dissolved reactive phosphorus (DRP) (Peterjohn and Correll, 1984; Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008). However, in soils rich in iron and aluminum minerals, DRP transport by subsurface flow is minimal because DRP is removed from soil water as it binds to soil particles (Hoffmann et al., 2009). Ammonia is also subject to binding to soil particles (Bock and Wagner, 2006). Particulate contaminants, including inorganic nutrients bound to soil or sediment particles and particulate organic material, tend to be transported exclusively by overland runoff processes. In most soil textures, soil structure filters particulate contaminants out of percolating water within the top few inches of the soil profile (Rosen, 2000; Newman et al., 2003; Saini et al., 2003).

2.6.1 Overland Flow

The risk posed to surface water by particulate nutrient contaminants depends on soil permeability, ground cover, slope, hydrologic position, and distance to surface water.

Phosphorus concentrations in runoff are directly related to phosphorus concentrations in the soil, suggesting that soil erosion is a significant source of exported phosphorus (Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008; Hubbard et al., 2004). Conversely, nitrogen concentrations in runoff have no significant relationship with soil nitrogen concentrations (Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008).

Many studies have examined the efficacy of vegetated buffers of varying designs in reducing nutrient export to surface water, from which a number of generalizations can be made. Most buffer studies note some decrease in surface runoff contaminant load as it traverses the buffer. The magnitude of the decrease in contaminant loads depends on the distance runoff must traverse, and the amount of vegetative ground cover present in the buffer. Butler (2004) conducted a rainfall simulation study in North Carolina, which examined nutrient loads and export in surface runoff from small wetland and upland plots that had been amended with cattle manure. TN and TP export in runoff was higher from plots amended with manure as compared to background levels. TSS export did not differ between waste-free controls and plots that had been amended with manure.

TN and TP export from manure amended plots was much lower for plots containing any amount of vegetated cover as compared to bare soil plots. It was observed that runoff volumes and total cumulative rates of TSS, TN, and TP export were higher from wetland plots than comparable upland plots. Wetland plots with 95 per cent ground cover were approximately 2 times, 1.9 times, and 1.6 times more effective than upland plots at retaining TSS, TP, and TN, respectively. In both upland and wetland sites, nutrient exports tend to decrease with increasing ground cover.

For upland plots:

- TSS export was reduced by 92, 96, & 98 per cent for 45, 70, & 95 per cent ground cover, respectively.
- TN export was reduced by 69, 85, & 80 per cent for 45, 70, & 95 per cent ground cover, respectively.
- TP export was reduced by 68, 77, & 80 per cent for 45, 70, & 95 per cent ground cover, respectively.

Peterjohn and Correll (1984) conducted a larger scale study in Maryland, which investigated reduction of contaminant loads in runoff passing through a riparian forest situated between a stream and a cultivated field. It was found that:

- all chemical parameters were reduced by some degree while traversing the buffer zone;
- most of the decreases occurred within the first 19 meters of the buffer; and
- nutrient loads were higher at the edge of the riparian forest nearest the stream than midway through the riparian forest.

The increase observed between the middle and the end of the riparian forest is possibly due to contributions made by plants shedding tissue; the concentration of organic matter in runoff increased by 2.8 times as runoff traversed the buffer, and 60 per cent of this increase occurred between the middle and the exit of the riparian forest. Also of note:

- In the first 19 meters of the buffer, nitrate, ammonia, and particulate organic N were reduced by 79 per cent, 73 per cent, and 62 per cent, respectively.
- Between entering and leaving the riparian forest, a distance of approximately 50 meters, TP and DRP loads decreased by 84 per cent and 74 per cent, respectively.

Lowrance and Sheridan (2005) conducted a study in Georgia examining surface runoff quality as runoff traversed a three-zone riparian buffer consisting of:

- a grass buffer 60–75 meters away from the stream, followed by
- a 45–60 meter band of conifers, followed by
- a 15 meter wide band of deciduous trees immediately adjacent to the stream.

As found in the study conducted by Peterjohn and Correll (1984):

- nutrient contaminants showed net decreases between entering and leaving the buffer zone;
- most substantial reductions occurred in the grass region at the beginning of the buffer; and
- a net increase in nutrient loads was observed between the middle and the end of the buffer.

- Nitrate, ammonia, TN, DRP, TP, and sediment-bound phosphorus loads in surface runoff were decreased by 59 per cent, 48 per cent, 37 per cent, 56 per cent, 56 per cent, and 63 per cent, respectively, between entering and leaving the riparian buffer.

Meals and Hopkins (2002) conducted a study in Vermont examining the effects of excluding cattle from sections of streams, and allowing the recovery of riparian vegetation on degraded streambanks. Results indicated that these two factors reduced annual TP export to surface water by 20–50 per cent, with greater reductions noted in more extensively treated streams.

Vegetated buffers are not necessarily an effective means of reducing water-soluble contaminant loads in surface runoff. A combined grass and riparian buffer was reported to reduce TP by 50 per cent, but 80 per cent of DRP passed through the buffer without being removed from flow. The same study found the buffer to be more effective in filtering nitrate from runoff, and only 50 per cent of the nitrate that entered the buffer reached the other side (Lowrance and Sheridan, 2005).

All buffers have an upper limit in filtering contaminants out of runoff due to differences in particulate contaminant size. Large-textured particles will settle much more quickly than fine-textured particles, and some may be so finely textured that they will not settle out of flow (Butler, 2004). Buffers are also less effective in filtering particulate organic nutrients, because organic particles have a lower density, and settle out of surface runoff more slowly than mineral-based particles (MacDonald and Coe, 2007).

Butler (2004) conducted a literature review on the maximum efficacy of vegetated buffers in removing contaminants from surface runoff:

- An Ontario study found that a buffer two metres wide trapped 65 per cent of sediment being carried by surface runoff, while a 91 per cent reduction was noted for a buffer 15 meters wide.

- In Montana, a buffer containing wetland vegetation was found to retain 83 per cent of sediment carried by runoff in a one meter wide buffer, and 99 per cent of sediment in a six meter wide buffer.

Buffer efficiency increases with buffer length/width, but usually reaches a maximum at less than 100 per cent contaminant removal, and some contaminants will pass through any buffer regardless of width or density of vegetation. Given sufficiently high runoff volumes and flow rates, buffers may be overwhelmed and become ineffective in removing contaminants from runoff. In extreme runoff events, contaminants deposited in a buffer during a previous runoff event may be remobilized into flow (Mapfumo et al., 2002; Lowrance and Sheridan, 2005). A study conducted in Vermont concluded that TP export was chiefly influenced by infrequent precipitation events of extreme intensity, which were able to overwhelm riparian buffers, while little TP export was observed during light or moderate precipitation events (Meals and Hopkins, 2002).

Climate is also a significant factor affecting surface water contamination by overland runoff. In northern climates subject to frost, there are several factors that increase the potential for nutrient export during the winter and early spring, when compared with seasons when soils are not frozen.

In Alberta, much of the annual runoff volume is generated during spring snowmelt while soils are still frozen and mostly impermeable to water. The majority of the TN and TP export from Alberta grasslands is observed during this time (Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008). During snowmelt runoff, vegetation is dormant, and much less effective at filtering than at other times of the year (Hoffmann et al., 2009). Frozen soils are impermeable, so winter feeding sites where cattle are concentrated pose a particular risk of nutrient export to surface water. On frozen soils, volume and rate of overland flow will be higher than at times of year when soils are permeable, resulting in higher runoff intensities than at other times of the year (Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008).

There is no consistent relationship between cattle presence in extensive grazing situations and nutrient concentrations in surface runoff:

- Doran et al. (1981) conducted a study on a grazed pasture in Nebraska, which examined the quality of runoff from grazed and ungrazed pastures. They found concentrations of nitrates, DRP, TP, and organic material to be slightly elevated in runoff from the grazed pasture when cattle were present, as compared to when cattle were absent (Doran et al., 1981).
- A study conducted at Stavely, Alberta examining the relationship between grazing intensity and runoff water quality found that, even at a stocking rate of 4.8 AUM/ha, there was no clear impact of grazing on surface runoff TN and TP concentrations (Mapfumo et al., 2002).
- Miller et al. (2010c) conducted a small plot rainfall simulation study in the Lower Little Bow watershed in southern Alberta. This study compared runoff quality from a pasture that was grazed at a rate of 0.40–0.50 AUM/ha to runoff quality from a pasture from which cattle had been excluded. Over the course of three years:
    - nutrient concentrations in runoff from grazed and ungrazed sites were similar for most nutrient parameters;
    - TN concentrations were greater for the grazed than the ungrazed pasture in one year out of three;
    - no significant difference was noted in runoff concentrations between grazed and ungrazed pastures for any individual N parameter;
    - TP concentrations were greater for the grazed than the ungrazed pasture for only one year out of three.

2.6.2 Subsurface Flow

Subsurface flow occurs where precipitation is able to percolate through the soil profile until it reaches groundwater, at which point it travels laterally through the soil profile towards surface water. Manure-derived contaminants may be leached from manure and carried by the percolating water through the soil profile. In most soils, subsurface flow is only a significant flow path for inorganic, water-soluble nutrients.

Soil properties are an important factor in determining the extent to which manure-derived contaminants may pose a risk to surface and groundwater quality.

The majority of nitrogen leached from soils is in the form of nitrates, because nitrates are repelled by clays, and do not become bound within the soil matrix, so nitrate ions travel freely with percolating water (Hubbard et al., 2004; Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008). Inorganic forms of phosphorus are often very strongly adsorbed to soil minerals in soils, so leaching of phosphorus is less of a concern (Miller et al., 2010b).

Soil texture is also influential on nutrient export by leaching. Nitrogen leaching occurs most significantly in coarse-textured soils, and at a much lower rate through fine-textured soils. As such, groundwater underlying coarse-textured soils tends to have a higher nitrogen concentration than groundwater underlying fine-textured soils (Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008). Phosphorus leaching is also most common in coarse-textured soils, but even in coarse soils phosphorus leaching is rarely significant. Medium- and fine-textured soils may hold large surpluses of phosphorus before significant leaching will occur (Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008).

Miller et al. (2010b) conducted a study on the Lower Little Bow River in southern Alberta examining rates of nitrogen and phosphorus leaching and accumulation in soils underlying offstream watering troughs, as well as onstream watering sites. They found no evidence of phosphorous enrichment of soils below the surface, suggesting that no phosphorus leaching had occurred. Substantial nitrogen leaching was found to have occurred in the soil underlying an offstream watering trough that had been in place and utilized for seven years, while less nitrogen leaching was detected under watering troughs that had only been utilized for two to three years.

Inorganic forms of phosphorus may be released by soils that are rich in mineral bound phosphorus, if dry soils become saturated, the mechanism for which is outlined in section 2.5.2 (Hoffmann et al., 2009). Inorganic phosphorus may also become available for export in subsurface flow when a soil that had been dry for a long period of time becomes saturated, and there is a release of inorganic phosphorus resulting from death and decomposition of microbial biomass during dry periods (Jacobs et al., 2007).

2.7 Instream Persistence of Nutrients

The length of time nutrients persist in surface water is highly variable. Instream survival is determined by the form of contaminant in question, and the hydrological/biological properties of the stream. In the stream, nutrients tend to cycle between organic and inorganic forms as they are taken up and released by aquatic organisms (Mulholland, 2004). Once instream, there are two main retention mechanisms for nutrients: biological uptake and physical storage (Triska et al., 1989).

Depending on flow conditions, streams may have two distinct nutrient retention phases (Royer et al., 2004):

4. Where flow rates are low, substantial processing and retention of nutrients may occur
5. Where flow rates are high, retention of nutrients is minimal, as nutrient inputs to the stream are quickly exported downstream

2.7.1 Instream Biological Uptake

Uptake processes affect inorganic water-soluble nutrients, and are strongly influenced by seasonal factors, such as light availability, flow rate, stream stage, prior nutrient conditions, and the composition of the phototroph and decomposer communities. Nutrients may be taken up as a growth requirement by phototrophic and detritivorous organisms. Uptake by phototrophs is regulated chiefly by light availability, while uptake by detritivores depends on the availability of decaying organic material in the stream (Mulholland, 2004).

Which group of organisms represents the more significant mechanism for nutrient retention depends on local conditions. Light availability is cyclical, both daily and annually (Triska et al., 1989). In streams dominated by tree or shrub cover, light availability and phototrophic activity are highest in the spring before riparian vegetation leafs out, and once leaves are present they may intercept most available light before it reaches the stream (Mulholland, 2004). In densely forested areas, the stream may be completely shaded, resulting in very low rates of phototrophic activity, and thus very low rates of instream nutrient uptake (MacDonald and Coe, 2007). Nutrient uptake by phototrophic organisms is a much more substantial sink for inorganic nutrients in undisturbed streams than it is in streams that drain agricultural land, particularly areas of intensive agriculture (Royer et al., 2004).

Nutrient uptake also depends on prior nutrient conditions in the stream and the composition of the stream phototrophic and decomposer communities. There is often a temporal lag between nutrient enrichment of a stream and efficient instream nutrient uptake, particularly in nutrient-limited streams. Under nutrient limitation, phototrophic cells will be small or dormant, with very low metabolic rates and nutrient requirements. As nutrient concentration increases, physiological changes will be induced in the phototrophic community, leading to increased metabolic activity (Triska et al., 1989). If contamination occurs in pulse-like rather than chronic fashion, nutrients may pass through reaches relatively unchanged, as the phototrophic community is not active and able to take up nutrients.

The rate of nutrient uptake in streams also depends on stream stage (depth) and flow rate. Stage affects uptake by changing the surface area-to-volume ratio of the stream (the area of contact between the stream and its bed relative to stream volume). Biological uptake processes are most efficient where surface area-to-volume ratios are high (Wickham et al., 2003; Mulholland, 2004; MacDonald and Coe, 2007). Flow rate affects nutrient uptake in that:

- at higher flow rates, water passes through a given stream length quickly;
- biological nutrient uptake decreases with increasing flow speed as nutrients are transported downstream before they can be taken up (Wickham et al., 2003; MacDonald and Coe, 2007).

Since stage increases with increasing flow rate, the importance of biologically mediated retention mechanisms decreases rapidly with increasing flow rate (Royer et al., 2004).

2.7.2 Instream Physical Storage

Nutrients may also be retained in the stream by physical storage, through deposition on the stream bottom at low-flow rates. Physical storage processes act on waterborne contaminants immediately after they have been introduced to surface water, while there may be a delay between nutrient loading and effective retention by biotic processes (Triska et al., 1989).

In undisturbed watersheds, most nitrogen and phosphorus export is in particulate forms, with inorganic, water-soluble contaminants representing only a small fraction of nutrient exports to surface water.

- A study conducted in agricultural watersheds of varying intensity in Alberta found the bulk of nitrogen export to be in the form of particulate organic nitrogen, and the bulk of phosphorus export to be in the form of mineral bound phosphorus. The amount of water-soluble inorganic nitrogen and phosphorus in surface water increased with increasing agricultural intensity (Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008).
- A long-term surface water quality monitoring project conducted in the Oldman River in southern Alberta found the magnitude of the average organic and particulate fractions of TN and TP to be approximately two and 9.5 times greater than the magnitude of the inorganic fractions in surface water, respectively (Hebben, 2007).

Another study conducted in Alberta examined the surface water quality of three agricultural watersheds, ranging from low to high ratings of agricultural intensity (Anderson et al., 2009). The study found:

- Particulate fraction was larger in magnitude than the water-soluble fraction for all streams in the case of nitrogen, and for two out of three streams for phosphorus
- Instream concentrations of particulate nitrogen were found to range from 3.4 to 18 times larger than water-soluble nitrogen concentrations.

- Instream concentrations of particulate phosphorus were found to range from 0.95 to 53 times larger than water-soluble phosphorus concentrations.
- Relative magnitude of the water-soluble nitrogen fraction increased with increasing agricultural intensity.
- No relationship was found between agricultural intensity and the magnitude of the water-soluble phosphorus fraction found in the stream.

Given that nutrient loads found in surface water are often particulate in nature, deposition on the streambed may be a substantial mechanism for instream physical retention of nutrients (Anderson et al., 2009). From the above study:

- In two of three streams, phosphorus concentrations were higher than nitrogen concentrations in sediments.
- Sediment TN concentrations were 215–495 times larger than those in overlying water.
- Sediment TP concentrations were 1100–6200 times larger than those in overlying water.

Studies conducted in the United States have also found significant nutrient accumulation in streambed sediments (Larsen and George, 1995).

Patterns of nutrient export also indicate substantial retention of nutrients in streambed sediments. In many streams, a substantial fraction of annual nutrient export occurs during periods of high discharge, with base flow conditions being much less influential on nutrient export (Verhoff et al., 1982; Owens et al., 1983; Meals and Hopkins, 2002; Mulholland, 2004; MacDonald and Coe, 2007).

2.8 Downstream Transport of Nutrients

Nutrient export from manure to surface water is less of a concern for water quality than microbial export. Water quality monitoring studies often identify significant increases in microbial concentrations, but do not find similarly significant increases in nutrient concentrations in grazed areas (Robbins, 1979). However, the sensitivity of stream nutrient concentrations to land use is scale dependent. Nutrient concentrations tend to be less variable, and less strongly influenced by local land use in larger streams, while smaller streams (such as headwaters streams) may show considerable fluctuation in nutrient concentrations in response to near-stream land use (Buck et al., 2004; MacDonald and Coe, 2007). Downstream nutrient concentrations represent the cumulative effects of upstream hydrological, biological, and chemical processes (Wickham et al., 2003; Mulholland, 2004). Nutrient transport is a heterogeneous process, and under low-flow conditions, nutrient concentrations in surface water may vary at a spatial scale of 50 meters (Triska et al., 1989).

The rate at which nutrients travel downstream depends on several factors, including form, rate/stage of flow, and the efficiency of physical and biotic retentive processes. In the absence of retentive processes, water-soluble contaminants would move downstream at approximately the rate of stream flow. However, this is usually not the case, because dispersion and dilution result in nutrient loads transported downstream more slowly than the rate of stream flow. Due to these processes, a given load of nutrients will decrease in concentration as it is carried downstream (Triska et al., 1989).

Downstream transport of inorganic, water-soluble nutrients is not dependent on flow rate as they are equally mobile in the water column at any flow rate. Export of these contaminants depends almost exclusively on season and nutrient cycling between plants and decomposers (Mulholland, 2004).

Downstream transport of particulate contaminants depends strongly on flow rate. Particulate contaminants are transported on a size-selective basis in a series of pulses, characterized by deposition to the streambed when flow rates are low, followed by resuspension into the water column when flow rates are high.

The details of particulate contaminant transport are similar to sediment transport discussed in section 1. Fine-textured particulate nutrients will be expected to travel much further downstream than those with coarse textures before settling out of flow. Fine-textured particulate nutrients will also be resuspended at lower flow rates than coarse-textured particles. Organic particulate contaminants are lower in density than mineral sediment particles and will be transported further downstream before settling out of flow (MacDonald and Coe, 2007).

Nutrient concentrations in surface water vary between and within watersheds. While land use certainly has an impact on surface water quality, it is difficult to predict water quality based on land use alone. Factors that accurately predict contaminant loading and export in surface water in one watershed may completely fail to do so in another (Christensen et al., 2002).

Average nutrient concentrations from a long-term water quality monitoring study in the Oldman River are reported in Table 2.2. Monthly concentrations of particulate nutrients showed seasonal patterns indicating the influence of snowmelt runoff on annual nutrient export where:

- TN concentrations were fairly consistent, but slightly elevated in May and June most years.
- TKN concentrations were elevated in April, May and June, and consistently low at other times.
- Nitrate concentrations show a distinct seasonal pattern, with higher concentrations from November to March, and lower from April to October.
- Ammonia concentrations were low, and showed very little variability over the year.
- TP concentrations showed seasonality, with levels consistently low from September to February, and higher from March to August, with maximum concentration occurring in May.

- DRP concentrations showed no apparent seasonality, but levels were so low that seasonality is difficult to resolve.
    - In the Oldman River downstream of Lethbridge, DRP concentrations were much higher and a seasonal trend could be observed.
    - DRP concentrations downstream of Lethbridge were lowest in June to August, and increased to a maximum in January (Hebben, 2007).

Another water quality monitoring study conducted in Alberta found TN and TP concentrations to range from 0.28 to 5.07 mg/L and 0.04 to 0.88 mg/L, respectively, across agricultural regions. Grassland watersheds have TN and TP exports in surface water of 0.2 kg/ha/year and 0.017 kg/ha/year, respectively. In grassland watersheds, nitrogen export occurred predominantly in organic forms, and phosphorus export occurred predominantly in particulate forms (Palliser Environmental Services and Alberta Agriculture and Rural Development, 2008).

The relationship between cattle grazing and nutrient concentrations in surface water is complex and not strictly dependent on cattle density in the watershed. Robbins (1979) conducted a study comparing nutrient concentrations in surface water draining areas grazed at varying intensities:

- TN concentrations downstream from an extensive grazing operation were similar to those downstream of an ungrazed pasture.
- TP concentrations varied from 0.2 mg/L in the ungrazed stream to 1.1 mg/L in the extensively grazed stream.
- Two streams downstream of dairy operations (intensive) were also examined, and had nutrient concentrations much higher than the extensively grazed stream, with TN and TP concentrations ranging from 7–19 mg/L and 4.6–18 mg/L, respectively.

Owens et al. (1983) conducted a study in Ohio comparing water quality during the grazing period vs. during a non-use period in a pasture grazed by cattle at a stocking rate of 3.3 AUM/ha. For most nutrients, concentrations did not increase significantly with cattle presence; however, organic nitrogen concentrations showed a slight increase from an average of 0.5 mg/L to 0.7 mg/L.

Gary et al. (1983) conducted a study comparing impacts of cattle presence and absence on water quality in a mountain stream in Colorado that ran through an extensively grazed pasture. Stocking rates during the study were either 40 or 150 cattle grazing in pastures of 75 to 85ha for periods of 2 to 4 months in length.

- Over the course of two years, it was found that nutrient concentrations were very low, with nitrate levels ranging from 84-524 μg/L, and ammonia levels ranging from 140-420 μg/L.
- Instream nutrient concentrations were not significantly higher when cattle were present.

Sheffield et al. (1997) conducted a study on two streams in Virginia exposed to extensive rotational grazing activities. The study examined the efficacy of offstream watering troughs in reducing manure-derived nutrient loading to surface water and found that implementing alternative watering sources decreased concentrations of TSS and TP (118.07 mg/L and 0.131 mg/L, respectively), and slightly decreased TN concentrations compared to exclusive use of the stream for watering.

The most significant water quality impacts associated with grazing activities are noted where cattle have unrestricted stream access. If steps are taken to reduce time cattle spend in the stream and the saturated zone immediately adjacent to the stream, grazing activities may have little or no significant impact on nutrient loading and export to surface water (Robbins, 1979; Mosley et al., 1999; Miller et al., 2010a).

Section 3: Fecal Bacteria and Protozoa

3.1 Microbial Contents of Manure

Livestock waste contains bacteria and protozoa that may be harmful in high concentrations. Cattle in extensive grazing systems have been found to defecate an average of 12 times/day, with each deposition weighing approximately 2.3kg, yielding average daily fecal output of about 27.2kg of fresh manure per cow. Of each 2.3kg deposit, 88 per cent is estimated to be water, yielding a dry mass of approximately 0.3kg per defecation, and a total of 3.3kg dry weight of manure deposited per day. Each deposit will contain approximately 3.20 x 109 fecal coliforms, and 6.00 x 107 fecal Streptococci (UCCE Rangeland Watershed Fact Sheet No. 25).

Bovine urine is a significant source of nitrogen, with 70-75 per cent of TN excreted in urine, and the remaining 25 - 30 per cent excreted in manure (Zemo and Klemmedson, 1970). Phosphorus is almost exclusively excreted in manure (Butler, 2004).

3.2 Microbial Surface Water Quality Guidelines

Bacterial concentrations in surface water are typically measured in colony forming units/100mL (CFU/100mL). Guidelines for recreational use of surface waters (Alberta Environment, 1999) specify that:

- For fecal coliforms, the geometric mean concentration of five water samples should not be higher than 1,000 CFU/100mL for indirect contact, and no more than 200 CFU/100mL for direct contact
- For *Escherichia coli (E. coli)*, the geometric mean concentration of five water samples should not exceed 200 CFU/100mL

3.3 Waterborne Disease

Water quality concerns are related to the microbial component of manure and the potential of fecal organisms contributing to waterborne diseases, several of which may be transmitted from animals to humans. These transmittable diseases include salmonellosis, leptospirosis, anthrax, tuberculosis, Johne's disease, brucellosis, listeriosis, tetanus, tularemia, erysipelas, and *E. coli* infections, as well as the protozoan parasites *Cryptosporidium* and *Giardia* (Buckhouse and Gifford, 1976; Larsen et al., 1994; Rosen, 2000).

In the United States, most outbreaks of waterborne diseases are associated with water contaminated by human feces (such as swimming pools and recreational waterbodies), rather than waters contaminated by agricultural runoff or wildlife activity. Of 69 outbreaks of human cryptosporidiosis in 1999 in the United States, only three cases were suggested to have originated from contamination of surface water by livestock (Rosen, 2000). Also in the U.S., of 95 reported outbreaks of giardiasis, 71 per cent of outbreaks resulted from sewage contamination of surface water, while 12 per cent resulted from sewage contaminated groundwater (Newman et al., 2003).

Likewise, in British Columbia, cattle have not been implicated in a waterborne outbreak of giardiasis for as long as records have been kept. Protozoan pathogens are considered to be of more concern to drinking water quality than bacterial pathogens. Bacterial pathogens in drinking water can be killed by chlorine disinfection while protozoan pathogens require filtration (Rosen, 2000; Newman et al., 2003).

3.4 Protozoan Pathogens

Cryptosporidium parvum is a protozoan parasite which is spread by the shedding and ingestion of the egg stage (oocyst) of the parasite. It can infect the digestive tract of cattle and humans, and is a leading cause of diarrhea in both species (Rosen, 2000; Newman et al., 2003). Calves less than 3-4 weeks old are most susceptible to infection, though it may occur in calves up to 3 months of age. Infected calves can shed up to 10 billion oocysts per day for a period of two weeks. Adult cattle are much less prone to *Cryptosporidium* infections, and may shed oocysts, but not in significant numbers (Newman et al., 2003).

Cryptosporidium is widely distributed among cattle and wildlife in North America, and is commonly found in watersheds where livestock are excluded (Rosen, 2000; Newman et al., 2003). It has been reported on 40 per cent of beef farms in the United States, and in Manitoba, 26 per cent of beef herds with diarrhea tested positive for cryptosporidiosis (Newman et al., 2003). Wildlife species susceptible to cryptosporidiosis include wolves, deer, deer mice, and a variety of birds; however, oocysts derived from bird or fish hosts are not infective in mammals (Rosen, 2000; Newman et al., 2003). In British Columbia, oocysts were recovered in 2.5 per cent of water samples taken throughout the province (Newman et al., 2003). In the United States, oocysts were reported in 39-87 per cent of surface waters tested nationwide (Rosen, 2000).

Giardia lamblia is a protozoan parasite which is spread by the shedding, and then ingestion, of infective cysts (Rosen, 2000; Newman et al., 2003). Infected calves shed cysts intermittently, making estimation of daily cyst production more difficult for *Giardia* than it is for *Cryptosporidium* (Newman et al., 2003). Infection with *Giardia* is most common in calves of less than six months of age (Rosen, 2000).

Giardia is widely distributed in both cattle and wildlife in North America, and is almost ubiquitously present in surface waters as a cyst (Rosen, 2000; Newman et al., 2003). Like *Cryptosporidium*, *Giardia* infection is much more common in young calves than in cattle over six months of age (Newman et al., 2003). In British Columbia, 14 per cent of wildlife fecal samples tested were positive for *Giardia* cysts, and the species that were most susceptible to *Giardia* infection and shedding of cysts were muskrats, beavers, and deer. *Giardia* cysts were recovered in 17 per cent of water samples taken throughout British Columbia (Newman et al., 2003), while in the United States, *Giardia* cysts are reported in almost all surface waters, with concentrations of 5 cysts/L in river water, and 400 cysts/L in sewage (Rosen, 2000).

The contribution cattle make to human *Giardia* and *Cryptosporidium* infections is poorly understood. Current methods used to enumerate *Cryptosporidium* and *Giardia* in surface water samples do not assess the host species or viability of recovered oocysts/cysts. These factors limit the scope of inference that can be drawn from water samples, with respect to both the influence cattle have on the loading of *Cryptosporidium* and *Giardia* to surface water, as well as the risk contaminated water poses to human health (Rosen, 2000; Newman et al., 2003).

Studies attempting to determine impacts grazing cattle have on water quality indicate general association between increased agricultural intensity and elevated concentrations of *Cryptosporidium* and *Giardia* in surface water (Rosen, 2000; Newman et al., 2003).

- One study reviewed in Atwill (1996) examined *Cryptosporidium* concentrations in streams subject to livestock grazing, streams that had been exposed to treated sewage, and streams draining rangeland. Concentrations were reported to be approximately 6,500 times higher in streams draining areas of high agricultural intensity and those exposed to treated sewage than they were in streams draining rangelands. However, the study does not report whether the rangeland is subject to grazing or not. The same study found water bodies subject to unspecified human recreational use had oocyst concentrations approximately 127 times higher than the oocyst concentration in streams draining rangeland.
- Another study, reviewed in Newman et al. (2003), found *Giardia* cyst concentrations to be approximately twice as high in reaches sampled downstream of cattle, sheep, and chicken farms, than from reaches sampled upstream of these intensive livestock operations.
- Yet another study reviewed in Newman et al. (2003), found *Giardia* cyst concentrations to be approximately 1.7 times higher downstream than upstream of a 200 head cattle operation.

Peaks in oocyst/cyst concentrations are noted during calving periods. However, the extent of the impact that grazing cattle have on surface water oocyst/cyst counts is difficult to resolve. Existing literature often does not include sufficient information regarding stocking rates, grazing management practices, or watershed land use to adequately assess the contribution of cattle to the loading of *Cryptosporidium* and *Giardia* to surface waters (Newman et al., 2003).

3.5 Fecal Indicator Bacteria

Bacterial indicators are used to indicate contamination of surface water with animal feces (Rosen, 2000; Newman et. al, 2003). Concentrations of indicator bacteria are thought to be a more sensitive indicator of a grazing impact on surface water quality than sediments or chemical contaminants (Robbins, 1979).

Commonly used bacterial indicators include total coliforms (TC), fecal coliforms (FC), *Escherichia* coli (*E. coli*) (which is a species within the group fecal coliforms), and fecal *Streptococcus* (FS), among others (Rosen, 2000; Newman et al., 2003).

Bacterial indicators themselves pose little risk to human health, but are used to identify fecal contamination of surface water due to ease of detection, ability to culture, and associations with other mammalian intestinal pathogens (Newman et al., 2003).

Bacterial indicators are largely reliable in determining fecal contamination; however, they are not as reliable in indicating the presence of protozoan parasites or pathogenic bacteria (Rosen, 2000; Newman et al., 2003). Additionally, it has long been assumed that fecal bacteria cannot survive for long periods of time outside of an animal host, so fecal bacteria found in surface water is interpreted as indication of recent fecal contamination. However, there is some evidence that fecal bacteria can survive and reproduce in stream bed sediment and persist in surface water for months or years after fecal pollution occurred (Rosen, 2000; Newman et al., 2003).

Cattle excrete fecal organisms in large numbers, but water quality monitoring studies conducted at a watershed level indicate that wildlife also contribute significant amounts of fecal indicator bacteria to surface water. Meays (2005) investigated the sources of *E. coli* in water sampled from streams in three grazed watersheds in British Columbia. Wildlife were found to contribute more than 84 per cent of instream *E. coli* for the first year of the study, and more than 73 per cent for the second, while cattle contributed 6.45 per cent and 18.3 per cent of *E. coli* isolated from stream water, respectively (Meays, 2005).

A paired watershed study conducted in Montana compared a watershed protected from human activities for over 40 years with another that was open to (unspecified) human activities. The protected watershed was found to have consistently higher stream bacteria counts than the open one, which the authors speculated was due to increased wildlife use of the closed watershed, which was supported by a later study that used immunological methods to confirm that bacteria in the closed watershed were indeed sourced from wildlife (Buckhouse and Gifford, 1976).

A study conducted in Nebraska which compared the runoff water quality between a grazed and an ungrazed pasture found that fecal bacteria in runoff from both areas was characteristic of wildlife feces, concluding that background bacterial inputs unrelated to grazing may be significant (Doran et al., 1981).

3.6 Microbial Survival on Land

The risk manure poses to surface water quality depends on the longevity of the microbes in question, how easily they are transported from the site of deposition, and how much runoff is generated on the site.

It is commonly assumed that enteric bacteria have no significant environmental source unrelated to fecal contamination. However, some studies suggest that fecal bacteria can survive for some time, and even proliferate in the environment (Hubbs, 2002; Meays, 2005). Bacterial populations in fecal deposits may continue to grow until the nutrients contained in the manure are exhausted, at which point populations will begin to decline (Hubbs, 2002).

Protozoan pathogens do not have an environmental source unrelated to fecal contamination (Rosen, 2000). *Cryptosporidium* oocysts do not remain viable for long when excreted on land, and are killed rapidly by desiccation. Oocysts are reported to lose infectivity under the conditions found in a barn within 1- 4 days after deposition. If fecal matter containing oocysts dries thoroughly before reaching surface water, oocysts should no longer be infective (Atwill, 1995; Rosen, 2000).

Oocysts are also sensitive to temperatures below freezing, and exposure to freezing temperatures for more than 10 days will reduce viability by 90 per cent. *Giardia* cysts are longer lived in the environment than *Cryptosporidium* oocysts, exhibiting the longest survival at low water temperatures, and highest survival rates at 0.5°C. Cysts can be killed by desiccation and freeze-thaw cycles. Protozoan cysts have been reported to survive a maximum of five days on dry plants (Rosen, 2000).

Field studies report that fecal coliform populations decline once manure has been deposited, but the length of time that fecal coliforms can survive in the environment is variable. A study conducted during the summer in the interior of British Columbia found *E. coli* to be viable in simulated fecal pats for at least 45 days. Another study found fecal coliforms to be viable for nine weeks under conditions of intense summer sunlight and heat in Utah. Others estimate *E. coli* survival of more than 200 days in soil, and up to one year in fecal pats (Buckhouse and Gifford, 1976; Rosen, 2000; Hubbs, 2002; Meays, 2005)

The length of time after deposition that fecal deposits pose a risk to bacterial loading of runoff has been estimated to range from 7 days to at least 100 days. Rates of loading would be expected to be much lower from a 100-day-old pat than from a 2-day-old pat due to mortality in the intervening period (Larsen and George, 1995; Meays, 2005).

The crusting of fecal pats is often identified as an important factor in the survival of bacterial and protozoan fecal organisms. Crusting forms a protective barrier between fecal organisms and environmental factors such as UV light and desiccation (Buckhouse and Gifford, 1976; Hubbs, 2002; Saini et al., 2003; Meays, 2005). However, the hard, hydrophobic surface of a crusted over pat may ultimately prevent microbial contamination as water cannot penetrate the crust and runoff does not come into contact with fecal microbes (Hubbs, 2002; Meays, 2005).

Ultraviolet radiation is a well-documented cause of microbial inactivation (Rosen, 2000). A study conducted in interior of British Columbia found that after exposure to summer field conditions for 45 days, there was approximately 24 times more viable *E. coli* in simulated fecal pats that had been completely shaded than in fecal pats that had been completely exposed to direct sunlight (Meays, 2005).

Bacteria mortality also occurs from freezing temperatures and cycles of freeze-thaw. When temperatures are above freezing, microbial die off tends to be lower at mild temperatures than at high temperatures (Rosen, 2000; Hubbs, 2002). *E. coli* populations have been observed to have a 90 per cent reduction time of 3.3 days in summer, and 13.4 days in fall (Hubbs, 2002).

Soil moisture is also significant to microbial survival, and increases in fecal coliform populations have been reported following rainfall events (Hubbs, 2002).

3.7 Microbial Transport on Land

Fecal microbes may be introduced to surface water by direct deposition, overland flow and subsurface flow. Direct deposition of manure in a stream represents the worst-case scenario with respect to microbial loading of surface water, with risk decreasing as the manure source moves further from water (Buckhouse and Gifford, 1976; Biskie et al., 1988; Sherer et al., 1988; Larsen et al., 1994; Tian et al., 2002; Collins and Rutherford, 2004.

Rainfall simulation experiments examining vertical migration of *Cryptosporidium* oocysts through soil cores found that while relatively small numbers of oocysts were able to leach 30cm vertically through soil cores at extremely high simulated rainfall rates, the majority of oocysts were filtered out within the top 2cm (Rosen, 2000; Newman et al., 2003).

Rainfall simulation experiments examining the vertical migration of *E. coli* through soil cores reported between 25-63 per cent of inoculated *E. coli* recovered in the top 2.5cm of soil cores, with bacterial counts decreasing at increasing depths (Saini et al., 2003).

It has been suggested that groundwater should not contain any bacteria, unless it is directly connected to surface water (Rosen, 2000). However, vertical migration of bacteria may be more significant in coarse-textured soils with large structural pores (Rosen, 2000; Saini et al., 2003).

At field scale or lower, rainfall simulation studies tend to find increased bacterial concentrations in runoff from plots that contain manure than from plots that do not.

- In Louisiana, Hubbs (2002) conducted rainfall simulations on plots amended with simulated fecal pats composed of dairy manure. The simulations found that runoff from manure amended plots had fecal coliform concentrations ranging from 1,000-10,000 CFU/100mL, while non-amended plots had concentrations ranging from 10 – 1,000 CFU/100mL.
- In Nebraska, Doran and Linn (1979) examined water quality from grazed and ungrazed pastures, and found that fecal coliform counts were 5-10 times higher in runoff from grazed pastures than ungrazed pastures.
- Larsen et al. (1994) conducted laboratory experiments simulating rainfall on fresh manure. They found runoff fecal coliform counts ranging from 100 to 91,000 CFU/100mL at a distance of 2.13 meters away from the manure, to as high as 2.5 to 6.9 million CFU/100mL immediately adjacent to the manure.

It is worth noting that rainfall simulation experiments of the type described above tend to use uncommonly high rates of rainfall intensity, and the runoff is sampled after having traversed a relatively short distance. Under more realistic conditions, bacterial loading of runoff would probably be lower than reported in this type of study (Hubbs, 2002).

Rainfall intensity and soil permeability are the most important factors influencing bacterial loading of runoff. Laboratory experiments simulating rainfall on fresh manure deposited 2.13 meters from the point of runoff collection found cumulative fecal coliform export to be 2.2 million cells on a highly permeable soil, and 13.7 million cells on a soil with low permeability (Larsen et al., 1994).

Fecal organisms in manure deposited on frozen soils are particularly susceptible to transport by runoff, because frozen soils are not permeable, and generate more runoff than non-frozen soils (Hoffmann et al., 2009). However, Doran and Linn (1979) found fresh manure made a much larger contribution to fecal coliform loading than manure deposited during the previous grazing period, even where runoff volume was higher for manure from the previous grazing period due to frozen soils (Doran and Linn, 1979).

Other identified factors influencing bacterial loading of runoff include the location of manure deposition, vegetative ground cover, slope, bacterial mortality, stocking rate, and the length of time between deposition of manure and a precipitation event (Larsen et al., 1994; Larsen and George, 1995; Hubbs, 2002).

3.8 Microbial Survival in Surface Water

Microbial survival in surface water is complex, and depends on numerous biotic and abiotic processes. Instream survival is reported to be higher in stream bottom sediments (particularly those enriched with organic material) than in overlying stream water, due to greater nutrient availability (Biskie et al., 1988; Sherer et al., 1992). Sediments have been found to contain between 100 and 1,000 times larger populations of fecal coliforms than overlying waters (Sherer et al., 1988).

Protozoan cysts are able to survive more than 180 days in water. However, in the case of *Cryptosporidium* oocysts, 89–99 per cent of oocysts initially deposited should no longer be viable after six months in river water (Rosen, 2000).

Fecal coliforms are short-lived when suspended in stream water, with survival times ranging from a few days to a few weeks. In stream bottom sediments, fecal bacteria have been reported to survive for more than three months (Sherer et al., 1988; Sherer et al., 1992; Rosen, 2000; Meays, 2005).

Lower water temperatures decrease microbial metabolic rates, resulting in longer survival (Rosen, 2000). In a laboratory incubation study, *E. coli* was incubated in stream water amended with manure. Higher survival was noted at 6°C than at 20 or 26°C, but only for the first 16 days of the experiment. By the 23rd day of the experiment *E. coli* populations in all temperature treatments were roughly the same (Meays, 2005).

Competition and predation may be more influential on bacterial survival in stream water than abiotic factors. Studies examining *E. coli* survival found survival rates of 260 days in autoclaved stream water while survival was between 4 to 12 days in unfiltered river water, indicating that the biological content of river water may have a significant effect on bacterial survival in streams. Predation by protozoans may have a significant effect on bacterial survival; protozoan concentrations have been shown to increase rapidly with a concurrent rapid decline in *E. coli* concentrations. If protozoan growth was inhibited, the decline in *E. coli* concentrations was reduced or even eliminated (Meays, 2005).

Microbial survival is influenced by stream depth. In shallow streams, UV radiation penetrates to the bottom, while in deeper streams it may not, suggesting higher rates of UV microbial inactivation in shallow streams (Newman et al., 2003). Microbial survival is also higher in highly turbid streams as suspended sediment absorbs UV light, preventing damage to microbial cells.

3.9 Microbial Transport Processes in Surface Water

At a watershed scale the relationship between grazing cattle and microbial surface water quality is complex, and the literature on the subject often contradictory. Some studies find significant increases in indicator bacteria concentrations in runoff or stream water in grazed areas; others find no relationship between the presence of cattle and microbial water quality.

On a large spatial scale, the factors that influence microbial loading of surface water include:

- the proximity of grazing activity to surface water,
- recentness of grazing,
- season of grazing,
- physical and hydrological properties of the grazed area,
- precipitation characteristics of the grazed area, and
- wildlife activity

(Buckhouse and Gifford, 1976; Doran and Linn, 1979; Sherer et al., 1988, Larsen et al., 1994; Larsen and George, 1995; Tian et al., 2002; Mapfumo, 2002; Collins and Rutherford, 2004; Miller et al., 2010a).

A study conducted in Utah by Buckhouse and Gifford (1976) assessed the water quality impact of cattle grazing at a stocking rate of 0.50 AUM/ha. They concluded that under experimental conditions, unless feces was deposited directly into or immediately adjacent to a stream, livestock grazing in a semiarid watershed posed little risk of bacterial contamination of surface water.

Sherer et al. (1988) examined bacterial water quality in a stream in central Oregon, which had been exposed to both confined and extensive grazing operations. The authors found that intensive stocking rates were the most influential factor on stream and sediment bacteria concentrations. The highest concentrations observed during the study were noted immediately downstream from a 6ha feedlot, on which 255 cattle were confined for winter feeding. Streambed sediments adjacent to intensive feeding operations acted as a long-term source of fecal bacteria, and stream and sediment bacterial concentrations remained significantly elevated immediately downstream of the feedlot after cattle had been absent for 59 days.

Seasonal variability in water temperature and flow rate have been noted as influential, where fecal coliform concentrations in the stream and bottom sediments were higher during the summer and fall than in the winter and spring. The authors proposed that warmer water temperatures and lower flow rates in the summer and fall were conducive to survival and accumulation of fecal bacteria. (Sherer et al., 1988)

Gary et al. (1983) conducted a study investigating bacterial concentrations in a stream bisecting an 85ha pasture in Colorado. The authors found that the presence of grazing cattle caused fecal coliform counts in the stream to increase by from 1.6 to 12.5 times the background level. However, increased bacterial concentrations were only noted when 150 cattle were present in the pasture over a two month period (intensive stocking rate), while bacterial concentrations were similar to background levels when only 40 cattle were present in the pasture for periods of 2 to 4 months (extensive stocking rate).

Miller et al. (2010a) conducted a study on the Lower Little Bow River in southern Alberta, which examined the bacterial water quality implications of fencing cattle out of the stream to create a 40-80 meter wide buffer of the riparian area adjacent to the stream. The study concluded that fecal coliform concentrations were not significantly affected by the presence of grazing cattle at a stocking rate of 0.40 AUM/ha, but did note an increase in *E. coli* concentrations in the stream for two of the four years over which the study was conducted. However, the observed increase in *E. coli* concentrations was less than one order of magnitude.

A common theme of studies that note an increase in fecal bacteria concentrations associated with the presence of cattle is that the most severe bacterial loading occurred where cattle had unrestricted access to streams. If, on the other hand, grazing took place some distance from the stream, bacterial contamination of surface water was less likely to occur, or occurred to a lesser degree (Buckhouse and Gifford, 1976; Doran and Linn, 1979; Sherer et al., 1988, Larsen et al., 1994; Larsen and George, 1995; Mapfumo, 2002; Tian et al., 2002; Collins and Rutherford, 2003; Miller et al., 2010a).

Bacterial concentrations in surface water are also influenced by the flow conditions of the stream receiving fecal contamination. Under low-flow conditions, most fecal organisms deposited settle out of the stream into the bottom sediments. Experiments conducted on a stream in Oregon examining downstream transport of indicator bacteria estimated that as much as 95 per cent of the bacteria introduced to the stream settled to the stream bottom within 50 meters of the point of entry, with further settling suspected to occur over the next 250 meters (Biskie et al., 1988). Fecal bacteria that settle to the stream bottom are most likely bound to large manure particles with a high rate of sedimentation. Fecal bacteria may also be washed free from large manure particles immediately upon introduction the stream, and then have a very low rate of sedimentation, leading to transport downstream as a solvent (Biskie et al, 1988; Sherer et al., 1992). Bacteria that do settle out of flow to the stream bottom will either die off in sediments, or be resuspended from the bottom sediments by disturbance, and carried some distance downstream before settling out of flow again (Biskie et al., 1988).

Stream bottom sediments in grazed areas can accumulate considerable populations of fecal bacteria where cattle have access to the stream. If disturbed by hoof action or increased flow velocities, sediments can act as significant sources of fecal bacteria (Biskie et al., 1988; Sherer et al., 1988; Sherer et al., 1992; Larsen and George, 1995).

A study conducted in Oregon mechanically disturbed stream bottom sediments by raking them, resulting in an increase in fecal coliform concentrations by 17.5 times above background concentrations. Rakings were found to release between 1.8 and 760 million FC/m2 of streambed raked. Increased turbulence can also resuspend fecal bacteria deposited on a streambed. The same study found that by experimentally doubling the discharge rate of the stream, fecal coliform concentrations increased from 500 CFU/100mL at base flow conditions to approximately 4,000 CFU/100mL. However, after three hours at the doubled flow rate, fecal coliform populations in sediments began to decline and instream concentrations dropped to approximately 2,000 CFU/100mL (Sherer et al., 1988).

Conclusion

Available evidence suggests that when properly managed, extensively grazed livestock have minimal impact on chemical and microbial surface water quality. Soil erosion and sedimentation due to livestock use may have a negative impact on fish habitat quality, but multiple use landscapes are subject to many land uses such as recreational access (motorized and non-motorized) and industrial activity such as oil and gas development, forestry, electrical transmission infrastructure, etc., all of which contribute to accelerated erosion and sedimentation. However, the relative sediment contribution from each land use is not well understood at present.

The best insurance against water quality degradation is to maintain healthy, functional watersheds. Poor upland or riparian health is an indicator that excessive sedimentation and nutrient and microbial export may be occurring and that ecosystem function is degrading. To guard against these potential negative impacts livestock managers should prioritize healthy upland and riparian areas by managing for range and riparian health.

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Appendix: Surface Water Quality Implications of Extensive Grazing in Southern Alberta

Relationship Between Surface Water Quality and Grazing

The relationship between extensive grazing activities and surface water quality is extremely complex, and involves dozens of factors which influence the amount of fecal contamination that is able to reach and be transported by the stream. Cattle behaviour, management practices, climate, topography, hydrology, soil characteristics, the characteristics of terrestrial and aquatic plant and micro-organism communities, slope, stream gradient, stream discharge, and stream size significantly influence the potential of extensive grazing activities to contribute to surface water contamination. The question is further complicated by inputs of contaminants due to other land uses unrelated to grazing.

There have been few studies that are directly applicable to public rangelands in southern Alberta excepting one conducted in the Foothills Fescue Natural Subregion (Mapfumo et al., 2002) and a handful of studies conducted in the Mixedgrass Natural Subregion (Miller et al. 2010a, b, c).

Andrews (2006) conducted a study on the impacts of human activity on water quality in the Ghost-Waiparous watershed, which include extensive grazing. However, this study examined cumulative effects of all land uses, and was not specifically designed to assess the impacts of grazing, or to separate the water quality impacts of multiple simultaneous land uses. Andrews' study will be discussed below, but the scope of inference is limited.

Extensive grazing activities in southern Alberta spans the Dry Mixedgrass, Mixedgrass, Foothills Fescue, Foothills Parkland, Montane, Subalpine, and Alpine Natural Subregions. Grazing activities occur on Rocky Mountains Forest Reserve grazing allotments administered under the *Forest Reserves Act* and public land grazing dispositions (including leases, licenses, and permits) administered under the *Public Lands Act*.

Unless stated otherwise, contaminant transport refers to the movement of contaminants above the soil surface, carried by either runoff or streamflow. While subsurface flow may also contribute to contamination with water-soluble nutrients, water-soluble contaminants do not appear to represent a large proportion of the total nutrient load in streams in southern Alberta (Andrews, 2006; Hebben, 2007). Particulate and organic fractions of nutrients, which are not transported by subsurface flow in most soils, tend to appear in much higher concentrations in streams.

Riparian Health

Maintaining riparian and range health is the most effective way to limit negative livestock impacts on surface water. Upland and riparian vegetation provides resistance to overland water flow, and filters sediment and micro-organisms from runoff. Healthy vegetation also takes up nutrients from runoff and soil water, and so reduces or helps prevent nutrient contamination of surface water. Healthy riparian areas generally contain deep-rooted tree and shrub species that bind stream bank soils together, preventing bank erosion and trapping sediment on floodplains during flood events. Deep-rooted plants promote the development of spongy, permeable soils that absorb rainfall.

As grazing intensity increases, tall perennial grasses and sedges, young trees, and shrubs are removed by livestock and replaced by shallow-rooted grasses and annual forbs. Mature trees and shrubs that are too tall to be browsed by livestock will persist for some time, but with continued heavy grazing, new woody growth will not be available to replace the old. Under heavy grazing pressure, tall woody plants eventually disappear from the site altogether, reducing stream bank stability.

Where grazing pressure is extreme, plant cover may be lost altogether and riparian soils become compacted, reducing soil permeability and increasing surface runoff during rainfall events. Surface runoff results in erosion, and transportation of sediment, nutrients, and fecal microbes. Healthy rangelands and riparian areas retain manure-based contaminants close to where they were deposited, but as health declines the likelihood of surface water contamination increases.

Healthy sites perform all riparian functions, and are efficient in preventing surface water contamination due to livestock activity. Sites rated healthy with problems are still fully vegetated, rarely exhibit bare soil, and perform most key riparian functions. Sites rated as healthy with problems exhibit sections that are mostly in good health, interrupted by a few patches of moderate to severe human-caused impact, but can be expected to recover with management adjustments to timing of use, stocking rate, or livestock distribution. Unhealthy sites represent the greatest risk to surface water quality, exhibiting reduced vegetation cover and bare and compacted soils, with animal impact likely widespread along the length of the stream. Unhealthy sites pose the highest risk to water quality because they are at risk of erosion during even relatively minor runoff and flood events, and their ability to retain sediments and contaminants is impaired.

Location of Manure Deposition

A second consideration is the location in which manure accumulates relative to the location of surface water. The most severe water quality impacts are expected when manure is deposited directly into the stream. Where direct deposition does not occur frequently, the most severe impacts on surface water quality will likely be observed from “hotspots” arising heavily utilized areas.

The location of manure deposition in extensive grazing situations is not homogenous and depends on cattle behavior, with higher accumulation rates in primary use areas such as watering locations, sources of supplemental feed and salt, and shade (Tate et al., 2003).

A GPS collar study conducted on Bob and Sharples creeks in southwestern Alberta examined the distribution of cattle within extensively grazed pastures where streams are the sole water source. Cattle were found to spend a disproportionately high amount of time within or near streams, and time spent by cattle in a 20 meter wide buffer on either side of the stream was found to be 2.3-3.6 times greater than would be expected if cattle distributed themselves equally across the pasture. Another significant finding by DeMaere and Alexander (personal communication on quantifying livestock distribution along stream channels in forest allotments, 2011) is that under extensive management, livestock activity is focussed on a few points along the stream, and the whole stream length does not receive equal use by cattle and problematic health areas are point sources as was DeMaere and Alexander, personal communication, 2011).

There are a number of factors that explain the heterogeneous pattern of stream utilization. Veira and Liggins (2002) proposed stability of footing, visibility, security from predators, and water temperature as factors influencing cattle when choosing watering locations. Cattle tend to use areas less frequently as soil moisture increases, and avoid flooded areas when possible. These factors help to explain the non-uniform utilization of streams observed by DeMaere and Alexander (personal communication, 2011) and suggest that there will be localized areas along the length of an extensively grazed stream that will exhibit disproportionately high manure accumulation and animal impact.

Studies observing behaviour of extensively grazing cattle tend to find manure accumulation roughly proportional to the amount of time spent in a specific area (Bagshaw, 2002). Areas of high utilization have important water quality implications, because along with manure accumulation they can be expected to generate more overland runoff, and provide less resistance to overland transport of contaminants. Soil permeability will be reduced by hoof action, and grazing will decrease ground cover. These factors, interacting with the fact that saturated soils near streams tend to contribute more surface runoff than drier upland soils, result in highly impacted “hotspots”. Hotspots pose the greatest risk to surface water quality due to coincidence of manure accumulation and degradation of contaminant-retaining factors.

Timing of Deposition

The risk extensive grazing activities pose to surface water on extensively grazed public lands also depends on the timing of manure deposition, since contamination is dependent on contaminant availability during periods of runoff. The most severe impacts on surface water quality will be observed when runoff events coincide with the presence of fresh manure adjacent to the stream.

The critical period of runoff occurs between April and June in most years. Streamflow is strongly seasonal, with very little discharge in January and February, a slight increase in March, followed by a substantial increase in April, growing to a maximum in June. From June through December, discharge gradually decreases until levels are similar to those observed in January and February.

The rapid increase in discharge from April to June is due to the interaction of snowmelt and rainfall, as average rainfall volumes increase and reach an annual maximum between March and June. At elevations where snowmelt and rainfall coincide, surface runoff volumes are particularly high (Kaushal et al., 2006). Significant runoff events may also occur during the summer under intense rainfall.

The timing of sediment and contaminant transport in streams suggests that critical runoff events occur mostly during spring runoff between April and June. The timing of sediment transport in streams follows a very similar pattern to that of streamflow. Average sediment loads measured in streams tend to be very low in January, February and March, then increase sharply from April to a maximum in June. Sediment loads decline sharply between June and December, decreasing to almost nothing by September.

Water quality monitoring in the Beaver Creek watershed, conducted by the Oldman Watershed Council (2003, 2004, 2005 and 2006), suggests that timing of fecal micro-organism and nutrient transport is somewhat similar to that of sediment transport. However, the availability of fecal nutrients and micro-organisms may be more influential on the downstream transport of these contaminants than flow rate is. There tends to be one large spike in contaminant transport per year, occurring during the spring, when discharge is increasing. However, not all increases in discharge result in increased instream contaminant concentrations, so it appears that a sufficiently large runoff event is capable of flushing most or all of the contaminants from the streambed. Small scale precipitation events may only wash contaminants from the land to the stream bottom, where they remain until the next large discharge event occurs and they are scoured into the water column.

During low discharge years, contaminants may accumulate in a watershed as flow rates only occasionally exceed the thresholds required for contaminant transport. During high discharge years, flow rates may exceed transport thresholds for much of the year, resulting in transport of recently deposited contaminants as well as flushing of contaminants that have accumulated over several years (Walling, 1983).

For nutrient and microbial contaminants, the year can be partitioned into three periods of risk based on the timing of grazing activities:

- The highest risk of surface water contamination is during spring runoff, generally from March until June.
- An intermediate, variable risk level is found after spring runoff, generally between June and the end of October.
- The least risk will be observed from November until March.

The risk of surface water contamination is highest from March until June, due to the fact that manure deposited during this period will be relatively fresh when the spring runoff occurs, and few mitigating factors will be effective at this time of year. The risk of surface water contamination with fecal micro-organisms is high, because mild temperatures lead to increased microbial survival. The risk of nutrient contamination may also be high, because for much of this period, phototrophic organisms are dormant, leaving nutrient contaminants unchanged from the forms they were in when deposited. If runoff occurs while soils are still frozen, vegetation will not be effective in filtering particulate contaminants out of surface flow, because runoff cannot infiltrate the soil profile.

In the time following spring runoff contamination risk should be lower per kilogram of manure due to increased effectiveness of factors that mitigate and retain contaminants. Increases in temperature and UV radiation result in mortality of fecal micro-organisms, and elevated temperatures also accelerate the crusting process, providing a physical barrier between fecal contaminants and runoff. Increased decomposer activity decreases the availability of organic nutrients, and nutrient uptake by plants decreases the amount of inorganic nutrients available for export. Fully leafed out vegetation in upland and riparian areas provides resistance to the efficient flow of runoff, and filters particulate contaminants out of flow.

It must be noted that most of these retentive processes can be circumvented, given sufficiently high runoff intensities. In areas subject to high frequency or high intensity precipitation events, contaminants may be washed from fresh manure before mitigation processes have been able to act.

The lowest level of risk occurs between November and March when winter temperatures kill off most fecal microbes and risk of nutrient export from manure deposited during this period is decreased due to crusting of fecal pats.

One final consideration is the role “hotspots” of manure accumulation play during this period. Given spatially heterogeneous streambank utilization exhibited by watering cattle (DeMaere and Alexander personal communication, 2011), watering sites are expected to produce more runoff, and provide less resistance to its flow. Hotspots contribute contaminants to surface water under less intense precipitation than areas less frequented by cattle. These locations may be responsible for the majority of grazing-related contaminant export from extensively managed pastures. Furthermore, if livestock remove tall woody plants from streambanks, soils become unstable and more vulnerable to erosion during runoff and flood events.

Livestock impact on surface water quality varies between years and sites, according to how much surface runoff is generated. Where precipitation events are infrequent, or of low intensity, water quality impacts should be minimal. Where precipitation events are frequent, or of a high intensity, water quality impacts may be considerable.

Grazing Impacts and Multiple Use of Rangelands

Extensive grazing activities are conducted on large areas of southern Alberta alongside many other land uses. Despite the fact that there have been very few studies conducted to directly assess extensive grazing impact on surface water quality, there have been studies examining other processes that assess water quality in areas subject to extensive grazing:

Andrews (2006) conducted a study on the water quality impacts of human recreational activity on three streams in the Ghost-Waiparous watershed, which was also subject to extensive grazing activities from mid-June to mid-October, at a stocking rate of 1583 AUMs.

- Over the study period, TN and TP concentrations were very low.
- TN concentrations did not exceed water quality guidelines in any of the streams.
- TP concentrations exceeded guideline concentrations only once in two of the streams, and twice in the third, but all of these events occurred before cattle were present in the watershed.
- FC and EC concentrations were quite low for most of the study period.
- FC concentrations exceeded irrigation guidelines at least once in all of the streams studied.
- EC concentrations did not exceed the recreational contact guideline during the period of the study but both EC and FC concentrations were seen to increase and peak during the period over which cattle were present in the watershed.

The Beaver Creek watershed is host to a variety of land uses including crop agriculture, confined livestock feeding operations, and extensive grazing operations. A water quality study was done on Beaver Creek between 2003 and 2006:

- Over four years of monitoring, water quality guidelines were routinely violated for TN, TP, and FC concentrations.
- Nutrient contamination appears to be less cause for concern than bacterial contamination, because TN and TP concentrations remain at or below the guideline concentration for most of the year, only violating guidelines during periods of highest discharge.
- FC concentrations remained at or above guideline concentrations for several months of the year in this watershed (Oldman Watershed Council, 2003, 2004, 2005 and 2006).

Note again that neither of these studies was designed to specifically assess the effects of extensive grazing activities and, as such, the reported measurements of surface water quality integrate the cumulative effects of all upstream land uses. This makes it impossible to resolve what fraction of the observed contaminant concentrations originated from extensively grazing cattle.

Given the difficulty in obtaining a definitive estimate of the impacts that extensive grazing will have on surface water quality, the following exercise - though speculative - may help to illustrate the risks that extensive grazing poses to surface water quality.

If one assumes that the figures provided in UCCE Rangeland Watershed Fact Sheet No. 25 can be applied to cattle grazing on southern Alberta's public lands, cattle defecate an average of 12 times per day, and each deposit contains 12.9g of TN, 4.2g of TP, and 3.20 x 109 fecal coliforms.

DeMaere and Alexander (personal communication, 2011) undertook a study on Bob and Sharples creeks in southwestern Alberta found that:

- over the course of two years, cattle were found to utilize a 20 meter wide buffer on either side of the stream at a rate ranging from
    - 0.7 to 1.4 AD/ha per season on Sharples Creek and from
    - 1.3 to 4.4 AD/ha per season on Bob Creek.

If the manure composition figures are applied to these utilization rates, estimated rates of contaminant loading can be calculated. If the absolute worst case scenario is assumed, and all manure that has accumulated within 20 meters of the stream was washed into the stream, this would result in a maximum loading rate of:

- 0.22 kg TN/ha, 0.07 kg TP/ha, and 6.5x109 FC/ha for Sharples Creek, and
- 0.68 kg TN/ha, 0.22 kg TP/ha and 16.9 x 109 FC/ha for Bob Creek.

To quantify these results we can compare them to nutrient export coefficients for different types of land use in Table 1.

Upon comparison it can be seen that:

- The proposed nutrient export coefficients for Bob and Sharples creeks are much lower than those observed from undisturbed forest areas, as well as areas subject to crop agriculture in Alberta and the U.S., particularly those where soils have been amended with manure.
- The range of the proposed nutrient export coefficients is also much lower than those of confined feeding and wintering sites. For both TN and TP, the proposed export coefficients fall within the range reported for grasslands, and in both cases are lower than the reported nutrient export from undisturbed grasslands in the United States.

The proposed FC export coefficients may be more of a cause for alarm, with the upper range predicting a potential export of up to 17 billion FC/ha/year. This could have impacts on water quality, particularly in lower order streams with low discharge. However, the organisms of greatest concern regarding surface water quality are the protozoan pathogens *Cryptosporidium* and *Giardia*, which are only excreted in significant quantities by calves under three months of age (for *Cryptosporidium*) and six months of age (for *Giardia*). The risk of surface water contamination with *Cryptosporidium* or *Giardia* can be minimized by limiting access to surface water for calves under six months of age.

The above discussion assumes the worst case scenario possible, that all manure deposited within 20 meters of the stream will be washed into the stream throughout the course of the year, with the contents of the manure unchanged from the time of deposition. This assumption is not valid, as degradation of manure occurs over time, and it is not possible to have 100 per cent of manure deposited washed into the stream, even in hypothetical cases of extremely high rates of precipitation on sites with heavily degraded range and riparian health. For most streams it is reasonable to assume that contaminant levels in manure will be decreased somewhat by mitigating and retentive processes.

Table 1. Nutrient export coefficients by land use. Export coefficients for extensive grazing are based on theoretical calculations, all other coefficients are based on rates of nutrient export observed by surface water quality monitoring studies.

Land Use	Location	TN (kg/ha/year)	TP (kg/ha/year)	Source
Extensive Grazing	Sharples Creek, Alberta	0.06-0.26	0.02-0.08	DeMaere (2011)
Extensive Grazing	Bob Creek, Alberta	0.20-0.68	0.06-0.22	DeMaere (2011)
Grassland	Alberta	0.2	0.017	Palliser Environmental Services (2008)
Low Intensity Agriculture	Alberta	0.22-3.81	0.02-1.01	Anderson et al. (1998b)
Medium Intensity Agriculture	Alberta	0.02-4.31	0.001-1.01	Anderson et al. (1998b)
High Intensity Agriculture	Alberta	0.02-1.64	0.2-0.32	Anderson et al. (1998b)
Confined Cattle Wintering	Alberta	0.69-7.53	N/A	Anderson et al. (1998a)
Confined Cattle Wintering	Alberta	1.15-94.29	0.13-9.26	Anderson et al. (1998a)
Undisturbed Forest	United States	3-13	0.03-0.9	Robbins (1979)
Undisturbed Grassland	United States	0.65	0.76	Robbins (1979)
Crop Agriculture	United States	0.1-13	0.06-2.9	Robbins (1979)
Soil Amended with Manure	United States	4-13	0.8-2.9	Robbins (1979)

Finally, it is assumed that the only area utilized by cattle is a buffer 20 meters wide on either side of the stream. This is clearly not true, and if loading from the buffer area was divided by the total area that cattle utilized in each distribution unit, the export coefficient for extensive grazing as a land use would be much lower than the estimates provided.

This case study and hypothetical exercise provide some insight into the contamination loading associated with extensive grazing activities, and illustrate that even in the worst case scenario, contaminant loading from extensive grazing activities is not resulting in nutrient export above background levels in rangeland watersheds, and extensive grazing should not be a land use of concern regarding water quality impacts. Maintaining functional watersheds is the best way to guard against negative impacts on water quality, and well-managed extensive grazing is a compatible land use.

Alberta