Relevance and Effectiveness of Best Management Practices to Mitigate *Cryptosporidium* Contamination of Drinking Water from Community Watersheds in British Columbia by Grazing Cattle

by

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the degree of Doctor of Philosophy

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Abstract

The literature has shown that grazing cattle can potentially contaminate surface drinking water with *Cryptosporidium parvum (C. parvum)*, a public health concern. In 2010, an audit by the British Columbia's (BC) Forest Practices Board sampled cattle faeces in Oyama Creek watershed that tested positive for *Cryptosporidium*. In response, stakeholders piloted six best management practices (BMPs) to mitigate the perceived risk to human health, including access scheduling, exclusion fencing, controlled access to water, off-stream watering, key area management, and silvopasture. A review of the literature revealed that these practices should avert human health risks.

To verify BMP effectiveness, water, cattle faeces, and sediment samples were collected from May to October during 2013, 2014, and 2015, and analyzed for *Cryptosporidium* presence and *Escherichia coli*. *Cryptosporidium* positive samples were sequenced to determine species. The maximum concentration of *Cryptosporidium* oocysts detected was 17.1 oocyst/l in an ephemeral tributary to Vernon Creek and 12.9 oocyst/l at the Oyama Creek intake, both well below what Canadian drinking water treatment systems are designed to remove.

Successfully sequenced samples were identified as *C. andersoni*, which is not generally problematic to human health. This indicates that normal BC ranching practices mitigate the hazard even without BMPs. *E.coli* presence did not correlate with *Cryptosporidium* presence.

Of the BMPs tested, access scheduling, keeping young calves away from vulnerable streams seems very effective. Exclusion fences and key area management are also effective. Controlled access watering as implemented proved problematic. No conclusions about off-stream watering or silvopasture could be made on the basis of the samples collected.

BC Centre for Disease Control (BCCDC) provided data for 56 cryptosporidiosis incidences from 2005 to 2014 in the nine Local Health Reporting Areas (LHAs) of the Okanagan Health Services Delivery Area (HSDA). The presence of grazing cattle in watersheds did not correlate with increased incidences of cryptosporidiosis in LHAs.

The conclusion from both the field and lab research, and the analysis of the BCCDC data is that grazing cattle in community watersheds in BC are not the risk to human health for cryptosporidiosis they might be perceived to be.

Lay Summary

Historical incidences and a recent audit of community watersheds in the BC interior has raised a concern about the presence of grazing cattle because of their potential to contaminate drinking water with the parasite *Cryptosporidium* causing cryptosporidiosis in humans. Stakeholders piloted a series of best management practices (BMPs) to assure the safety of drinking water sources. Water and faeces samples were collected and analyzed to verify their effectiveness. In doing so, it was determined that not only did the BMPs generally work, but that grazing cattle present a minimal risk to the water supply even without BMPs. Furthermore, reported incidences of cryptosporidiosis did not correlate with cattle presence in community watersheds. In conclusion, grazing cattle in BC's community watersheds do not pose a risk to human health.

Preface

All work presented in this document was conducted either at the University of British Columbia's Okanagan Campus, or in the Duteau Creek, King Edward (Deer Creek), Oyama Creek or Vernon Creek Community Watersheds in the Province of British Columbia and facilitated by the BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) and by the District of Lake Country and the Greater Vernon Water division of the Regional District of North Okanagan. All maps, charts, graphs, and figures in this thesis were created by the author.

Chapter 2: An extract of Chapter 2 was published in in *Agriculture, Ecosystems, and Environment* Volume 259, May 1, 2018, pages 184-193 under the title "Theoretical implications of best management practices for reducing the risk of drinking water contamination with *Cryptosporidium* from grazing cattle."

Chapter 3: The project was commissioned by FLNRORD and conceptualized and supervised by Dr. Deborah Roberts. I was responsible for providing a review of the literature pertaining to the effectiveness of BMPs and for supervising and assisting in field sample collection. Sample collection and analysis was assisted by undergraduate research assistants Alyson Stout, Noah Dietrich, Melissa Larrabee, Lindsey Hovey, Ramishka Bopearatchy, and Karen Reimann, visiting student Dikshant Sharma, and graduate student Keith Story.

A final report co-authored by Dr. Deborah Roberts, Keith Duhaime, and Keith Story on the efficacy of BMPs was submitted to FLNRORD, the BC Ministry of Agriculture, and Agriculture and Agri-food Canada in 2016. The report was titled "Verifying Best Management Practices (BMPs) for Livestock Grazing in Community Watersheds in the Okanagan Valley of BC: Final Report." Results of the research were also presented at the annual meeting of the BC Cattlemen's Association Research Forum on May 26, 2016 by Dr. Deborah Roberts and Keith Duhaime.

Chapter 4: To acquire reported individual incident data for cryptosporidiosis in the Okanagan Health Services Delivery Area, a formal data request application was made to the BC Centre for Disease Control on September 15, 2016 with notice of approval on January 17, 2017. This data is held in confidence at UBC Okanagan and is only presented in summary within this thesis.

Funding for this project has been provided by the BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development, and Agriculture and Agri-Food Canada (AAFC) and the BC Ministry of Agriculture through the Canada-BC Agri-Innovation Program under Growing Forward 2, a federal-provincial-territorial initiative. The program is delivered by the Investment Agriculture Foundation of BC. Opinions expressed in this document are those of the authors and not necessarily those of AAFC, the Ministry of Agriculture or the Investment Agriculture Foundation.

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List of Abbreviations

BC	British Columbia
BC CDC	BC Centre for Disease Control
BCGW	BC Geographic Warehouse
BMP	Best Management Practice
DWI	Drinking Water Intake
FAO	Food and Agriculture Organization
FLNRORD	BC Ministry of Forests, Lands, Natural Resource Operations, and Rural Development
FPB	Forest Practices Board
FPC	Forest Practices Code
FRPA	Forest and Range Practices Act
GIS	Geographic Information System
GPS	Geographic Positioning System
HSDA	Health Service Delivery Area
IHA	Interior Health Authority
LHA	Local Health Reporting Area
WHO	World Health Organization

Dedication

The creation of this dissertation has been less about an objective or goal as it has been about a personal journey of gaining insight and understanding. As with any significant journey in our lives, it would not have been possible without the love, faith, and guidance of supportive family, friends, and peers.

I would like to begin by recognizing my supervisors, Dr. Deborah Roberts and Dr. John Janmaat for all their guidance and support. To them I am eternally grateful for their wisdom and knowledge in providing me direction on my journey. I would next like to recognize the many good friends, professional colleagues, and acquaintances that have provided encouragement and moral support throughout the journey.

I would like to especially recognize my loving wife, Aldyn Overend, my partner in life, and in this project no less for all her encouragement, support, and patience. The journey has been long, and at times challenging, but there is no other individual I would have or could have shared it with better.

I would also like to recognize my personal family at this time. I dedicate this dissertation to the memory of my loving parents Hughen and Fredericka Duhaime, and to my two brothers Mark and Murray, both taken from us before their time.

And finally, most recently, to the memory of my dear nephew Spencer, who was taken from us so recently as I was in the midst of completing this dissertation. He was such a delightful young man to have along on our journeys in the woods. He will be dearly missed as I continue on my own life journey.

Chapter 1.0 Introduction

The objective of this chapter is to provide a context to understand the history and circumstances both locally and globally that has created the need for this research, the specific research objectives, and present the structure of the thesis. The purpose of this thesis is to address whether grazing cattle in pastures upstream of community water drinking systems pose a threat to human health and the role and necessity of six proposed and piloted best management practices (BMPs) in mitigating this potential threat to human health. The proposed BMPs are:

1. Access scheduling.
2. Exclusion fencing.
3. Controlled access to water.
4. Off-stream watering.
5. Key area management.
6. Silvo-pasture.

Grazing cattle on crown pastures is a common practice in parts of the province of British Columbia, Canada and on public lands in other locations around the world. Unfortunately, cattle are a host of *Cryptosporidium parvum*, a parasite that can cause illness in humans. This thesis addresses the extent to which grazing cattle in community watersheds pose this specific health risk, and the relevance and efficacy of the piloted BMPs to mitigate this risk.

1.1 The Challenge of Protecting Water Quality in Multi-use Watersheds

In many parts of the world, communities are dependent on surface water sources for at least part of their drinking water supply. In the province of British Columbia (BC), approximately 87% of the population relies on surface water sources for this purpose. Similarly, 70% of Canadians are dependent on surface water sources (Statistics Canada, 1996). Globally, surface water is also a significant portion of national and regional water supplies (Wada et al., 2014, FAO, n.d.).

Heavy reliance on surface water sources for drinking and other purposes makes assuring its safety and quality a paramount concern. In many instances, surface water catchments and watersheds are not exclusively used for providing drinking water. A diverse set of stakeholders require and use the resources in these watersheds for other purposes, including agriculture, forestry, and recreation. When watersheds are used for multiple purposes, concerns arise as to how these other uses might impact water quality and safety for human consumption (Wilber, 1940, Liang et al. 2013, FPB 2012). In multi-use watersheds and catchments used for drinking water, potential exists for conflict between upstream and downstream stakeholders (Postel et al. 2005, Ffolliott et al. 1986). The primary concern is that activities conducted by upstream stakeholders might compromise the ability of downstream stakeholders in realizing their benefits through compromised water quality or safety.

1.1.1 Multi-Use Watersheds

Figure 1.1 illustrates the complexity that results with multiple land uses in a watershed, the stakeholders and activities involved, and how these activities might adversely affect drinking water. Humans, livestock, and wildlife all engage in activities in watersheds that might result in physical, chemical and biological hazards adversely affecting drinking water sources. These hazards can be aggravated by the basic geographic properties of the watershed such as soil, terrain, hydrology, and land cover, and by both the natural (climate and weather) and anthropogenic (political, and economic) environments in which a watershed or drinking water catchment exists. Ultimately these hazards might affect residential, agricultural and other water users. Examples respectively include increased turbidity from forestry operations, petrochemical spills from recreational vehicles, and microbial hazards including parasites from wildlife, livestock or human presence in the watershed.

As illustrated in Figure 1.1, stakeholders conduct these activities with their associated risks in community watersheds with the expectation of gaining benefits from the landscape. These include economic benefits such as the production of timber or cattle, and social benefits such as recreational activities like hunting, hiking, or biking. Furthermore, these same stakeholders may also be reliant on the same watersheds as a source of safe, high quality water for drinking, agricultural, or other purposes.

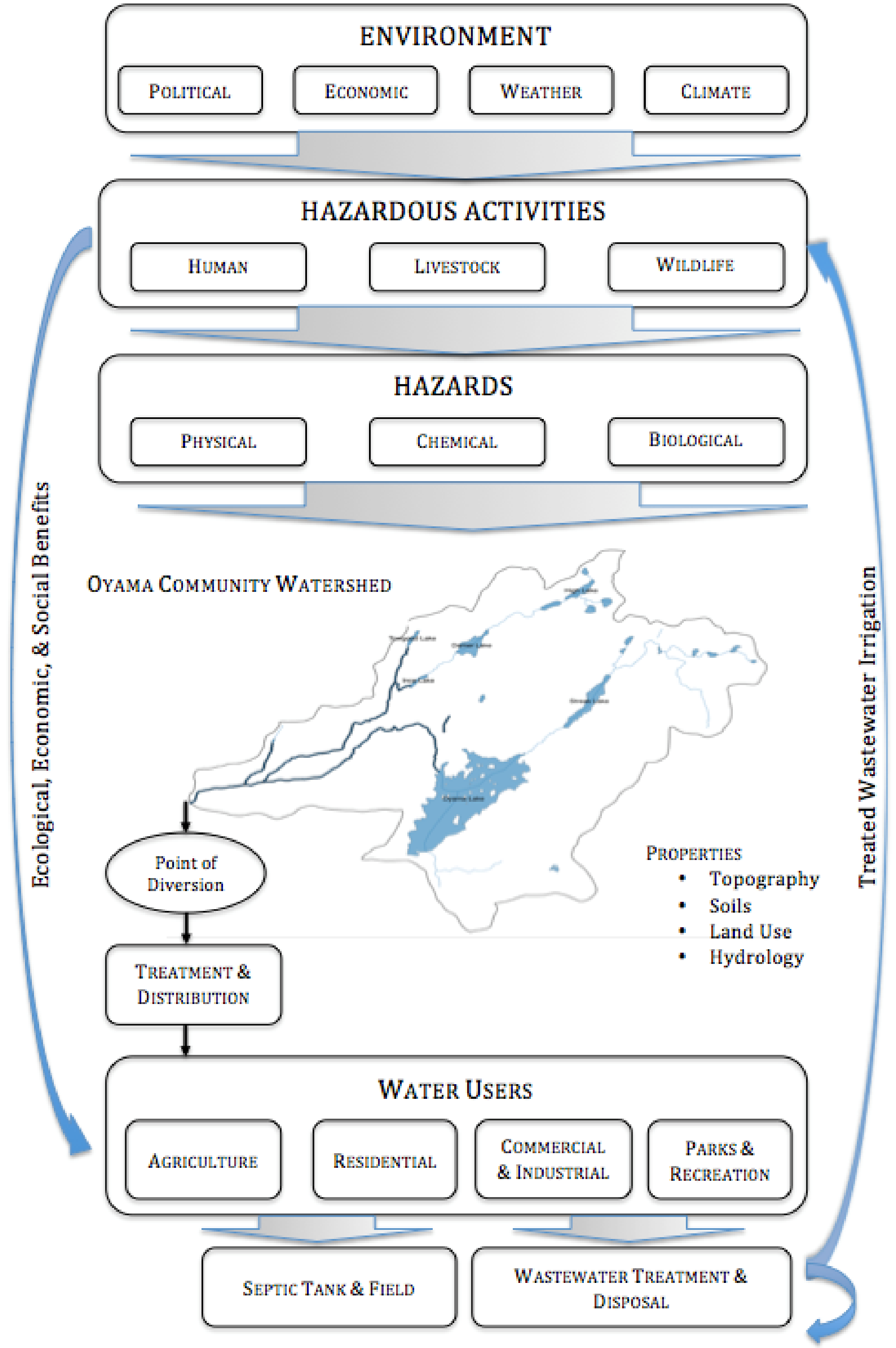


Figure 1.1 The complexity of multi-use watersheds.

As previously stated, potential exists for conflict between upstream and downstream stakeholders. This might be conflict between downstream users dependent on the watershed as a drinking water source versus upstream users dependent on the watershed for economic activities such as forestry and cattle grazing. The same users in some instances might be dependent on a watershed for both drinking water and for other beneficial activities. In the instance where the watershed is used for both purposes by users, it may be expected that the users will manage their upstream activities to not compromise their downstream benefits.

1.1.2 Grazing Cattle

In the province of BC, 94% of the 944,735 sq. km. (Statistics Canada, n.d.) land base is publicly owned and referred to as 'Crown land'. This land is administered by the BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) under the Forests and Range Practices Act (Province of BC, 2002). FLNRORD is charged with leasing land for multiple uses. One of these uses is as rangeland to cattlemen for grazing purposes.

Grazing cattle on rangeland within community drinking water catchments is recognized for providing a number of benefits including being an economical source of forage for cattle, increasing biodiversity, inhibiting the spread of invasive species, and reducing fuel-loads for fires (Huntsinger et al. 2007). However, grazing cattle in community watersheds is also an activity of concern both locally in BC (FPB 2012) and globally (Atwill 1996) for its potential to contaminate drinking water surface sources with *Cryptosporidium parvum* (*C. parvum*) oocysts via either defecation directly into these surface water sources or by defecation very near them where runoff, erosion, and other mechanisms might result in contaminated faeces subsequently being transported into surface water sources.

C. parvum is an enteric protozoan parasite that causes cryptosporidiosis in humans (Holscher et al. 1976, J.B. Rose 1988, US CDC n.d.). It also infects cattle (Xiao et al. 2004). *C. parvum* is transported from one host to host by non-reproductive oocysts (see Figure 1.2). *C. parvum* oocysts are typically 4 to 6 μm in diameter with a specific gravity of about 1.05 g/cm^3 (Searcy et al. 2005).

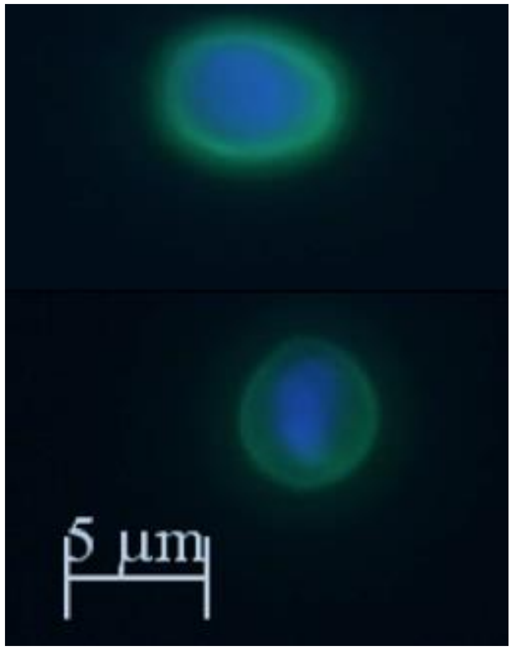


Figure 1.2 Epifluorescent images of FITC-mAb immunofluorescence and DAPI stained *C. parvum* oocysts.

A single defecation from an infected individual can introduce from 10^5 to 10^9 oocysts into the environment in a faecal pat and an infected cow can produce as many as 10^{10} oocysts in a 24-hour period (Chappell et al., 1996). Humans cans be infected through the ingestion of as few as 10-30 oocysts (Chappell et al., 1996; DuPont et al., 1995).

Figure 1.3 illustrates the threat posed by grazing cattle using the Oyama Creek Community Watershed as an example. Horse Lake Pasture overlies Oyama Creek watershed and is leased to cattlemen for grazing purposes. The cattle herd consists of 300 cow-calf pairs turned into the pasture for periods in the summer and fall months. The possibility exists for some of these cattle to shed *C. parvum* oocysts in their faeces (Atwill 1996, Gow et al. 2006). Cattle may deposit their faeces directly into watercourses with the possible consequence of *C. parvum* oocysts being washed directly into a drinking water intake. Alternatively, cattle may deposit contaminated faeces on the ground near watercourses with subsequent transportation into the stream via climate driven hydrological processes or other mechanisms. In either instance, there is a perceived possibility that a threat is posed to the health of the 12,000 residents served by Oyama Creek Community Watershed. Other mechanisms that might transport contaminated faeces into water sources may include off-road vehicle tires and human footwear (Chambers et al. 2009).

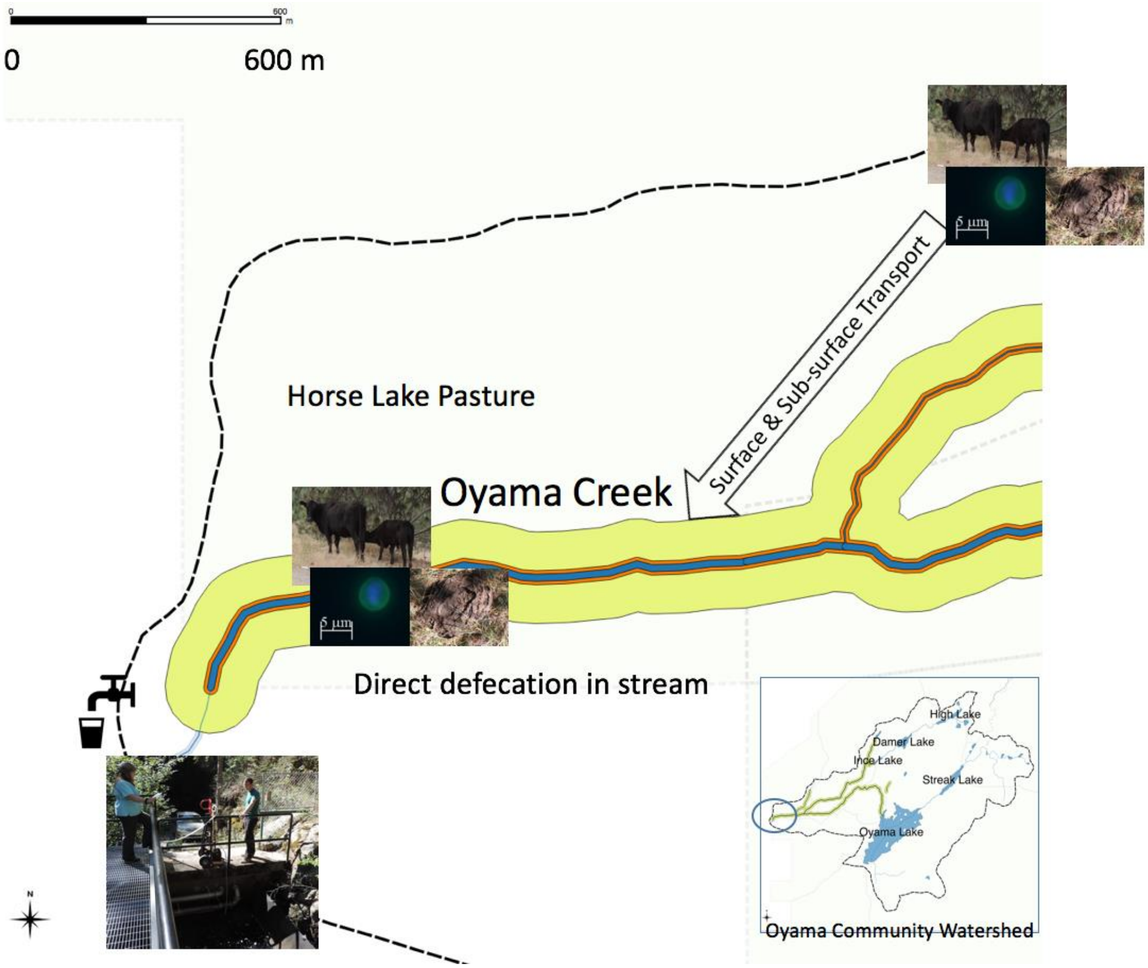


Figure 1.3 Grazing cattle hazard in a community watershed.

To mitigate the threat grazing cattle pose community watershed pastures, cattle grazing must be managed in a manner that even though the cattle may carry *C. parvum* and deposit oocysts in their faeces, their potential to deposit contaminated faeces in or near surface water sources is minimized. The purpose of this thesis is to verify the extent of the threat posed by cattle grazing and *C. parvum* in community watersheds, to verify the effectiveness of management practices trialed to mitigate this hazard, and to provide data, information and decision support in the selection of management practices to mitigate the hazard.

1.2 Background and Historical Context

The purpose of this section is to provide the reader with the historical contexts that have motivated the research upon which this thesis is based.

1.2.1 Range Program and Grazing Leases

The BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORDa, n.d.) explicitly recognizes that "the economy of BC and of local communities is dependent on resource industries having access to Crown land." FLNRORD recognizes the long history of multiple uses in BC watersheds to accommodate forestry, mining, guide outfitting, recreational uses, and cattle grazing. The need of cattlemen for access to public land to graze cattle has a history extending back over 140 years. This has been formally regulated since the formation of the BC Forest Service in 1912 and to this day under the Forest and Range Practices Act (FRPA) (Province of BC, 2002). FLNRORD administers crown land for cattle grazing purposes under its Range Program (FLNRORDb, n.d.). The province of BC's GIS (Appendix A) inventory indicates there are 4356 recognized crown range pastures comprising 8.7 million hectares of land for lease to cattlemen for cattle grazing (BCGDS, n.d.). The value to the cattlemen of the BC interior is captured in the rents paid to FLNRORD for the pasture leases. Currently, this is approximately $4.25 million per annum[1]. Figure 1.4 provides an illustration of the extent and distribution of these pastures in BC.

1.2.2 Community Water Supply Watersheds ('Community Watersheds')

While BC government agencies recognize the need for multiple stakeholders to access Crown land, there are also concerns with respect to how these other uses might impact the quality and safety of water resources in the province of BC. Of particular concern were those catchments and/or watersheds that provide water to licenced community water systems. As a result, in 1980, an interagency task force of the province of BC, recognizing the heavy reliance on surface water for community drinking water needs, established the designation Community Water Supply Watershed ('community watershed') (BC Ministry of Environmental Protection and Sustainability, 2016). The primary purpose for designating community watersheds is to recognize them for special management practices and considerations to assure the safety, quality and quantity of the water supply to the communities they serve. Community watersheds were defined as 'any natural watershed area on which a community holds a valid water license'. The province's Comptroller of Water Rights issues water licenses under the Water Act (Province of

1 pers. communications. Robert Dinwoodie, Range Agrologist, BC Ministry of Forests, Lands, and Natural Resource Operations, Thompson-Okanagan Region.

British Columbia, 1996). Community watersheds currently supply approximately 75% of the population of BC (4.68 million, Statistics Canada 2015) with drinking water (Table 1.1). Another 12% of the population of BC are served by surface water sources without community watershed status. Originally 285 watersheds were designated as community watersheds. There are currently 466 designated watersheds in BC.

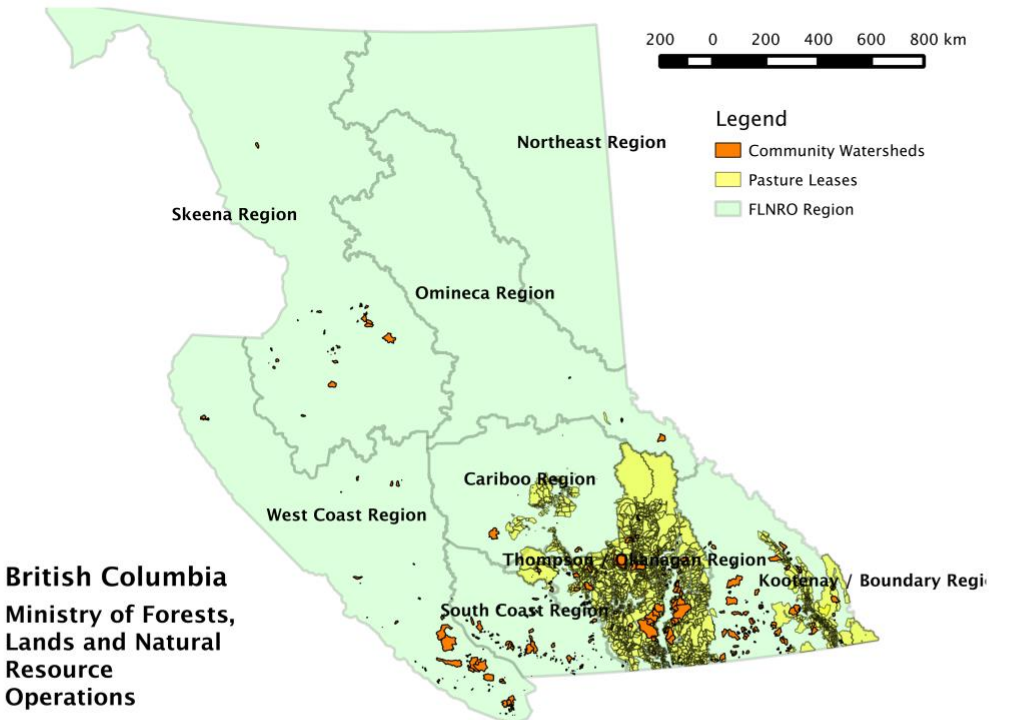


Figure 1.4 Community watersheds and pasture leases in the Province of BC

Table 1.1 Water source supplies in BC communities (FLNRORD, 1996)

Water supply source	Percentage of BC population served
Forest Practices Code Community Watersheds	
Greater Vancouver (Crown lease land)	52
Rest of province	23
Subtotal Community watersheds	**75**
Other Watersheds & Sources	
Owned land (Greater Victoria Water District)	9
Large Lakes	8
Wells, springs	8
Subtotal other watersheds/sources	**25**
Total all watersheds & sources	**100**

Section 9, paragraph 150 of the FRPA specifically recognizes the need and authority to create and regulate community watersheds and to 'establish water quality objectives in relation to a community watershed', subject to the Water Sustainability Act (Province of BC, 2014). However, designation as a 'community watershed' does not confer exclusive use of community watersheds for community drinking water needs except in special cases. The community watersheds supplying the Metro Vancouver region are a special case because they have been purchased and they are designated exclusively for the provision of drinking water (BC Tap Water Alliance, n.d.). The Capital Regional District of BC, including the city of Victoria, has also pursued a closed watershed policy (CRD, n.d.). Almost all other community watersheds in BC do not have this level of assurance to protect water quality.

1.2.3 Cattle Grazing and *Cryptosporidium*

As previously discussed, cattle grazing is a permitted use of crown land in community watersheds. Cattle grazing is the placement of cattle (predominantly cow-calf pairs) on range land for foraging within crown range pastures. Under the province of BC's Range Act (Province of BC 2004a), leases can be contracted with cattlemen for this purpose from 15 to 25 years subject to the conditions of the Forest and Range Practices Act (Province of BC 2004). Cattle grazing provides revenue to provincial coffers, economic activity for the communities served by watersheds, and environmental benefits.

Initial analysis of the province of BC's GIS data (Appendix A) indicates that of the 466 community watersheds in BC, there are 122 community watersheds with crown lease grazing pastures present. Because of two events in BC in 1996, both the public and health authorities perceive a potential threat of contamination of drinking water source streams with faeces containing pathogens, and in particular *Cryptosporidium* either through direct defecation into water sources or nearby from which it might be then transported into a water source by natural or anthropogenic mechanisms.

1.2.3.1 Cryptosporidiosis Incidents in BC

In 1996, outbreaks of cryptosporidiosis in the cities of Kelowna and Cranbrook (both municipalities within BC) raised public concerns of the potential for cattle faeces to contaminate drinking water with *Cryptosporidium* and other pathogens (Newman et al. 2003). The Cranbrook incident was estimated to have affected over 2000 people, and the Kelowna incident 10,000 people. In neither case was there conclusive evidence to prove that cattle were the source of these outbreaks, but public perceptions still exist.

In response to elevated levels of faecal coliforms at the Vernon Creek and Oyama Creek intakes for the District of Lake Country, BC., in October of 2010 an audit of these two community watersheds by the Forest Practices Board (FPB) of BC was conducted (FPB, 2012). The two major activities in the watersheds that the FPB focused on were forestry and cattle grazing. The FPB expressed satisfaction with the practices and processes used by forestry industry operators to mitigate adverse effects on water quality, but expressed concerns over cattle grazing activities. Of particular concern were cattle faeces samples collected within close proximity to the North Fork stream in the Oyama Creek community watershed that tested positive for *Cryptosporidium*. Grazing leases exist within both of these watersheds.

Figure 1.5 illustrates the area where the FPB audit was conducted on both the Oyama Creek and Vernon Creek community watersheds along with overlaps of the Crown grazing pastures with cattle that are of concern. Of special note is the area where the faeces was sampled that subsequently tested positive for *Cryptosporidium*. It is directly upstream of an intake providing drinking water for the municipality of the District of Lake Country.

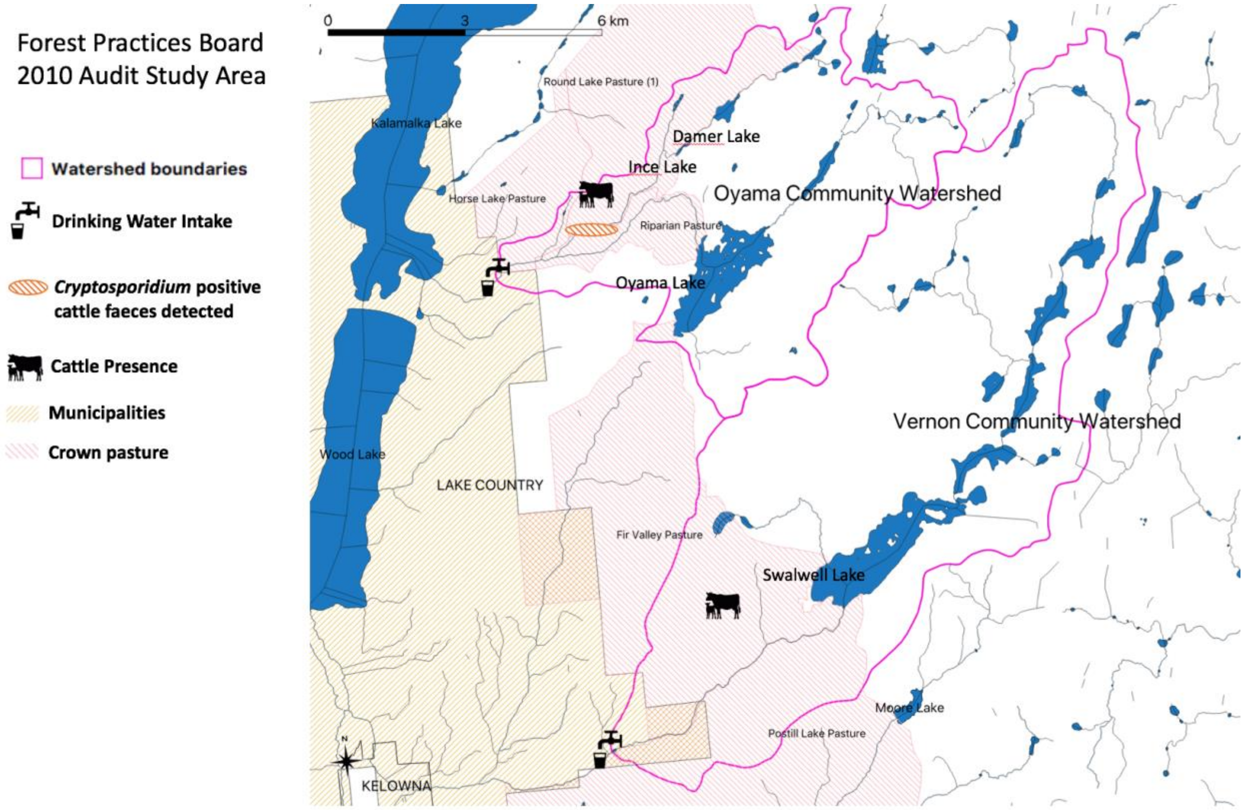


Figure 1.5 FPB (2012) audit watersheds

1.2.3.2 Public Health Authority Concerns

In addition to the concerns raised by the Forest Practices Board audit of 2010, the Interior Health Authority (IHA) of the BC Ministry of Health has also expressed concerns with respect to the presence of grazing cattle within community watersheds. Figure 1.6 illustrates IHA's jurisdiction within BC (Appendix A). Each health authority in BC is in turn divided into Health Service Delivery Areas (HSDA) of which IHA contains four; Thompson Cariboo Shuswap, East Kootenay, Kootenay Boundary, and Okanagan (Appendix A). As illustrated in Figure 1.6, the Okanagan HSDA contains significant overlap of community watersheds on crown pastures available for cattle grazing.

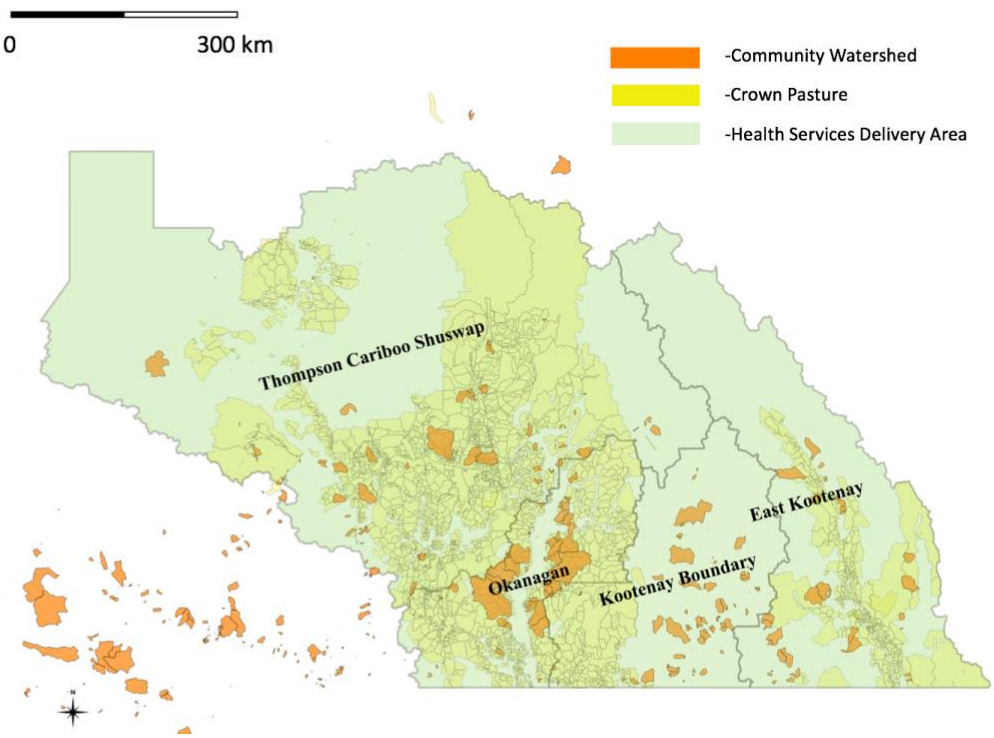


Figure 1.6 Health Service Delivery Areas within the Interior Health Authority

Figure 1.7 illustrates the reported incidences of cryptosporidiosis in BC from 2003 to 2014 (BC CDC, n.d.). The overall trend for incidences of cryptosporidiosis over this period is down from 3 to 4 incidents per year per 100,000 population to approximately 2 per year per 100,000 population. Figure 1.7 also contrasts the reported incidences in the Okanagan HSDA with the reported incidences in the other three HSDAs within the IHA, HSDAs under the jurisdiction of Vancouver Coastal Health Authority (VCHA), and the HSDAs in the remainder of the province. It is noteworthy that HSDAs within the VCHA have the highest reported incidences of cryptosporidiosis over the period from 2003 to 2014, whereas with the exception of 2006, the Okanagan HSDA often has the lowest incidence of reported cryptosporidiosis. This is particularly noteworthy given that the community watersheds serving the communities within the VCHA have been completely fenced off from access and have a policy in place permitting access only under very specific circumstances to assure water quality and safety. This contrasts with the public health data on cryptosporidiosis in the Okanagan HSDA, where community watersheds are hosts to a number of anthropogenic activities including cattle grazing.

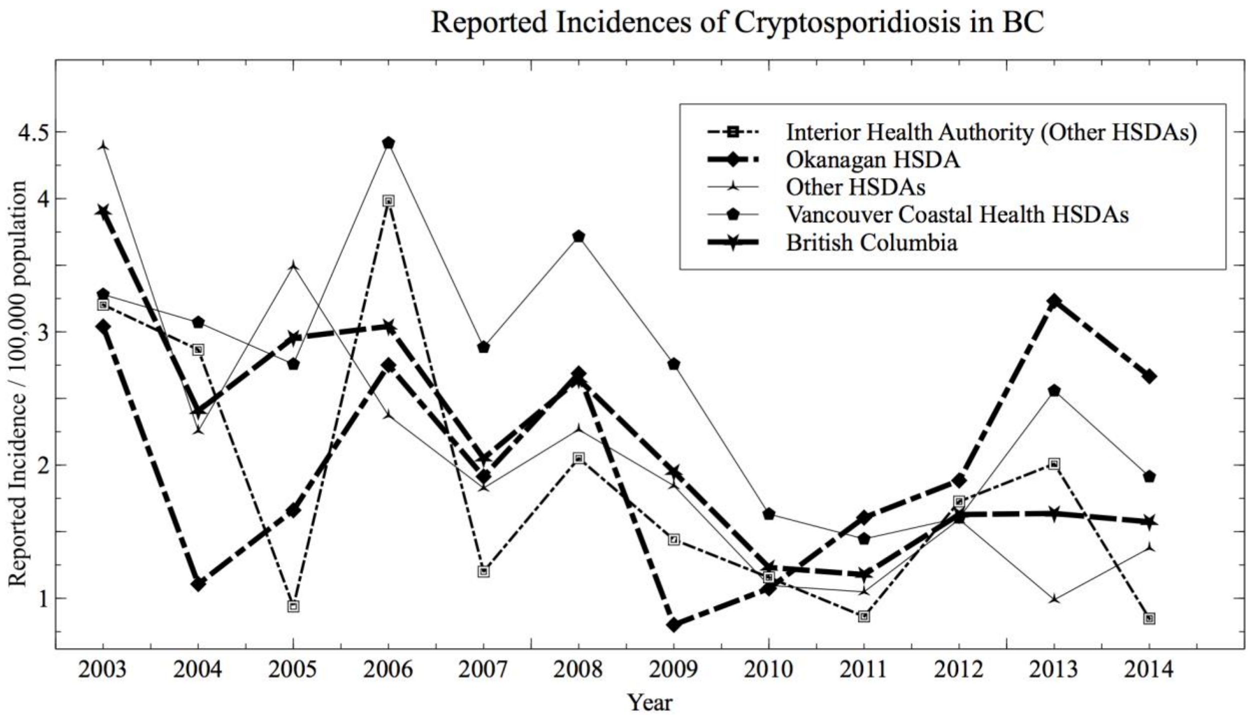


Figure 1.7 Incidences of cryptosporidiosis in BC.

1.2.3.3 Best Management Practices Pilot Project

In response to the FPB audit, FLNRORD collaborated with the cattlemen grazing cattle in these two watersheds and pastures in the Duteau Creek and King Edward (Deer Creek) community watersheds to pilot a set of best management practices (BMPs) as a proof of concept to demonstrate the ability to mitigate adverse effects on surface water resources even with grazing cattle present. This project was initiated in 2012 with full implementation of the BMPs under trial beginning in the 2013 grazing season.

In the context of cattle grazing in community watersheds, a Best Management Practice can be broadly defined as a policy, practice, or physical infrastructure improvement that is expected to reduce the potential for the contamination of drinking water from cattle faeces. The intention in the design and implementation of the BMPs is to 1) restrict and/or control access of potentially infectious cattle to drinking water source streams, and/or 2) attract cattle away from drinking water streams to other areas.

Figure 1.8 provides an illustration of the four watersheds comprising the pilot study area; Duteau Creek, Vernon Creek, King Edward (Deer Creek) and Oyama Creek watersheds. Figure 1.8 also illustrates the pasture leases overlaying these watersheds deemed to have the greatest potential to contaminate water from pathogens in cattle faeces; CJ Express, King Edward, Round Lake, Riparian, and Fir Valley pastures being of particular concern. These pastures were deemed particularly problematic due to their proximity to drinking water intakes and/or diversions for human use in the community watersheds. As previously discussed, the Oyama Creek and Vernon Creek community watersheds serve the District of Lake Country. The Duteau Creek and King Edward (Deer Creek) watersheds serve the Greater Vernon Water authority. It should be noted that the King Edward (Deer Creek) watershed does not currently have an active drinking water intake present.

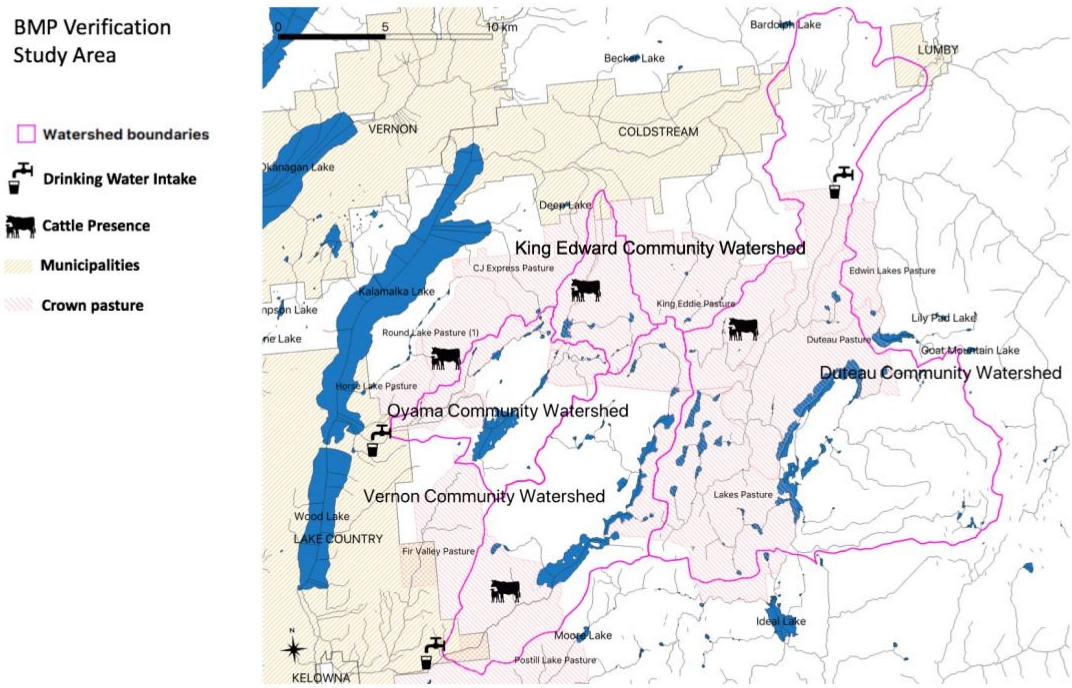


Figure 1.8 BMP pilot project study area.

1.2.3.4 Piloted Best Management Practices

Six best management practices (BMPs) were implemented and assessed in the pilot project area. The underlying theory guiding the implementation of each of these BMPs for the pilot project is the result of the current understanding of the threat posed by grazing cattle and *C. parvum*. This threat will be discussed within the literature review of this thesis (Chapter 2). Chapter 3 will further discuss the theory and rational implicit in the use of each of the BMPs. The BMPs implemented in the pilot project can be summarized as:

1. Scheduling the access of cattle to potentially sensitive areas so that calves less than three months of age are not present in watersheds to deposit faeces in watercourses.

2. Restricting direct access to watercourses and immediate riparian areas with fences and other barriers to prevent cattle from directly defecating in them.
3. Controlling the type of physical access to water sources that cattle have. For example, using a nose hole in fences bounding streams to provide cattle with water access but with mitigated ability to defecate in watercourses, or alternatively using a debris field of downed trees crisscrossing streams.
4. Managing key areas to mitigate the ability for cattle faeces to be transported into watercourses. For example, monitoring stubble height and assuring that it provides an effective means of filtering and restricting faeces movement to streams and watercourses.
5. Providing water sources such as watering tanks, nose pumps, and similar devices that are physically removed from streams and riparian areas to attract cattle away from these sensitive areas.
6. Providing foraging and other resources such as silvo-pasture that attract cattle away from sensitive areas such as watercourses and adjacent riparian areas.

1.2.3.5 BMP Effectiveness?

A central question to this thesis and of concern to the FPB, health authorities, FLNRORD, water purveyors, and other stakeholders is the effectiveness of the BMPs in the pilot project at mitigating the potential adverse impacts grazing cattle might have on drinking water sources, especially contaminating water sources with *C. parvum* oocysts.

To verify BMP efficacy in the pilot project, FLNRORD approached the Biological Solutions Laboratory at UBC-Okanagan under the direction of Dr. Deborah Roberts in the spring of 2013 to assist with validating the BMPs as they are currently implemented. FLNRORD provided financial support to the research in the first year (2013). The Regional District of North Okanagan via the Greater Vernon Water Authority also contributed funding to develop sampling plans and the laboratory methodology for tracking the source of *Cryptosporidium* pathogens in Okanagan watersheds in 2013. Subsequently, support was also provided by the BC Cattlemen's Association and the District of Lake Country. Further funding was also provided by FLNRORD in 2014 and 2015 to support field sampling and laboratory analysis and related research. The Investment Agriculture Foundation of BC also contributed support to the research under the Growing Forward 2 federal-provincial partnership program to encourage innovation in Canada's agricultural sector. Undergraduate students were also engaged in the research via the UBC Work Study Program.

Field and lab research was conducted through the late spring, summer, and fall of 2013, 2014, and 2015 grazing seasons. The focus of the work in 2013 was to establish methodologies and protocols for both water and faeces sampling, and analysis for subsequent work to more thoroughly validate the BMPs in use as a means of mitigating the hazard of *Cryptosporidium* contamination of drinking water surface sources. The initial work also provided an opportunity to review the scientific literature for similar and related research into cattle grazing as a potential hazard to drinking water safety and quality. An additional outcome was the realization that there is no support tool, framework, or process that the BC government and the cattle agriculture industry can use to analyze the potential hazard posed by grazing cattle in pastures on crown land and in the selection of BMPs to address those hazards.

During the 2014 and 2015 grazing seasons, further field sampling of water and faeces was conducted in the study area. In parallel, a controlled field study to determine the persistence of *Cryptosporidium parvum* in the climate and environmental conditions of the Okanagan was also conducted. A final report has been submitted to FLNRO detailing both the field research and the persistence study (Roberts et al. 2016).

1.2.3.6 Extending the Research: Cattle Grazing BMPs beyond the Study Area.

In crown pastures not part of the study area, cattle grazing may contaminate drinking water sources. As previously cited, 122 of the 466 community watersheds contain pastures for cattle grazing. Table 1.2 provides a summary of these watersheds by each FLNRORD administrative region as well as the number of pastures spanning community watersheds in each region. The Thompson/Okanagan region of FLNRORD is the primary region where potential community drinking water sources may be adversely affected by the presence of grazing cattle due to the overlapping land uses. Pressure from local governments, provincial government agencies, water purveyors, and other stakeholders exists to expand the use of BMPs to other watersheds beyond the four used in initial pilot project. A question many stakeholders have is which BMPs are applicable in each watershed and pasture situation where potential exists for grazing cattle to contaminate drinking water surface sources. Can tools be developed that use the results of the study area research in conjunction with data and information available about each pasture and watershed to determine the most effective and efficient BMPs to use?

Table 1.2 Community watersheds and grazing pastures by FLNRORD region

FLNRORD Region	Community Watersheds	Pastures*
Cariboo	1	1
Kootenay / Boundary	32	64
Southeast Coast	1	1
Thompson / Okanagan	88	361
Total	122	419
* Note that in several instances, pastures span both multiple watersheds and FLNRORD regions.		

To address this need, Investment Agriculture Foundation of BC funded a second body of research to develop information and decision support tools to extend the research results from the study area to the other 118 community watersheds in the province of BC with grazing cattle pastures. The intention of these tools is to aid stakeholders and decision makers in these watersheds to determine which BMPs can be expected to be most effective, and which will be the most efficient at reducing risk relative to impacts on human health, invested time, effort, financial resources, and opportunity costs.

1.3 Objectives of the Research, Thesis Structure, and Key Questions

The over-arching objective of the research is to assist decision makers and stakeholders in minimizing the risk of *Cryptosporidium* contamination from grazing cattle to the safety and quality of drinking water from community water supply watersheds (‘community watersheds’). This research has been conducted to prove the efficacy and limitations of BMPs in a study area consisting of four watersheds. The objective now is to extend the results of this research into other watersheds that host grazing cattle in crown lease pastures to mitigate the potential human health hazard of cryptosporidiosis from cattle faeces contaminated drinking water.

The goals of the research are to provide information and decision support that is objective, transparent, and consistent in evaluating;

1. the risks posed by grazing cattle to community watersheds,
2. how BMPs might mitigate those risks, and
3. which BMPs can do so in the most efficient manner to the benefit of all stakeholders.

1.3.1 Thesis Structure

To achieve this objective, the research and thesis is structured in components, each with its own objective, and each comprising its own chapter within the thesis. The goal is to transition the reader from an initial understanding of how *Cryptosporidium parvum* and cattle pose a potential hazard to human health in community drinking water sources to an assessment of the hazard and how the hazard can be mitigated.

The components of the research and thesis chapters are summarized as follows:

1. Chapter 2: Provides a review of the literature with respect to *C. parvum,* cattle grazing as potential *C. parvum* hazard to drinking water, the factors on a landscape and in the environment that might affect the potential hazard, how cattle and *Cryptosporidium* interact with their environment to create this hazard, and how the potential for the hazard to occur might be mitigated with BMPs. The results of the literature review will then be used to explore two scenarios, one without BMPs, and one with BMPs to determine the potential of BMPs as a means of mitigating the hazard.
2. Chapter 3: Through field sampling and laboratory analysis of faecal and water samples collected over three grazing seasons, verifies that the BMPs developed and implemented within the pilot study area watersheds are effective, the limits to their effectiveness, their failings, and where and under what conditions they demonstrate an actual change in water quality for the residents of the communities they serve.
3. Chapter 4: Provides a better understanding of true magnitude of the threat grazing cattle pose to public health when present on crown pastures in community watersheds. Data provided by the BC Centre for Disease Control (BC CDC) on the reported incidents of cryptosporidiosis in BC will be correlated with cattle presence in community watersheds to determine the true extent of the hazard.
4. Chapter 5: In this chapter, the expected results from the literature will be compared and contrasted with the results of the BMP verification project (Chapter 3) and the data received from the BC CDC (Chapter 4) to gain an understanding of the discrepancies between the theoretical extent of the hazard grazing cattle pose in community watersheds, and the threat they actually pose.
5. Chapter 6: Provides an overview of the results and discussion of the research along with final conclusions and recommendations for future research

1.3.2 Key Questions

In addition to achieving the objectives previously described, if the research is to be deemed successful by the supporting partners and stakeholders, there are a series of key questions that must also be answered. These questions are important to validating the underlying assumptions inherent in achieving the overarching objective. These can be summarized as follows:

1. Are the BMPs currently being used effective in reducing the potential microbial hazards to drinking water from cattle faeces?
2. Are the BMPs currently in use the most efficient in reducing the potential microbial hazards to drinking water from cattle faeces relative to required effort and resources for their implementation?
3. Are grazing cattle in BC's community watersheds a real and ongoing threat to public health?
4. Can the risks associated with different watershed scenarios involving cattle grazing, best management practices, and water consumers be better quantified?
5. Given a new community watershed scenario, can best management practices be selected and implemented that will provide both effective and efficient risk mitigation?

Research to date and the further work to be proposed are all focused on answering these questions to validate whether the research has achieved its objectives.

Chapter 2.0 Literature Relevant to this Research

This chapter of the thesis provides a review of previous research and outcomes from the academic literature relevant to the current research. Chapter 1 has established that the motivation for the research in this thesis is the presence of grazing cattle within a landscape common to the provision of drinking water, the potential for these cattle to contaminate these water sources with the parasite *Cryptosporidium parvum (C. parvum)*, and the initiation of a pilot project to determine the potential of BMPs to mitigate the hazard to human health. The purpose and goal of this literature review is to provide a better understanding of grazing cattle and *C. parvum* as a hazard to human health, the factors that affect the manifestation of the hazard, and the potential for BMPs to mitigate this hazard. To this end, the literature review will cover the following:

1. An introduction to *Cryptosporidium*, cryptosporidiosis and *Cryptosporidium parvum*, its infectivity, and why it is problematic relative to other waterborne pathogens.
2. An overview of previous research characterizing the presence of *Cryptosporidium* in grazing cattle including a brief review of the history of *C. parvum* incidences that have focused attention on grazing cattle as a source and the incidence of *C. parvum* in grazing cattle.
3. A review of the spatial and temporal pattern of grazing cattle behaviour, their defecation on rangeland and the behaviour that contributes to this pattern, and how grazing cattle behaviour contributes to the hazard.
4. An explanation of the fate of *C. parvum* oocysts in the environment. If not directly deposited in sensitive watercourses, what do we know about the transport of oocysts to watercourses? Also, given the exposure that oocysts will receive in the natural environment, what does the current research tell us about their persistence and ability to remain infectious should they reach a diversion to a drinking water system?

In closing, two hypothetical scenarios will be explored on the basis of the findings in the literature. The first scenario will explore the potential for drinking water from a community watershed after treatment to contain a sufficient dose of *C. parvum oocysts* to result in human illness. In contrast, the second scenario will explore whether or not drinking watershed from a community watershed with the piloted BMPs in place is still likely to be a hazard to human health. A synopsis of this literature review along with the two scenarios explored has been published in the journal Agriculture, Ecosystems, and the Environment (Duhaime et al., 2018).

In subsequent chapters, further literature will be introduced with respect to Best Management Practices (BMPs) to mitigate the hazard (Chapter 3), the analysis of public health data from the BC Centre for Disease Control (Chapter 4), and the analysis of rangeland and cattle behaviour to explain discrepancies between the theoretical exposure to *C. parvum* from grazing cattle and those experienced from the field sampling conducted to verify the efficacy of the piloted BMPs (Chapter 5).

2.1 *Cryptosporidium* and Cryptosporidiosis.

Cryptosporidium is a family of obligate enteric protozoan parasites now recognized as an important pathogen. It was first identified by Edward Tyzzer (1907) in the gastric glands of mice. The particular species of *Cryptosporidium* discovered by Tyzzer was subsequently identified as *Cryptosporidium parvum (C. parvum)*. It would not be until 1976 that it would be recognized as the cause of the illness cryptosporidiosis in humans and animals (Holscher et al., 1976, J.B. Rose, 1988). Incidences of cryptosporidiosis can be found all across the world (Carey et al., 2004). There are approximately 748,000 cases in the United States (Scallan et al. 2011) and 25,000 cases in Canada (Thomas et al., 2013) per annum.

2.1.1 Species of *Cryptosporidium*

There are currently 27 different species of *Cryptosporidium* that have been identified (Ryan et al., 2015). Each species requires a relatively narrow range of host conditions; hence only certain animal species can host a particular *Cryptosporidium* species. Only three species (*C. parvum*, *C. hominis*, and *C. meleagridis*) are known to use humans as a major, or preferred host. *C. parvum* has the ability to infect both cattle and humans has made it a major concern of range, water quality, and public health professionals (Ryan et al. 2014).

Multiple species of *Cryptosporidium* have been shown to infect humans. *C. andersoni, C. meleagridis, C. felis, C. canis, C. suis, C. cervine,* and *C. muris* have all been identified from human stool samples (Leoni et al. 2006; Morse et al. 2007; and Yoder et al. 2012). *C. andersoni* from cattle has not been identified as a particular human health concern. A genetic analysis of *Cryptosporidium* collected from 2414 stool samples from 1985 to 2000 in England found that only 0.1% were identifiable as *C. andersoni* in contrast to 56.1% for *C. parvum* and 41.7% for *C.*

hominis (Leoni et al. 2006). Though other species of *Cryptosporidium* can cause illness in humans, it is *C. parvum* in particular that is most problematic as a zoonotic disease.

In British Columbia (BC) all major and minor hosts of *C. parvum* are present including cattle, sheep and goats, and in addition other wildlife species common to British Columbia have also been identified as possible hosts including beavers, black bears, coyotes, mule deer, raccoons, white tailed deer, and wolves (Centre for Coastal Health, 1996). Hence, when there is a cryptosporidiosis outbreak in BC, identifying a specific source host in the environment can be challenging. Given both its prevalence over other *Cryptosporidium* species for causing human illness, and the presence of zoonotic sources in BC, the predominant public health concern in relation to the potential for incidents of cryptosporidiosis in BC is *C. parvum*.

2.1.2 Host-to-Host Transmission and Prevention

C. parvum is transmitted from one host to another by non-reproductive oocysts. *C. parvum* oocysts are typically 4 to 6 μm in diameter and they have a specific gravity of about 1.05 g/cm^3 (Searcy et al. 2005). In the environment, zoonotic transmission is easily facilitated via faecal contamination of drinking water sources. Contaminated water is the primary means of transmission of *Cryptosporidium* (Ryan et al. 2014). Sheep and goats are also major hosts to *C. parvum*, and deer, mice, and pigs are minor hosts.

C. parvum oocysts exhibit high durability due to their disulfide and glycoprotein reinforced cell wall (Jenkins et al. 2010). This has resulted in conventional water treatment technologies such as flocculation, chlorination, and filtration often being inadequate for the removal of oocysts to meet drinking water guidelines. In the design and implementation of drinking water treatment facilities, Health Canada (2012) requires at least 99.9% removal (a 3 $\log_{10}$ reduction) and the US Environmental Protection Agency (US EPA) requires 99% removal (a 2 $\log_{10}$ reduction). Achieving even 99% removal requires approximately 180,000 times the concentration of chlorine as required for *E. coli* (Rochelle et al. 2005), making it impractical. Flocculation can also achieve a 99% removal rate (a 2 $\log_{10}$ reduction), but can be greatly inhibited by turbidity (Dugan et al. 2001). A 99.99% level (a 4 $\log_{10}$ reduction) oocyst reduction can be achieved with filtration, but due to their size (4 to 6 μm), filtration is only realistic with expensive synthetic or diatomaceous earth filters (Jacangelo et al. 1995). One promising approach to the treatment of oocysts contaminated water is the application of ultraviolet light, which can achieve a 99.99% deactivation (a 4 $\log_{10}$ reduction) of viable oocysts, but its effectiveness is also vulnerable to turbidity (Bolton et al. 1998).

Given that an infected animal in the environment can release 10^8 to 10^9 oocysts in a single defecation and ingestion of a dose of only 10 to 30 oocysts can result in human infection, it becomes evident that only reductions in oocysts in the range of 10 $\log_{10}$ or greater are going to be adequate to assure drinking water safety. This can only be accomplished with expensive, multi-barrier approaches to water treatment making the more prudent option prevention and/or mitigation of surface water contamination via better management of cattle within community watersheds prior to drinking water source diversion to community water systems.

2.1.3 Cryptosporidiosis

As previously discussed, cryptosporidiosis is a disease resulting from infection by the parasite *Cryptosporidium* (US CDC, n.d.). It is a disease of the intestines of humans and animals Clinically, cryptosporidiosis can manifest itself as watery diarrhea, weight loss, fever, nausea, vomiting, and pain in the abdomen (US CDC, n.d.). With some individuals it may be asymptomatic. With others, the infection can manifest itself as a life-threatening illness. Greater sensitivity to severe infection has been shown in children under ten years of age (Lozano et al. 2013) and adults over 65 years of age (Naumova et al. 2003). The incubation period averages 7 days, but can range from 2 to 10 days. Very watery diarrhea is the most frequent symptom. In healthy individuals, the symptoms will generally subside in one to two weeks. In individuals with compromised immune systems though, symptoms can be chronic. The infection is usually in the small intestine, but infections on occasion have been found in other organs including other parts of the digestive tract, the lungs, and even the conjunctiva (inside of the eyelids).

2.1.4 Life Cycle of *Cryptosporidium* and Infection

Cryptosporidium complete their entire life cycle within their hosts. Ingestion of *C. parvum* oocysts (Figure 1.2) is the most common means of infection. Once ingested, body temperature, stomach acids, and bile salts have all been implicated in the activation of the excystation of the oocysts. In vitro studies have demonstrated pH and in particular, elevated temperature, as two of the most critical factors (Feng et al. 2006, Smith et al. 2005) to excystation. Other factors are known to play a role, but are not yet completely understood (Smith et al. 2005).

C. parvum oocysts infect the microvillous region of the epithelial cells in the digestive tract of its host. Excystation results in each oocyst releasing four sporozoites. The parasites then undergo both asexual reproduction and sexual reproduction. This ultimately leads to the creation of two types of oocysts in the next generation; those that are thin-walled, and those that are thick-walled. Thin walled oocysts repeat the cycle by again going through excystation and releasing sporozoites to attach to new epithelial wall cells and reproduce. Thick-walled oocysts are instead passed via the host's faeces back into the environment to await ingestion by the next host.

Healthy individuals can expect to experience symptoms of infection from to 2 to 10 days after infection and experience symptoms from 1 to 2 weeks after initial symptoms. A single defecation from an infected individual can introduce a range from 10^5 to 10^9 oocysts back into the environment (Chappell et al., 1996).

A series of studies (Chappell et al. 1996; Chappell et al. 2004; DuPont et al. 1995; Messner et al. 2001, Teunis et al. 2002) has determined that cryptosporidiosis infection in humans can be achieved with a dose as small as 10-30 oocysts. To assess the dose-response rate, several human feeding studies were conducted. Volunteers were first screened for signs of previous incidences of cryptosporidiosis (i.e. anti-*cryptosporidium* anti-bodies) and current health status. They were then required to fast for 8 hours prior to be administered with a single dose of oocysts via a gelatin capsule, monitored intensively for 14 days, and then less intensively for the following 4 weeks (32 days total). Infection was defined as either the presence of oocysts in faeces or clinical signs of cryptosporidiosis. A total of four different *C.parvum* isolates (strains) were tested (Iowa, UCP, TAMU, and Moredun). A range (see Table 2.1) of ID_{50}s (dose concentration to achieve 50% infection) were found both in the hosts and between isolates. In a subsequent study comparing individuals with no previous exposure to *C. parvum* to individuals with pre-existing anti-bodies for *C. parvum*, it was determined that those with the anti-bodies required 14 to 20-fold the number of oocysts to achieve infection and only those receiving the highest doses demonstrated any illness from the infection, potentially contributing the range of results for different isolates detailed in Table 2.1.

Table 2.1 Infectious doses for *C. parvum* isolates (Chappell et al. 2004).

***C. parvum* isolate**	**ID_{50} (oocysts)**
TAMU	10
Iowa	100
Moredun	300
UCP	1000

To develop a dose-response relationship, the data was subsequently analyzed as a binary (yes/no) response with a single hit model developed for microbial infection. The assumption for the single hit model is that exposure and infection are conditional events. In contrast to toxic chemicals, for which small doses can still consist of millions of molecules, with microbial contaminants, the dose may only be a few hundred particles. Therefore, there is a possibility of low doses containing no particles (oocysts). For infection to occur, the following conditions need to be met:

1. At least one particle (oocyst) must be ingested.
2. It must survive and find a suitable site for growth.
3. The sporozoites must still be in a condition to infect host cells and complete the life cycle.

The ingested organism(s) may experience a number of potential barriers limiting their ability to infect. These include mechanical barriers like peristalsis or diarrhea, or chemical impediments like low pH of the bile or pancreatic juices. Regardless of the potential barriers in an individual though, only ten oocysts needs to make it past them for infection to take place.

2.2 Cattle and *Cryptosporidium*.

Cattle have been firmly established as a potential source of *Cryptosporidium* contamination in drinking water sources in the public consciousness, and with public health authorities and stakeholders. This section will provide an historical context with respect to this concern, and an overview from the literature with respect to cattle and *Cryptosporidium*, particularly with respect to grazing cattle and calves.

2.2.1 Historical Incidents of *Cryptosporidium* Contamination

The first documented case of cryptosporidiosis in cattle took place in 1971 (Panciera et al., 1971), but it was a consequence of a major outbreak in Milwaukee, Wisconsin (pop. 1.61 million) in 1993 that this protozoan parasite became a more significant concern to both the public and public health authorities. The outbreak was initially attributed to faecal runoff from cattle pastures but ultimately failings in human sewage treatment systems running into Lake Michigan were identified as the source (Mac Kenzie et al. 1994). The outbreak was estimated to have resulted in 403,000 cases of cryptosporidiosis with 104 deaths, and cost an estimated $96.2 million in healthcare and opportunity costs (Hoxie et al. 1997).

Though cattle were absolved as the primary source of the *Cryptosporidium* parasite in the Milwaukee incident, public concerns of cattle as a hazard to drinking water sources had been set. Residents of San Francisco expressed their concerns during the municipal elections of 1996. In early 1997, the San Francisco Public Utilities Commission was directed to place a moratorium on livestock grazing in the Southern Alameda County Watershed (Stephens, 1997). This action would have removed 15 ranchers with pasture leases from the watershed. To counter this threat, an innovative plan based on Best Management Practices (BMPs) and Hazard Analysis and Critical Control Points (HACCP) was developed by the University of California (Davis) Cooperative Extension in conjunction with the Alameda County Resource Conservation District (Barry et al. 1998).

British Columbia experienced two outbreaks of cryptosporidiosis in 1996. Both were identified specifically to be *C. parvum*. The city of Cranbrook experienced 136 confirmed cases from June 19th to July 12th of 1996. A subsequent survey of residents experiencing symptoms during the period resulted in an estimated total of 2097 cases. The city of Kelowna incident also transpired in 1996 with 157 confirmed cases and an estimated total of 10,000 cases.

In the case of the Cranbrook incident, the two main sources of water are Joseph Creek and Gold Creeks, and in the instance of Kelowna, the source watershed is so big, that the origin of the contamination could not be determined (Newman et al. 2003). Newman et al. (2003) also note that both the Kelowna and Cranbrook incidents exemplified the challenges in conducting a complete and definitive exposure assessment with respect to the source of the contamination and infection of drinking water in each community, including:

- **Identifying the source host:** Cattle are a major host of *C. parvum*., but not the exclusive hosts present in the watersheds that provide Cranbrook and Kelowna with drinking water. Wildlife, including beavers, black bears, and coyotes are also present as well as sheep, goats, and deer.

- **Amplifying hosts:** It is possible that some animals might appear as the source of the infection, but rather had contracted the disease themselves due to their presence in the watershed. These animals can act as amplifying hosts, providing *C. parvum* with the opportunity to rapidly multiply to a higher level of concentration.
- **Climate events:** In advance of the Cranbrook outbreak, there may have been significantly altered flow patterns in the Joseph and Gold Creeks resulting from rainfall and snowmelt events. This may have created scouring events in the creek beds, releasing *C. parvum* oocysts stored in the sediments.
- **Historical grazing by cattle:** Cattle had grazed in the watershed for years without incident, creating doubts as to their presence being the primary source.
- **Human activities:** The watersheds are also open for camping, hunting, fishing, and boating. These can result in garbage, including diapers and animal carcasses.
- **The age of calves:** It has been determined that calves from 3 to 35 days of age are the most potentially infectious (Aiello, 1998). Both the Cranbrook and Kelowna incidents transpired when calves would have been at least 3 months (90 days) of age.

All of these factors contribute to the ambiguity by decision makers in determining whether or not the actual source of contamination in each event was cattle. Regardless, public perceptions have been set that grazing cattle in community watersheds are a potential hazard.

Though there is ambiguity in the source of the cryptosporidiosis incidents in BC in 1996, other incidents have been more conclusive in the source of drinking water source contamination by *C. parvum*. Desilva et al. (2016) documented an outbreak in Baker City, Oregon that was subsequently estimated to have affected 2780 persons (28.3% of the population). Analysis of stool samples indicated that it was a *C. parvum* sub-type common to cattle, and cattle had been observed at the watershed boundaries and cattle faeces were found within the watershed.

It should be noted that a third incidence of cryptosporidiosis outbreak also occurred in April 1998 in the community of Chilliwack, BC in the Fraser Valley. This was attributed to wildlife and domestic animals (horses and dogs) contaminating the drinking water sources, not cattle. All cattle in the immediate area tested negative for *Cryptosporidium* (Ong et al. 1999).

2.2.2 Prevalence of *Cryptosporidium* in Cattle

As previously cited (Xiao et al. 2004; Olson et al. 2004), cattle have been identified both as major hosts to two species of *Cryptosporidium*; *C. parvum* and *C. andersoni*, and as potential sources of *Cryptosporidium* contamination to surface drinking water sources. As previously cited, *C. andersoni* has proven of little to no consequence to human health, but *C. parvum* has demonstrated otherwise. This has prompted several research efforts to ascertain the potential magnitude of this hazard to human health and factors that impact the potential for this risk.

Understanding the prevalence of *C. parvum* in cattle and the factors that effect that prevalence is therefore paramount to understanding the hazard to human health. Early work with beef cattle in the United Kingdom revealed incidences of *C. parvum* as high as 62.4% in healthy adult cattle and in more than 80% of calves (Scott et al, 1995). However, Gow and Waldner (2006) conducted an examination of beef cow-calf herds in western Canada that indicated a different order of magnitude with respect to *Cryptosporidium* shedding from cows and calves. A total of 560 cows and 605 calves from 59 and 100 farms respectively were monitored for both *Cryptosporidium* and *Giardia* presence in their faeces. Only 5 (1.1%) of the cows were positive for *Cryptosporidium* and 19 (3.2%) of the calves were positive. In their research, Gow and Waldner found that cattle were much more likely during calving season to be shedding *Giardia* cysts instead of *Cryptosporidium* oocysts, and that *Cryptosporidium* posed a "limited risk from most cow-calf herds as a source of environmental contamination." They concluded that it is almost a given that for any cattle herd turned out in to a community watershed, there is a high likelihood of at least one animal being infected with the parasite.

Recent research in both Ontario (669 cows on 39 farms) and BC (193 calves on 10 farms) beef cattle herds revealed that *C. parvum* could be present in beef cattle in Canada from a low of 5.2% of gestating cattle in a herd to a high of 28% during calving (McAllister et al. 2005). In BC, calves have a typical *Cryptosporidium* infection rate of 13%. This confirmed previous work specifically examining beef calves and their dams for both cryptosporidiosis and giardiasis in which of a limited sample size (20 calves), only one calf was positive for *C. parvum* but *Giardia* was present in all calves (Ralston et al., 2003).

Both dairy and beef cattle have been identified as potential sources of *Cryptosporidium*. Dairy cattle have been shown to be far more problematic, but the potential threat still exists within beef herds (Olson et al. 2004). In a study (Fayer et al. 2006), of 571 dairy heifers from a1 to 2 years of age on 14 farms, oocysts were detected in faeces from 13 of the farms with an incidence rate of 11.9% in the sample. Previously, the sampling of 393 pre-weaned calves from the same herds indicated an infection rate of 41% and 26.3% for 447 calves post-weaning.

Cattle age has also been demonstrated as a factor in the incidence of *Cryptosporidium* in a herd. Work with spring and fall calving cow-calf herds in California indicated typically 3.9% of cattle shedding *C. parvum* on average with up to 13% of calves shedding *C. parvum* oocysts, whereas cattle a year or greater in age typically shed oocysts 0.6% of the time (Atwill et al. 1999, 2003). The study was conducted across seven distinct geographical regions of the state of California with 38 cooperating ranchers sampling faeces from 915 calves 1 to 11 months in age and 484 adult cows greater than 12 months in age. Atwill et al. (1999) noted that the incidence of shedding was 41 times greater for calves from 1 to 4 months in age than among cattle older than 4 months in age. The geography and climate across the seven regions did not contribute to any statistical differences between the regions. Atwill et al. (1999) also noted that the potential for contamination from calves was 8.7 times greater in May than in June, July, or August.

In reviewing previous research on both *Cryptosporidium* and *Giardia* in cattle, Olsen et al. (2004) concluded that calves usually become infected between one and four weeks of age, with the infection typically lasting two weeks. Shedding of oocysts however can begin in as little as two days and reach a peak around 14 days. In severe cases calves can take four to six weeks for full recovery. As previously noted, beef calves seem to be less susceptible to cryptosporidiosis. Several factors have been attributed to why dairy and beef herds experience different levels of cryptosporidiosis. Calving frequency and duration in dairy versus beef herds is one factor. Cattle in dairy herds calve throughout the year. This creates a potential temporal chain of contamination within the herd as calves recovering from the illness pass it to newborns. In contrast, beef herds are managed so that all calving preferably occurs in the spring over a few weeks. From birth, dairy calves are also normally confined to hutches and pens in close proximity to each other, facilitating animal to animal transmission of oocysts. In contrast, beef calves are quickly turned on to open range and/or pasture, mitigating transmission potential. Finally, beef calves consume much greater quantities of their dames' milk, which contains colostrum, and is believed to possibly provide transmitted protection because of the dames' previous exposure to *C. parvum* and resulting immunity.

2.3 Grazing Cattle Behaviour and Distribution on Rangeland.

Since previous research indicates that at least some cattle in a herd could be shedding *C. parvum* oocysts in their faeces, the amount of time cattle spend in close proximity to vulnerable surface water drinking sources can potentially have a strong correlation with contamination of the surface water source (Gamskopp et al. 2007). One solution to mitigate the hazard is to fence cattle off from sensitive areas in a watershed, including surface drinking water sources, but this can require both a significant initial investment and resource commitment to maintenance over time.

An alternative to fencing is manipulating grazing patterns and the behavior of cattle to alter their distribution patterns on the landscape, mitigating their potential impacts including defecation in sensitive riparian areas and surface water sources. The intent of this section is to provide an understanding of the current theory with respect to grazing cattle behaviour and distribution on rangeland both spatially and temporally as a basis for development and implementation of BMPs. In this section, the mechanisms that drive cattle behaviour and distribution will first be explored, then how these behaviours play out in the daily life of a cow grazing on rangeland, and finally how cattle distribution is expressed over the grazing season on range.

2.3.1 Factors affecting Cattle Movement and Distribution

The decisions cattle make and how they distribute themselves on the landscape are primarily driven by three different sets of mechanisms; biotic factors, abiotic factors and cognitive functions and memories. These mechanisms impact decisions both at the smallest spatial and temporal scales such as which leaf or plant stem that an animal wishes to choose in the next few seconds to consume, to a scale where it must decide on how to relocate itself in a pasture once it has depleted the grazing resources in its current vicinity. Understanding a grazing cow's daily routine is a good starting point to comprehending these mechanisms.

2.3.1.1 A Day in the Life of a Grazing Cow.

Cattle have needs that they must attend to each and every day while on rangeland. They must see to their nutritional needs through grazing forages. They also need time to rest and ruminate. They must also satisfy their need for water. Finally, cattle also need, or at least desire, to do this in the most comfortable and efficient manner possible by avoiding extremes of cold, heat, wind, and sunlight by using the landscape in a manner that best affords protection from extremes of each. How cattle meet these needs within a given environment is a function of that environment and the resources it provides. The desire to manage grazing cattle on rangeland in a manner that optimizes the use of its resources while minimizing their impacts has been the subject of extensive research (Bailey et al. 1996, Bailey et al. 2008, Ganskopp et al. 2007, Roath et al. 1982; Senft et al. 1987).

Cattle are herbivores that are dependent on the landscapes they exist in providing a surplus of low and variable nutritive quality food widely spread in patches over the landscape (Senft et al. 1987). They also need water from available sources on the landscape on a daily basis. To satisfy their needs, grazing cattle have daily routines. These routines are usually tied to a *camp.* A camp is not a particular site, but a region within which animals will venture into their local landscape each day for several days to forage and carry out related activities. A camp is almost always anchored to a site that provides water for them. After spending several days within a particular camp and depleting its resources, cattle move on to establish a new camp, again usually tied to a source of water (Ganskopp et al. 2007). Contiguous camps across a landscape for a cow or group of cattle might be referred to as their *home range.*

The routine is not necessarily exactly the same from one day to the next. The amount of time they spend on each activity; foraging, resting, and ruminating, can vary. They do not necessarily travel in the same direction to the same feeding sites each day either. Research has actually shown they seldom start their day grazing at the same site for more than two days in a row (Bailey et al. 1996). How far, in which direction, and for how long are functions of both biotic and abiotic factors. Memory and cognitive processes also seem to play roles in cattle behavior and distribution decisions and movement activities.

A cow's day typically begins just before sunrise with a *foraging bout* (Bailey et al. 2008). *Foraging bouts* are active grazing periods which can typically last for four to five hours in length. When forage is scarce, bouts may be extended. Generally grazing cattle engage twice daily in foraging bouts, one in the early morning and one in the afternoon or evening. Studies have indicated cattle may forage from 8 to 11 hours per day depending on the availability and quality of forage and factors such as ambient temperature.

Typically, foraging bouts involve a cow visiting *feeding sites. Feeding sites* are defined as a collection of vegetation patches that animals graze during a *foraging bout.* Each patch usually consists of a collection of plants favourable to the animal for grazing. A foraging bout may consist of an animal visiting multiple feeding sites to satisfy its nutritional requirements. The selection of a feeding site can be driven by both biotic factors such as palatability and nutritional quality of the forages available at different sites, and abiotic factors such as the distance to a site, and the slope of the terrain that must be traversed to reach it.

Completion of the morning foraging bout is usually followed by a period of rest and rumination. Cattle will typically seek out an area of shelter and/or shade where they can do this with some comfort. Approaching midday, cows will typically travel to water to drink, again followed by a period of rest to ruminate.

In the late day or evening, cattle often engage in a second foraging bout, but often not at the same feeding site as used earlier in the day. In summer conditions, high ambient temperatures have been noted to delay cattle grazing in the afternoon. It has also been observed that cattle may tend towards feeding sites uphill and towards ridges during warm summer conditions. This allows the animals to avail themselves of evening breezes for both thermoregulation and to avoid insect pests. After spending the night at higher elevation, cattle may then begin the following day grazing downhill, moving towards riparian areas and water sources.

These daily routines have been observed repeatedly over several decades by researchers, but what drives the decisions that lead to these routines? Current theory is that they are a product of biotic and abiotic factors, and of cognitive processes and memories experienced by each animal within its environment.

2.3.1.2 Biotic Factors affecting Cattle Movement Decisions

Biotic factors are both internal to the individual animal and a function of the environment. Cattle have preferences for high quality forages in high quantity that can fulfill their nutritional requirements. Forages with high protein content are particularly attractive. Researchers have found that riparian areas are particularly well suited to meeting these preferences. Cattle tend to spend less time grazing when high quality forages are available in abundance and more time grazing when only sparse, low quality forages are available.

The quality of forages available to a grazing cow can effect both its speed of travel while foraging (*foraging velocity*) within a landscape and its propensity to change its direction of travel while foraging (*turning frequency and angles*) (Bailey et al. 1996). Animals tend to reduce their foraging velocity in the presence of rich, high quality forages and speed up as forage quality diminishes. In nutritionally rich feeding sites, cattle also tend to turn and twist a lot more in their path to better avail themselves of the forages available. In feeding sites with sparser and/or lower quality forages, they are more likely to travel in a straight line.

It is also believed that animals balance their nutritional intake through post-ingestive feedback. The presence of toxins (e.g. tannins, alkaloids and glycosides) may discourage animals from further consumption of a particular forage. Conversely, shortcomings in energy or protein in the diet may encourage animals to continue consumption. This may explain why grazing animals tend to select different feeding sites, populated with different forages, in the afternoon than in their morning foraging bouts.

Cattle are also driven by the need to regulate their body temperature. Ideal temperatures for beef cattle range from 15 to 25°C (National Research Council 2000). Thermoregulation drives cattle to seek out microsites within terrain that afford them shade and other shelter that help them stay within this range. Rangeland that provides cattle with trees, shrubs, and other features that can provide shade and shelter can be quite attractive to cattle. Studies in California have found that cattle can spend as much as 8 hours per day under shade in sunny summer conditions and are motivated to graze towards high elevations and ridgelines in the afternoon and evening to take advantage of cooling breezes (Harris 2001). Cattle also spend less time traveling on windy days to conserve energy.

Pest avoidance is another biotic factor affecting cattle distribution on landscapes. In research where cattle were provided the opportunity to access open pasture, forests with open canopy, and forests with closed canopy in a drought year when flies were more problematic, they chose the open pasture. In contrast, during a wet year with few flies, they chose open canopy forests, and in neither year did they opt for closed canopy forests (Ganskopp et al. 2007).

2.3.1.3 Abiotic Factors affecting Cattle Movement Decisions

In contrast to biotic factors such as the need to meet nutritional requirements, regulate body temperature and avoid pests, abiotic factors are a function of the landscape itself. Factors such as the location of water and supplements, and distances and slopes to be traversed in traveling from these resources to grazing sites play a role in the decisions cattle make that ultimately distributes them on a landscape, including the amount time they spend in sensitive riparian areas where vulnerable surface water sources exist.

Water is essential to all living things. Cattle are no exception, and as with most animals, access to water is essential on almost a daily basis. Hence cattle prefer feeding sites close to water and those are the first to be depleted. Under typical conditions, with gentle topography, Holochek (1988) noted that cattle travel a maximum of 3.2 km from their daily drinking water source to acquire feed. However, it was also observed that they typically utilize less than 50% of the potential grazing sites beyond the first 1.6 km. Holochek also noted a strong relationship between reduction in grazing capacity with slope. Cattle fully used potential feeding sites on slopes up to 10% slope, with a typical reduction of 30% on slopes up to 30%, and a 60% reduction on slopes up to 60% and no grazing on slopes greater than 60%.

In rougher topography, other researchers have noted that cattle prefer feeding sites within 200 m of their water source and seldom venture beyond 600 m (Ganskopp et al. 2007). In other studies, cows demonstrated a greater aversion to elevation gain above their watering site than distance. Roath and Krueger (1982) noted cows did not go more than one mile (1.6 km) from water but more importantly, did not venture more than 260 feet (79 m) above their water site.

The physiological state of a cow also influences how it uses terrain. Lactating cows have a greater need for water. In combination with the need to care for their calves this places limits on their use of rough terrain. Non-lactating cows have been observed to graze higher and at greater distances from riparian areas. This change in behaviour has been especially noted after calves are weaned (DelCurto et al. 2005).

Fences may impede cattle movement and distribution on a landscape, but steep slopes, thick brush, and other natural barriers can also limit cattle movement. Conversely, roads, railroad beds, utility right-of-ways, and other man-made corridors facilitate the ability of cattle to traverse terrain that would otherwise be difficult for them to move about on, and can aid in distributing cattle on the terrain and away from sensitive riparian areas.

2.3.1.4 The Effect of Memory and Cognitive Processes on Cattle Movement Decisions

Memory and experience also affect how cattle behave and distribute themselves on a landscape. Cattle learn about their landscape and develop memories with respect to the location of more preferential forages, watering sites, and supplement locations, and these abilities are essential to their efficient use of their environment, and they pass this knowledge on to their calves creating a herd memory for preferred feeding, watering, and resting sites over multiple years (Bailey et al., 2008). Once learned, this behavior can be difficult to change. When cattlemen use the same entry points to pastures, and place supplements and watering troughs in the same locations, cattle behaviour can be reinforced.

Memory and cognitive processes are also central to the Marginal Value Theorem of Optimal Foraging (MVTOF) (Charnov 1976) for predators and other species, including grazing cattle. The central concept being that to maximize their foraging efficiency, cattle compare their current rate of nutritional intake against that which they remember and remain at the same location if it is above the average rate of intake they remember. It has been noted though that cattle move on to new sites even though there appears to be very sufficient grazing resources at their current location. Current theory proposes that the Satiety Hypothesis in Diet Selection (Provenza et al. 2003) may be at work and that grazing livestock select each day for foraging sites with the richest nutritional content for their first foraging bout, but then choose to diversify to sites populated with alternative forages to mitigate the intake of toxins present in vegetation at the first site.

Bailey et al. (1996, 2008) note that cattle demonstrate cognitive behaviours and memory in a number of ways. Once cattle have familiarized themselves with a number of feeding sites, they tend to frequent those with greater nutritional resources and avoid those with lesser resources. They also note that in practice, cattle apply the MVTOF to their average feed intake as reference for their current feeding site and decision to stay or move on when their feed intake at the current site drops below the average of the previous two to four days.

2.3.2 Range Scale Movement of Cattle

Camps alone do not define cattle behaviour on a landscape over the course of a grazing season nor at what happens within a cow's daily use of a landscape. Senft et al. (1987) postulate that to satisfy their needs, herbivores, including cattle, interact with their landscapes at several levels of ecological resolution to address inter-related challenges. These scales involve decisions from the finest level such as the selection of a single leaf on a plant, a plant, or a patch of plants to course decisions with respect to the regional use of the landscape such as relocation of the camp to another location in the watershed with better resources to meet an animal's needs including water, shade, and rest. This creates a hierarchy in which animals make decisions about their movement on the landscape.

Senft et al. (1987) also note that successfully observing cattle behaviour at each scale is a function of observation frequency matching the behaviour. Diet selection decisions require a high frequency of observation whereas regional scale patterns of movement are easily observed at lower observation frequencies.

Matching is an important concept in understanding cattle behaviour and decision making. Regardless of the scale of a decision by cattle and other herbivores, three potential patterns can result; matching, defined as an appropriate scale of response to a required decision, over-matching, defined as a change in behaviour in excess of that required to address the challenge of the decision at hand, and under-matching, an inadequate response to the required decision.

Large herbivores have been noted to over-match in their selection at the plant community or patch level scale. This is the result of their senses being overwhelmed by forage abundance and diversity, and by both positive and negative factors such as preference for palatability that reinforce each other to motivate decisions to change the particular plant or patch of plants an animal is foraging on. Herbivores may make these decisions several thousand times each day with little consequence to individual decisions, hence over-matching is to be expected.

In contrast, Senft et al. (1987) note that herbivores match well at the landscape level. Their preferences for feeding areas that satisfy their needs are linear as a function of the size those areas relative to their home ranges. Factors that have been demonstrated to affect those preferences include topography, and access to water and salt licks. Avoidance of insects, predators, and desire for favorable microclimates can also affect decisions for feeding areas. Landscape level decisions are less frequent but more important to an animal's ability to access key resources such as water, shade and rest and ruminating areas, hence the reason why decision making at this level exhibits better matching.

Matching also takes place at the regional scale, but for grazing cattle, decisions like pasture allocation are made by cattlemen rather than the cattle themselves and in the instance of BC's community watersheds, always as a function of range lease conditions set out by FLNRORD.

Bailey et al. (1996) built upon the ideas of cattle behaviour and distribution on the landscape originally defined by Senft et al. (1987) by proposing a formal hierarchy as illustrated in Figure 2.1. The decisions of grazing cattle are defined in two dimensions; spatial and temporal.

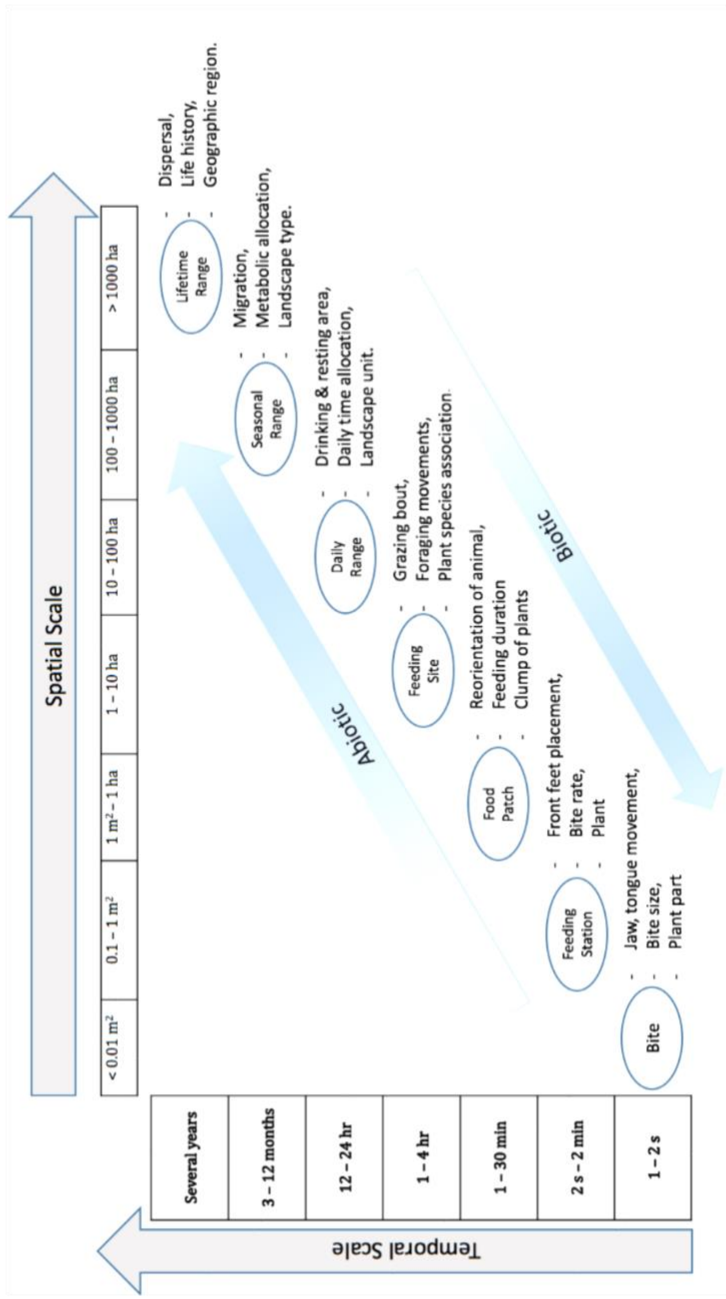


Figure 2.1 Cattle behaviour as a function of space and time (after Bailey et al. 1996).

At each spatial and temporal scale, particular behaviour characteristics, response variables, and vegetation and landscape entities can be observed. Depending on the scale of decision in the hierarchy, decisions and movement may be influenced more by biotic or abiotic factors. Biotic factors such as palatability and preferences dominate finer level decisions, such as which plant part, plant, or patch of plants are more desirable as forage. Abiotic factors such as slope, and distance to water or resting areas tend to dominate courser level decisions such as the need to change *camp* or move to another location within a watershed.

At finer scales of movement, the observed behaviours in cattle are movements of the neck, jaw, and mouth as cattle select plants and forages in response to palatability preferences. The time horizon for these activities is only a few seconds, and movement is measured in centimetres. At larger scales, cattle may change their position, or feeding station within the patch of plants they are consuming by repositioning their front feet to take advantage of forage previously beyond neck reach. This may take place over a period of up to two minutes. Once an animal has depleted a patch at a feeding site, it may move on to another patch or clump of plants it finds attractive within the same site by fully repositioning its body over a period of up to a half hour within the confines of an area of 1 ha of rangeland.

As previously discussed, a foraging bout may typically last four hours with retreats for water, rest, and/or rumination, all while traversing an area of up to 10 ha. This 10 ha area defines the camp comprising feeding sites, watering locations, rest and rumination areas, and shelter sites over 12 to 24 hours in a cow's daily range.

2.3.3 GPS Verification and Insights to Cattle Behaviour on the Range

More recent work by Larson-Praplan et al. (2015) utilizing GPS collars affixed to cattle has verified the previous understanding of grazing cattle movement and behaviour on range by Senft, Bailey, Ganskopp, and other range management scientists. In particular, this work verified the existence of 'food patches' and 'feeding sites' as distinguishable scales in grazing cattle behaviour. A total of 40 cattle were broken into two herds of 20 each and in each instance six cows were equipped with GPS collars recording position, temperature and head movements. Data was collected at 5 minute intervals in four pastures for six days each over three grazing seasons in 2001, 2002, and 2003. The pastures were located at the Sierra Foothill Research and Extension Centre in the Sierra Nevada foothills about 27 km northeast of Marysville, California.

Analysis was performed with R (R Core Team 2014) and the adehabitatLT package (Calenge 2006).

In addition to confirming the previous work, Larson-Praplan et al. (2015) gained a number of other insights with respect to grazing cattle behaviour. Differences were noted in behaviour between sites being initially grazed (‘virgin-grazing’) and those being revisited (‘repeat-grazing’). Cattle seemed to exhibit a circadian pattern, grazing new areas in their main morning feeding bout while revisiting other sites in their mid-day bouts. Main grazing bouts tended to be long circular trips or one-way trips from one resting area to another. Short bouts tended to be in small round trips with motivations to maintain herd cohesiveness. Cattle also tended to exhibit opportunistic behaviour to diversify their diets during short bouts.

Timing and duration of feeding bouts changed with both the availability of forage and the temperature. Higher temperatures tended to result in shorter grazing periods and demonstrated the importance of shade. In the spring and summer when forage was more limited, cattle tended to graze for longer periods of time durng cooler temperatures. Cattle also exhibited a third large feeding bout during the night under these conditions. In the summer, midday and afternoon temperatures discouraged feeding between bouts. In contrast, in the spring, with lower temperatures, cattle exhibited much more grazing behaviour between 10 am and 6 pm. In the winter and spring, cattle also exhibited a grazing peak between 10 pm and 11 pm due to presence of very high quality but limited availability of forage.

Cattle also exhibited interactions between spatial and temporal distribution of meals, resting, and other activities with temperatures strictly governing the start and end feeding bouts. Cattle tended to stay closer to protective canopies for shade in warmer temperatures. Warmer temperatures also seem to result in the haphazard selection of resting sites. Cattle seem opportunistic in their grazing behaviour in hot weather, engaging in short feeding bouts in the immediate proximity to their resting areas.

Cattle were also noted to vary their grazing behaviour dependent on season but maintained the spatial and temporal structure of their grazing and behaviour patterns independent of the pasture they were in. Another finding noted by Larson-Praplan et al. (2015) is that cattle generally established ‘large-scale’ feeding alleys after about 3 days and then tended to graze within 20 m of those alleys, however this might be a function of the particular landscape in both spatial and temporal scales. The need for further research was identified to answer this question.

Grazing bouts were also noted to be very marked. In seasons with moderate temperatures, they would begin their morning graze away from their resting site and then worked their way back or to a new resting site. In late morning and afternoon, grazing bouts tended to be short and irregular around the resting site. During hotter seasons, cattle tended to graze in shorter trips close to resting sites. This resulted in a lower proportion of available pasture being used in summer grazing and pastures with more canopy being used to a greater extent.

2.4 Distribution of Grazing Cattle Defecation on Rangeland.

A typical 800 lb (363 kg) beef cow will deposit an average of 48.5 lbs (22.5 kg) of faeces each day on the landscape (Barker et al. 2002). Grazing cattle typically defecate 10 -12 times per day (Wagnon 1963, Bagshaw 2002). Crown pasture grazing licences can allow 300 or more cow-calf pairs into a pasture of which at least a portion may be infected with *C. parvum* and have potential to contaminate drinking water sources (Atwill 1996). Larsen (1996) identifies the need to keep cattle from defecating in streams and in riparian areas in close proximity to streams as a primary objective to managing water quality and mitigating its contamination by faecal pathogens from cattle. Hence to understand the nature of the threat, it is necessary to understand both where and how often cattle defecate on the landscape, and factors that affect each.

In the work by Tate et al. (2004), transects of range land in a designated study area were measured for fecal deposition over a four year period (1995 – 1998) and analyzed to determine if there was the possibility to predict where defecation rates might be higher. The research was conducted on the San Joaquin Experimental Range in Sierra Nevada foothills in Madera County, California. The transects were classified as either being on a ridge, a hillside, or in a ‘variable source area’ defined as a 3 m buffer from a watercourse’s centre-line and/or from the edge of any wet or marshy areas. A linear mixed effects model was used to analyze the data. Key findings and conclusions of the study included:

- A very strong negative association between deposition and slope, however there was also a significant interaction with aspect. Fecal deposition sensitivity was much greater on north facing slopes with significantly lower deposition than equivalent south facing slopes. As slope declined to nil, the differences became negligible.
- Little significant effect was noted on deposition by factors including surface rock cover, canopy cover, and distance to livestock concentration sites, or trails used by cattle.

- A significantly lower daily load in the variable source area was noted during the wet season compared to the dry season.
- Ridges were noted as having higher rates of faeces deposition than either hillsides or the variable source areas.
- Stocking rate seemed to play a significant role in the rate of faeces accumulation from one year to another.
- Water troughs and other attractants (e.g. supplemental feed) significantly increase fecal deposition at or near their location, and hence these should be placed away from streams to mitigate hazard potential.

Overall, the results of this program accomplished two things. It supported and verified almost all previous work on environmental factors affecting faeces deposition and the movement and preferences of cattle. It was confirmed that cattle are not attracted to grades in excess of 10%. It was confirmed that cattle timing and placement of faeces relative to rainfall events is an important indicator as to the potential hazard to water sources. Most importantly, it indicated a complex but quite predictable interaction of management and environmental factors dictating where cattle might be expected to defecate on the landscape within a watershed.

Bagshaw (2002) specifically looked at the factors influencing defecation frequency and distribution of beef cattle in riparian zones in New Zealand hill country. Three experiments were carried out with direct observation of cattle behaviour by trained observers. The riparian area of interest was defined as a 2 m buffer on each side of a stream. The research confirmed that cattle were noted to be attracted to riparian areas for four specific resources; water to drink, water for cooling, shade, and forages specific to riparian areas. Results indicated cattle typically defecated within the riparian zone 0.2 times per day and approximately half those defecations were directly into the watercourse itself. It was concluded that the incidence of defecation by a beef cow in a riparian zone is strongly correlated with the amount of time the cow spends there. It was also acknowledged that though the cattle in the experiments typically spent only about 4% of their time in riparian areas, their defecation during this period could still greatly affect water quality. It was also noted that the frequency of defecation in riparian areas was not affected by season, the presence of a trough next to the stream, or pasture size or availability. It was finally concluded that the research validated previous research suggesting that manipulating resources such as providing off-stream water and forage sources in close proximity to shade could be an effective strategy for manipulating cattle behaviour and encouraging them to not defecate within riparian areas with potentially adverse effects on water quality.

2.5 Fate, Transport, and Persistence of *C. parvum* on Rangeland

To threaten human health, faeces containing *C. parvum* oocysts must be deposited directly into drinking water surface sources, or alternatively deposited on land in proximity to these sources. In the latter case it must then be transported into the drinking water surface source via hydrologic processes (Tate et al., 2000). Hydrologic processes might include weather events resulting in the breakdown and flushing of faeces patties with material subsequently transported by surface runoff or soil erosion and transportation to surface water sources. Other means potentially exist for faeces to be transported to surface water sources. For example, recreational vehicle tires could break down faecal patties with material adhering to tires which then transport it to surface water sources.

Even if *C. parvum* oocysts are transported to or deposited in a surface drinking water source, there is a question of persistence of the viability of those oocysts. Are they still capable of infecting a host upon ingestion, leading to cryptosporidiosis? Under what conditions in the environment is this likely? Alternatively, under what environmental conditions would oocysts be rendered non-viable and unable to infect a host?

2.5.1 Release of *C. parvum* Oocysts from Faeces

Before *C. parvum* oocysts can be transported to a surface water source, they must be released from the faeces in which they have been deposited on the landscape. Calves can deposit up to 10^{10} oocysts per day or 10^{7} oocysts per gram in their faeces (Atwill, 1996), but little previous research has been done to determine exactly how this occurs and the magnitude of oocysts released. The research to date has also been exclusively done in laboratory conditions and not actual field conditions. In one study (Bradford et al., 2002, Schijven et al., 2004), a series of simulations under controlled conditions were conducted to specifically look at factors impacting the flushing of *C. parvum* oocysts and *Giardia* cysts from samples of dairy manure, including flow rates, temperature and salinity, to determine the effects of the volume and salinity of the flushing solution on the release of oocysts from the organic matrix constituting the faeces. The research looked specifically at dairy calf manure.

Dairy calves were housed in conditions under which their faeces could be flushed with four liquid solutions with salinity ranging from that of tap water to that of cattle urine (respectively with electrical conductivities of 0.3, 5.0, 9.5, 14.8 dS/m). Prepared disks of dairy calf faeces were flushed with each solution over a 250-minute period. Effluents were found to initially contain manure particles, cysts and oocysts at several orders of magnitude below starting concentrations (7.1×10^4 oocysts/gm) within prepared manure disks with decreasing concentrations over time until exhibiting a persistent concentration. Increasing salinity resulted in a decreased concentration of oocysts in effluents. This was theorized to have resulted from reduced electrostatic interactions between charged particles within the manure matrix, including biocolloids such as oocysts. In dairy housing situations, flushing with solutions containing urine and hence higher salinity is expected to be the norm, but with beef calves on open pasture, the norm will tend to be rainwater with much lower levels of salinity and hence higher concentrations of oocysts in effluents from faeces depositions.

Further work (Schijven et al. 2004) also compared the release of *C. parvum* oocysts from cow faeces versus calf faeces. Sample disks were prepared consisting of a range of mixtures of both calf and cow faeces fractions to simulate the mixing of faeces typical of a dairy environment. In each instance fresh faeces was used and at the beginning of each experiment, the disks were saturated with water. Water was then applied for 250 minutes to each disk as both a mist and as droplets to simulate rainfall. The results indicated drip application resulted in release rates of oocysts and manure as great as seven times that from mists being applied to the disks due to increased mechanical action. Disks with higher fractions of calf faeces initially released both more manure and oocysts than those with higher fractions of faeces from mature cows. This was attributed to the fact that the calf diets consist predominantly of milk resulting in faeces with a high proportion of fine material. This contrasts with mature cows whose diets are dominated by forages, resulting in larger particles of undigested hay and grains. Replication of the experiments over a temperature range from 5 deg-C to 23 deg-C demonstrated little effect over the 250 minute period of the experiment, but researchers did expect that further research over longer periods will demonstrate an impact due to microbial activity.

2.5.2 Transport of *C. parvum* Oocysts to Surface Water Sources

After being released from faecal pats, if *C. parvum* oocysts are not directly deposited into drinking water surface sources, they must be transported either over the soil surface or through the soil column beneath the pat from which they have been released to a surface water source if they are to pose a hazard to drinking water and human health.

2.5.2.1 Transport of C. parvum Oocysts Through Soil Columns

Mawdsley and associates (1996) demonstrated the ability for oocysts to leach in to the soil cores beneath faecal pats. Three different soil cores, a loamy sand, a silty loam, and a clay loam were extracted from rye grass fields. After being brought to maximum water holding capacity, each core was treated with 1×10^8 oocysts and then subjected to 21 days with irrigation water applied each second day. Leachates were collected after each 24 hour period and the cores were destructively sampled at the end of the 21 day study. Results indicated that oocyst transport was greater in the silty loam and clay loam soils than in the sandy loam. Leachates from the silty loam and clay loam columns were low in oocysts but oocysts were almost non-existent in the loamy sand. Analysis of the soil in the cores at the end of the study revealed that on average 73% of the oocysts were retained in the first 2 cm of each with numbers falling to 5.4% by 30 cm of depth. Subsequently the need has been identified for further research into the groundwater fate *of C. parvum* oocysts (Harter et al. n.d.), however the primary concern of this research has been with respect to faeces from concentrated animal feeding operations more typified by dairy cattle operations and finishing feedlots for beef cattle (Petersen et al. 2012), not from grazing beef cattle on dispersed pastures.

2.5.2.2 Transport of C. parvum Oocysts over Soil

In contrast to the transport of *C. parvum* oocysts on soil columns, significant research has been conducted on overland transport of oocysts to surface water sources. Using soil boxes tilted to 7.5% grade, Mawdsley et al. (1996) demonstrated both overland and subsurface leaching and movement of *C. parvum*.

Tate et al. (2000) conducted a paired plot study on the San Joaquin Experimental Range in Madero, California. A total of six plots on vegetated course soils were prepared at three slopes (10%, 20%, and 30%), with two replicates at each slope. Each plot was 22.1 m in length by 2 m in width. Two experiments were conducted. In the first experiment, four 200 g. faecal pats prepared with 1×10^5 oocysts/g were placed 1 m above the bottom of each of the columns. At the end of four storm events over a six week period, composites of the overland flow were collected and analyzed for the presence of *C. parvum* oocysts. In the second experiment, a rainfall simulator was used on a separate plot at 10% grade to simulate a rainfall in excess of a 100-year return period. Again four 200 g faecal pats were applied. All overland flow was captured for every 10 minutes up to 90 minutes from the start of the experiment. The results of the experiment showed that greater concentrations of *C. parvum* oocysts could be expected in runoff with increasing slope as a result of increased overland flow velocity and reduced infiltration. It was also noted that oocyst concentrations tended to decrease with subsequent storm events. The second experiment demonstrated a strong flushing of oocysts early in the rainfall with a subsequent decline within 60 minutes of the initiation of the experiment.

Further work by Atwill et al. (2002) with soil boxes explored the potential use of buffer strips along watercourses to mitigate contamination from cattle faeces. Sandy loam, loam, and silty clay loam soils were selected with perennial fescue covers, bulk densities ranging from 0.6 to 1.7 g/cm^3, and slopes of 5 to 20%. The vegetated buffer strips were evaluated as a means to remove *C. parvum* from surface and shallow subsurface flow under simulated rainfall events. Rainfall events were simulated for 240 minutes and both overland flow and leachate were independently collected and analyzed. Soil type and slope were found to significantly affect the total number of oocysts in overland flow but with a strong influence from soil bulk density. Overland movement of oocysts increased relative to subsurface transport as a function of soil density due to decreased infiltration or because of detachment across the buffer. Sandy loam was found to be the least effective of the three soils at removing oocysts. Soil type and infiltration rate were significant factors affecting the movement of oocysts in subsurface flow with strong influence from rainfall intensity. Sandy loam buffers resulted in many more oocysts in subsurface effluents than either of the other soils. Linear mixed-effects models were developed to calculate the impacts on oocyst reduction in effluents as a function of soil type, slope, and bulk density for a 100 cm vegetated buffer, subsequently indicating $\log_{10}$ reductions in oocysts from 1.0 to 3.1. Similar work with vegetated and bare soil blocks by Davies et al. (2004) found that runoff volumes on bare soils can be up to five times that over vegetated soils, and that the vegetated blocks promoted much greater infiltration. In their final conclusions, Atwill et al. (2002) concluded that on slopes of less than 20% grade, a buffer of greater than 3 m could remove in excess of 99.9% (a 3 $\log_{10}$ reduction) of *C. parvum* oocysts during mild to moderate precipitation events (up to 4 cm/hr). This indicates that there is a very low probability of oocysts entering a watercourse from any distance. Significant rainfall events were also identified in this work as necessary to dislodge oocysts from faeces depositions. Furthermore, the research also indicates that land use practices that alleviate soil compaction resulting in lower soil density can increase infiltration capacity and improve water quality whereas those that promote compaction and increased soil density could impeded the effectiveness of vegetated buffers and adversely affect water quality.

2.5.3 Fate of *C. parvum* Oocysts in Surface Water Sources

Once *C. parvum* oocysts are released from faecal pats on the landscape and transported and deposited into surface water sources by hydrological processes or other means, the question becomes what is their fate. *C. parvum* oocysts are typically 4 to 6 μm in diameter with a specific gravity of about 1.05 g/cm^3 but their physical characteristics have been shown to be significantly altered due to attachment to suspended sediments (Searcy et al. 2005), and these attachments result in much greater rates of removal of oocysts from water columns and their accumulation in sediment beds.

Further work by Searcy et al. (2006) in flume experiments characterized the potential interactions potentially responsible for the removal of oocysts from the water column, including stream-subsurface interactions as a mechanism to deliver oocysts to sediment beds, and led to the successful development of a model to predict the sedimentation of both free oocysts and oocysts attached to suspended sediments. Four different suspended particles were used in the experiments; kaolinite, iron oxide, Des Plaines River sediments, and Salt Creek sediments. All were found to significantly increase the effective size, specific gravity and settling velocity of the oocysts. A predictive model was developed to calculate the required length of a watercourse to effect a $\log_{10}$ reduction in oocysts concentration in stream discharge. Table 2.2 provides the modeled results for two potential scenarios, a typical small agricultural headwater stream and a moderate sized river. In each case, three scenarios were considered; only classic sedimentation, classic sedimentation with stream subsurface exchange, and finally classic sedimentation with stream subsurface exchange and the presence of suspended sediments. The results indicated that both subsurface exchange and the presence of suspended sediments in the watercourse can act to reduce the concentration of oocysts being transported downstream significantly.

Table 2.2 Modeled distance of stream travel to achieve log_{10} reduction of oocysts concentration in streams

	Agricultural Headwater Stream	**Moderately Sized River**
Depth (cm.)	*15*	*80*
Velocity (cm/s)	*15*	*20*
Discharge (m^3/s)	*0.05*	*3*
1. Classic sedimentation to achieve log_{10} reduction of oocysts. (km.)	*7.3*	*52*
2. Sedimentation with Stream subsurface exchange to achieve log_{10} reduction of oocysts. (km.)	*1.1*	*7.6*
3. Sedimentation with Stream subsurface exchange and with sediments to achieve log_{10} reduction of oocysts. (km.)	*0.37*	*2.6*

2.5.4 Persistence of *C. parvum* Oocysts in the Environment.

In its audit of the Oyama Creek and Vernon Creek watersheds in 2010, the Forest Practices Board (FPB 2012) noted that faecal pats located near exclusion fencing tested positive for *Cryptosporidium* throughout the year even though there was no scheduled cattle access to either watershed before June 6 of each year, and the latest cattle were permitted on pastures in these watersheds is October 15 of each year (Roberts et al. 2016). The quantity of *C. parvum* oocysts entering community water drinking systems impacts the magnitude of their ability to adversely affect human health, but this now raised the concern with respect to the viability of oocysts deposited on the landscape to persist as infectious agents that might be transported into a watercourse at some point in time after defecation. Several factors exist in the natural environment of a community watershed in BC that may affect the ability of oocysts to persist including extremes and fluctuations in temperature, and exposure to natural ultraviolet light. As discussed previously, cattle faeces not directly deposited in streams can be flushed via rainfall events, transporting oocysts into surface water sources in close proximity.

In addition to rainfall events, the Okanagan Basin of BC experiences a period of intense snowmelt each year referred to as the spring freshet. The freshet can represent up to 90% of the basin's annual intake and typically lasts from April to June (Dobson 2004). Stream reaches can easily overflow their banks during this period washing faecal deposits from both cattle and wildlife into watercourses. As such, the freshet has been flagged as a major carrier of sediment posing challenges to drinking water treatment systems as well as fish (OBWB n.d). Cattle can still be present in Okanagan Basin community watersheds until October 15 of each year under current grazing licences. Assuming a freshet beginning on April 1 of substantial volume to overflow stream banks, cattle faeces with *C. parvum* oocysts deposited less than 5 ½ months (165 days) previously could be captured and diverted into a community drinking water system. Will they still be problematic to human health or not?

Under laboratory conditions, temperature has been explored for its effects on *C. parvum* oocyst viability. Fayer and Nerad (1996) determined that at temperatures below – 20 °C, oocysts can be rendered non-viable within in 24 hours. However, at -15 °C, oocysts could remain viable for one week. It was also determined that at temperatures in excess of 72.4 °C, they can be rendered non-viable within one minute. Pokorny et al. (2002) confirmed this work and also determined that from 4 to 25 °C, oocysts could remain viable for up to 7 months, particularly at lower temperatures. Viability dropped off significantly at temperatures above 25 °C. Sherwood et al. (1982) noted a loss of viability within 5 days at 37 °C. Freezing and thawing has also been noted as a method of deactivating oocysts through rupturing (Jiang et al. 2005). Winter temperatures in BC communities in the Okanagan Valley can reach average minimums of -20 °C or colder (Schertzer et al., 2009). Both the late fall and the spring can exhibit the conditions for freezing and thawing of oocysts too, potentially rendering them non-viable.

Exposure to natural ultraviolet (UV) light in the environment has also been postulated as potentially mitigating the persistence of *C. parvum* oocysts in the natural environment too. In water treatment facilities, UV has been demonstrated to be capable of a 4 $\log_{10}$ reduction in oocysts if not impeded by high turbidity (Bolton et al. 1998). Irradiation of the DNA after UV light penetrates oocyst cell walls results in the formation of cyclobutane pyrimidine dimers and photoproducts that can inhibit housekeeping genes or stimulate apoptosis (Sinha and Hader, 2002). Since *Cryptosporidium* does not initiate a response to repair damage to its DNA (Rochelle et al. 2005), it is potentially possible for even mild doses of UV light in the natural environment to render oocysts non-viable.

To better understand the true impacts of temperature and UV light on the persistence of *C. parvum* oocysts in the natural environment of the BC interior community watersheds, Story (2016) conducted two controlled studies of fecal pats spiked with *C. parvum* oocysts under light, moderately and heavily forested conditions at the University of British Columbia's Okanagan campus. The first study (winter persistence) explored the ability under winter conditions for oocysts to remain viable from deposition during fall pasture lasting to October 15 until the spring freshet (April 1). The second study (summer persistence) explored the viability and persistence of oocysts deposited in faecal pats during spring pasture and their ability to survive through the summer and fall and into the freshet of the following spring.

The results of Story's (2016) winter persistence study indicated that in heavily and moderately forested sites, viable *C. parvum* can remain detectable for up to 67 days, but in lightly forested sites, they were still detectable after 106 days. It was also shown that after only 3 freeze-thaw cycles, only 19% of the oocysts appeared to still be intact. When the pats were subsequently flushed at the end of the winter study, there was no evidence of residual *C. parvum* oocysts. In contrast, the summer study results demonstrated that under lightly forested conditions, plots were devoid of oocysts after only 71 days, but in heavily and moderately forested conditions, oocysts were still detectable at 261 and 227 days respectively. The conclusions of the experiments were that both freeze-thaw events and UV light do affect and impede the viability and persistence of *C. parvum* oocysts in the environment, however, it has also been hypothesized that conditions may exist under moderate and heavy forest conditions to protect oocysts from these mechanisms and increase persistence, potentially into the freshet of the following spring. These conclusions have practical implications for the development and implementation of management strategies to mitigate the potential contamination of drinking water surface sources with *C. parvum* via defecation from grazing cattle.

2.6 The Potential of Best Management Practices

FLNRORD partnered with local ranchers and water purveyors to pilot a series of Best Management Practices (BMPs) as a means to potentially mitigating the hazard that grazing cattle and *C. parvum* present to human health. To understand the potential for success and shortcomings of the proposed BMPs, two scenarios might be considered and contrasted as illustrated in Figure 1. The first is the status quo with no BMPs implemented. The second is the scenario in which BMPs have been implemented. Based on the literature, each explores the pathways by which oocysts from infected cattle faeces might enter drinking water surface sources, possibly resulting in viable *C. parvum* oocysts in treated drinking water that exceed public health standards.

A significant body of research has led to the development and verification of BMPs to manage riparian habitat subject to cattle grazing (Clary et al., 1989), mitigate adverse effects on water quality from both low intensity agricultural uses (Chaubey et al. 2010) and high intensity agricultural use (Collins et al. 2007; Cook et al., 1997; Hall et al., 1995, Johnson, 1992; Wilcock et al., 2009; Yates et al., 2007).

BMPs can be classified as either global or site specific. Global BMPs are policies and/or practices that protect an entire pasture or watershed from the hazard or adverse effects of grazing cattle on water quality and safety. Site specific BMPs are those that are focused on a specific site or region within a watershed to mitigate the potential impacts of grazing cattle on surface drinking water sources. The BMPs trialed in FLNRORD's pilot project to be verified include; scheduling access, exclusion fencing, controlled access to water sources, managing key areas, providing off-stream watering, and providing off-stream foraging (silvopasture).

Little research has been done to verify the efficacy of these practices in BC's community watersheds in mitigating their actual efficacy to mitigate grazing cattle from contaminating surface drinking water sources with *C.parvum*. The work that has been done is almost always under controlled trial conditions. The purpose of this work is to study the effects of BMPs implemented in actual field conditions in BC watersheds.

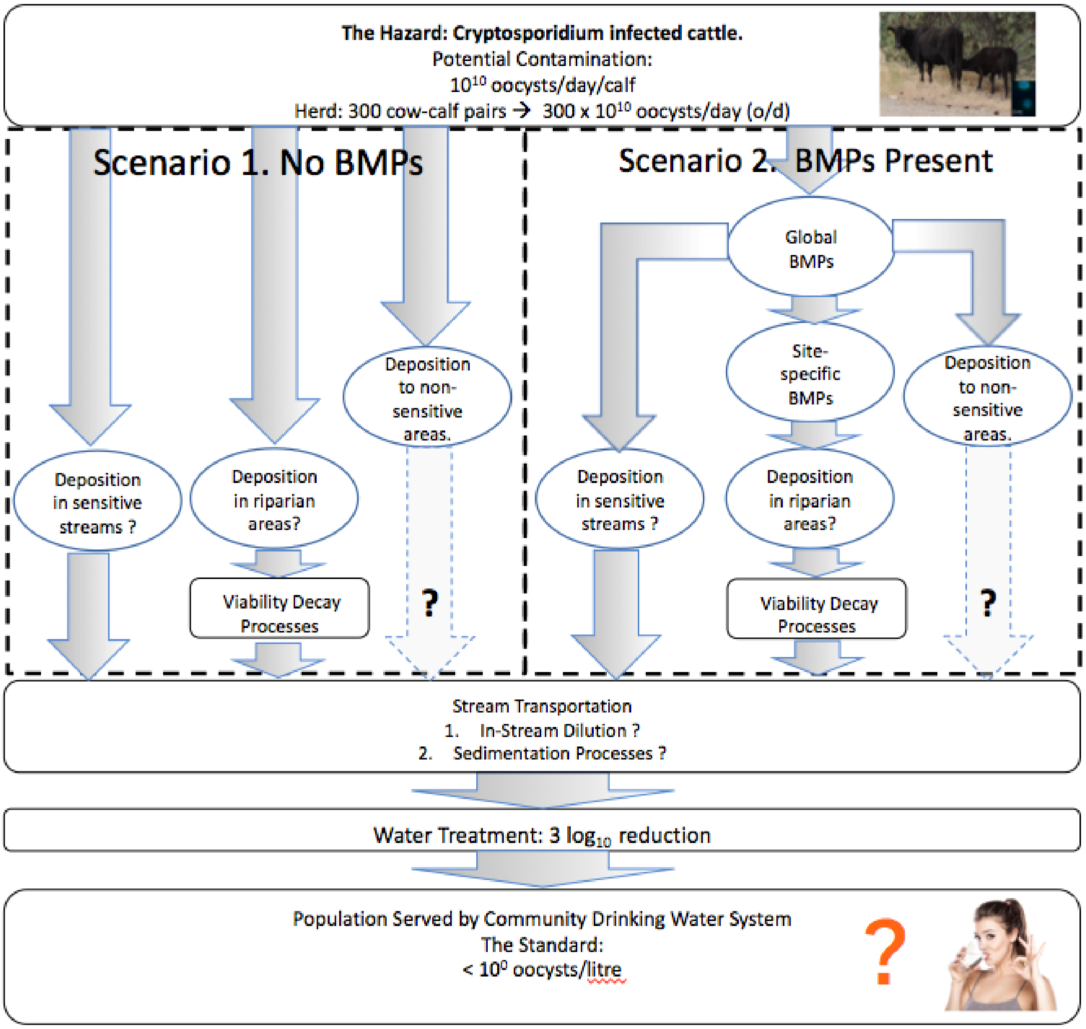


Figure 2.2 BMP versus non-BMP scenarios.

In the instance of each scenario, it has been assumed that there are 600 animals (300 cow-calf pairs) on a pasture as typical of a crown pasture lease. Common to both scenarios, each beef cow or calf that is infected with C. parvum can potentially release 10^{10} oocysts per day via defecation (Chappell et al., 1996), however, the literature has shown that it is calves that are of concern (Atwill et al. 1999). If all the calves in the herd are ill, potentially 300 x 10^{10} oocysts per day could be released at peak via defecation. In each scenario, the acceptable concentration of C. parvum in drinking water is such that an individual ingests less than 1 oocyst per day (essentially 0 oocysts per litre, a quantity less than 100 per litre).

Contaminated faeces can take three paths in either scenario. The first path is of least concern and results when cattle deposit their faeces in hydrologically remote areas distant from sensitive streams feeding drinking water intakes. This does not mean cattle faeces and oocysts deposited in these areas do not present any challenges to drinking water safety. Theoretically, a single infected animal defecating in a hydrologically remote location within a watershed could result in contaminated faecal material being transported to a surface water source, ultimately being ingested and infecting a human. Recent work by Miller et al. (2017) highlights the potential for cattle trails to act as stream network extensions, potentially facilitating transport from these areas, especially during heavy rain events. Recreational use of off highway vehicles and other activities could also potentially transport contaminated faeces to surface water sources. Wildlife present within BC's interior watersheds are also potential propagators of *C. parvum*.

The second path, of greater concern, arises when cattle defecate in sensitive riparian areas very close to streams directly feeding drinking water system intakes. In this case, intense rainfall events coupled with processes such as erosion might transport contaminated faeces and/or oocysts into the watercourse. The final path and of greatest concern is the direct deposition of contaminated faeces into watercourses upstream of drinking water intakes.

In neither scenario is there control over what happens to faeces and oocysts once they enter watercourses upstream of drinking water intakes. The fate of faeces and/or oocysts is directed by dilution and sedimentation processes during in-stream transport. The last chance to mitigate the hazard is at the drinking water intake where Health Canada (2012) guidelines require a treatment system that will remove 99.9% (a 3 $\log_{10}$ reduction in concentration) of any remaining oocysts from source water at the intake.

Since cattlemen and partners have little or no control over in-stream processes and water treatment requirements, their only role in mitigating drinking water source contamination is in assuring minimal probability of infected cattle in a herd from defecating in sensitive areas in a community watershed. This leads to two possible scenarios. In Scenario 1, cattle are not managed for this hazard. In this scenario, the concentration of oocysts reaching a drinking water intake in a community watershed will be a function of the incidence of *C. parvum* in the herd, the probability of cattle to directly defecate in sensitive streams and/or riparian areas in close proximity, and the probability of the oocysts traveling all the way to the drinking water intake..

In Scenario 2, the implementation of BMPs is considered. BMPs can take two forms; global BMPs mitigate the presence of potentially infected cattle into the watershed, and site specific BMPs that mitigate defecation by infected cattle in particularly sensitive areas such as streams directly feeding drinking water systems, or areas in close proximity. Comparing and contrasting Scenario 1 and 2 provides insights to the value of BMPs in assuring the quality and safety of water sources for human consumption and health.

2.6.1 Scenario 1: No BMPs.

In the first scenario without BMPs, calves are permitted into the pasture potentially at the peak of infection, delivering 300 x 10^{10} oocysts daily into a pasture in the watershed. Figure 2.3 summarizes this scenario.

2.6.1.1 Frequency and Distribution of Defecation

As previously discussed (Section 2.4), the distribution of cattle and frequency of defecation will directly impact the magnitude of the hazard to drinking water sources. Bagshaw's research (2002) indicates that cattle typically defecate 0.2 times per day within riparian zones, half of that time directly into the watercourse itself and that defecation incidence in riparian zones is strongly correlated with the amount of time the cow spends there. Regardless of season, trough presence next to streams, or pasture size or availability, cattle spend only about 4% of their time in riparian areas possibly affecting water quality. Transects of rangeland on the San Joaquin Experimental Range in California's Sierra Nevada foothills (Tate et al. 2003) yielded similar results. These results suggest that typically 5% of the faecal deposits of grazing cattle can be expected to be found to occur in a sensitive riparian area with an even split between faeces in the water and on the riparian area next to it. This translates into a worst case scenario on a given day if all 300 infected calves were to defecate into a stream at the same time, creating a load of 7.5 x 10^{10} oocysts directly deposited into a stream (Figure 2.3).

2.6.1.2 Fate of Oocysts in Sensitive Riparian Areas.

An equal number of oocysts is expected to be deposited on adjacent riparian areas where they are subject to decay and inactivation processes including predation, freeze-thaw cycles, and exposure to ultraviolet (UV) light, and must be released from fecal pats and transported to sensitive watercourses if they are to be of concern to human health.

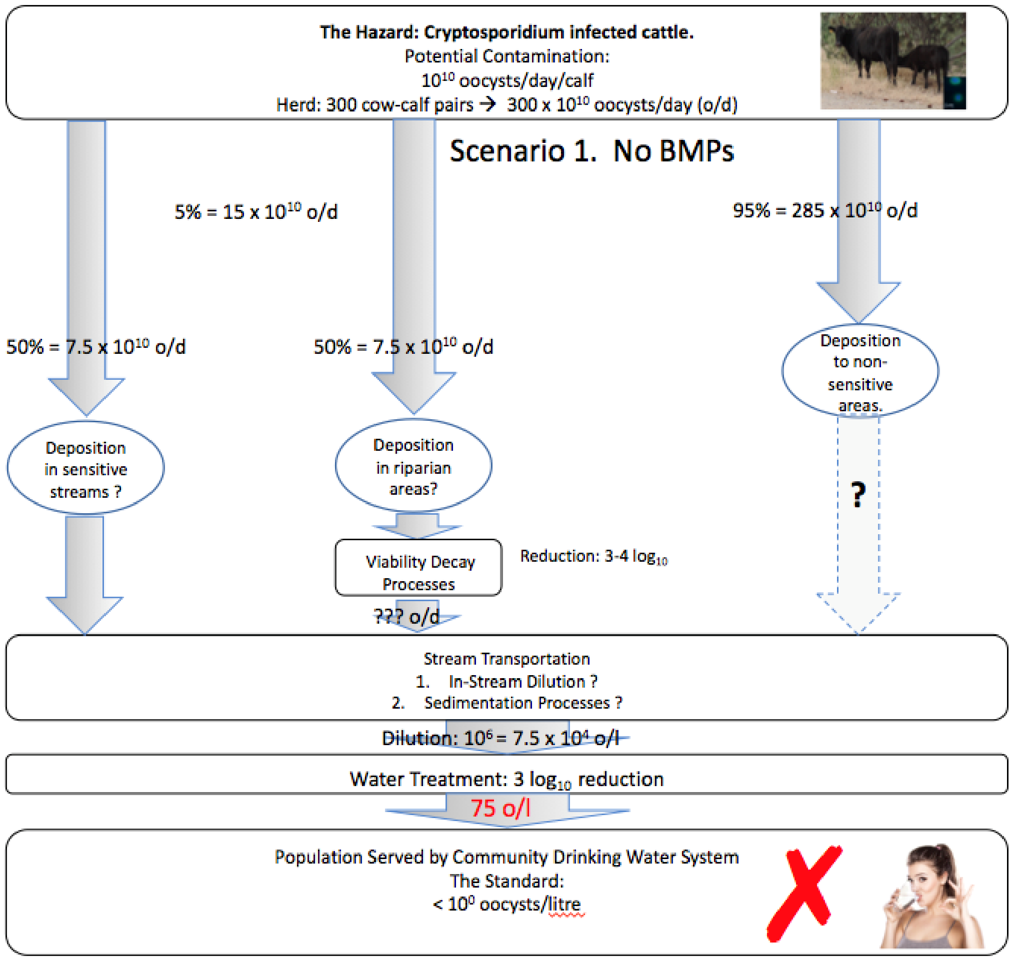


Figure 2.3 A non-BMP scenario.

2.6.1.3 Persistence, Release, and Transportation of C. parvum Oocysts in Faecal Material.

Both Story's (2016) summer and winter persistence studies (Section 2.5.4) indicated that though freeze-thaw cycles and UV light can affect the persistent viability of *C. parvum* oocysts, conditions can exist in moderate and heavily forested situations that may protect oocysts and maintain their cell structure, potentially into the following spring with its freshet.

Even when oocysts remain viable, they must be released from their faecal pats. Previous work (Bradford et al., 2002, Schijven et al., 2004) found that effluents from flushing faecal pats typically contained concentration of oocysts several orders of magnitude below starting concentrations with total reductions in the pat concentrations by half within 250 minutes and then only marginal reductions subsequently (Section 2.5.1).

In addition to temperature and UV light effects explored by Story (2016), other processes have been identified that can adversely affect the survival of *C. parvum* oocysts in the environment (King et al., 2007). The combination of reduced viability over time, and release rates from faeces under laboratory conditions suggests that the number of oocysts available in a 24 hour period potentially released in sensitive habitats are in the order of 3 to 4 $\log_{10}$ below that initially deposited.

Oocysts must also be transported from their faecal deposits to the stream. Significant research has been conducted on overland transport of oocysts. As previously discussed (Section 2.5.2), Tate et al. (2000), greater concentrations of *C. parvum* oocysts can be expected in runoff with increasing slope due to higher overland flow velocity and reduced infiltration. It was also noted that oocyst concentrations tended to decrease with subsequent storm events. A strong flushing of oocysts early in a rainfall event can be expected with a subsequent decline within 60 minutes.

Buffer strips along watercourses were also explored to mitigate contamination from cattle faeces (Atwill et al. 2002, Section 2.5.2). Results of the linear mixed-effects models developed to calculate the impacts on oocyst reduction in effluents as a function of soil type, slope, and bulk density for a 100 cm vegetated buffer subsequently indicated $\log_{10}$ reductions in oocysts from 1.0 to 3.1. Similar work with vegetated and bare soil blocks by Davies et al. (2004) found that runoff volumes on bare soils can be up to five times that on vegetated soils, and that vegetated blocks promoted much greater infiltration. Ultimately it was concluded that on slopes of less than 20% grade, a 3 m or greater buffer could remove 99.9% (a 3 $\log_{10}$ reduction in concentration) or more *C. parvum* oocysts during mild to moderate precipitation events (up to 4 cm-hr^{-1}) (Atwill et al. 2002).

The implications of results from the literature on the fate of *C. parvum* oocysts deposited in sensitive riparian areas is for a 3 - 4 $\log_{10}$ reduction in concentration due to a reduction in viability over time in addition to a reduction of 2 - 3 $\log_{10}$ in concentration resulting from transport losses from fecal pat to watercourse for a total reduction of 5 – 7 $\log_{10}$ in concentration. This implies that of the 7.5 x 10^{10} oocysts-day^{-1} deposited adjacent to streams, only 7.5 x 10^{5} oocysts may reach the stream, a magnitude 5 $\log_{10}$ below the faeces directly deposited in the watercourse.

2.6.1.4 In-Stream Transport and Oocyst Reduction Processes.

Transitioning from the solid phase (faeces) to the in-stream water column involves dilution. Flow rates from example watersheds in the Okanagan valley that supply community water systems range from 300 L-s^{-1} to 500 L-s^{-1} median discharge rate during the summer cattle grazing months of June to October (Ecoscape, 2010; RDNO 2008). As previously discussed (Bagshaw, 2002), cattle typically defecate in proportion to their time in an area. This would imply that if cattle are defecating 4% of the time in sensitive riparian areas, they are roughly spending 4% of their time in area. In a worst-case scenario, if all 300 calves were to defecate over this period directly into a stream with a flow rate of 300 L-s^{-1}, this would imply a dilution of roughly 7.5 x 10^{10} oocysts into 10^6 litres, resulting in a concentration of 7.5 x 10^4 oocysts/L. The concentration would be much lower for the oocysts deposited in faeces in the riparian area.

Once *C. parvum* oocysts have been transported to surface water sources or directly deposited in to a creek, the question becomes how many will be transported to a drinking water intake? *C. parvum* oocysts are typically 4 to 6 μm in diameter with a specific gravity of about 1.05 g-cm^{-3} but their physical characteristics have been shown to be significantly altered due to attachment to suspended sediments (Searcy et al. 2005), resulting in much greater removal rates of oocysts from water columns and their accumulation in sediment beds.

Searcy et al. (2006) characterized and modeled the potential interactions responsible for removing oocysts from the water column (Section 2.5.3). Table 2.4 summarized the results for both a typical small agricultural headwater stream, and a moderate sized river considering all three mechanisms for oocyst removal; classic sedimentation, classic sedimentation with stream subsurface exchange, and classic sedimentation with stream subsurface exchange and the presence of suspended sediments.

Actual reductions in oocyst concentrations in streams from sedimentation and other processes will be a function of the hydrology of each individual stream, and the proximity to intakes for community drinking water systems. In cases where the pasture is approximately 10 km upstream of the drinking water intake there is a significant opportunity for the reduction in oocyst concentration from sedimentation and other in-stream processes, providing potential reductions of up to 3 $\log_{10}$. In contrast when a pasture is only a few hundred meters from a drinking water intake, in-stream processes to reduce oocyst concentration are minimized.

2.6.1.5 Potential Drinking Water Source Contamination without BMPs.

The net effect is that without BMPs in place, water subject to grazing cattle could be contaminated with as many as 7.5 x 10^4 oocysts-L^{-1}. Treatment requirements, if to current

Health Canada guidelines, may only reduce the concentration by 3 $\log_{10}$. This implies that a worst-case scenario exists with consumers ingesting water with up to 75 oocysts-L^{-1}, possibly risking illness.

2.6.2 Scenario 2: BMPs Present

In the second scenario, BMPs are considered and their potential impacts on the oocyst load that might eventually enter drinking water systems. As previously discussed, BMPs can be classified as global, mitigating the load of oocysts across the entire watershed, or site specific. The six BMPs to be used in the pilot project are considered here. The implications of each BMP is discussed independently with respect to its potential to mitigate drinking water source contamination with *C. parvum*. Figure 2.6 illustrates the three possible fates for *C. parvum* oocysts in a community watershed, while reflecting the impacts of the BMPs.

2.6.2.1 Access Scheduling

The first BMP to be verified is the scheduling of cattle grazing activities to simply keep cattle deemed high risk for being carriers of *Cryptosporidium* out of community watersheds and in particular, away from vulnerable surface water sources. Grazing leases from FLNRORD only allow cattle into pastures for specified periods and only with calves greater than four months in age. This policy can be classified as a global BMP. The implication of this BMP is that of the 300 calves typically allowed onto a pasture in a community watershed, it is very probable that as few as 1% of them might be infectious shedders of *C. parvum* oocysts in their feces, representing a 2 $\log_{10}$ oocyst reduction before any other BMPs are implemented.

The scheduling access BMP is based in research (Gow et al., 2005, McAllister et al. 2006) indicating that the incidence of *C. parvum* infection in beef cow-calf herds in western Canada is very low (~5%) except during calving season when it can spike (28% for cows, 13% for calves). Atwill et al. (1999) also showed that the incidence of oocyst shedding for calves 1 to 4 months of age was 41 times greater than older calves, and cattle greater than 1 year of age typically shed oocysts only 0.6% of the time. Hence the scheduling access BMP embodies the assumption that calves greater than 3 months of age are a lower threat to contaminate water sources with *C. parvum* than younger calves and the threat decreases as the animal ages.

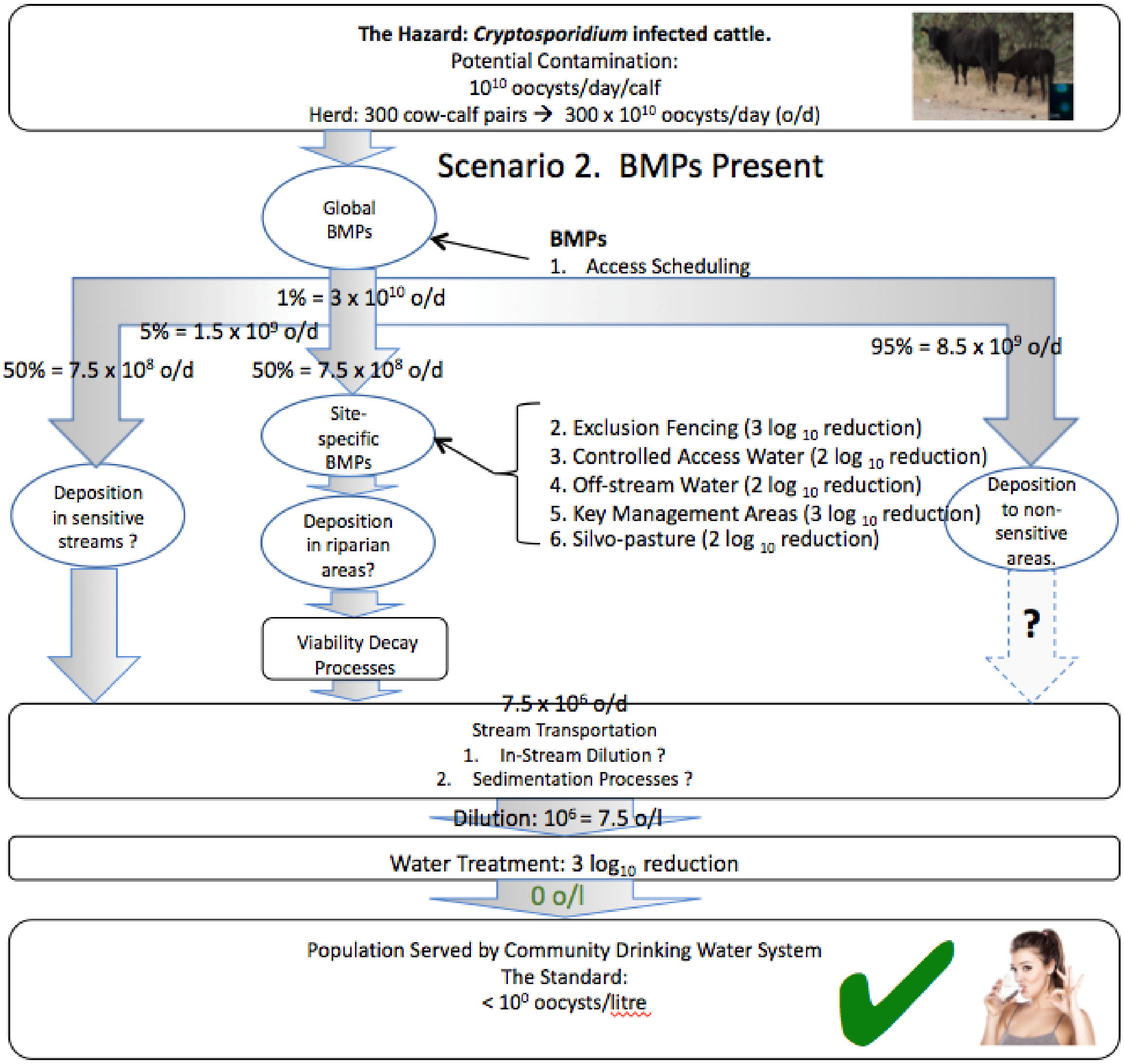


Figure 2.4 The BMP scenario.

A second factor considered in the development of this BMP is the freshet, which in BC's central interior typically lasts from early April to early June (OBWB n.d., Dobson 2004) of each year. This surge of snowmelt water in the stream network could potentially result in faeces deposited next to streams in sensitive riparian areas being washed into watercourses feeding drinking water systems. Potentially infectious cattle in sensitive areas during the freshet could be very problematic for water quality and is not permitted.

Finally, *C. parvum* persistence in the environmental conditions typical of BC's interior watersheds must also be considered. Oocysts can remain viable for periods in excess of 167 days or longer under the environment conditions of BC's interior watersheds (Story 2016). The potential for faeces to contaminate drinking water sources with oocysts after cattle have been vacated from pastures means that scheduling access must also be considered in pasture lease agreements as to when cattle are permitted to be in pastures, particularly those directly upstream of drinking water intakes.

Currently scheduling is implemented within the grazing lease conditions that each lessee must abide by. All scheduled periods of access for cattle to both pastures in whole or part are the product of the range use plan (RUP) (BCMoF, 2000) for the pasture. RUPs are required for all grazing and hay cutting activities under the BC Range Act (Legislation) Sec. 10 (1) A). In developing the RUP, several factors are considered, including the types of classes of livestock that will be present, the number of livestock to be allowed into the pasture or areas of the pasture, and the schedule indicating when they can enter the pasture, and by when they must leave the pasture.

In addition to prohibiting cattle with young calves into pastures that might shed *C. parvum* in their faeces, restrictions on access might be put in place as a function of the forage available to mitigate over-foraging, particularly in areas that are particularly sensitive to over-grazing or the consequences of over-grazing. Leases are usually limited in the number of cattle that can be placed on a pasture to half the maximum capacity determined in the development of the RUP for a crown pasture. Particularly sensitive areas to over-grazing are also noted, and these areas are usually flagged as ‘key management areas’ by FLNRORD personnel and key stakeholders (see Section 3.2.5).

2.6.2.2 Exclusion Fencing

The second BMP being piloted is exclusion fencing to inhibit cattle from gaining access to specific streams and riparian areas that are sensitive to *C. parvum* contamination. Ideally, cattle are not allowed to come within 5 m of stream banks, allowing riparian vegetation to inhibit feces and oocyst transport into watercourses. Research suggests that properly placed and maintained fences should result in a 3 $\log_{10}$ reduction in oocyst exposure and transfer to watercourses (Atwill et al. 2002, Tate et al. 2000).

The primary form of fencing is man-made fencing consisting primarily of barbed wire mounted on posts and/or trees. In addition to man-made fencing, natural barriers may also be incorporated to control access. Fencing also necessitates the use of gates and structures to allow for the controlled movement of cattle into and from pastures. These may include cattle guards that allow access to humans and vehicles while discouraging cattle from crossing. Exclusion fencing may be placed along streams and riparian areas to prohibit cattle from directly accessing surface water sources and potentially defecating in them. Lakes, which have been assumed to be barriers to oocyst transport, are also used as a means of removing *C. parvum* from drinking water sources by sedimentation, usually have 200 m. to each side of their outflows fenced off as a BMP.

Exclusion fencing can be an effective BMP, however there are limitations and concerns:

1. It is costly. Current fencing costs in the study area are approximately $12,000/km[2].
2. Though they can be effective at preventing direct deposition of faeces from cattle in surface water sources, depending on their location, they do not prevent the faeces from moving into the water sources by the spring freshet and/or other weather events.
3. In forests with heavy canopy, there are usually travel corridors along one side of each fence that act as transit corridors for cattle and other animals. Trampling by animals results in bare earth that is easily eroded transporting both soil and deposited faeces into water courses during heavy rain or the freshet.
4. Fences require maintenance to offset the deterioration from natural processes such as rot and rust, and from vandalism. Either way, this incurs effort and financial resources on a continuous basis.
5. Gates can be inadvertently left open, granting unintended cattle access to sensitive streams and riparian areas.

Fence location relative to streams is a particular concern. Vegetated buffer strips of 3 to 7 m in width have been identified as useful for mitigating the transport of oocysts from cattle faeces into streams (Atwill et al. 2002, Tate et al. 2000), leading to the development of the ‘5 m rule’ by FLNRORD. The ‘5 m rule’ stipulates that water courses should be safe from contamination if cattle are kept at least 5 m from stream banks in sensitive riparian areas. The basis of this rule being conclusions by Atwill et al. (2002) that on slopes less than 20% in grade, over 99.9% of oocysts would be removed by a vegetated buffer greater than 3 m in width from surface water sources.

[2] pers comms. Rob Dinwoodie P.Ag. Range Agrologist BC Ministry of Forests, Lands, and Natural Resource Operations. April 9, 2015.

Though fences should be at least 5 m from sensitive surface water sources, it can be quite difficult to install them in heavy forest canopy, and their construction can result in the creation of corridors. Furthermore, historically streams have served as boundaries between pastures in BC interior community watersheds and fences are put into place to respect these boundaries. This often results in fence placement within the riparian area directly adjacent to the stream.

These corridors can be attractive to cattle as pathways of least resistance (Ganskopp et al. 2007). Cattle traffic over these pathways can result in trails without vegetative cover, compacted soil with low infiltration. These trails often resemble ‘narrow, linear troughs’ that are ‘major conduits for concentrated runoff of water and contaminants’ (Miller et al. 2017). This means that fences established near streams in medium to heavily forested areas without due care might be problematic if within 5 m of the stream banks should cattle be attracted to the resulting corridor.

Exclusion fencing is also used as a BMP at the outflows of lakes and reservoirs. Fences are established to keep cattle from these water sources at least 200 m from outflows. Research (Searcy et al., 2006, Medema et al., 1998, Dai et al., 2006) has also indicated that *C. parvum* oocysts are susceptible to sedimentation by stream-subsurface interaction processes. It has been theorized in developing BMPs that oocysts are susceptible to these processes in lakes and reservoirs, and hence they act as barriers to *C. parvum* oocysts being transported downstream to drinking water intakes. Hence, in theory, BMPs need only be implemented for stream reaches below the lowest lake or reservoir in a watershed’s stream network.

2.6.2.3 Controlled Access to Water

In conjunction with exclusion fencing, a second site-specific BMP used to mitigate potential contamination of surface water sources by cattle faeces is controlled access to these water sources (popularly referred to as ‘nose holes’). Nose holes (see Figure 3.1) take the form of exclusion fencing that has been placed at specific points in a stream. The theory is that they encourage cattle only to place their noses in the surface water source to consume water while discouraging them from defecating directly in the stream and allow only a very limited number of cattle access to a stream at a time, effectively creating a 1 – 2 $\log_{10}$ reduction in the subsequent concentration of oocysts in water after dilution from stream flow. At only about $300[3] in incremental fencing costs, nose holes are inexpensive relative to other means of providing water to cattle. They do have potential limitations however:

1. Nose holes are within the riparian area, and cattle traffic can result in the trampling of vegetation on the site, and deteriorated soil structure. There is greater risk of any deposited faeces being washed into watercourses during the spring freshet and/or extreme weather.
2. As with exclusion fencing, they can result in bare earth corridors with compacted soils leading directly to and from that can be problematic for water quality when they become extensions of the stream network carrying runoff and contaminants.
3. Depending on the placement of the nose hole, shading and the cool water of the stream could potentially act as an optimal environment for increasing the persistence of any *C. parvum* present in faeces deposited near the nose hole.

2.6.2.4 Off-stream Watering

The alternative to providing a nose hole is the provision of water off-stream. This site-specific BMP that can take several forms including a water trough fed by gravity or a stream driven, or solar or wind powered pump. Alternatively, a nose pump can be provided to allow cattle to pump their own water. Given a choice between drinking from a stream or an off-stream source, research indicates that over 90% of the time cattle prefer the off-stream water source (Sheffield et al. 1997). This effectively represents a $\log_{10}$ reduction in stream exposure to contamination, however, it can cost $3000[3] or more per site, and must be maintained.

2.6.2.5 Key Area Management

Stubble height management in meadow areas with low velocity streams is another BMP. This site-specific BMP provides direct access for cattle to the watercourse and riparian area for water and forage but the stubble height of the forage is monitored and managed to a minimal height of 10 cm. to prevent the movement of feces into the watercourse. The cattle can access the water to drink at any point in the meadow mitigating the creation of compacted, bare earth trails. As previously discussed, research suggests vegetated buffers are potentially very effective in

[3] pers comms. Rob Dinwoodie P.Ag. Range Agrologist BC Ministry of Forests, Lands, and Natural Resource Operations. April 9, 2015.

meadows with good forage production to mitigate oocysts transport into watercourses (Atwill et al. 2002, Tate et al, 2004) with an effective 3 $\log_{10}$ reduction in feces transport to stream for deposits greater than 3 m from the stream banks. Ultraviolet light exposure in these areas also limits viable *C. parvum* oocysts persistence (Story 2016). On-going monitoring and management is required to prevent over grazing of stubble as an effective filtering material. Low water velocity combined with the tortuosity of the streams in these meadow areas also means there is significant potential for sedimentation and other in-stream processes too as observed by Searcey et al. (2006). In the context of key area management this could result in a 2 – 3 $\log_{10}$ reduction in oocyst concentration just within the extents of the meadow itself.

2.6.2.6 Silvo-pasture

The final BMP to be discussed is the introduction of silvo-pasture. Silvo-pasture can be defined as the ‘deliberate integration of trees and grazing livestock operations on the same land’ (USDA, 2013). This is a site-specific BMP targeted to mitigate contamination of water in specific stream reaches in a watershed. It is characterized as being the intentional, integrated, interactive and intensive use of land for both forest and cattle production (Fike et al. 2004). Silvo-pastures have the potential advantages of providing attractive forage in addition to off-stream watering to attract cattle away from riparian areas.

Silvo-pastures potentially provide a number of benefits to different stakeholders, but most important to water quality, silvo-pastures can be developed upstream of lakes and reservoirs, away from critically vulnerable streams and riparian areas that feed into drinking water systems. Silvo-pastures also promote cooperation between a diverse group of stakeholders including, regulators, forestry operators, and cattlemen to manage the landscape in an integrated fashion to assure the best outcomes for all parties involved.

When properly managed, silvo-pastures also represent an opportunity to:

1. Provide a cooler summer environment for livestock.
2. Shorten timber rotations because of forage fertilization and better control of competition.
3. Improve timber production through better pruning and tree density management.
4. Provide higher quality forage due to shading.

No specific work has yet been done to indicate the potential reduction in sensitive stream exposure to *C. parvum* oocysts, but it can be expected that it would be at least the same order of magnitude as off-stream watering, a $\log_{10}$ reduction.

2.6.2.7 Potential Drinking Water Source Contamination mitigation with BMPs.

The net effect of applications of BMPs is summarized in Figure 2.6. If the BMPs perform as suggested, even in worst case scenarios, the concentration of oocysts in surface drinking water sources in a community watershed should be less than or equal to 7.5 oocysts-L^{-1}, prior to treatment requiring a further reduction of 3 log_{10}. This implies that the BMPs should assure that drinking water is safe for consumption with few or no incidences of cryptosporidiosis.

2.8 Quantitative Microbial Risk Assessment

Assessing human health risks from microbial contaminants is similar to but distinct from assessing health risks from chemical contaminants. Soller (2008) cites the primary difference as being the sources of exposure. Exposure to chemicals is purely environmental. Exposure to microbes in contrast can be both from the environment and from other infected individuals. To account for this and other subtle differences, a formal framework has been developed to assess the risk from microbial contaminants. This framework is referred to as the Quantitative Microbial Risk Assessment framework (QMRA). Variations on QMRA have been developed by World Health Organization (Medema et al. 2009), the US Environmental Protection Agency (Soller, J., 2008), and the European Commission. Soller (2008) defines QMRA as, "a formal process analogous to chemical risk assessment of estimating human health risks due to exposures to microbial pathogens." QMRA is viewed as a component to the WHO's Safe Water Framework (Fig. 2.5).

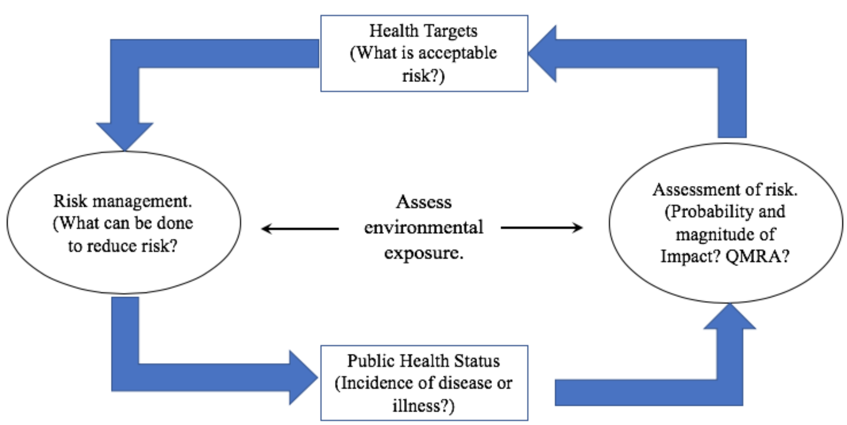


Figure 2.5 Safe Drinking Water Framework. After Fewtrell and Bartram (2001).

QMRA is defined to have four basic elements, analogous to those used in the risk paradigm for chemical contaminants. These are (Medema et al., 2006, CAMRA, n.d.):

1. Problem Formulation: A characterization of the problem setting, including identification of the hazards and hazardous events. This should include an identification of the microorganism and the disease it causes, including potentially sensitive populations.
2. Exposure assessment. The objective is to describe the pathways by which sensitive populations might come in to contact with the microorganism. This includes consideration of:
    a. Identification of source water and pathogen concentration.
    b. Treatment or systems of pathogen removal inactivation.
    c. Distribution systems.
    d. Consumption, the volume of water consumed.
3. Effect assessment. This means using the appropriate dose-response relationships for the microorganism and exposed population that provide an estimate of the number of people that might be affected by the microorganism.
4. Risk characterization: An estimate of the pathogens potential impacts on the population. This can be more complicated for microbial contaminants than chemical contaminants because of the ability for microbial contaminants to move from an infected to a non-infected individual.

Figure 2.6 provides a context for the QMRA in the Safe Drinking Water Framework (Fewtrell et al., 2001).

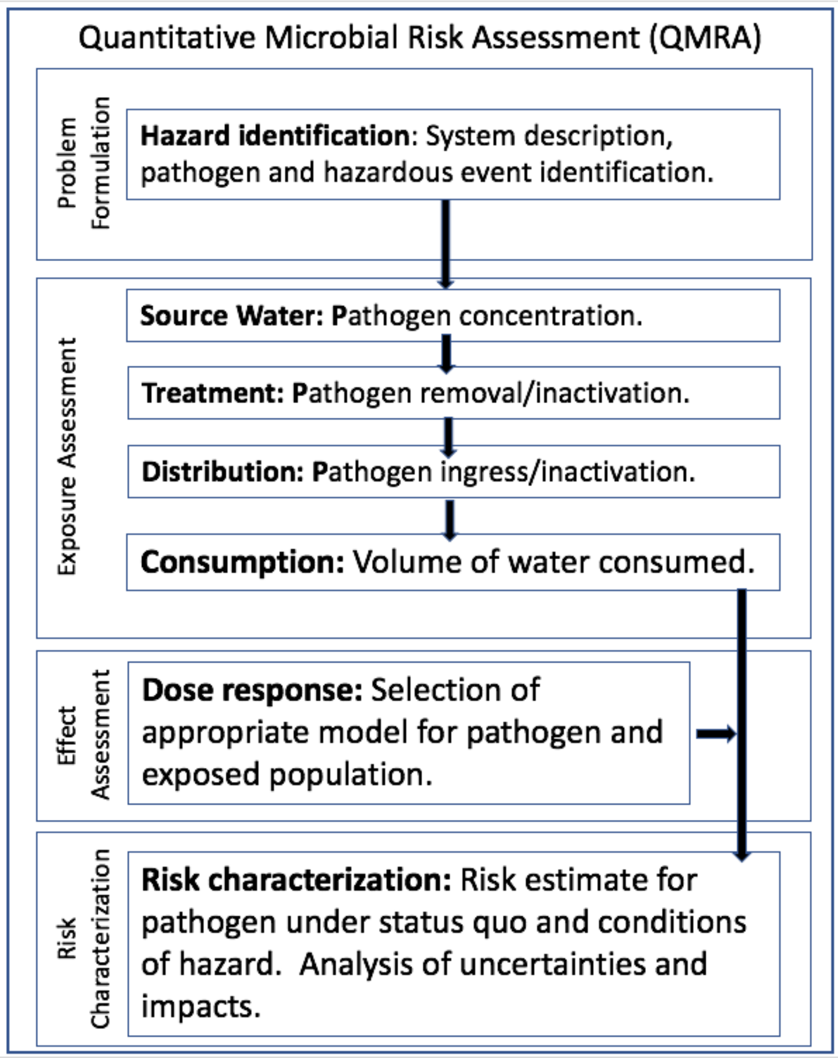


Figure 2.6: QMRA in the context of the Safe Drinking Water Framework (after Fewtrell and Bartram, 2001) .

2.8 Summary

Cattle grazing in watersheds that provide surface water to community drinking water systems can pose a significant hazard to the health of consumers because of potential contamination with *C. parvum* in cattle faeces. Best management practices (BMPs) are perceived as a means of mitigating this potential hazard. In exploring the literature with respect to the magnitude of the potential hazard, the implication of not invoking any measures to mitigate contamination, it is conceivable that there is a real and considerable risk to human health. The primary reason for this being that the concentration of *C. parvum* oocysts at a community drinking water intake may be higher than the required removal or deactivation under current drinking water guidelines.

In exploring the possible effects of the six BMPs under consideration for a pilot project for the mitigation of *C. parvum* from cattle entering streams, the literature suggests that sufficient reduction and/or inactivation of *C. parvum* oocysts can be assured to mitigate the hazard to human health. This does not mean that *C. parvum* oocysts will be completely removed or inactivated before drinking water intakes, but that treatment systems should be adequate in eliminating the remaining risk to human health.

Of the six BMPs discussed, the literature suggests that the most important is access scheduling because it significantly reduces the exposure of community watersheds in total to animals that may be problematic for infection with *C. parvum*.

Additionally, fences and nose holes may be problematic, fence lines often straddle streams near to or within sensitive riparian areas, this may result in cattle using the resulting corridors to the point that damage to riparian habitat might not inhibit the transport of oocysts into drinking water sources. Nose holes may further aggravate this situation in that they require placement of exclusion fencing right into the watercourse itself.

With respect to off-stream watering and silvo-pasture, the literature suggests that both show significant potential as BMPs to reduce cattle grazing as a hazardous activity to community drinking water sources. Key management areas in which minimal stubble height is monitored and controlled also shows significant promise.

As a result of this review, it can be concluded that cattle are a potential hazard but if BMPs have been effectively implemented, then with the potential exception of the exclusion fencing and nose hole in particular situations, drinking water consumers should be at much lower risk from developing cryptosporidiosis as a consequence of the presence of grazing cattle in community watersheds. Note that lower risk implies mitigation, not elimination of the hazard. As previously discussed, there will always be the potential for *C. parvum* contaminated drinking water from surface sources in the BC interior watersheds either from cattle or wildlife defecation.

The conclusion reached from this review pre-supposes that previous research reflects what is happening in the community watersheds of the BC interior. This may not be the case.

1. In many instances, the previous research does not necessarily reflect the *conditions* of the BC interior. Aside from research to determine the incidence of *C. parvum* infection in beef cattle

herds in western Canada no research has been done to verify that grazing cattle are a significant potential source of *C. parvum* contamination to surface drinking water sources. It might even be questioned whether grazing cattle are a threat at all for *C.parvum* contamination of surface drinking water sources in the BC interior. A review of the literature has in fact not revealed any case of grazing cattle being the definitive source of *C. parvum* contamination of community drinking water sources.

2. The literature suggests that BMPs, if properly implemented, should mitigate the potential for grazing cattle to adversely affect human health, but very little research has been done in actual commercial operations as opposed to research environments. Hence there is a need for field research to determine whether BMPs are effective in actual practice in mitigating *C. parvum* contamination of surface drinking water sources exposed to grazing cattle.

3. As stated in the introduction, the BC government has leased crown pastures for grazing cattle for over a century. In parallel to this, the BC Ministry of Health also maintains a database of reported human health incidences of cryptosporidiosis in the province. There has been no previous research correlating the incidence of cryptosporidiosis in a human population with the presence of grazing cattle on pasture upstream of intakes to community drinking water systems.

Chapter 3.0 Field Verification of BMP Effectiveness in BC's Interior Watersheds.

3.1 Background

In the summer of 2010, the District of Lake Country noted spikes in faecal coliforms at their drinking water intakes in the Vernon Creek and Oyama Creek community watersheds. As briefly discussed in Chapter 1, the Forest Practices Board (FPB) of BC responded by conducting an audit of forestry and range activities in the two watersheds providing water to the District of Lake Country municipal water systems. In their results and final report, the FPB expressed concerns with respect to grazing cattle and their potential effects on water quality and safety.

Auditors were particularly concerned with the potential for cattle infected with *Cryptosporidium parvum (C. parvum)* to contaminate drinking water and cause illness within the human populations served by these watersheds. In Chapter 2, the extent of this potential threat to human health was explored within previous research. Cattle grazing leases by the BC Ministry of Forests, Lands, and Natural Resource Operations and Rural Development (FLNRORD) typically allow 300 cow-calf pairs into pastures in community watersheds for periods of up to six weeks at a time. Mature cows are at very low risk of being a source of *C. parvum*, but each of the 300 calves accompanying them can potentially be a source of 10^{10} oocysts/day if infected (Atwill 1996) resulting in a of 300 x 10^{10} oocysts being introduced each day to the landscape within a pasture.

To alleviate the concern that grazing cattle in community watersheds and *C.parvum* pose a risk to human health, FLNRORD responded to the FPB audit in 2012 by partnering with ranching operations in watersheds serving both the District of Lake Country and the City of Vernon to develop and implement a pilot project of best management practices (BMPs) to mitigate this possibility. BMPs consist of policies, procedures, and physical infrastructure improvements in watersheds with the objective of mitigating the potential contamination of surface drinking water sources by grazing cattle. The BMPs developed and implemented for the pilot project were developed from a literature review conducted by FLNRORD staff.

3.1.1 Research Objectives

The overall objective of the BMPs currently being piloted is to assure that grazing cattle on crown land do not impact the quality of water provided by the community watersheds (CWs) with pathogens such as *C. parvum* and *Escherichia coli (E. coli)*, and specifically with the objective to prevent incidents of viable *C. parvum* oocysts reaching drinking water system intakes, assuring both water purveyors and provincial health authorities of water safety.

To verify the effectiveness of the BMPs implemented in the pilot project, FLNRORD engaged the Biological Solutions Laboratory in the School of Engineering at the University of British Columbia's Okanagan campus (UBC-O). A three-year study plan was developed consisting of a literature review, field sampling, laboratory analysis, and controlled field research (Story 2016). The specific objectives of this research were to:

1. Verify the effectiveness of the BMPs implemented in the pilot project.
2. Verify the assumptions under which the BMPs were effective.
3. Where possible, determine background levels of *Cryptosporidium* oocysts contributed by wildlife.
4. Implement US EPA method 1623 and describe the costs and other challenges associated with testing for the presence of *Cryptosporidium* in drinking water, test whether monitoring for *E. coli* can serve as a proxy indicator for *Cryptosporidium* presence.
5. Develop recommendations for the implementation of further BMPs within the study area and in other community watersheds with grazing cattle present.

An effective BMP is defined as one that achieves a reduction or prevention of *C. parvum* oocysts from potentially reaching a drinking water intake. Ideally, drinking water at the tap will have less than one oocyst per liter (Chappell et al. 2004). Health Canada (2012) stipulates that water treatment should be capable of a 3 $\log_{10}$ reduction in oocyst concentration during treatment, in theory meaning that oocyst concentration at a drinking water intake could be as high as 10^3 oocyst/l. The BMPs implemented during the pilot project were predicated on information gleaned from empirical evidence in the literature, mostly from dairy operations or cattle feed lots. Their validity in the dispersed cattle grazing in the mountainous landscape of BC must also be assured if their use is to be expanded both within the study area and in other watersheds in BC. Wildlife are also a potential source of *C. parvum* in BC watersheds (Centre for Coastal Health, 1996) and hence assessing their contribution is also necessary in planning the development of water treatment systems and managing upland water resoures.

3.1.2 Project Advisory Committee

To ensure the success of the BMP verification project to the satisfaction of the diverse stakeholders involved in BC's interior community watersheds, an advisory committee was struck to review and contextualize the research. In addition to members directly representing agricultural interests being affected (e.g. members of the BC Cattlemen's Association), the committee was also comprised of a diverse group of representative stakeholders in both the management of community watersheds, and in outcomes that might affect water quality and safety for human consumption. Table 3.1 summarizes the makeup and affiliations of the advisory committee. Notable among these is representation of the water purveyors that receive water from the study area and representation of the regional health authority that is empowered under BC's Drinking Water Protection Act to ensure that drinking water is safe for human consumption.

Table 3.1 Industry advisory committee.

Name	Affiliation
Robert Dinwoodie	BC Ministry of Forests, Lands, Natural Resource Operations, and Rural Development (FLNRORD)
Lee Hesketh	BC Cattlemen's Association (BCCA)
Renee Clark	Regional District of North Okanagan (RDNO)
Patti Meger	District of Lake Country
Dr. Cindy Meays	BC Ministry of Environment (MoE)
Dr. David Lapen	Agriculture and Agri-food Canada (AAFC)
Robert Birtles	Interior Health Authority (IHA)

3.2 Best Management Practices to be Verified

A significant body of research has led to the development and verification of BMPs to manage riparian habitat subject to cattle grazing (Clary et al.,1989), mitigate adverse effects on water quality from both low intensity agricultural uses (Chaubey et al. 2010) and high intensity agricultural use (Collins et al. 2007; Cook et al., 1997; Hall et al., 1995, Johnson, 1992; Wilcock et al., 2009; Yates et al., 2007).

BMPs can be classified as either global or site specific. Global BMPs are policies and/or practices that protect an entire pasture or watershed from the hazard or adverse effects of grazing cattle on water quality and safety. Site specific BMPs are those that are focused on a specific site or region within a watershed to mitigate the potential impacts of grazing cattle on surface drinking water sources. The BMPs trialed in FLNRORD's pilot project to be verified include; scheduling access, exclusion fencing, controlled access to water sources, managing key areas, providing off-stream watering, and providing off-stream foraging (silvopasture).

Little research has been done to verify the effectiveness of these practices in BC's community watersheds, and the work that has been done is almost always under controlled trial conditions (Section 2.7). The purpose of this work is to study the effects of BMPs implemented in actual field conditions in BC watersheds.

3.2.1 Scheduling Access

The first BMP to be verified is the scheduling of cattle grazing activities to simply keep cattle deemed high risk for being carriers of *Cryptosporidium* out of community watersheds and in particular, away from vulnerable surface water sources. Grazing leases from FLNRORD only allow cattle into pastures for specified periods and only with calves greater than four months in age. This policy can be classified as a global BMP. Previous research (Chapter 2) suggests that if this BMP is implemented that of the 300 calves allowed into a community watershed, it is very probable that as few as 1% of them might be infectious shedders of *C. parvum* oocysts in their feces, representing a 2 $\log_{10}$ oocyst reduction before any other BMPs are implemented.

3.2.2. Exclusion Fences

The second BMP being piloted is exclusion fencing to inhibit cattle from gaining access to specific streams and riparian areas that are sensitive to *C. parvum* contamination. Ideally, cattle are not allowed to come within 5 m of stream banks, allowing riparian vegetation to inhibit feces and oocyst transport into watercourses. Previously research (Chapter 2) suggests that properly placed and maintained fences should result in a 3 $\log_{10}$ reduction in oocyst exposure and transfer to watercourses (Atwill et al. 2002, Tate et al. 2000), however, in heavily forested watersheds they may be problematic if cattle use fence lines along vulnerable streams as corridors.

3.2.3 Controlled Access to On-Stream Watering (Nose Holes)

In conjunction with exclusion fencing, a second site-specific BMP used to mitigate potential contamination of surface water sources by cattle faeces is controlled access to these water sources. In this instance, it takes the form of a nose hole, exclusion fencing that has been placed at specific points in a stream (see Figure 3.1).

3.2.4 Off-Stream Watering

Off-stream watering is a site specific BMP that can take several forms. A water trough can be gravity fed or pumped from the stream uphill of the trough. A pump can be stream flow driven, or solar or wind powered. Nose pumps (Figure 3.2) can also be provided to cattle to pump their own water from a stream or other source. This BMP is attractive for removing cattle from sensitive areas, but can be costly ($3000[4] or more per site) and requires maintenance.

Figure 3.1 Nose hole for controlled access on-stream watering.

Figure 3.2 Nose pump for off-stream watering.

3.2.5 Key Management Areas

Stubble height management in a key management area is another site-specific BMP. Cattle have direct access to the watercourse or riparian area on open, flat meadows for water and forage. The height of the stubble in the area is monitored and managed to a minimal height of 10 cm. to prevent the movement of faeces into the watercourse. The BMP is based on research that suggests vegetated buffers are very good for mitigating oocyst transport into watercourses (Atwill et al. 2002, Tate et al, 2004). Good access to ultraviolet light in these areas might also be effective in limiting viable *C. parvum* oocyst persistence. This BMP does require on-going monitoring and management to prevent over grazing.

3.2.6 Silvo-pasture

The final BMP currently under evaluation is the introduction of silvo-pasture. Silvo-pasture can be defined as the 'deliberate integration of trees and grazing livestock operations on the same land' (USDA, 2013). Again, this is a site specific BMP targeted to mitigate contamination of water in specific stream reaches in a watershed. It is characterized as being the intentional, integrated, interactive and intensive use of land for both forest and cattle production. Silvo-pastures have the potential advantages of providing attractive forage in addition to off-stream watering to attract cattle away from riparian areas as well. When properly managed, silvo-pastures also represent an opportunity to:

1. Provide a cooler summer environment for livestock.
2. Shorten timber rotations because of forage fertilization and better control of competition.
3. Improve timber production through better pruning and tree density management.
4. Provide higher quality forage due to shading.

Most important to water quality, silvo-pastures can be developed upstream of lakes and reservoirs, away from critically vulnerable streams and riparian areas that feed into drinking water systems. Finally, silvo-pastures also promote cooperation between a diverse group of stakeholders including, FLNRORD, forestry operators and cattlemen to manage the landscape in an integrated fashion to assure the best outcomes for all parties involved.

3.3 Research Methods

To achieve the research objectives, a pilot study area of community watersheds with licenced grazing pastures in use was identified where BMP effects on water quality could be measured via the sampling of water, faeces, and stream sediments. Sampling apparatus and procedures were developed for each along with laboratory procedures to test for the presence of *Cryptosporidium* and to speciate it when detected.

For site specific BMPs, specific locations were identified in the study area where water and faeces samples could be collected to test for *Cryptosporidium* presence. Ideally, these sites would have allowed for sampling above and below the BMP site. For example, the nose hole has a specific location at which samples could be collected both upstream, and at or below the site to test its specific effect on water quality. In practice, this was not always achievable.

In the instance of global BMPs, analysis of samples across the entire study area provide evidence to judge effectiveness. For example, lease agreements require that only mature calves greater than three months of age be allowed on crown leased pastures. Hence, where *Cryptosporidium* is detected in water and faeces samples, if subsequent analysis indicated it is *C. parvum*, then the source is more probably younger animals. If instead it is *C. andersoni,* then it is more probably from older cattle.

In addition to the locations identified for BMP testing, additional sampling sites were also identified with no BMPs implemented to provide some control measure relative to BMP sites.

For example, all reservoir outlets were sampled to both assure that no *Cryptosporidium* was present as naturally expected from the literature and to verify that any positive tests for downstream samples were the result of cattle in local presence to the BMP test site.

3.3.1 Study Area, Sampling Sites and Cattle Presence

The pilot project study area consisted of four community watersheds southeast of the City of Vernon, BC and to the east of the District of Lake Country (see Figure 1.8). Vernon Creek (Figure 3.3) and Oyama Creek (Figure 3.4) both supply the District of Lake Country. King Edward (Deer) Creek (Figure 3.5) and Duteau Creek (Figure 3.6) both serve the City of Vernon and several smaller surrounding communities via the Greater Vernon Water Authority. Despite a drinking water intake being depicted in Figure 3.5 on Deer Creek, this point of diversion is not currently in use.

It should be noted that with the exception of sampling sites and site specific BMP locations, the GIS datasets used create the maps in Figures 3.3 to 3.6 and all subsequent maps within this thesis were provided by the province of BC. These datasets are itemized in Appendix A. In addition to the watershed boundaries, Figures 3.3 to 3.6 illustrate the specific crown lease pastures that overlap each watershed and site specific BMP test sites, municipal boundaries, lakes and streams, and the dates in which cattle are expected to be present in pastures.

Previous research (see Section 3.2.2.) has indicated that lakes and reservoirs are expected to be barriers to the transport of *C. parvum* oocysts to drinking water intakes. Based on this assumption, the mainstem and tributary streams, and associated riparian areas that are vulnerable to *C. parvum* contamination in testing the BMPs have been identified as vulnerable riparian in Figures 3.3 to 3.6. These streams are highlighted and marked every 1 km from the drinking water inlet they feed. Tributary streams are also marked every 1 km. beginning at the mainstem they feed.

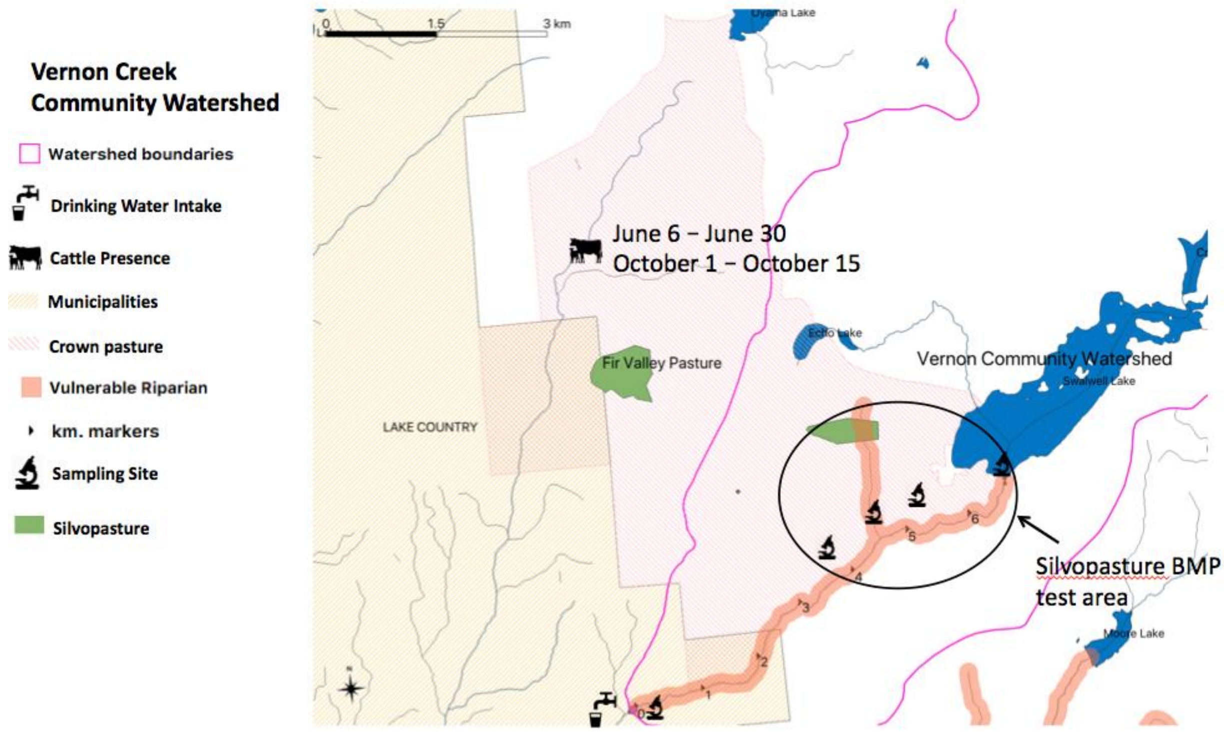


Figure 3.3 Vernon Creek Community Watershed, pastures, and sampling sites.

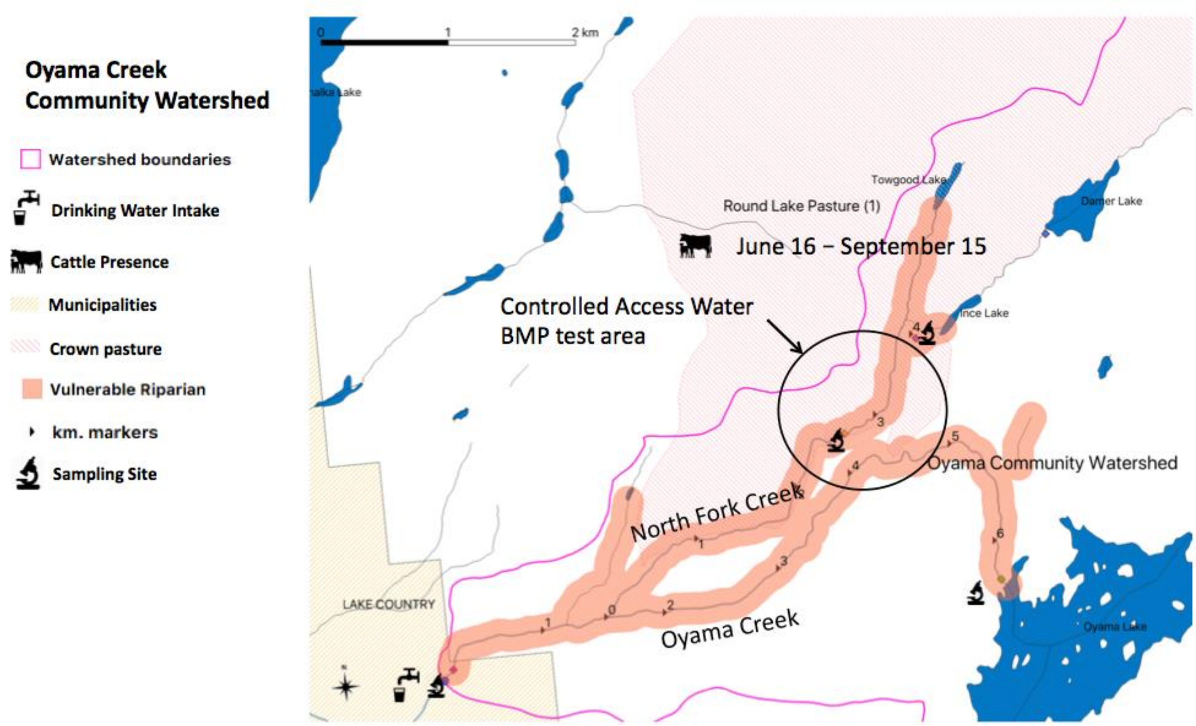


Figure 3.4 Oyama Creek Community Watershed, pastures, and sampling sites.

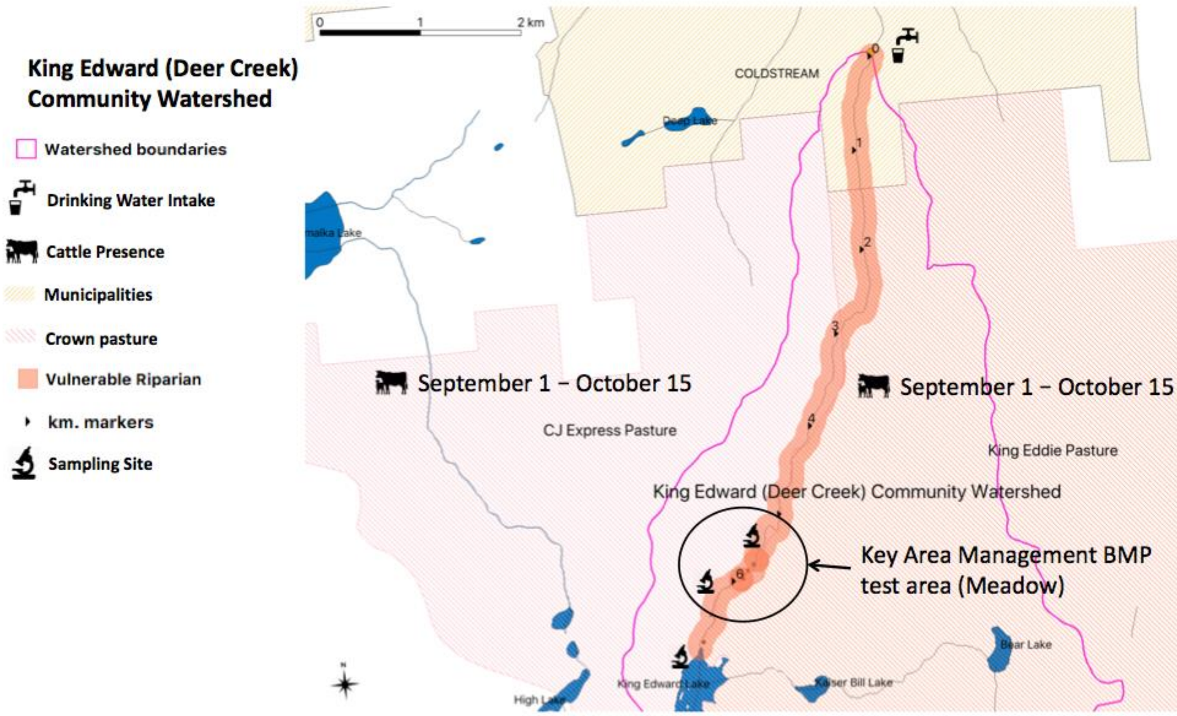


Figure 3.5 King Edward (Deer Creek) Community Watershed, pastures, and sampling sites.

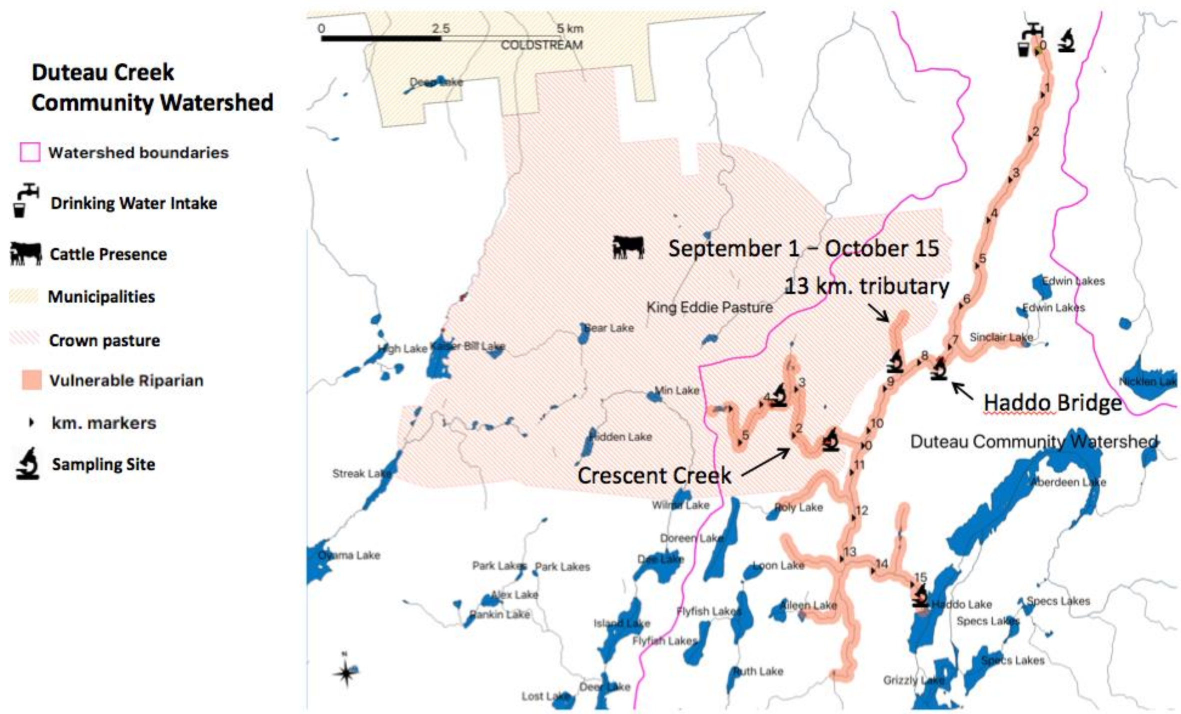


Figure 3.6 Duteau Creek Community Watershed, pastures, and sampling sites.

The study area ranges from 480 to 1980 m above sea level and lies within the Thompson Plateau. The province of BC's 25 m gridded Digital Elevation Model was used to derive a Triangulated Irregular Network (TIN) from provincial datasets. Derivation of the TIN is detailed in Appendix B. Slope was calculated for each TIN face. The resulting slopes were classified as per the legend in Figures 3.7 to distinguish between terrain that cattle are most comfortable on (slope classes 0 – 10% slope), moderately comfortable on (slope classes 10 – 30% slope), less comfortable on (slope classes 30 – 60 % slope) and very unlikely to traverse (slope classes > 60% slope). As illustrated in Figure 3.7, the vast majority of the landscape is not inaccessible to cattle on the basis of slope.

The study area is dominated by Montane Spruce and Engelmann Spruce Sub-Alpine Fir biogeoclimatic zones at mid to higher elevations with Interior Douglas Fir and Interior Cedar Hemlock at lower elevations. The watersheds are currently undergoing extensive timber harvesting by forestry licensees in areas not currently being grazed by cattle. Each watershed is characterized by at least one man-made reservoir for the retention of snow melt and precipitation primarily for both drinking water systems and agricultural irrigation.

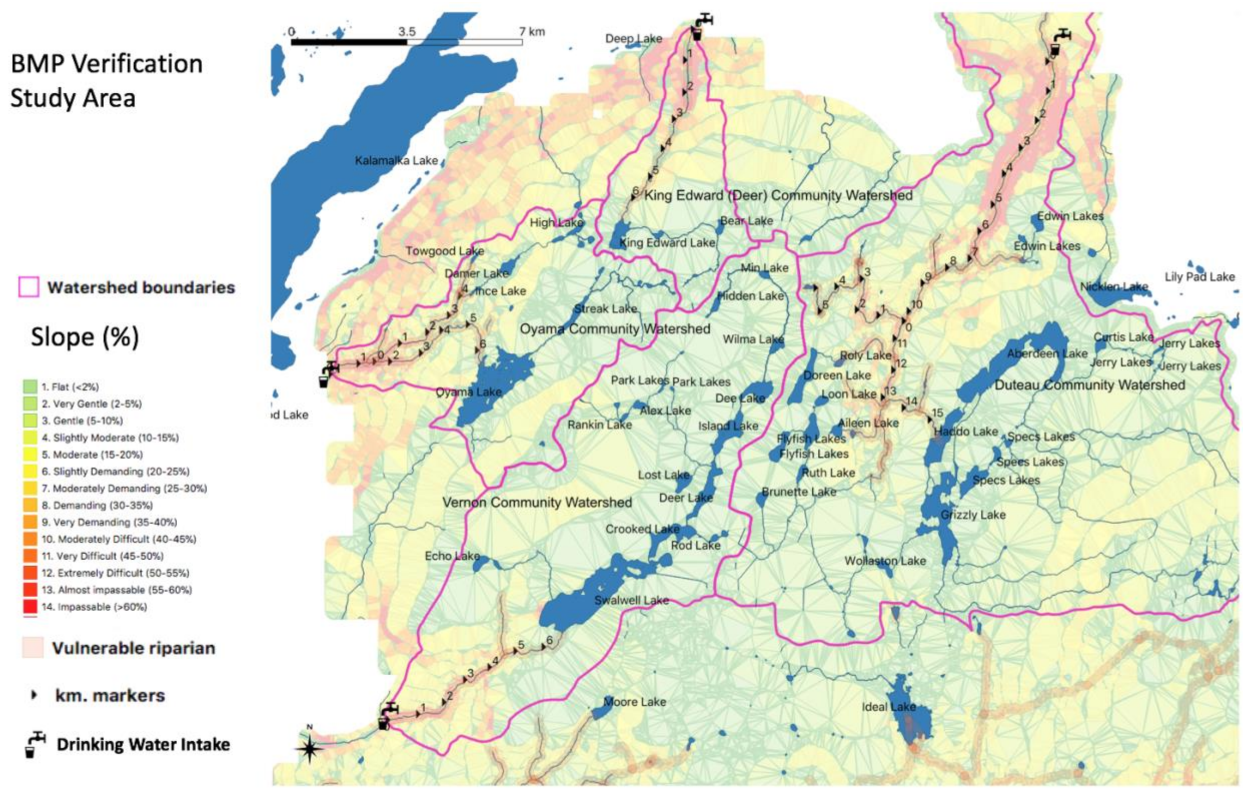


Figure 3.7 BMP verification study area slope.

Two ranching operations are present in the study area with grazing leases on the crown pastures of interest. Both operations are populated with commercial Angus cross cattle and both ranches complete calving by the end of March. Calves exhibiting illness are held back from crown land pastures along with their dames. Younger and smaller calves judged at greater risk to predation by carnivorous wildlife may also be held back with their dames. The current grazing leases for the affected pastures and watersheds in the study area are for 300 cow-calf pairs. Table 3.2 reflects the stocking rates these leases represent in animal-unit days.

Table 3.2: Stocking rates in pastures in BMP study area.

Pasture	Area (acres)	Cows (#)	Calves (#)	Days in Pasture	Stocking Rate (AUD)
Fir Valley Pasture	7446	300	300	28	1.6
CJ Express Pasture	4943	300	300	45	3.8
Round Lake Pasture	4194	300	300	15	1.5
King Eddie Pasture	16171	300	300	45	1.2
1. Cows (1000 lb.) (1 AU/cow) 2. Calves (300 lb.) (0.4 AU/calf)					

Several campgrounds and resorts are also present, including Beaver Lake Resort on Swalwell Lake, Oyama Lake Resort at the outflow of Oyama Lake, and a campground at the outflow of King Edward Lake. These are quite active from late spring to early fall.

Prior to each grazing season, FLNRORD facilitates stakeholder meetings to discuss issues relevant to each of the four watersheds in the coming year. These meetings usually involve all ranchers, resort operators, and forestry licensees, government ministries including environment, and agriculture that oversee activities in the watershed, and regional health authority representatives (representing the BC Ministry of Health). Representatives from local municipalities and water purveyors may also attend. Absent from these meetings however is direct representation from recreational users. The objective of these meetings is to foster a sense of mutual respect and shared resource stewardship between stakeholders in these multi-use watersheds, including their joint responsibility to assure water quality and safety for the communities that receive water from these watersheds for drinking, agricultural, and other uses.

3.3.1.1 Vernon Creek Watershed BMPs to be Verified.

Vernon Creek Watershed (Fig. 3.3), total area 8568 ha, is overlapped by two pastures with current grazing leases; Fir Valley Pasture and Postill Creek Pasture. Fir Valley Pasture is of primary interest, covering a total of 3013 ha of which 1202 ha lies within the watershed.

Up to 300 cow-calf pairs can be expected to be present in the early summer (June 6^{th} to 30^{th}) and in the fall (October 1^{st} to 15^{th}). To provide feed and water, two silvo-pasture sites have been established within Fir Valley Pasture. The lower site is outside of the watershed boundary and is at 1320 m elevation covers approximately 45 ha. The upper site is at 1470 m elevation and covers approximately 25 ha within the watershed (Scherer et al. 2016). Vernon Creek extends from Swalwell Lake (colloquially known as Beaver Lake) approximately 7 km to the drinking water intake. A receiving pond exists at the intake to the drinking water treatment facility itself. The intake pond also has a weir to allow excess water to overflow and continue down the creek. The lower 4.5 km of the creek above the intake is characterized by a ravine with slopes greater than 60 percent, rendering it generally inaccessible in any direct form to cattle. The mainstem does however receive water from three tributaries flowing generally south into Vernon Creek. One (illustrated) passes directly through the upper silvo-pasture trial site.

Two other tributaries were identified for sampling during the initial grazing season (2013) that are not part of the province’s stream centre-line network dataset, and hence not illustrated. All three streams proved to be ephemeral with only the intermittent presence of water over the three years of field sampling. This created challenges for sample collection and verification of the water quality from the silvo-pasture sites.

Sites were identified along each of the three tributaries below the silvo-pasture sites for water sampling to determine if any *C. parvum* oocysts were being transported into Vernon Creek from Fir Valley Pasture and the silvopasture site within the watershed. The outflow of Swalwell Lake and the drinking water intake were also identified as water sampling sites. The sampling sites at the three tributaries were also flagged as locations for the collection of faeces samples within 5 m of the accessible areas of the tributaries. Note that no sampling sites for neither water nor faeces were identified within or above the silvopasture site.

Data collected from the analysis of any water, faeces, and sediment collected with the Vernon Creek watershed is expected to provide insights on the effectiveness of three BMPs; 1) access scheduling, 2) exclusion fencing, and 3) silvopasture including off-stream watering.

3.3.1.2 Oyama Creek Watershed BMPs to be Verified.

Oyama Creek Watershed (Fig. 3.4), total area 4223 ha, is overlapped by nine different pastures, but the pasture of interest for the study is Round Lake Pasture, total area 1693 ha of which 531 ha lies within Oyama Creek watershed. Oyama Creek extends from Oyama Lake approximately 6.5 km down to the drinking water intake. The lower 2.5 km consists primarily of a ravine inaccessible to cattle. At 1.5 km above the intake, North Fork tributary extends approximately 4.5 km to Ince Lake. Approximately 1.5 km above where North Fork tributary enters Oyama Creek, a nose hole BMP has been put in place. The nose hole is part of the fence that straddles the creek within 5 m of the bank for several hundred meters through a heavily forested area. The fence separates Round Lake Pasture from Riparian Pasture and is on the north side of the creek. Construction and maintenance of the fence has created a path through the forest to construct and maintain the fence and it has become a trail for cattle to both access and egress from the nose hole site. The nose hole site itself is devoid of vegetative cover. In contrast to Vernon Creek and Duteau Creek, there is no receiving pond at the drinking water intake. Water is diverted directly from the flowing stream.

To verify the effectiveness of the nose hole as a BMP, water sampling sites were identified above and below it. Sweeps were conducted within 5 m of the watercourse by the nose hole and any faecal pats identified in the sweep were sampled and flagged for re-sampling in the event of a positive test for *Cryptosporidium* oocysts. Both the Oyama Lake outflow and the drinking water intake were also identified as water sampling sites.

Water sampling sites were also identified further above the nose hole at Ince Lake and the Damer Lake outflow. These sites have the benefit of no cattle presence during the three grazing seasons of the study, providing the potential to establish a baseline level of *Cryptosporidium* incidence in the watershed from wildlife and other possible sources.

3.3.1.3 King Edward (Deer Creek) Watershed BMPs to be Verified.

King Edward (Deer Creek) Watershed (Fig. 3.5), total area 2031 ha, is overlapped by both CJ Express Pasture and King Eddie Pasture. CJ Express Pasture covers a total area of 2001 ha, of which 450 ha lies within the watershed, and is of primary interest. Deer Creek extends from King Edward Lake is a dammed reservoir approximately 7 km from a licenced point of diversion (POD) for a drinking water intake. Currently, no intake exists. The lower 4 km of the creek above the POD is a ravine with slopes greater than 60 percent, rendering it inaccessible to direct contact by cattle. For approximately 1 km below King Edward Lake, a meadow exists within CJ Express Pasture. This meadow is treated as a key management area. Cattlemen intensively monitor stubble height to assure that cattle do not graze stubble to less than 10 cm in height as a BMP to mitigate the transport of cattle faeces and *Cryptosporidium* oocysts into Deer Creek. Grazing cattle are present from September 1 to October 15 of each year.

To test the key management area BMP, water sampling sites were identified above and below the meadow. The meadow itself was also identified as a collection site for faeces samples.

3.3.1.4 Duteau Creek Watershed.

Duteau Creek Watershed (Fig. 3.6), total area 21275 ha, is overlapped by 13 crown pastures available for grazing cattle leases. King Eddie Pasture is of prime interest with total area 6544 ha of which 1492 reside within the watershed. Cattle graze in this pasture from September 1st to October 15th annually. Duteau Creek extends approximately 15.5 km from the outflow of Haddo Lake reservoir to a receiving pond at the drinking water intake. The lowest 7 km of Duteau Creek is a steep ravine inaccessible to cattle. Crescent Creek extends from King Eddie Pasture down into Duteau Creek at 10.5 km upstream of the water intake. No site specific BMPs exist along Crescent Creek and hence it is vulnerable to cattle defecation affecting water quality. This makes the Crescent Creek drainage ideal as a control area for testing site-specific BMPs.

Sampling sites were identified at two locations along Crescent Creek. One site was approximately 3.75 kms upstream of Duteau Creek and the second site was where Crescent Creek exited King Eddie Pasture. Haddo Lake outflow was sampled to assure that no oocysts were being transported from above Haddo Lake in the watershed. Samples were taken at either Haddo Bridge or the drinking water intake to determine whether oocysts were reaching the water intake. The Crescent Creek sites were also swept for faecal pats within 5 m of the streambanks. Pats were sampled and marked to re-sampling if positive for *Cryptosporidium*. A small, ephemeral tributary at the 13 km. mark on the forest service road was also sampled in the 2014 and 2015 grazing seasons when water flowed in it.

The 2014 results also subsequently identified the need to collect sediment samples at a former beaver pond site located on Crescent Creek between the upper and lower Crescent Creek water sampling sites, approximately 2 km from the junction with Duteau Creek.

3.3.1.5 Global BMP Verification Sites.

In addition to the specific sites previously discussed, samples were also collected at other locations in the study area to verify that global BMPs and assumptions were functioning as expected. As previously discussed, this included collecting and analyzing water samples from lake and/or reservoir outflows to assure that evidence did not conflict with the theory that lakes and reservoirs inhibit oocyst transport and that exclusion fencing to 200 m each side of lake outflows is also effective to this end. Water samples were also taken at drinking water intakes as a final check that few or no oocysts were being diverted into community drinking water systems.

3.3.2 Field Sampling of Water, Faeces, and Sediments

Field sampling for water, faeces, and sediments was conducted over three field seasons from early May to mid-October of 2013, 2014, and 2015. The primary goal of the 2013 sampling season was to develop sampling procedures and equipment, to identify the specific sampling sites in the study to test the BMPs and assumptions, to develop the laboratory procedures to analyze samples for the presence of *Cryptosporidium* and *E. coli*, and to speciate any *Cryptosporidium* identified in the samples. From July to October of 2013, 26 water samples were collected. Procedures and lessons learned were then applied to the subsequent grazing seasons of 2014 and 2015 to test both the BMPs, and the assumptions upon which they were based.

3.3.2.1 Water Sampling Method

Water samples collected and processed to detect *Cryptosporidium* presence using US EPA Method 1623 (US EPA 2005). To collect the sample, the apparatus depicted in Figure 3.8a was developed during the 2013 sampling season. Figure 3.8b depicts the sampler in use. As per Method 1623, the apparatus was fitted with an unused Envirochek™ HV sampling filter before each sample was to be collected. A record was made of the starting volume for each sample collected. The intake hose of the apparatus was submerged in water to be sampled and a minimum of 20 litres was subsequently pumped through the sampling filter. The final volume was then recorded to calculate the concentration of any oocysts identified and enumerated during lab processing. Sampling filters were subsequently stored in ice-chilled coolers until transferred to a refrigerator at the Biological Solutions Laboratory at UBC-Okanagan.

Figures 3.8 a) Water sampling apparatus for BMP verification. and b) Water sampling at Haddo Lake outflow.

For each sample collected, a field sheet was completed noting the date, time, and location of the sample collected, the filter serial number, and the approximate stream width and depth. Both air and water temperature were also measured and recorded. Notes were made of prevailing weather conditions, evidence of cattle and/or wildlife presence, and the presence of faecal deposits within the stream or riparian area within 5 m of the stream bank. The canopy cover was also noted at each site as open meadow, lightly forested, or fully forested.

3.3.2.2 Faeces and Sediment Sampling

Faecal samples were also collected at each of the BMP test sites. A 5 m buffer extending 100 m. along each side of the stream at each site specific BMP was surveyed for the presence of faecal deposits. When faecal deposits were found, each was sampled (see Figure 3.9) and tagged with a unique identifier. The location of the deposit was also recorded using a GPS. The condition of the sample was noted to distinguish between fresh, moist deposits, those several days old with a crusted exterior, and those older and dried out. Soil cover beneath the faeces was noted as rock, bare soil, leaf and woody debris, or grass. Distance to stream bank was recorded as well as canopy cover. Deposits were flagged for subsequent sampling if identified as positive in lab analysis for the presence of *Cryptosporidium*.

Figure 3.9 Faecal sample collection.

In addition to faecal samples, sediment samples were also collected during the field research to provide better insight with respect to *Cryptosporidium* as a potential hazard to water in community watersheds, In addition to sample collection, its location, the water temperature and depth, and canopy cover was also noted. All faecal and sediment samples were stored in an ice-chilled cooler until transferred to a refrigerator at the Biological Solutions Laboratory.

3.3.3 Laboratory Analysis of Water, Faecal, and Sediment Samples

All field samples were transferred on the day of collection to the Biological Solutions Laboratory for refrigeration prior to laboratory analysis.

3.3.3.1 Analysis of Water Samples

To detect and quantify the presence of *Cryptosporidium* oocysts in water EPA Method 1623 was used. After stream water is filtered in the field using the Envirochek^{TM} filter, the materials on the filter were eluted. The eluate was then centrifuged to pellet the oocysts and the supernatant fluid was aspirated. Magnetic beads conjugated to anti-*Cryptosporidium* antibodies were then attached to the oocysts. Magnetized oocysts were then separated from extraneous materials using a magnet. The oocysts were then detached from the magnetic beads and deposited on microscope slides which were then stained with fluorescently labeled monoclonal antibodies and 4’, 6-diamidino-2-phenylindole (DAPI). The samples were then examined using fluorescence microscopy. In addition to processing the samples for the presence of *Cryptosporidium*, a portion of the filter eluate was also used for DNA extraction to speciate any *Cryptosporidium* present.

The primary concern for interference in the lab processing of samples are particles collected in the field samples causing turbidity and plugging the filter. These can also interfere with the separation and detection processes. Algal and yeast cells that autofluoresce or demonstrate non-specific immunofluorescence can also interfere with oocyst detection and lead to false positives via immunofluorescence assay (IFA). Spiked samples and negative controls were both used as checks through the entire process for quality assurance.

3.3.3.2 Analysis of Faecal and Sediment Samples

To detect and quantify *Cryptosporidium* oocysts in faecal samples, the samples were suspended in a phosphate buffered saline (PBS) solution, mixed using a vortex, and then sieved through a tea-strainer (~ #40 mesh) to remove detritus. The filtrate was then suspended again in PBS, and separated by centrifugation. The supernatant was discarded, and the pellet again mixed with PBS and three aliquots drawn as pseudo-triplicates. The pelleted subsamples were then subjected to five freeze-thaw cycles of 15 minutes duration each at -80 ^{o}C in a metal bead bath for DNA extraction (Jiang et al. 2005).

3.4 Discussion of Results: Implications for BMPs and Assumptions

The complete results of the analysis of the samples collected in the field have been compiled in Appendix C. In each instance, water, faeces and sediment sample analysis are presented for each site within each watershed. In this section, results are limited to those relevant to verifying the effectiveness of the BMPs piloted within the study area. The objective for this section is to draw conclusions and recommendations relevant to the continued use of BMPs in the study area or their implementation in other pastures within community watersheds.

3.4.1 Scheduling Access

All watersheds and grazing pastures were subject to scheduling access as a global BMP under the terms of the grazing leases.

The best data available from the field research conducted by the BSL to support or challenge the effectiveness of this BMP is the results of the analysis of faecal samples. From 2013 to 2015, a total of 96 faecal samples within 5 m of stream banks were collected and subjected to analysis for *Cryptosporidium*. Only four samples tested positive. Three of these samples were from the nose hole site in Oyama Creek watershed and arranged in a pattern on the ground that suggest they might have come from one animal only. The fourth sample was from the meadow. All four samples sequenced to *C. andersoni* and not *C. parvum,* indicating that the faeces more likely came from adult cattle (> 1 year in age) and not calves.

The data suggests that 2 of 600 animals (300 cow-calf pairs) or 0.3% of each herd are carrying *C. andersoni* suggesting the BMP is effective for preventing *C. parvum* from cattle from entering the study area.

3.4.2 Exclusion Fences

This study did not specifically look at exclusion fencing as a BMP, but with the exception of the Crescent Creek area in Duteau Community Watershed and Vernon Creek tributaries, it was ubiquitous in the four watersheds of the study area, preventing access by cattle both directly to streams in sensitive areas and to reservoirs and lakes within 200 m of their outflows. In the case of Crescent Creek and the 13 km tributary, cattle had direct access to each stream, and neither had any other site specific BMPs present. As evidenced in Figure 3.10, *Cryptosporidium* presence was considerably higher in samples from the Crescent Creek tributary than from the

Duteau Creek mainstem and as was experienced generally in the three other watersheds in the study area. Fortunately, with dilution in Duteau Creek, samples collected at the Haddo Bridge site and downstream to the drinking water intake revealed significantly lower concentration of oocysts when present.

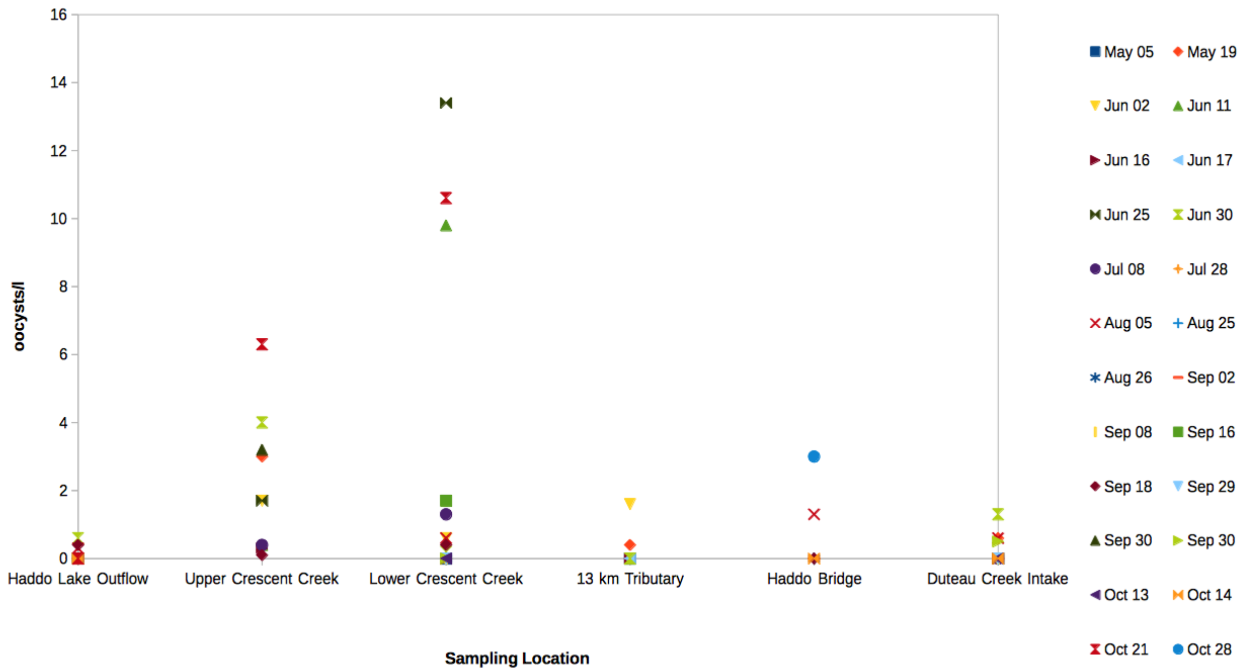


Figure 3.10 Duteau Creek *Cryptosporidium* results by sampling site.

Table 3.3 provides a summary of the results within Duteau Creek Watershed. The Crescent Creek and 13 km tributary are classified as control sites without BMPs of any type. Of the 63 samples collected over the three grazing seasons, 28 were from sites in these control areas, and as the results indicate, *Cryptosporidium* was detected at higher concentrations within the control area than at other sites in the watershed, supporting the use of exclusion fencing as an effective BMP.

Table 3.3: Summary of Oocyst concentrations in Duteau Watershed.

Site Classification	Average Oocysts/l	Std. Dev	n
Control	1.2	2.4	28
Fenced	0.7	1.2	6
Intake	0.2	0.4	14
Lake Outflow	0.1	0.2	15

Finally, exclusion fencing is also used for 200 m on each side of lake and reservoir outflows to mitigate transport of oocysts from cattle faeces and sediments contaminating outflows. The low *Cryptosporidium* numbers, with one exception, at lake and reservoir outflows in each of the four watersheds tend to support that exclusion fencing in this instance is an effective BMP. Fencing within 200 m of these outflows is also assuring the reduced transport of oocysts downstream to water intakes. Table 3.4 summarizes the results of all water samples taken by their relative location in each watershed; lake or reservoir outflow, within sensitive riparian areas between the outflows and the drinking water intakes if present, and finally at the drinking water intakes. It should be noted that in each instance, median *Cryptosporidium* presence in lake outflows were extremely low with many samples indicating no oocysts present, suggesting that exclusion fencing within 200 m of the outflow is a potentially effective BMP.

Table 3.4: Summary of oocyst concentrations.

Watershed	Average oocysts/l		
	Lake/ Reservoir Outflows	Sensitive Riparian Areas	Drinking Water System Intakes
Vernon Creek	0.1	4.2	0.1
King Edward	0.4		0.2
Oyama Creek	0.2	1.8	2.3
Duteau Creek	0.1	1.2	0.4
All Watersheds	0.2	1.8	0.7

The results in Table 3.4 broadly suggests support for the exclusion fencing BMP, but there is also evidence to suggest that the exclusion fences may not be effective and might even be problematic in some circumstances. Oyama Creek’s water intake has a notably higher concentration of oocysts than either upstream samples indicate, or samples from the other three watersheds. This will be discussed in the results for the controlled access to water BMP.

3.4.3 Controlled Access On-Stream Watering (Nose holes)

The controlled access to water BMP was investigated as a fence nose hole on the North Fork Creek in Oyama Creek Watershed. Outflow samples taken at Damer Lake revealed very low levels of *Cryptosporidium* presence in both 2013 and 2014, however water samples at and below the nose hole (Figure 3.12), though still low, showed higher incidences of oocyst presence. The presence of positive faecal samples was also a concern as was the positive sample identified in the 2010 audit by the FPB (2012). This suggests that the nose hole and controlled water access BMP is problematic.

The '5 m rule' implemented by FLNRO suggests that if cattle are kept 5 m from a stream bank, oocyst transport into surface water sources should be greatly mitigated. However, it was observed on North Fork tributary in Oyama Creek watershed that this is not the case all the time. Fencing along North Fork Creek is within 5 m of the stream bank (Figure 3.11).

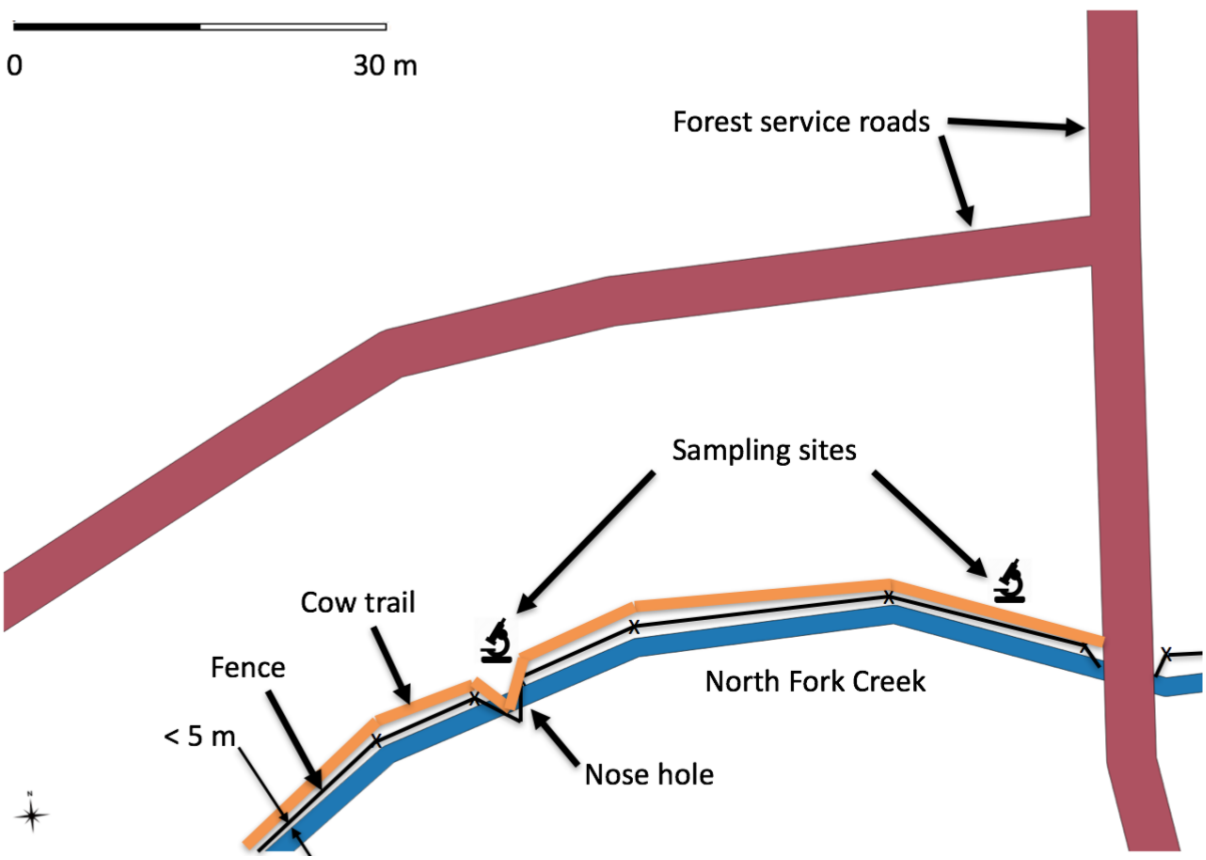


Figure 3.11 Nose hole BMP test site.

Constructing and maintaining the fence on North Fork Creek necessitated the creation of corridors within the forest cover to move equipment and supplies. Cattle have subsequently used this corridor as a path to access the nose hole for water and for transit. This traffic has created a trail within the sensitive riparian area as witnessed along North Fork tributary above the nose hole site. Recent research (Miller et al. 2017) suggests that these trails could be a problem for water quality and undermine the '5 m rule'. The forest canopy also inhibits the sunlight and UV that potentially degrades oocysts deposited in these areas.

In the instance of North Fork Creek and the fence leading to the nose hole, water samples were collected at and below the nose hole site. Though numbers were low (Figure 3.12), several samples were identified as positive for *Cryptosporidium.* Samples taken in the late fall just above the Nose hole and at the intake were notably higher than all other samples collected in the watershed. This is also the location where the FPB (2012) collected a faeces sample positive for *Cryptosporidium* in its 2012 audit. Faecal samples collected at the nose hole location in this study also tested positive for *Cryptosporidium*. Note again, that none of the *Cryptosporidium* samples were subsequently tracked to *C. parvum.* Those successfully sequenced were identified as *C. andersoni.* These results support the theory that poorly placed exclusion fences might not only be ineffective but aggravate the potential hazard that grazing cattle represent to sensitive surface water sources.

Samples collected at the Ince Lake sampling site were also positive for *Cryptosporidium* even though there were no cattle present. All samples that did not sequence to *C. andersoni* were not successfully sequenced to any other species, indicating a potential mix of

Cryptosporidium species in these samples.

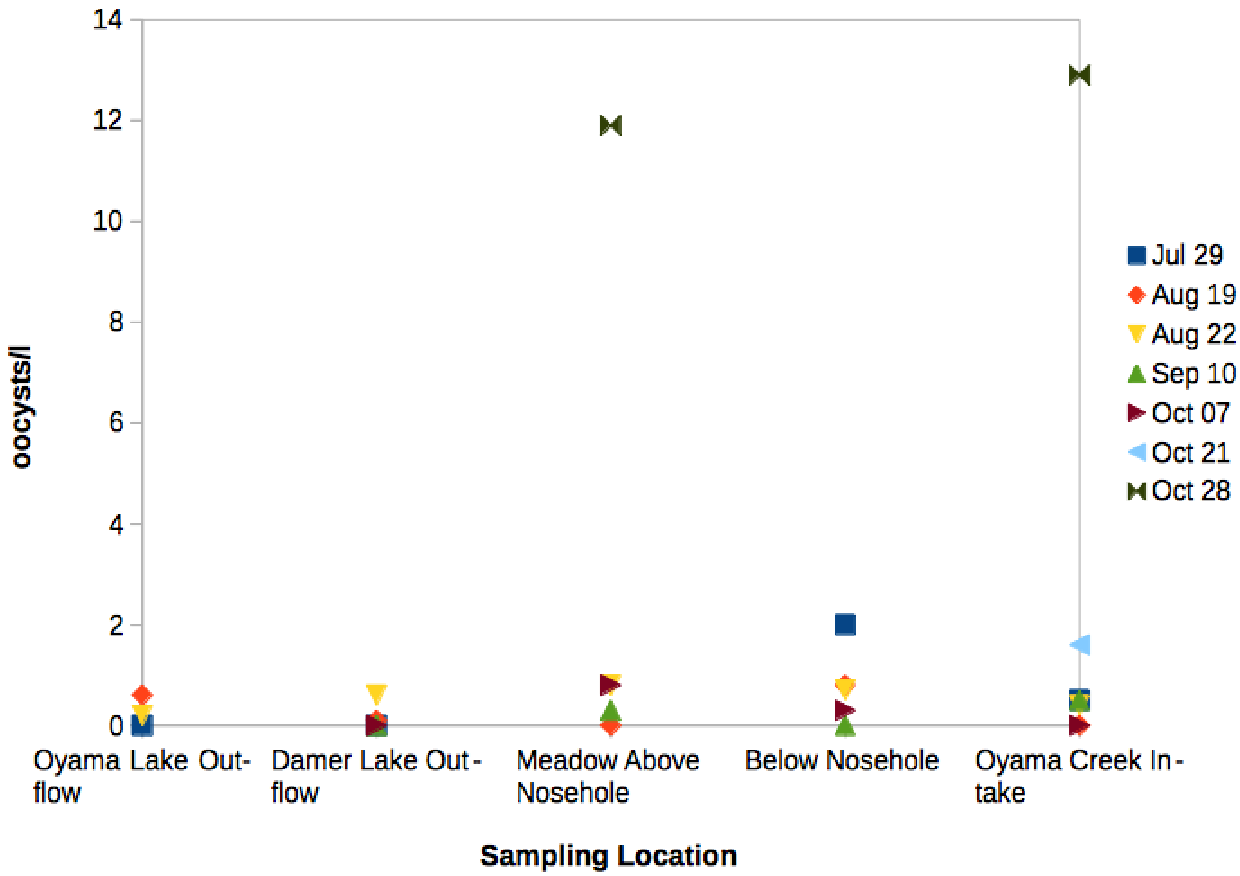


Figure 3.12 Oyama Creek *Cryptosporidium* results by sampling site.

3.4.4 Off-Stream Watering and Silvopasture

At no site within the study area were either the off-stream watering BMP or the silvopasture BMP employed in isolation as site specific BMPs to test their individual effectiveness. However, they were used together at the silvopasture pilot site in the Vernon Creek Watershed. The silvopasture pilot project was initiated in 2013 (Scherer et al. 2016). Cattle had access to the silvopasture site both in early summer and in the fall during two licenced grazing periods. Of the samples taken at the tributaries draining from the silvopasture sites to Vernon Creek, only two, one on September 23 and one on October 21 of 2013 (Figure 3.13) tested positive for *Cryptosporidium* at levels of concern. Of the faecal samples collected along the tributaries, none tested positive for *Cryptosporidium*. The drinking water intake for Vernon Creek did not produce any positive samples for *Cryptosporidium*.

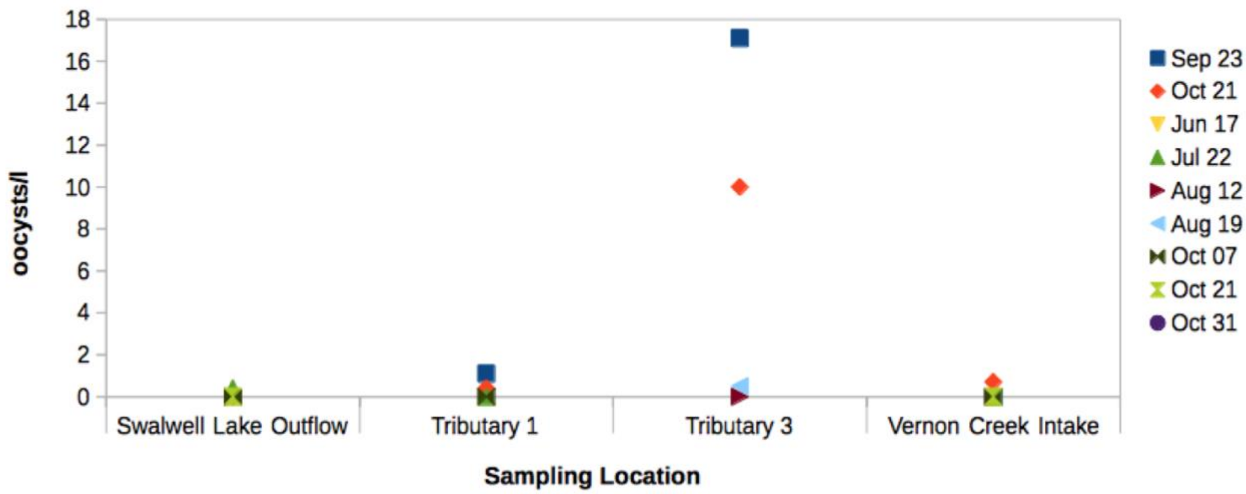


Figure 3.13 Vernon Creek watershed *Cryptosporidium* results by sampling site.

Another complication to testing this BMP was sample collection within the tributaries, which proved ephemeral. The literature (Searcy et al. 2005) suggests that even when there is flow, the very low flow rates of these streams could inhibit oocyst transport. At this point, no definitive conclusions can be drawn with respect to the effectiveness of either off-stream watering or silvopasture as site specific BMPs.

3.4.5 Key Management Areas

The key area management BMP was piloted in the King Eddy (Deer Creek) Watershed at a meadow below the King Edward Lake outflow. Literature suggests that if stubble height is maintained to a 10 cm height within the riparian area next to the watercourse oocyst transport to surface water sources can be significantly decreased (Atwill et al. 2002, Tate et al, 2004). Cattle are only present in the meadow in the summer for the first two weeks of July.

The results (Figure 3.14) indicate that the BMP seems to be quite effective, exhibiting negligible presence of *Cryptosporidium* in water samples downstream of the meadow. Of the 12 water samples collected in 2013 and 2014, only three were positive for *Cryptosporidium*, two of those were upstream of the meadow prior to any cattle presence and one was from below the meadow after the cattle were removed.

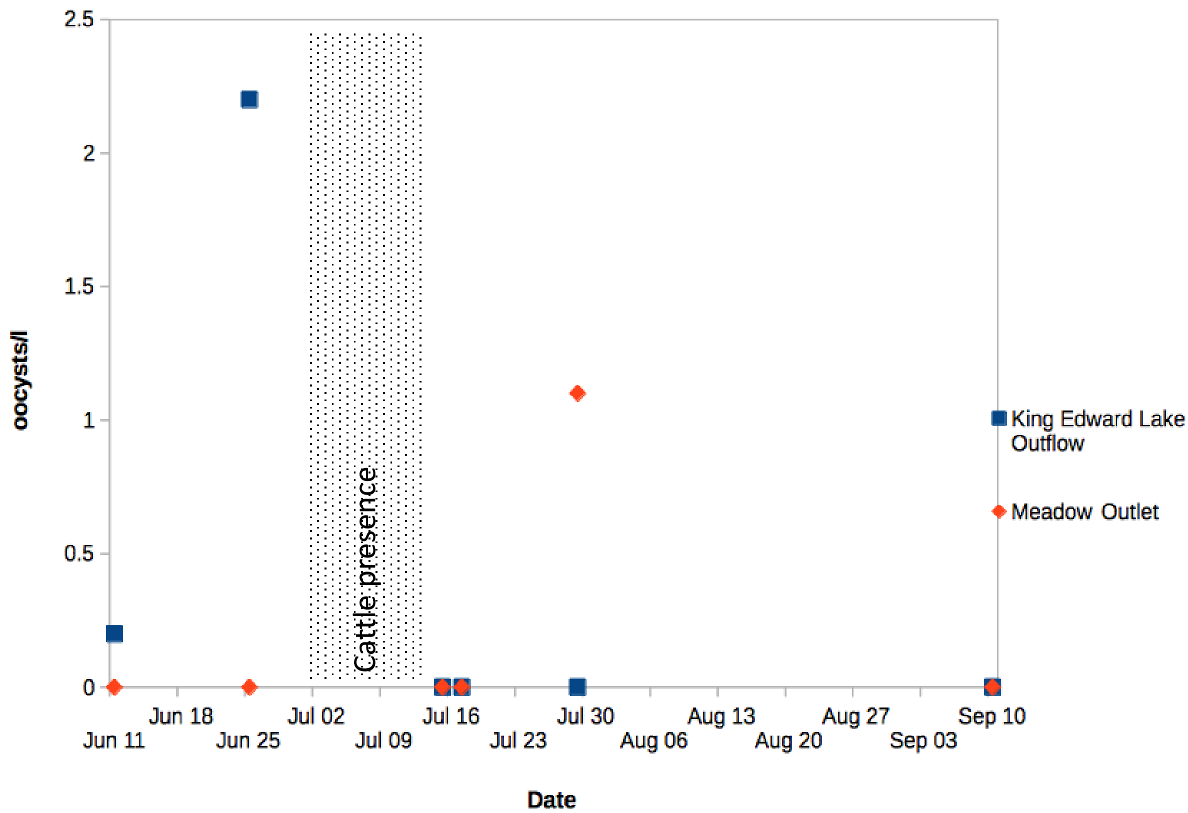


Figure 3.14 Detection of *Cryptosporidium* as a function of time in the King Edward (Deer Creek) watershed.

In addition to water samples, a total of 35 faecal samples were collected in 2013 and 2014, of which only one was positive for *Cryptosporidium*. This reinforces the original conclusion with respect to the scheduling access BMP. The open meadow also provides an opportunity for degradation of *Cryptosporidium* oocysts by UV from sunlight.

The creek meanders through the meadow at low velocity, possibly explaining why even though the highest concentration of oocysts were present in a water sample on June 25, 2014 above the meadow, the sample below was negative for *Cryptosporidium* because of conditions facilitating their sedimentation. This is consistent with the work of Searcy et al. (2005).

The nature of the site also contrasts with that of the nose hole. Being an open meadow, there was no well-travelled path to the water that would constitute a flow path during rain events for contaminated runoff, and no fence encouraging cattle to form one.

3.4.7 *E. coli* as an indicator of *Cryptosporidium* presence

An additional objective of the research was to determine if the presence of *E. coli* is a good predictor of the presence of *Cryptosporidium*. Of the 88 water samples collected for this research, 40 were positive for *Cryptosporidium*, 46 were positive for *E. coli* and 23 were negative for both organisms. Of the samples positive for *Cryptosporidium* or *E. coli* only 21 were positive for both organisms. This represents 26% of the samples. Figure 3.15 illustrates that there is no correlation between the numbers of organisms in samples that contained both *Cryptosporidium* and *E. coli*. When *E. coli* is high, *Cryptosporidium* is low and when *Cryptosporidium* is high, *E. coli* is low. *E. coli* cannot be used as a predictor of *Cryptosporidium* presence or the magnitude of the numbers.

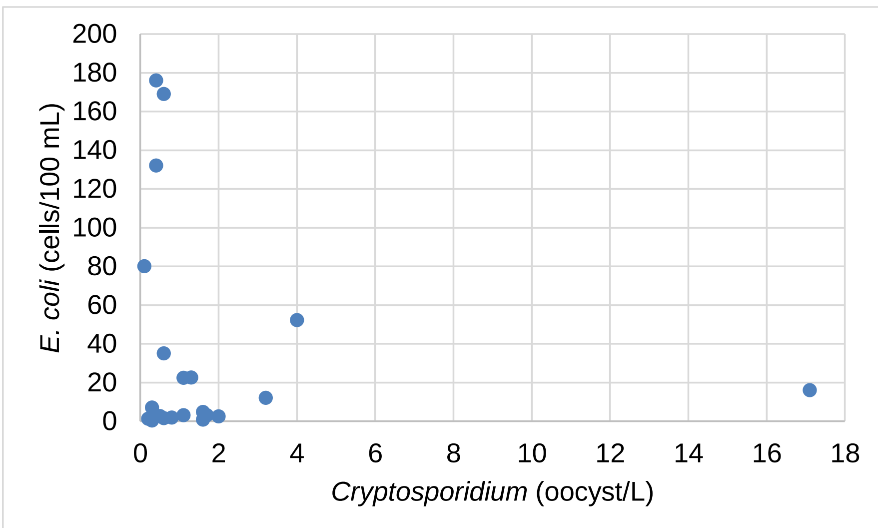


Figure 3.15 Correlation between *E. coli* and *Cryptosporidium* numbers in samples that were positive for both organisms.

3.5 Summary

The field research has provided evidence to draw conclusions and recommendations that can be applied both to the continued use of individual BMPs in the study area and to their potential implementations in other watersheds with grazing cattle present. It also provides insights to the actuality of the threat posed by grazing cattle in community watersheds and their potential to contaminate surface water sources with *C. parvum*. These conclusions can be summarized as follows:

1. Access scheduling is a prudent BMP to mitigate the exposure of sensitive areas within community watersheds to prevent potentially *C. parvum* infected calves from entering the watershed. The operational nature of the ranches in the study means there is no control to test this BMP with, but no field results indicate that it is ineffective. Complementary research on *C. parvum* oocyst persistence suggests that this is particularly important to restrict the ability of calves to access sensitive riparian areas in moderate or heavy canopy cover conditions in the summer.

2. It can generally be concluded that exclusion fences are an effective BMP, but there are circumstances when they would not be as effective. Fences should not be placed within 5 m of stream banks in sensitive riparian areas, especially in heavy forests. In these instances, such as along North Fork Creek, the results indicate that poor placement could potentially negate the benefits of exclusion fencing. Fences should not be near streams in moderate to heavy forest cover. Fencing is also an expensive BMP.

3. The field results indicate that the controlled access watering BMP (nose hole) is problematic as it currently exists. If nose holes are to be used in the future, it is recommended that consideration be given to site selection. Sites should be chosen that do not encourage cattle to create trails with 5 m of the stream bank for access and they should be in areas with little or no cover canopy to allow sunlight and UV to degrade and deactivate any oocysts that are deposited in or near the chosen site in summer conditions, or by freeze-thaw cycles through the winter.

4. No definitive conclusions can be drawn with respect to the off-stream watering and silvo-pasture BMPs. In theory, each should draw cattle away from sensitive riparian areas in community watersheds. The study currently in progress by BC Ministry of Agriculture using collars equipped with GPS receivers and data loggers to study cattle activity in the silvopasture may provide a better assessment proof of the effectiveness of off-stream watering and silvopasture as BMPs to mitigate cattle presence in sensitive riparian areas. Ideally studies would expose the same cattle to pastures areas with and without the BMPs present to determine if there is a discernable difference to their presence in sensitive riparian areas as a result.

5. Key area management is an effective BMP. Despite allowing direct access to surface water sources in sensitive riparian areas, effective management of stubble height inhibits faeces transport into water courses, and sunlight UV is virtually uninhibited in its ability to deactivate any *Cryptosporidium* present in faeces pats.

6. Evidence exists for sources of *Cryptosporidium* other than *C.parvum* and cattle within the study area. Water samples collected at the Ince Lake site were positive for *Cryptosporidium* presence despite the lack of cattle presence. These samples were not successfully sequenced, indicating a possible mix of *Cryptosporidium* species.

7. *E. coli* presence does not predict *Cryptosporidium* presence. Despite its attractiveness for cost and convenience, the results of analysis from current field research indicate the *E. coli* presence does not correlate with *Cryptosporidium* presence.

In addition to these conclusions, there is another overarching question that the results of the field research raises. In exploring both the non-BMP and BMP scenarios in Chapter 2, much greater counts of *Cryptosporidium* oocysts could be expected in the water samples collected in the field research than were found. This should have been particularly true at sampling points upstream of the drinking water intakes within the pastures, but was not. *C. parvum* oocyst concentration were far lower than might have been expected. Furthermore, where oocysts were identified and subsequently sequenced for their DNA, no samples proved positive for *C. parvum*.

These results raise the question as to whether grazing cattle and water contaminated with *C. parvum* are truly a hazard to human health within the contexts of BC's interior community watersheds and the crown pastures that overlap them. Public data on cryptosporidiosis in BC indicated that there is no greater incidence of illness in the Okanagan Health Services Delivery Area than in other delivery areas in the province. This suggests that a more detailed analysis is necessary to determine whether there is a real problem with grazing cattle and cryptosporidiosis in community watersheds.

Chapter 4.0 The Impact of Cattle and BMPs on Cryptosporidiosis Incidents

This chapter presents an analysis of the incidences of cryptosporidiosis in British Columbia’s (BC) community watersheds to determine whether or not the presence of grazing cattle poses a detectable threat and whether or not best management practices (BMPs) significantly impact the incidence of cryptosporidiosis. The BC Centre for Disease Control (BCCDC) provided confidential data for 56 incidents of reported cryptosporidiosis in the Local Health Reporting Areas (LHAs) of the Okanagan Health Services Delivery Area (HSDA) from 2005 to 2014, overlapping both the study area and period for the BMP verification project (Chapter 3).

4.1 Background

The BCCDC is part of the Ministry of Health of the Province of BC. The BCCDC maintains data on reportable illnesses in the province including incidences of cryptosporidiosis. The ministry is composed of 16 HSDAs, further divided into a total of 91 LHAs. Figure 4.1 illustrates the HSDAs and LHAs where there are community watersheds exposed to cattle grazing due to the presence of pastures. BC Stats (n.d) also maintains population estimates for each Health Services Delivery Area and Local Health Area with breakdowns by year, age, and gender for the province of BC. The BCCDC maintains its data on cryptosporidiosis by both HSDA and LHA, and the date on which the incidence was first reported.

Initial analysis of the spatial data from the BC government indicated that of the province’s 466 community watersheds, 122 have designated pastures available for use by grazing cattle (Chapter 1). By combining population estimates from BC Stats with the BC government’s spatial data it should be possible to determine the potential population within a LHA vulnerable to a water supply contaminated with *C. parvum* oocysts.

Two scenarios, one with and one without the presence of BMPs were presented in Duhaime and Roberts (2018) and Chapter 2, indicating the potential concentration of *C. parvum* oocysts in drinking water from community watersheds with active grazing licences under each scenario in the BC interior. The BMP verification pilot study has also provided insights to their effectiveness and shortcomings (Chapter 3). The results of the BMP verification study revealed much lower concentrations of *Cryptosporidium* oocysts that potentially expected. Publicly available data on the incidences of cryptosporidiosis in BC also noted little or no difference between the Okanagan HSDA and other HSDAs, raising the question of whether or not grazing cattle in community watersheds truly poses a threat to human health.

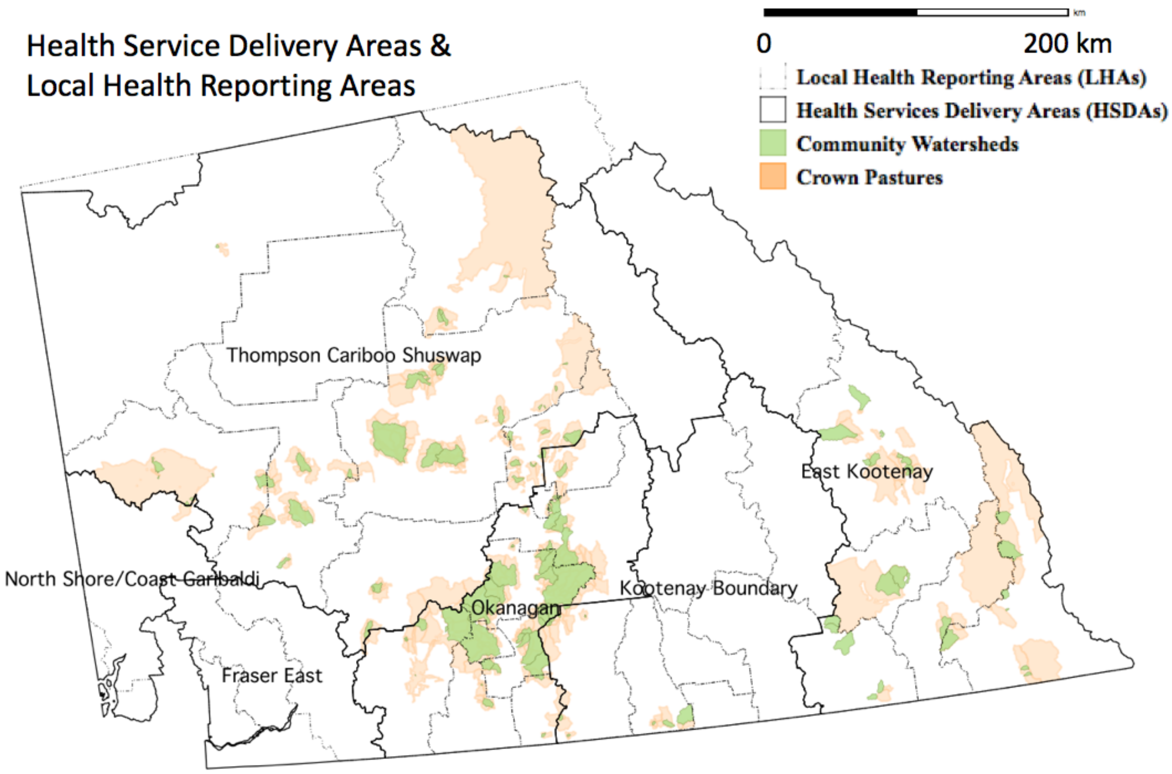


Figure 4.1 HSDAs and LHAs with community watersheds with crown pastures.

4.2 Objectives

Synthesizing the available data on community watersheds and reported cases of cryptosporidiosis in BC with the results of the BMP verification study and the insights on *C. parvum* infectivity from the literature should provide the opportunity to gain insights on the magnitude of grazing cattle as a hazard to human health in community watersheds and the benefits of BMPs in mitigating the hazard. By comparing actual reported incidences of cryptosporidiosis to the predicted incidences, it should be possible to achieve the following objectives:

1. Determine the extent of geospatial overlap between pastures with grazing cattle and vulnerable streams in community watersheds and the LHAs exposed to the hazard.

2. Determine the incidences of reported cryptosporidiosis as a function of the populations in each LHA and the vulnerable watersheds that provide surface water for human consumption.
3. Determine whether or not the reported incidences of cryptosporidiosis can be associated with the vulnerable streams and watersheds that contain pastures with grazing cattle.
4. Determine if pastures with BMPs result in lower reported incidences of cryptosporidiosis within the LHAs served by the watersheds in the pilot study area (Chapter 3).

The results should provide further insights as to the level of risk that grazing cattle pose to human health via their presence in community watersheds, and the benefits of BMPs.

4.3 Methods

In this section, the methods used to achieve each of the individual objectives will be discussed. There are primarily three sets of methods employed; 1) a GIS analysis to determine which crown pastures are a potential hazard to human populations, 2) an analysis of the populations served by community watersheds to estimate the population vulnerable to each crown pasture and the incidence of cryptosporidiosis in those populations, and 3) a statistical analysis to determine the degree to which populations exposed to grazing cattle in community watersheds differs from that that are not with respect to incidences of cryptosporidiosis.

4.3.1 Spatial Data Resources and Analysis

Unless noted, all initial spatial data for this analysis was retrieved from the BC Geographic Warehouse (BCGW n.d.) in ESRI arc shapefile format. The Albers Equal Area Conic (commonly referred to as BC Albers) projection was used for all data. Appendix A provides a listing of the individual datasets used in this research. The data has been archived at the University of British Columbia Okanagan campus on its network server infrastructure (P:\Research Projects\Biosolutions Lab\Source Tracking\GISdata\). All spatial analysis was performed with either the Quantum GIS (QGIS 2009) open source geographic information system (GIS) or with the ESRI ArcGIS ver. 10 desktop (ESRI 2011).

4.3.2 Identifying Community Watersheds at Risk from Grazing Cattle Presence.

The first phase of the analysis was to determine which of the province's community watersheds and community water supplies are potentially impacted by the presence of crown pastures. QGIS (2009) was used to intersect the province's community watershed dataset with the crown pastures dataset. Figure 4.1 illustrates the extent of the two datasets involved.

To correlate BC CDC reported incidences of cryptosporidiosis with community watersheds, it is also necessary to determine which Health Service Delivery Area (HSDA) and Local Health Reporting Area (LHA) each respective community watershed provides water to. The provincial Point of Diversion dataset was used to identify the location of the community drinking water system intakes for each of the watersheds. These points were intersected with the LHA boundary dataset to determine which LHA and HSDA each watershed belonged to.

Figure 4.2 provides an example of the result from the initial analysis using Oyama Community Watershed. Nine crown pastures are identified at least partially overlaying the watershed. The resultant polygons inherited attributes from both the community watershed dataset and the crown pastures dataset for further analysis. The area of each polygon was calculated using QGIS. The area of each polygon in the original watershed and crown pasture datasets were also calculated using QGIS tools. Microsoft Access (2013) was subsequently used to identify crown pastures in the original dataset that fell within community watersheds.

Intersecting the 466 community watersheds with the 4349 crown pastures for grazing identified 122 community watersheds with crown grazing pastures present. These 122 community watersheds cover an area of 643,000 ha in the province. Of the 4349 pastures for lease, 419 were identified as overlaying these community watersheds and potentially creating a potential hazard to human health. Collectively, these 419 pastures comprise a total of 2.7 million ha of the province's land base with 524,068 ha overlapping community watersheds. Appendix D provides a detailed analysis for each of the 122 community watersheds with pastures present within or overlapping their boundaries.

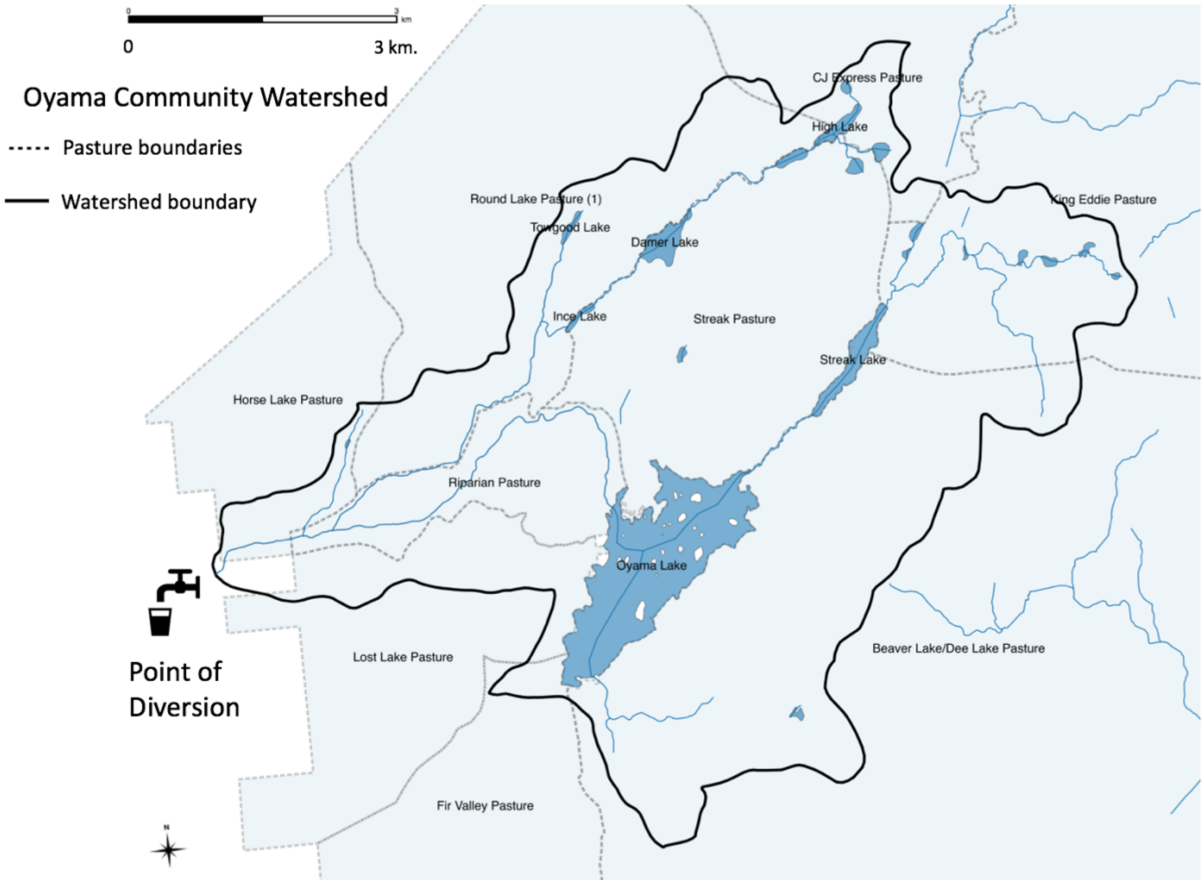


Figure 4.2 Intersection of crown pastures with Oyama Community Watershed.

4.3.3 Identification of Vulnerable and Critically Vulnerable Streams and Riparian Areas in Community Watersheds.

The second phase of the analysis determined which streams and riparian areas in each community watershed were vulnerable to *C. parvum* contamination from grazing cattle faeces. The literature (Chapter 2) identified lakes and reservoirs as barriers to the downstream transport of *Cryptosporidium* oocysts. Results of the BMP verification project (Chapter 3) did not contradict the literature. This means not all 419 crown pastures in community watersheds are problematic. Only pastures intersecting streams below the lowest lake or reservoir in a stream network are potentially problematic. Based on the literature and the BMP verification study, it is assumed that drinking water intakes located on lakes are safe in providing water for drinking and domestic use. On the basis of these findings, to determine which streams were potentially vulnerable to contamination, three analyses were conducted:

1. All streams from the most downstream lake in each watershed's stream network to the drinking water intake point of diversion were identified along with any tributary streams. These were identified as vulnerable streams.
2. Sources of contamination were identified as areas where vulnerable streams passed through crown pastures, possibly exposing surface drinking water sources to faecal contamination from cattle. These segments were defined as the critically vulnerable segments.
3. Finally, the critically vulnerable riparian areas where grazing cattle can potentially enter within 5 m of a stream bank were identified.

Five datasets were used for this phase of the analysis. All were obtained from the province's geographic data warehouse. These included the province's stream centre-line network, the community watersheds boundary dataset, the boundaries of the province's crown pastures, the waterbodies boundaries dataset, including lakes and reservoirs, and the points of diversion. The province's stream centre-line network is inclusive of all lakes and reservoirs through which water passes from the furthest reaches of a watershed until the final point of drainage of a watershed.

The previous intersection between the province's community watershed dataset and the crown pastures dataset had identified the 122 watersheds of interest for further analysis. Even though only 31 community watersheds have been identified as possible risks to human health, all 122 were analyzed for future consideration. The following GIS procedures were used to achieve the two objectives.

1. The stream network was first clipped to community watershed boundaries by intersecting the stream centre-line network with the watersheds boundaries. This resulted in 5000 km. of stream network being identified in the 122 watersheds of interest.
2. The stream centre-line stream network for each of the 122 watersheds was then visually inspected to determine which stream segments were potentially vulnerable to cattle faces without the benefit of a lake buffer for sedimentation of *C. parvum*. The resulting dataset was subsequently trimmed to erase stream segments that traversed lakes. This resulted in 3811 km of stream in 101 community watersheds being identified.

Figure 4.3 provides an example using Oyama Community Watershed. Stream segments below Oyama, Towgood, Ince, and one un-named lake are identified as most vulnerable to contamination by faeces from grazing cattle since these segments are also directly upstream of the community drinking water intake. GIS analysis reveals a total stream length in the watershed of 37 km. Further analysis reveals that 13.3 km have been identified as vulnerable to contamination because they lack a lake or reservoir to remove the contaminant.

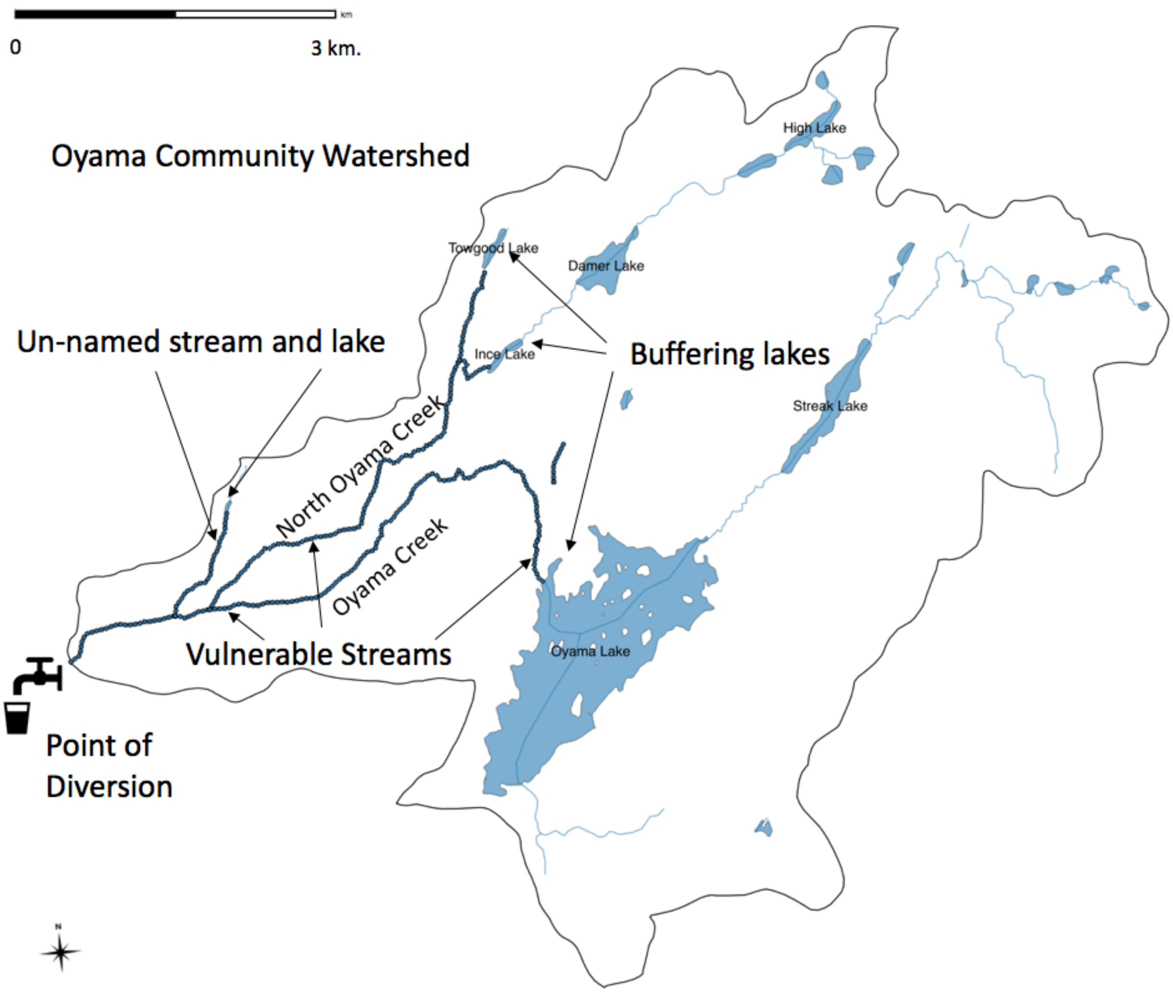


Figure 4.3 Identification of streams vulnerable to *C. parvum* from cattle faeces within Oyama Community Watershed.

4.3.4 Identification of Streams and Riparian Buffers.

FLNRORD developed the '5m rule' as a prudent setback for cattle from stream banks to identify critical riparian areas that might imperil drinking water surface sources should grazing cattle enter. On this basis, GIS analysis was used to create 5 m buffer setbacks from stream banks for each of the vulnerable stream segments.

The province's stream centre-line network was used to define the streams. Stream width assumptions were based on measurements as part of the BMP verification study (Chapter 3) taken during water sampling within the study area, and when faeces samples were taken within 5

m. of a stream bank. In total, 56 observations were recorded of gazetted stream reaches in the study area revealing an average mean width of 2.85 m, and 63 observations were made of non-gazetted stream reaches revealing an average mean width of 1.85 m. It should be noted that on a number of occasions during the sampling season, non-gazetted stream reaches were found to be dry, effectively meaning that there width was 0 m. These observations were not included in calculating the 1.85 m mean width for non-gazetted stream reaches. The measurements that were taken for the non-gazetted streams reflect early summer, post freshet conditions.

On the basis of these measurements, stream reaches with gazetted names were assumed for analysis and modeling purposes to be 10 m in width and those with un-named streams were assumed to be 2 m in width. The assumption's intent is to err to mitigating the risks of contamination to drinking water quality and safety. Stream banks were created by applying these assumptions to the stream centre-line network for all streams residing within the 122 community watersheds.

Subsequently, 5 m buffer zones were created for each of the vulnerable stream reach polygons as per the '5 m rule'. In addition, 30 m and 60 m buffers were also generated for further analysis. Under the Riparian Areas Regulation (Province of BC 2004b), 30 m is the minimal buffer for all riparian area assessments in community watersheds except where ravines are present, which require the use of 60 m buffers as part of the assessment.

Figure 4.4 provides an illustrative example from the Oyama Community Watershed. Oyama Creek has been assigned a width of 10 m by applying a 5 m buffer to the centre-line network, whereas an un-named tributary has been assigned a width of 2 m by applying a 1 m buffer. By applying these buffers, a polygon layer was generated from the stream centre-line which better represents the streams as they actually exist. The resulting stream banks were subsequently buffered with a 5 m setback in compliance with the '5 m rule' for analysis, and 30 m and 60 m setbacks in compliance with the province's requirement for riparian area assessments.

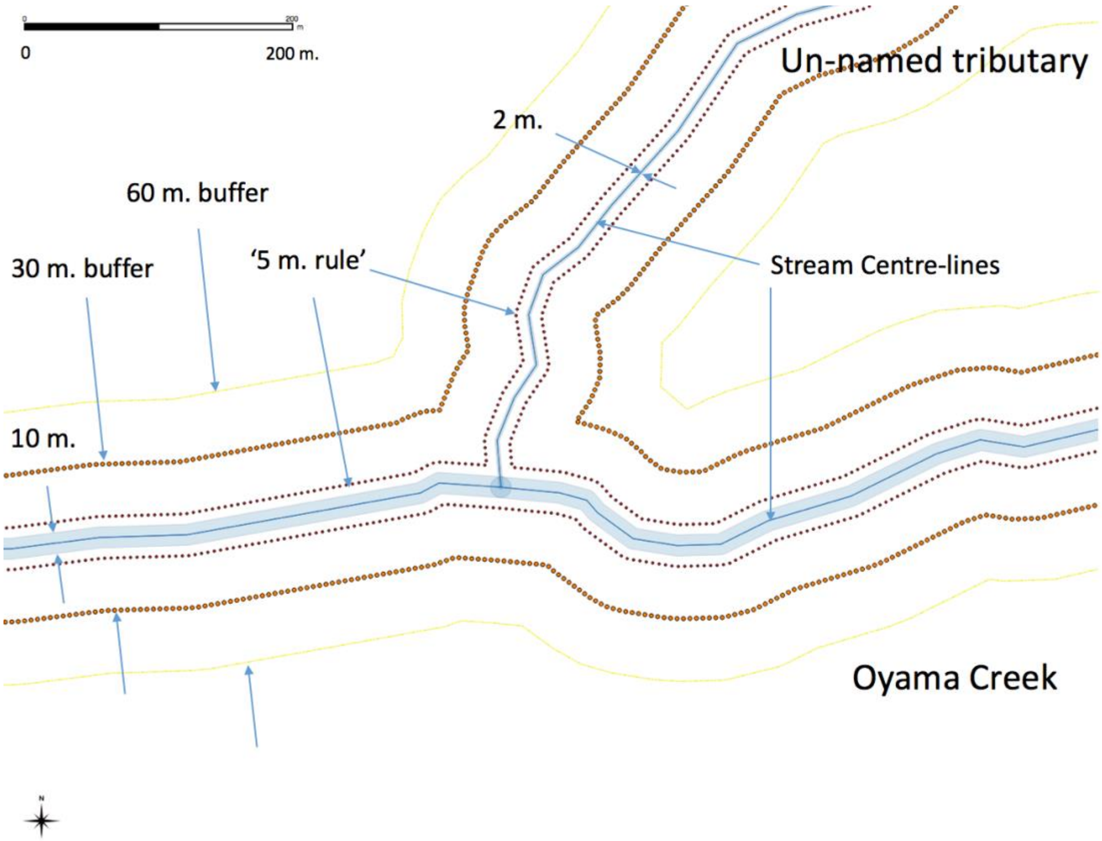


Figure 4.4 Example of application of stream width and buffer assumptions.

4.3.5 Identification of Critically Vulnerable Riparian Areas and Pastures in Community Watersheds.

The next phase of the analysis was to determine which vulnerable stream segments are most susceptible to potential grazing cattle within community watersheds due to the presence of crown pastures and the specific crown pastures of concern within each watershed. These were defined as streams within 5 m of a crown pasture. In addition, it is desirable to identify the pastures that would potentially have to be assessed for riparian protection under the BC Riparian Areas Regulation (Province of BC 2004b) so these were also identified.

To determine which streams and pastures possibly pose a threat to drinking water safety as per the '5 m rule', the 5 m buffer created for each vulnerable stream was intersected with boundaries of the 419 previously identified pastures. In addition, 30 m, and 60 m buffers were also created, and intersected with the 419 pastures to identify other pastures of concern for riparian protection. From the available data, 93 watersheds were identified with 259 pastures potentially posing a direct threat to surface water sources. An additional six pastures were found to be within 30 m of vulnerable streams and a further five are within 60 m. In total, of the 419 pastures within community watersheds, up to 270 pastures must be considered in assessing riparian protection under the BC Riparian Areas Regulation (Province of BC 2004b).

Figure 4.5 provides an example of how pastures were identified and classified within community watersheds as a potential threat to drinking water sources. In this instance, Oyama Community Watershed intersects with nine crown pastures. Of the nine crown pastures, four (Horse Lake, Round Lake (1), Streak, and Riparian, overlap with streams and/or associated riparian area deemed of highest vulnerability to contamination from cattle faeces to community drinking water and classified as ‘very possible hazard’. Lost Lake Pasture did not lie within these riparian areas, but at a point approximately 3.5 km. upstream of the drinking water intake, it did come within 60 m of Oyama Creek, and therefore may still pose a possible hazard. Finally, the remaining four pastures (CJ Express, King Eddie, Beaver Lake/Dee Lake, and Fir Valley) were classified as ‘very low potential hazard’ to the Oyama Creek as a drinking water source because of their distance from critically vulnerable stream reaches and riparian areas.

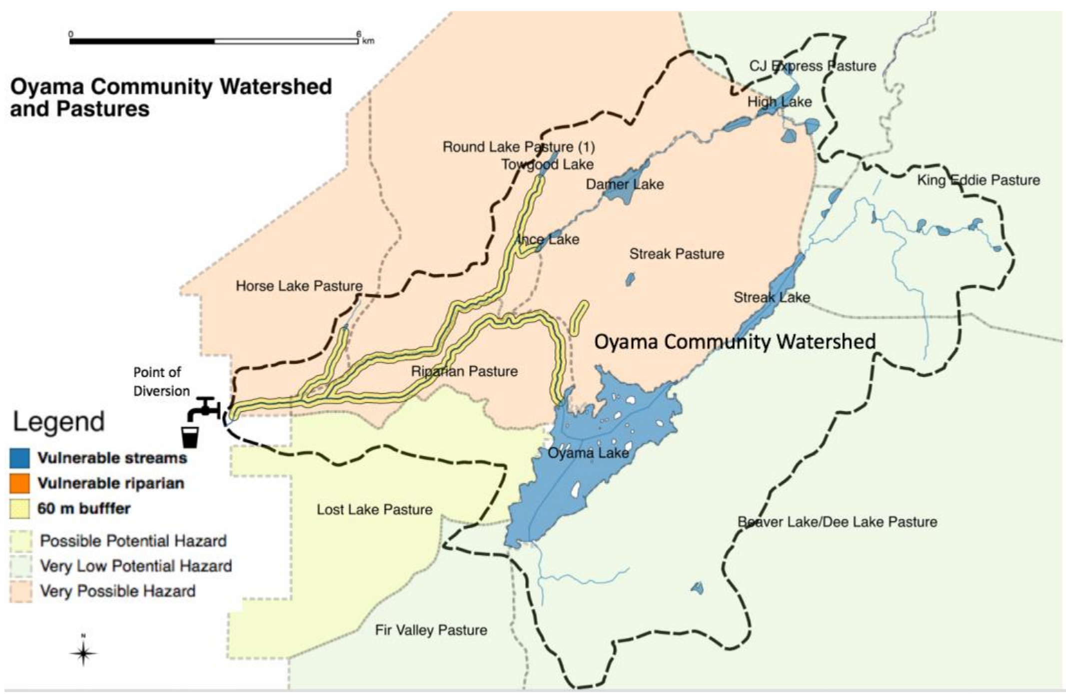


Figure 4.5 Example of hazardous pasture identification.

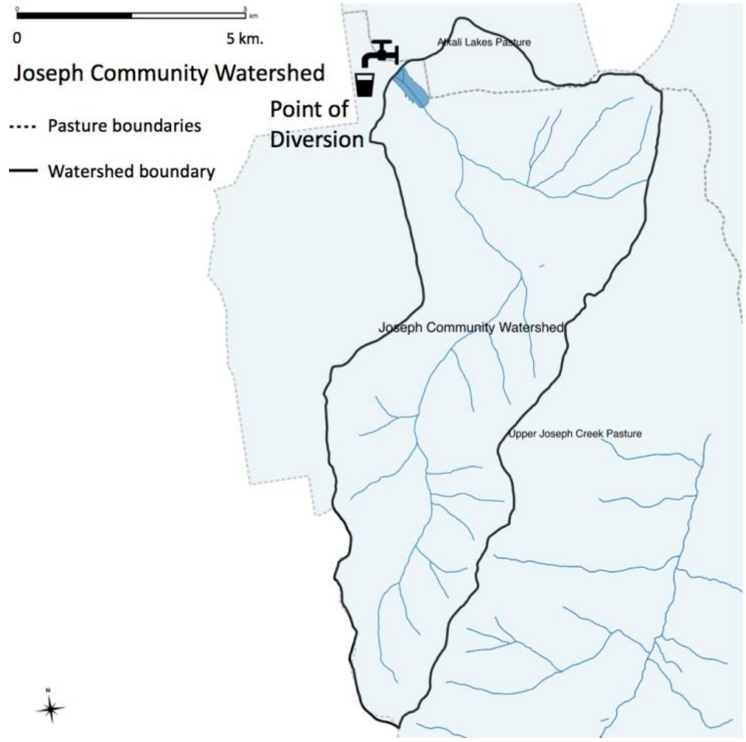
4.3.6 Limitations to the Identification of Vulnerable Streams in Community Watersheds.

Limitations existed within the provincial data for the analysis of watersheds for identification of vulnerable stream reaches. In some instances, streams identified within the province’s dataset did not match the location of streams as could be identified in available orthophotography and other available imagery. In other instances, no streams were identified as present within watershed boundaries from the province’s dataset. And finally, in several instances, watersheds drained into a lake or reservoir acting as a buffer to *C. parvum* contamination of water diverted to drinking water systems. Table 4.1 provides a list of five of the 122 watersheds with lakes and/or reservoirs as outlets.

Table 4.1 Community watersheds with terminal reservoirs and/or lakes

Community Watershed (CW)	**CW Code**
Paul Lake Community Watershed	129.014
Joseph Community Watershed	349.009
Trapping Creek Community Watershed	320.021
Abel Community Watershed	300.001
Farleigh Community Watershed	310.019

Figure 4.6 provides illustrative examples of two community watersheds where vulnerable streams were not identified. In the case of Joseph Community Watershed, the point of diversion to the community drinking water system is located on a reservoir or lake at the outlet. In the instance of Rosen Community Watershed, no streams have been mapped within the province’s. dataset, despite two pastures overlaying the watershed. Of the 122 watersheds identified, 16 did not have vulnerable streams that could be identified from the province’s stream centre-line dataset. Table 4.2 lists these watersheds. It should be noted that this does not mean that crown pastures and grazing cattle do not represent a threat to streams in these watersheds. Almost all of these watersheds are fully allocated as grazing pastures except for Weetman and Mellott Creek, which are respectfully only partially and minimally covered by pastures.



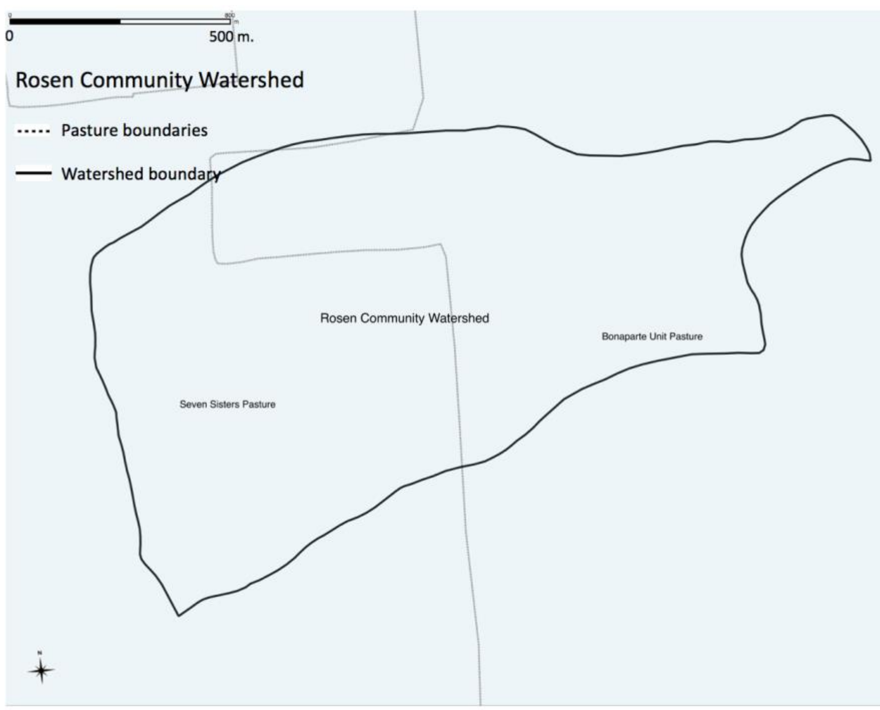


Figure 4.6 Examples of community watersheds lacking vulnerable streams or with indeterminate vulnerable streams.

Table 4.2 Community watersheds without identifiable vulnerable streams.

Community Watershed (CW)	CW_Code	Pasture Cover
Affleck Community Watershed	320.002	Full
Anglemont Community Watershed	128.002	Full
Blackbird Community Watershed	100.057	Full
Countless Community Watershed	100.058	Full
Currie Community Watershed	128.008	Full
Hope Community Watershed	310.023	Full
Norris Community Watershed	310.041	Full
Pye Community Watershed	300.045	Full
Rosen Community Watershed	129.021	Full
Skiing Brook Community Watershed	320.019	Full
Thomas Community Watershed	310.064	Full
Toops Community Watershed	128.029	Full
Wade Community Watershed	128.030	Full
Wiseman Community Watershed	128.034	Full
Weetman Community Watershed	100.088	Partial
Mellott Creek Community Watershed	100.212	Minimal

Appendix D provides a summary of the length of vulnerable stream reach in each watershed and a map of each watershed with identification of the vulnerable stream reaches.

4.4 Results of Initial GIS Analysis of Community Watersheds and Pastures

Of the 122 community watersheds in which vulnerable streams could be identified, 101 were identified with stream reaches that could potentially be vulnerable to contamination from cattle faeces with *C. parvum* oocysts. Upon further analysis, 93 watersheds were identified as having crown pastures overlapping vulnerable stream reaches within 5 m of the stream bank. In total, 3601 ha of crown grazing pasture was found to lie within these critically vulnerable areas. A detailed summary for each watershed can be found at http://www.watersheds.ok.ubc.ca/, including a map of the stream reach most vulnerable to the contamination of surface drinking water sources by grazing cattle.

4.4.1 Verification of Community Watersheds Vulnerable to *C. parvum* Contamination from Cattle Grazing.

To verify the vulnerability of each of the 122 community watersheds identified in the initial analysis, subsequent inspection was performed on each to determine its current state of use and its potential for providing *C. parvum* contaminated drinking water was assessed. For a risk of cryptosporidiosis to human health to exist from grazing cattle, a community watershed must still have pastures actively used for cattle grazing in immediate proximity to surface water sources (within 5 m) above a drinking water intake, and it must have a human population that consumes the water from these sources.

Inspection of the 122 community watersheds previously identified with pastures revealed that in nine instances, the pastures intersecting the watersheds were identified as too distant to vulnerable streams and of no threat for contaminating drinking water surface sources with *C. parvum* from grazing cattle faeces. Figure 4.7 illustrates the watershed boundaries and stream network for Floyd Community Watershed and Powerline pasture as an example.

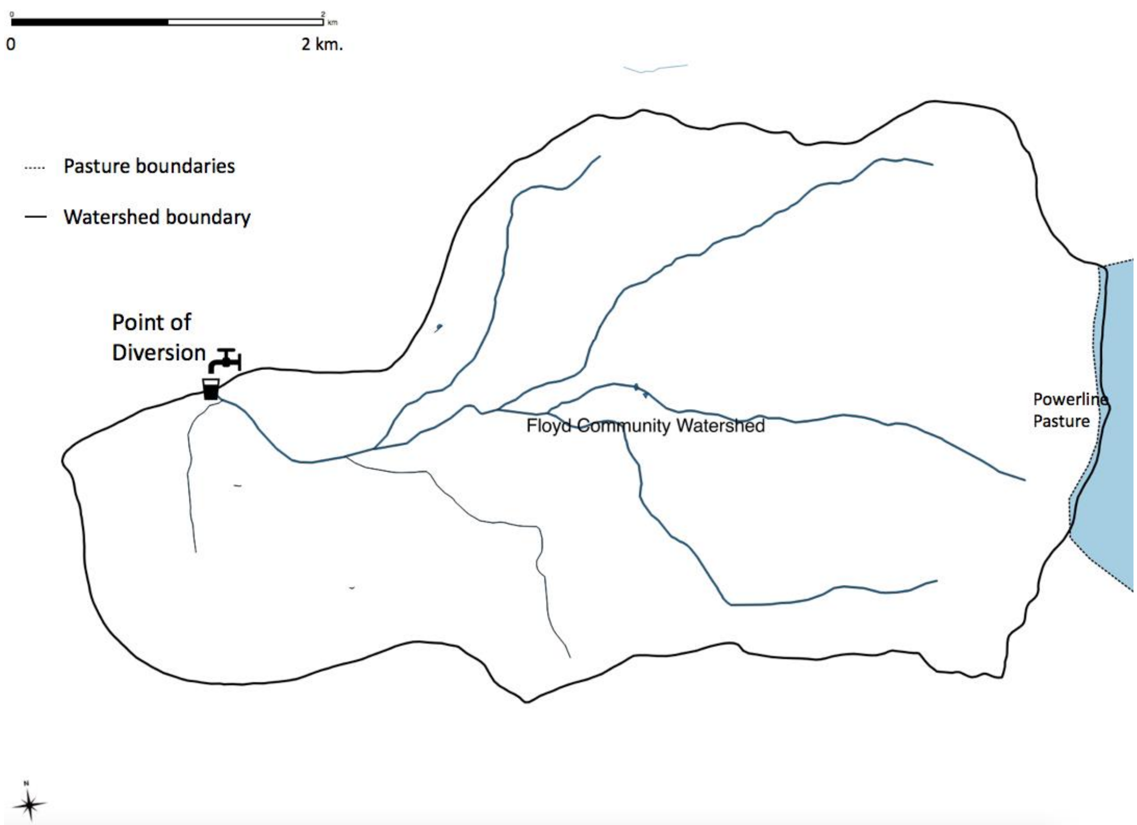


Figure 4.7 An example of a watershed with pastures of minimum threat to water quality from grazing cattle.

For the remaining 113 community watersheds, the BC water licensing database identified licensees within each watershed. In each instance, a licensee was contacted to verify the current data provided by the BC government and ascertain whether or not the conditions existed that could lead to the contamination of a human drinking water with *C. parvum* oocysts via the defecation of grazing cattle. Four questions were asked of each contact as necessary. These questions were:

1. Is the licence still used for drinking water from the licenced point of diversion?
2. If the licence is still being used, approximately how big a population is being served?
3. Is the water intake directly within the stream or is it now in a receiving pond, lake, or reservoir?
4. Are the pastures above the drinking water intake still being used for grazing cattle?

The results of this data verification exercise are itemized in Appendix D. Table 4.3 provides a summary of the results by HSDA. In 62 instances, alternative water sources are now being used instead of the original surface source. The two most common alternatives are newly established wells, and connections to a system serving a nearby municipality. In one instance, agreement has been reached with the local public health officials to boil water for human consumption. In five cases, pastures had been moved within community watersheds and are no longer used for cattle grazing. In one case, the water is diverted to another watershed with reservoirs, before being used for human consumption. Six drinking water systems have been upgraded with new intakes in lakes to improve water quality. In two instances, the pasture leases only served as a mechanism for crown land allocation for uses other than cattle grazing such as for development of commercial recreational skiing facilities. And in the case of one seasonal community, only bottled water is used for human consumption. Finally, in four cases, water is now diverted into a centralized treatment and distribution system or from one watershed to another. Therefore, there are currently only 31 community watersheds in the province where there is still a legitimate potential concern for *C. parvum* to contaminate drinking water via grazing cattle faeces. Most notable of the 31 watersheds identified as potentially being problematic for *C. parvum* contaminated drinking water from grazing cattle is that the majority (17) are located within the Okanagan HSDA with potentially over 182000 people consuming water from them.

Table 4.3 Summary of current use of community watersheds and potential hazard for *C. parvum* contamination in surface water sources from grazing cattle.

	Health Services Delivery Area					
Community Watershed Status	**East Kootenay**	**Kootenay Boundary**	**North Shore/Coast Garibaldi**	**Okanagan**	**Thompson Cariboo Shuswap**	**Total**
Abandoned - alternate source	10	4	1	19	28	62
Boil water advisory					1	1
Borderline pasture only	9					9
Cattle grazing discontinued.					5	5
Diverted				1		1
Integrated		1		3		4
Lake intake	4	1			1	6
No cattle		2				2
Seasonal (bottled water)			1			1
In use	4			17	10	31
Total	**27**	**8**	**2**	**40**	**45**	**122**

4.4.2 Population Estimates for Watersheds Subject to Cattle Grazing

To interpret data provided by the BC CDC as to the effectiveness of BMPs, population estimates served by each of the effected watersheds are essential. Population estimates for each LHA were acquired from BC Stats for the years 2005 to 2016 (see Appendix E).

As previously discussed, estimates of the population size for each of the 31 watersheds still at risk was canvassed from water purveyors and users. Table 4.4 provides current (2016) estimates from the purveyors and users summarized by LHA and HSDA and 2016 population estimates in each LHA and HSDA that receives their water from a community watershed where grazing cattle are present. For watersheds with only domestic licenses, an assumption of 3.5 residents was made for each dwelling unit. Also to be noted, in the Vernon LHA, the B.X. and Duteau community watersheds are diverted to a common distribution system by Greater Vernon Water Authority (GVW).

Table 4.4 Estimated population by community watershed and Local Health Reporting Area.

Health Services Delivery	Local Health Reporting Area	Population Estimates (BC Stats)	Community Watershed	Population Served (Purveyor/Users)	Population Served (%)
East Kootenay	Cranbrook	26436	Gold	19319	73.1
	Fernie	14838	Miller Creek	10	0.7
	Windermere	8971	Forster	777	8.7
	Total	50245		20106	40.0
Okanagan	Armstrong-Spallumcheen	10064	Fortune	500	5.0
			Glanzier	130	1.3
			Meighan	45	0.4
	Central Okanagan	196682	Hydraulic	6000	3.1
			Kelowna	18000	9.2
			Lambly	11000	5.6
			Mission	22500	11.4
			Oyama	1782	0.9
			Peachland	2600	1.3
			Powers	13000	6.6
			Trepanier	2080	1.1
			Vernon	4000	2.0
	Penticton	41293	Penticton	35000	84.8
			Shingle	501	1.2
	Princeton	4535	Dillard	384	8.5
	Summerland	11884	Trout	12000	100
	Vernon	68032	B.X.	53000	77.9
			Duteau		
	Total	332490		182522	54.9
Thompson Cariboo Shuswap	Kamloops	114429	Anglemont	300	0.3
			Bass	668.5	0.6
			Currie	35	<0.1
			Nelson	3	<0.1
			Peterson	52.5	<0.1
			Rosen	7	<0.1
			Toops	49	<0.1
	North Thompson	4224	Russell (1)	2400	56.7
	Salmon Arm	34323	Bastion	100	0.3
			Silver	100	0.3
	Total	152976		3715	<0.1
Total		535711		246343	46.0

To interpret the significance of the cryptosporidiosis data provided by the BCCDC for each of the LHAs within the Okanagan HSDA, two adjustments were made to the population data provided by BC Stats and purveyors:

1. Research suggests that children from one to nine years of age (Yoder et al. 2012), elderly persons greater than 65 years of age (Naumov et al. 2003), and those with compromised immune systems (US CDC n.d.) are more likely to be at risk of cryptosporidiosis than the general population.
2. The estimates in Tables 4.4 and 4.5 are current to 2016 and 2017, and were scaled for the period 2005 to 2016.

To adjust the populations to reflect those within the population more vulnerable to cryptosporidiosis, three age groups were created; 0 to 10, 11 – 64, and 65 plus years of age. The 0 to 10 and 65 plus groups were summed and divided by each total LHA population for each year to determine the portion more vulnerable to cryptosporidiosis in each year.

These portions for each year prior to 2016 were calculated as a percentage of the sum in 2016. The results were then applied to Table 4.5 to provide an estimate of the number of people in each LHA from 2005 to 2016 potentially at greatest vulnerability to cryptosporidiosis.

Table 4.5 Exposed population by LHA in the Okanagan HSDA.

Local Health Area	Exposed Population Estimate (2016)*	Cattle Presence
Armstrong - Spallumcheen	675	Yes
Central Okanagan	74962	Yes
Enderby	0	No
Keremeos	0	Yes
Penticton	35501	Yes
Princeton	384	Yes
Southern Okanagan	0	No
Summerland	12000	Yes
Vernon	53000	Yes
*Detailed by Community Watershed in Appendix D		

Figure 4.8 and Table 4.6 provide an example using the Vernon LHA. Five community watersheds with grazing pastures are of concern within the LHA. Greater Vernon Water (GVW) authority sources and distributes water from both Duteau Creek and B.X. community watersheds to the municipalities of Vernon, Coldstream, and Lumby. The total population including all

communities and areas within the LHA has been estimated at 68032 for 2016, of which 6829 are 10 years of age or younger, and 16588 are 65 years or older. These comprise 34.4% of the population. It has been assumed therefore that approximately 34.4% of the 53000 or 18232 individuals served by the GVW fall into the classification of being part of this more vulnerable population. Similarly, for each year, a corresponding estimate of the population within the Vernon LHA has been calculated from the original population estimates provided by BC Stats. Table 4.7 provides a summary of the application of this method to population estimates provided by BC Stats to all LHAs in the Okanagan HSDA from 2005 to 2014.

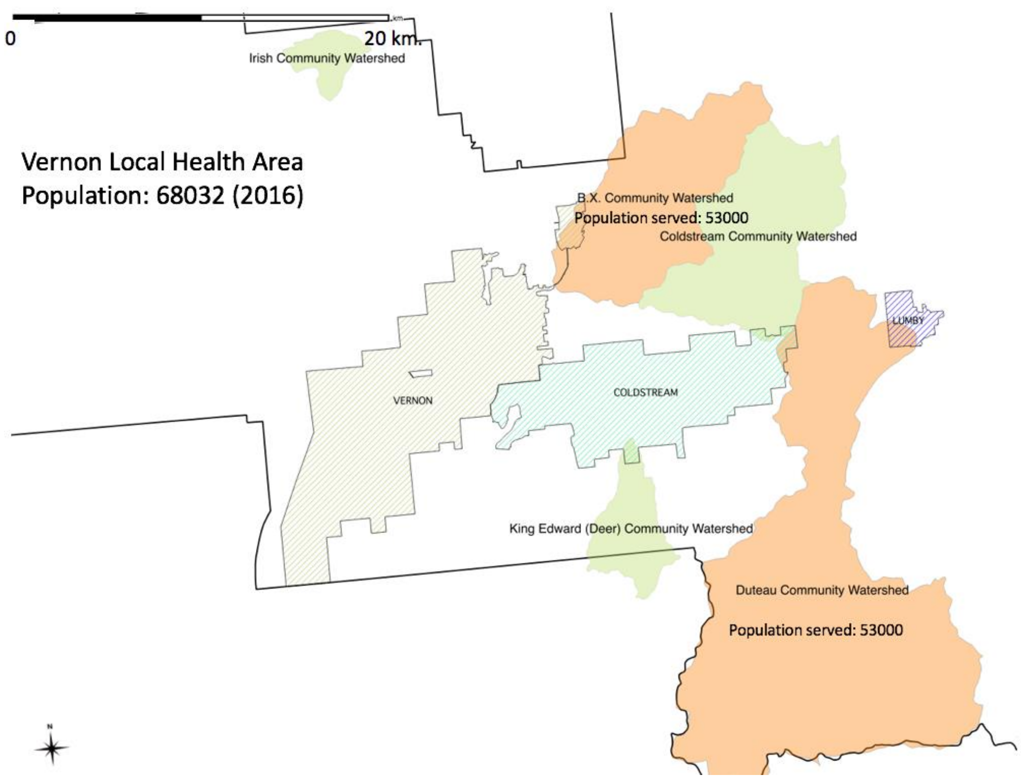


Figure 4.8 Vernon Local Health Reporting Area.

Table 4.6 Population estimates for Vernon LHA

	Age Group (years)				Vulnerable		Scaling	Vulnerable
Year	0-10	11-64	65+	Total	Pop.	%	%	Pop. Served
2005	6710	42848	11456	61014	18166	29.8	77.6	12252
2006	6751	43618	11808	62177	18559	29.8	79.3	12517
2007	6619	44180	12197	62996	18816	29.9	80.4	12733
2008	6689	44952	12573	64214	19262	30.0	82.3	13079
2009	6743	45452	12984	65179	19727	30.3	84.2	13528
2010	6755	44882	13188	64825	19943	30.8	85.2	13902
2011	6677	44858	13547	65082	20224	31.1	86.4	14235
2012	6649	44397	14098	65144	20747	31.8	88.6	14932
2013	6576	44086	14639	65301	21215	32.5	90.6	15605
2014	6593	44267	15393	66253	21986	33.2	93.9	16521
2015	6656	44786	16071	67513	22727	33.7	97.1	17335
2016	6829	44615	16588	68032	23417	34.4	100.0	18232

Table 4.7 Vulnerable population estimates for Okanagan HSDA by LHA and Year

Vulnerable Populations										
	Year									
Local_Health_Area	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Armstrong - Spallumcheen	2624	2633	2669	2776	2874	2908	3045	3141	3233	3367
Central Okanagan	47646	48397	49422	50912	51955	52398	53028	54249	55283	56558
Enderby	2111	2154	2210	2235	2257	2288	2292	2329	2430	2504
Keremeos	1824	1852	1944	2018	2024	1920	1980	2017	2051	2146
Penticton	13521	13573	13644	13695	13789	13738	14017	14353	14498	14865
Princeton	1512	1577	1436	1424	1413	1433	1548	1612	1676	1775
Southern Okanagan	7071	7091	7252	7378	7470	7324	7312	7426	7661	7832
Summerland	3877	3858	3941	4012	4061	4038	4188	4170	4207	4339
Vernon	18166	18559	18816	19262	19727	19943	20224	20747	21215	21986
- LHAs containing BMPs under trial from 2013 to present.										

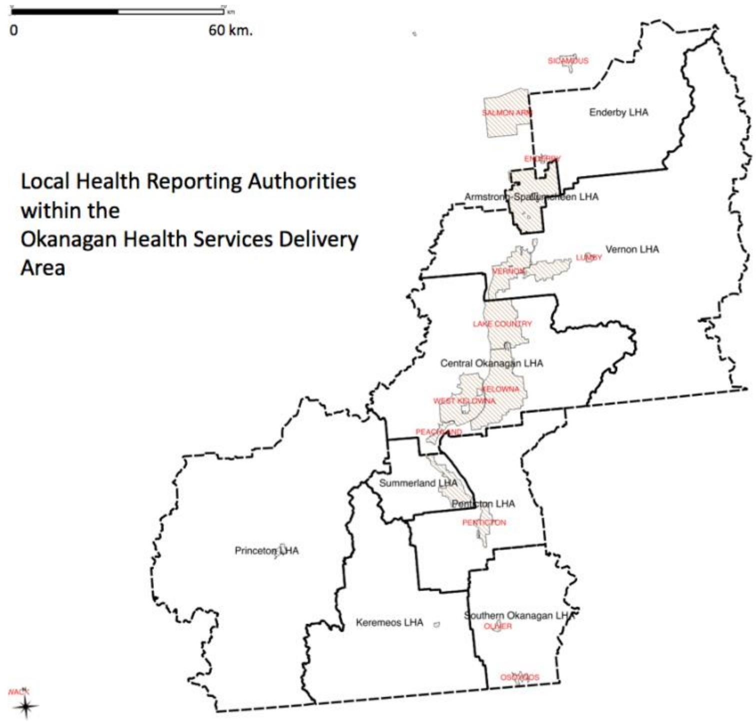


Figure 4.9 LHAs within the Okanagan HSDA.

4.4.4 Incidences of Cryptosporidiosis in the Okanagan HSDA from 2005 to 2015.

The BCCDC provided cryptosporidiosis incidence data for the nine LHAs in the Okanagan HSDA from 2005 to 2014. Only the reporting date and LHA were provided for each instance. No other details were provided. A total of 56 incidences were reported for this period. Tables 4.8 and 4.9 summarize this data. Note that as discussed in Chapter 2, cryptosporidiosis can be asymptomatic and hence cases may not have been reported resulting in underreporting. Alternatively, cryptosporidiosis incidents may have resulted from people traveling outside the Okanagan HSDA.

The data represents a window of 90 observations over 10 years across the nine LHAs in the Okanagan HSDA. Of the 90 observations, four were made in watersheds and years when BMPs were present; the Central Okanagan and Vernon LHAs for the years 2013 and 2014. Table 4.8 summarizes the data by the month in which it was reported.

To better understand the data, each year from 2005 to 2014 was divided into three periods for classifying each of the reported incidents. The periods were defined as:

1. April 15 to June 15: Incidences resulting from the spring freshet (April 1 to June 1).

2. June 16 to November 1: Incidences resulting from the period in which cattle might be actively grazing on pastures in a community watershed within the LHA. This reflects the earliest date (June 6) and the last date (October 15) cattle are permitted on pastures.
3. November 1 to April 15: Incidences arising during the off season when cattle are not present in a community watershed and not within the spring freshet.

A two week gap has been assumed between a change in these periods for classification from the change in exposure to grazing cattle on pastures in community watersheds. Chappell et al. (1996) identified a period of 2 to 10 days from exposure for cryptosporidiosis symptoms to appear. An allowance must also be made for the lag between cattle defecation in a stream before oocysts can be transported downstream, through a treatment plant and distribution system and then be present in drinking water from a consumer's tap. It is also reasonable to expect a lag between when symptoms are first noted by an individual and subsequently reported by an LHA.

In reviewing the data summary presented in Table 4.8, it is notable that of the 56 incidents reported from 2005 to 2014, 17 were reported within an LHA where grazing cattle have been determined not to be a hazard to water for human consumption. In particular, 15 of the incidents occurred in the Enderby LHA. Enderby has its own surface water intake as its primary water source and a multi-barrier treatment system that meets Canadian drinking water guidelines.

Table 4.8 illustrates that the month of September has the highest cumulative reported incidents of cryptosporidiosis with Vernon LHA reporting most frequently. Note that only 9 of the 56 incidents were reported in June and July. Since calving is usually completed by the end of March then extremely few animals should be shedding after August 1 as both the literature (Chapter 2) and the BMP verification study (Chapter 3) support.

Table 4.8 Monthly incidences of cryptosporidiosis in the Okanagan HSDA from 2005 to 2014.

Cumulative Cryptosporidiosis Incidents by Month and LHA from 2005 to 2014														
	Month	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**Total**
		Off-season			Freshet		Grazing							
Local Health Reporting Area	**Armstrong - Spallumcheen**		2	1	1		3			1				8
	Central Okanagan			2					2	2	4		1	11
	Enderby	1	1	1	1		3	1		3	1		3	15
	Keremeos							1						1
	Penticton					1						1		2
	Princeton						1							1
	Southern Okanagan	2												2
	Summerland					1								1
	Vernon	1		2		3			2	5		2		15
	Total	4	3	6	2	5	7	2	4	11	5	3	4	56

Table 4.9 provides a summary of the data provided by the BCCDC data by year and season (grazing, freshet, and off-season). Note that the peak year for reported incidences of cryptosporidiosis was 2006 with 13 incidents, of which 4 incidents were from the Enderby LHA.

Table 4.9 Incidences of cryptosporidiosis within the Okanagan HSDA from 2005 to 2015.

Local Health Reporting Area (LHA)		Year (2005-2014)										
	Cattle Presence	‘05	‘06	‘07	‘08	‘09	‘10	‘11	‘12	‘13	‘14	Total
Armstrong-Spallumcheen	Freshet				1				1		1	3
	Grazing						1			1		2
	Off-season							1	1	1		3
	Sub-total	0	0	0	1	0	1	1	2	2	1	8
Enderby	Freshet				1				1			2
	No Cattle	1	4		2	1	2	1	1	1		13
	Sub-total	1	4	0	3	1	2	1	2	1	0	15
Central Okanagan	Grazing		6		1					1		8
	Off-season					1	1				1	3
	Sub-total	0	6	0	1	1	1	0	0	1	1	11
Keremeos	Grazing								1			1
Southern Okanagan	No Cattle					2						2
Penticton	Freshet	1										1
	Off-season			1								1
	Sub-total	1	0	1	0	0	0	0	0	0	0	2
Princeton	Grazing					1						1
Summerland	Freshet								1			1
Vernon	Freshet	1			2							3
	Grazing	1	2	2	1					1		7
	Off-season		1	1				1		2		5
	Sub-total	2	3	3	3	0	0	1	0	3	0	15
Total		4	13	4	8	5	4	3	6	7	2	56
- LHAs containing BMPs under trial from 2013 to present.												

For further discussion and analysis, the BC CDC was normalized to the vulnerable and total populations summarized in Table 4.7 and normalized to incidences per 100,000 of population (Table 4.10) for further analysis and discussion.

Table 4.10a Cryptosporidiosis incidents within the Okanagan HSDA from 2005 to 2015.

Incidences per 100,000 Total Population (2005 – 2014)											
Local_Health_Area	‘05	**‘06**	**‘07**	**‘08**	**‘09**	**‘10**	**‘11**	**‘12**	**‘13**	**‘14**	**Cattle**
Armstrong - Spallumcheen	0	0	0	10.4	0	10.0	10.0	19.8	19.9	9.0	Yes
Central Okanagan	0	3.6	0	0.6	0.5	0.5	0	0	0.5	0.5	Yes
Enderby	13.8	54.4	0	40.6	13.5	27.1	13.6	27.4	13.6	0	No
Keremeos	0	0	0	0	0	0	0	19.7	0	0	Yes
Penticton	2.6	0	2.4	0	0	0	0	0	0	0	Yes
Princeton	0	0	0	0	22.0	0	0	0	0	0	Yes
Southern Okanagan	0	0	0	0	10.4	0	0	0	0	0	No
Summerland	0	0	0	0	0	0	0	8.6	0	0	Yes
Vernon	3.3	4.8	4.8	4.7	0	0	1.5	0	4.6	0	Yes
- LHAs containing BMPs under trial from 2013 to present.											

Table 4.10b Cryptosporidiosis incidents within the Okanagan HSDA from 2005 to 2015.

Incidences per 100,000 Vulnerable Population (2005 – 2014)											
Local_Health_Area	**‘05**	**‘06**	**‘07**	**‘08**	**‘09**	**‘10**	**‘11**	**‘12**	**‘13**	**‘14**	**Cattle**
Armstrong - Spallumcheen	0	0	0	36.0	0	34.4	32.8	63.7	61.9	29.7	Yes
Central Okanagan	0	12.4	0	2.0	1.9	1.9	0	0	1.8	1.8	Yes
Enderby	47.4	185.7	0	134.2	44.3	87.4	43.6	85.9	41.2	0	No
Keremeos	0	0	0	0	0	0	0	49.6	0	0	Yes
Penticton	7.4	0	7.3	0	0	0	0	0	0	0	Yes
Princeton	0	0	0	0	70.8	0	0	0	0	0	Yes
Southern Okanagan	0	0	0	0	26.8	0	0	0	0	0	No
Summerland	0	0	0	0	0	0	0	24.0	0	0	Yes
Vernon	11	16.2	15.9	15.6	0	0	4.9	0	14.1	0	Yes
- LHAs containing BMPs under trial from 2013 to present.											

4.5 Discussion

In the final stage of the analysis the number of reported incidences of cryptosporidiosis per 100,000 vulnerable population (Table 4.10a) and for the total populations (Table 4.10b) in each of LHAs of the Okanagan HSDA were calculated from 2005 to 2014. It should be noted that incident data from BCCDC indicates an average rate of 5.6 cases per year in an average population of approximately 342,000 people which equates to an incidence of 1.6 cases per 100,000. For the period 1999 to 2008, BCCDC reports that for all of BC, an average of 130 incidents per year in an average population of 4.16 million people, equating to an incidence rate of 3.1 cases per 100,000, roughly twice the rate of the Okanagan HSDA for 2005 to 2014.

In the case of Table 4.10a, the incidence of cryptosporidiosis was considered as normally distributed across the entire population estimated in each LHA for each year based on the assumption that all are equally susceptible to cryptosporidiosis. In the case of 4.10b, it has been assumed that incidences of cryptosporidiosis reported in each LHA are attributable only to members of the vulnerable portion of each LHA.

It is noteworthy that three of the LHAs (Keremeos, Enderby and South Okanagan) have reported incidences of cryptosporidiosis despite not being exposed to grazing cattle as a potential source of *C. parvum*. In particular, it is also noteworthy that the Enderby LHA has the highest average incidence per 100,000 population of cryptosporidiosis of the nine LHAs while also not being subject to gazing cattle presence.

4.5.1 Effect of Cattle Presence on the Incidence of Cryptosporidiosis.

The primary question is whether the presence of grazing cattle affects the incidence of cryptosporidiosis. Of the nine LHAs within the Okanagan HSDA, seven contain water systems subject to grazing cattle presence and two (Southern Okanagan and Enderby) do not, while one (Keremeos) has cattle present, but the population is not exposed to this hazard. The BCCDC provided no data other than date of reporting and LHA of each incident in the Okanagan HSDA from 2005 to 2014. The second question for consideration is the impact of BMPs where they exist on the incidence of cryptosporidiosis.

A simple Welch's t-test was first used to analyze the data. Table 4.11 provides a summary of a Welch's t-tests to determine whether the incidence of cryptosporidiosis in the populations of LHAs with cattle presence is different from those without cattle presence. Two cases were assumed. The first assumed the incidences of cryptosporidiosis across the entire exposed population. In the second case, it was assumed that the incidences occurred across only the previously defined vulnerable populations within the LHAs. In other words, in the second case it was assumed that none of the incidences of reported cryptosporidiosis occurred to people between the ages of 10 and 65 years.

Table 4.11 Effects of cattle presence on cryptosporidiosis incidences.

Effects of Cattle Presence on Incidences of Cryptosporidiosis.				
	Total Population		Vulnerable Population	
Cattle Present?	No	Yes	No	Yes
Number of Observations (n)	20	70	20	70
Mean incidences per 100,000 total population in each LHA.	10.7	2.4	10.7	7.4
Variance (s)	244.4	27.2	244.4	259.8
t-value (Welch's t-test)	-2.35		-0.83	
Degrees freedom	20		31	
$t_{.025}$	-2.086		-2.040	

In reviewing the results in Table 4.11, in both instances the predicted mean rate of incidence of cryptosporidiosis in LHAs without cattle is higher (10.7) than those with cattle (2.4 and 7.4) respectively for the total and defined vulnerable populations. The test results indicate that the null hypothesis (the means of both populations are the same) should be rejected if it is assumed that the reported incidences are a function of the total population, but not if the incidences are a function of only the vulnerable populations within each LHA and year. The results in both cases challenge the expectation that grazing cattle are potentially problematic to human health, and suggestion that in fact, water quality and safety might be better in community watersheds where grazing cattle are present.

4.5.2 Effect of BMPs on the Incidence of Cryptosporidiosis.

In considering whether BMPs mitigate the incidences of cryptosporidiosis, of the seven LHAs with cattle in them, only one (Central Okanagan) was subject to the application of BMPs and currently incident data with BMPs in place exists for only two years; 2013 and 2014. Table 4.12 summarizes the analysis of the data present for the seven LHAs in the Okanagan HSDA and indicates that the BMPs do seem to be having an effect in the limited number of observations regardless of whether the total population or only the vulnerable population is considered. It should be noted though that data is only available for the two LHAs in which the study area for the BMP verification study took place (Chapter 3).

Table 4.12 Effects of BMPs on incidences of cryptosporidiosis in Okanagan HSDA.

Effects of BMPs on Incidences of Cryptosporidiosis.				
	Total Population		**Vulnerable Population**	
BMPs Present?	No	Yes	No	Yes
Number of Observations (n)	68	2	18	2
Mean incidences per 100,000 total population in each LHA.	2.4	0.5	1.6	0.5
Variance (s)	27.9	5.4E-05	4.1	5.4E-05
t-value (Welch's t-test)	-2.93		-2.25	
Degrees freedom	67		17	
$t_{.025}$	-1.996		-2.11	

Welch's t-tests may not be the most appropriate tests for the data to answer the questons of interest. Two alternative means of testing are proposed. The first is a Poisson regression. In this instance, each LHA and year is treated as an observation with a resultant count of the incidences of cryptosporidiosis within a population. However, the data might be even better viewed as a population within which each individual may or may not report an incidence of cryptosporidiosis within a given year, and hence a Binomial regression may be the best method for testing the data for the effects of cattle presence in community watersheds on incidences of cryptosporidiosis in the respective populations served by the watersheds.

Tables 4.13a and 4.13b summarize analysis of the same hypothesis using Poisson and Binomial regressions. In the instance of the Poisson regression, the highest estimated mean (1.217e-05) for incidence of cryptosporidiosis in total populations occurs in LHAs with watersheds with no cattle however the results considering only the vulnerable population indicates ambiguity with the highest estimated mean (1.838e-05) being in LHAs with where cattle without BMPs are grazing. The results of the Binomial regression in both instances (total and vulnerable populations) indicated the highest expected incidences in LHAs where the watersheds have no grazing cattle, again counter to the expectations in the literature.

This conclusion was further reinforced by the application of a restriction on the data (Restriction #1) setting both the cattle presence with and without BMPs as equivalent. Alternatively, it could be assumed that the situation of cattle being present in a community watershed but with BMPs being used to negate the impacts. This is the assumption implicit in Restriction #2 of Tables 4.12a and 4.12b. using the Binomial regression. Again, whether cryptosporidiosis incidences are spread across entire populations or just vulnerable populations, the instances of no cattle presence implies higher expected incidences of cryptosporidiosis.

A third restriction (#3) was also applied to both datasets, setting the situation with cattle and no BMP to the situation of no cattle presence. This did reveal in both the total population and the vulnerable population instances that BMPs do have some value in lowering expected incidences of cryptosporidiosis in the respective populations.

A final regression was performed (Restriction #4) on both population assumptions to determine whether the model has any explanatory power. Both instances revealed no explanatory power.

Table 4.13a Impacts of cattle and BMP presence in community watersheds on cryptosporidiosis in total populations

<table>
<tr><th rowspan="2">Type</th><th rowspan="2">Stat.</th><th></th><th colspan="3">Treatment</th><th rowspan="2">Analysis of Deviance</th></tr>
<tr><th>Intercept</th><th>Cattle with BMP</th><th>Cattle no BMP</th><th>No Cattle</th></tr>
<tr><td rowspan="4">Poisson Regression</td><td>Est.</td><td>-7.513e-01</td><td>3.997e-06</td><td>5.727e-06</td><td>1.217e-05</td><td></td></tr>
<tr><td>Std. Error</td><td>2.001e-01</td><td>3.910e-06</td><td>2.210e-06</td><td>2.416e-05</td><td></td></tr>
<tr><td>z-value</td><td>-3.755</td><td>1.022</td><td>2.592</td><td>0.504</td><td></td></tr>
<tr><td>Pr(>|z|)</td><td>0.000173***</td><td>0.306642</td><td>0.009544 **</td><td>0.614600</td><td></td></tr>
<tr><td rowspan="4">Binomial Regression</td><td>Est.</td><td></td><td>-12.1437</td><td>-11.2271</td><td>-9.6383</td><td></td></tr>
<tr><td>Std. Error</td><td></td><td>0.7071</td><td>0.1644</td><td>0.2425</td><td></td></tr>
<tr><td>z-value</td><td></td><td>-17.17</td><td>-68.29</td><td>-39.74</td><td></td></tr>
<tr><td>Pr(>|z|)</td><td></td><td><2e-16 ***</td><td><2e-16 ***</td><td><2e-16 ***</td><td></td></tr>
<tr><td rowspan="4">Binomial Regression Restriction #1</td><td>Est.</td><td></td><td>-11.3012</td><td></td><td>-9.6383</td><td rowspan="4">Model 1: In/P ~ TrR1 - 1
Model 2: In/P ~ Tr - 1
Resid. Df Resid. Dev Df Deviance Pr(>Chi)
1 88 145.21
2 87 143.09 1 2.1171 0.1457</td></tr>
<tr><td>Std. Error</td><td></td><td>0.1601</td><td></td><td>0.2425</td></tr>
<tr><td>z-value</td><td></td><td>70.58</td><td></td><td>-39.74</td></tr>
<tr><td>Pr(>|z|)</td><td></td><td><2e-16 ***</td><td></td><td><2e-16 ***</td></tr>
<tr><td rowspan="4">Binomial Regression Restriction #2</td><td>Est.</td><td></td><td></td><td>-11.2271</td><td>-10.4195</td><td rowspan="4">Model 1: In/P ~ TrR2 - 1
Model 2: In/P ~ Tr - 1
Resid. Df Resid. Dev Df Deviance Pr(>Chi)
1 88 162.75
2 87 143.09 1 19.663 9.238e-06 ***</td></tr>
<tr><td>Std. Error</td><td></td><td></td><td>0.1644</td><td>0.2294</td></tr>
<tr><td>z-value</td><td></td><td></td><td>68.29</td><td>45.42</td></tr>
<tr><td>Pr(>|z|)</td><td></td><td></td><td><2e-16 ***</td><td><2e-16 ***</td></tr>
<tr><td rowspan="4">Binomial Regression Restriction #3</td><td>Est.</td><td></td><td>-12.1437</td><td>-10.9387</td><td></td><td rowspan="4">Model 1: In/P ~ TrR3 - 1
Model 2: In/P ~ Tr - 1
Resid. Df Resid. Dev Df Deviance Pr(>Chi)
1 88 165.96
2 87 143.09 1 22.87 1.733e-06 ***</td></tr>
<tr><td>Std. Error</td><td></td><td>0.7071</td><td>0.1361</td><td></td></tr>
<tr><td>z-value</td><td></td><td>-17.17</td><td>80.38</td><td></td></tr>
<tr><td>Pr(>|z|)</td><td></td><td><2e-16 ***</td><td><2e-16 ***</td><td></td></tr>
<tr><td rowspan="4">Binomial Regression Restriction #4</td><td>Est.</td><td>-11.0189</td><td></td><td></td><td></td><td rowspan="4">Model 1: In/P ~ 1
Model 2: In/P ~ Tr - 1
Resid. Df Resid. Dev Df Deviance Pr(>Chi)
1 89 170.12
2 87 143.09 2 27.028 1.352e-06 ***</td></tr>
<tr><td>Std. Error</td><td>0.1336</td><td></td><td></td><td></td></tr>
<tr><td>z-value</td><td>82.46</td><td></td><td></td><td></td></tr>
<tr><td>Pr(>|z|)</td><td><2e-16 ***</td><td></td><td></td><td></td></tr>
<tr><td colspan="7">Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Restriction #1: Tests difference between cattle and no cattle situation. Restriction #2: Tests to determine if Cattle with BMPs is equivalent to no cattle situation. Restriction #3: Tests to determine if there is a difference between cattle with BMP and cattle without BMP situation, Restriction #4: Tests to see if model has any explanatory power.</td></tr>
</table>

Table 4.13b Impacts of cattle and BMP presence in community watersheds on cryptosporidiosis in vulnerable populations

<table>
<tr><th rowspan="2">Type</th><th rowspan="2">Stat.</th><th></th><th colspan="3">Treatment</th><th>Analysis of Deviance</th></tr>
<tr><th>Intercept</th><th>Cattle with BMP</th><th>Cattle no BMP</th><th>No Cattle</th><th></th></tr>
<tr><td rowspan="4">Poisson Regression</td><td>Est.</td><td>-7.513e-01</td><td>3.997e-06</td><td>5.727e-06</td><td>1.217e-05</td><td></td></tr>
<tr><td>Std. Error</td><td>2.001e-01</td><td>3.910e-06</td><td>2.210e-06</td><td>2.416e-05</td><td></td></tr>
<tr><td>z-value</td><td>-3.755</td><td>1.022</td><td>2.592</td><td>0.504</td><td></td></tr>
<tr><td>Pr(>|z|)</td><td>0.000173***</td><td>0.306642</td><td>0.009544 **</td><td>0.614600</td><td></td></tr>
<tr><td rowspan="4">Binomial Regression</td><td>Est.</td><td></td><td>-12.1437</td><td>-11.2271</td><td>-9.6383</td><td></td></tr>
<tr><td>Std. Error</td><td></td><td>0.7071</td><td>0.1644</td><td>0.2425</td><td></td></tr>
<tr><td>z-value</td><td></td><td>-17.17</td><td>-68.29</td><td>-39.74</td><td></td></tr>
<tr><td>Pr(>|z|)</td><td></td><td><2e-16 ***</td><td><2e-16 ***</td><td><2e-16 ***</td><td></td></tr>
<tr><td rowspan="4">Binomial Regression Restriction #1</td><td>Est.</td><td></td><td>-11.3012</td><td></td><td>-9.6383</td><td rowspan="4">Model 1: In/P ~ TrR1 - 1
Model 2: In/P ~ Tr - 1
Resid. Df Resid. Dev Df Deviance Pr(>Chi)
1 88 145.21
2 87 143.09 1 2.1171 0.1457</td></tr>
<tr><td>Std. Error</td><td></td><td>0.1601</td><td></td><td>0.2425</td></tr>
<tr><td>z-value</td><td></td><td>70.58</td><td></td><td>-39.74</td></tr>
<tr><td>Pr(>|z|)</td><td></td><td><2e-16 ***</td><td></td><td><2e-16 ***</td></tr>
<tr><td rowspan="4">Binomial Regression Restriction #2</td><td>Est.</td><td></td><td></td><td>-11.2271</td><td>-10.4195</td><td rowspan="4">Model 1: In/P ~ TrR2 - 1
Model 2: In/P ~ Tr - 1
Resid. Df Resid. Dev Df Deviance Pr(>Chi)
1 88 162.75
2 87 143.09 1 19.663 9.238e-06 ***</td></tr>
<tr><td>Std. Error</td><td></td><td></td><td>0.1644</td><td>0.2294</td></tr>
<tr><td>z-value</td><td></td><td></td><td>68.29</td><td>45.42</td></tr>
<tr><td>Pr(>|z|)</td><td></td><td></td><td><2e-16 ***</td><td><2e-16 ***</td></tr>
<tr><td rowspan="4">Binomial Regression Restriction #3</td><td>Est.</td><td></td><td>-12.1437</td><td>-10.9387</td><td></td><td rowspan="4">Model 1: In/P ~ TrR3 - 1
Model 2: In/P ~ Tr - 1
Resid. Df Resid. Dev Df Deviance Pr(>Chi)
1 88 165.96
2 87 143.09 1 22.87 1.733e-06 ***</td></tr>
<tr><td>Std. Error</td><td></td><td>0.7071</td><td>0.1361</td><td></td></tr>
<tr><td>z-value</td><td></td><td>-17.17</td><td>80.38</td><td></td></tr>
<tr><td>Pr(>|z|)</td><td></td><td><2e-16 ***</td><td><2e-16 ***</td><td></td></tr>
<tr><td rowspan="4">Binomial Regression Restriction #4</td><td>Est.</td><td>-11.0189</td><td></td><td></td><td></td><td rowspan="4">Model 1: In/P ~ 1
Model 2: In/P ~ Tr - 1
Resid. Df Resid. Dev Df Deviance Pr(>Chi)
1 89 170.12
2 87 143.09 2 27.028 1.352e-06 ***</td></tr>
<tr><td>Std. Error</td><td>0.1336</td><td></td><td></td><td></td></tr>
<tr><td>z-value</td><td>82.46</td><td></td><td></td><td></td></tr>
<tr><td>Pr(>|z|)</td><td><2e-16 ***</td><td></td><td></td><td></td></tr>
<tr><td colspan="7">Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Restriction #1: Tests difference between cattle and no cattle situation, Restriction #2: Tests to determine if Cattle with BMPs is equivalent to no cattle situation. Restriction #3: Tests to determine if there is a difference between cattle with BMP and cattle without BMP situation, Restriction #4: Tests to see if model has any explanatory power.</td></tr>
</table>

4.5.3 Limitations

The results of the analysis indicate there may be significant limitations with the data and assumptions applied. Atwill (1996) indicated that grazing cattle with access to surface water sources should be potentially problematic for contaminating drinking water sources with *C. parvum* oocysts resulting in incidences of cryptosporidiosis infection in human populations served by these sources. However, the results indicate that within the Okanagan HSDA, grazing cattle present no significant effect on human health, and that there may in fact be less incidences of cryptosporidiosis in LHAs where grazing cattle are present are present in community watersheds. Confounding factors may explain these results.

The first confounding factor to consider is the inability to isolate true observations where no BMPs are present. One of the most effective potential BMPs is access scheduling, which restricts access to sensitive pastures in watersheds only to calves greater than three months of age (Duhaime et al, 2018, Atwill et al. 1999). Though this is now a formal requirement as a BMP in pasture lease agreements, it has also been a traditional practice of cattle ranching operations in BC to breed their cattle with the expectation of calving in early spring, typically starting in February (BC Ministry of Agriculture 2014). All cattlemen operating within the study area have their own pasture land for this purpose for grazing until the calves have been branded and inoculated against disease, and until the calves are of sufficient age to mitigate predation.

It is also worth noting that all faeces samples collected during the BMP verification field study that were successfully sequenced for their DNA were identified as *C. andersoni*, an indication of defecation more probable by mature animals and not young calves. Hence, even without the formal requirement in lease agreements for crown pasture land, both normal practices pre-BMP implementation and evidence from field sampling indicate that the majority of calves were already greater than three months of age by the time they access sensitive pastures. Given that this single BMP can result in a 2 $\log_{10}$ reduction in potential *C. parvum* oocyst loading within a community watershed, this traditional practice could have severely muted any signal as to the effectiveness of other formal BMPs.

A second confounding factor related to the sequencing of DNA where *Cryptosporidium* was detected is the failure to sequence. Several of these were from upstream of the nose hole at the Ince Lake sampling site where no cattle were present. A potential reason for these samples to not to sequence is the presence of multiple species of *Cryptosporidium*. Hence, water sources in the Okanagan HSDA may be contaminated at times by other sources of *Cryptosporidium* such as wildlife giving rise to reported incidences of cryptosporidiosis not resulting from the presence of cattle.

A third confounding factor is the extent of the data from BCCDC. Only 56 incidents of cryptosporidiosis were reported to the BCCDC for the years 2005 to 2014 inclusive. In analyzing the literature, two scenarios were developed, a non-BMP and a BMP scenario (Chapter 2, Duhaime et al., 2018). Under the non-BMP scenario, a worst-case scenario exists with a hypothetical concentration of 75 oocysts/l in drinking water, well above the 10-30 oocysts identified as infectious to healthy adults (Chappell et al., 1996; DuPont et al., 1995). A dose of 30 oocysts has been demonstrated to potentially cause disease in as many as 20% of healthy adults (DuPont et al. 1995). In the exposed population of 183,000 (Table 4.5) residents of the Okanagan HSDA, if this were true, a much higher incidence of cryptosporidiosis should be reported annually to the BCCDC. The fact that only 56 cases have been reported for the whole Okanagan HSDA from 2005 to 2014 suggests that the risk of hazard is much lower than theorized, even before the formal application of BMPs.

It needs to be noted that the highest average incidence of cryptosporidiosis over the period from 2005 to 2014 occurred in the Enderby LHA, even though no cattle were connected via water systems present to the residents of the LHA. There are several possible explanations. One of the basic assumptions in this analysis is that individuals are tied to the consumption of water solely from the LHA in which they reside. If cattle are the source of these incidents, it is possible these incidents arose from water consumed outside of the LHA in which they reside, and those sources of water may be either subject to unmitigated hazard of drinking water contaminated from cattle or these incidences may be the result of traveller’s diarrhea and not from domestic sources at all (Goodgame, 2003). Another possible explanation is the rural nature of population within the Enderby LHA, where residents might not be connected to community water systems and obtaining water from their own sources with minimal of no treatment processes for decontamination. Finally, wildlife cannot be ruled out either as a possible source of contamination.

A final confounding factor is the incidence reporting to the BCCDC itself. Cryptosporidiosis has been demonstrated to be asymptomatic in many instances (Chappell et al.

1996). Hence the true rate of incidences in the Okanagan HSDA may be much higher and more problematic than reported, and both its incidence and the effects of BMPs are being masked.

4.6 Summary

The overarching conclusion from the synthesis and analysis of the available GIS data, reported incidences of cryptosporidiosis in the Okanagan HSDA, the BMP verification project, and the literature is that there is no definitive proof that the presence of grazing cattle in community watersheds in the BC interior are a hazard to human health either at this time, nor prior to the introduction of formal BMPs to mitigate the risk to human health. The limited number of observations of the impacts of implemented BMPs does seem to indicate that they may be of value in the mitigation of grazing cattle as a hazard to drinking water quality and safety, but more research is required if a definitive conclusion is to be reached.

The reported provincial incident rate from 1999 to 2008 for cryptosporidiosis at roughly twice that of the Okanagan HSDA from 2005 to 2014 rate from suggests that if incidences are to be reduced from the current rate, then other potential sources of the illness should be explored. In particular, it is recommended that future research assess cryptosporidiosis incidents resulting from individuals acquiring the parasite while traveling outside of the Okanagan HSDA and/or province of BC.

A final question that might be asked is why does the presence of grazing cattle in community watersheds seem to correlate with lower incidences of cryptosporidiosis in the watersheds they serve? Is it simply that the available data is so sparse that this is the wrong conclusion to draw from it, or is it because of other factors such as the displacement by cattle of other species that might be carriers by the presence of the grazing cattle, resulting in contamination of surface water sources? Or might it be a consequence of more intense stewardship in these watersheds because of the presence of the cattle? As discussed previously (Chapter 1), cattle have been grazed for over a century in these watersheds. The ranchers involved in these operations have a long history of tenure over the pasture resources in community watersheds and a hence an appreciation for the necessity of responsible stewardship.

Chapter 5.0 Cattle Incursion into Sensitive Riparian Areas.

5.1 Background

Chapter 2 explored the literature pertaining to the potential hazard posed by the presence of grazing cattle in community watersheds of the interior of British Columbia along with the potential for six best management practices (BMPs) being piloted in a designated study area to mitigate the hazard. Specifically, the concern is that *C. parvum* oocyst concentrations greater than 10^3/L at a drinking water intake could be present and if so, would be in excess of what treatment facilities meeting Health Canada (2012) guidelines could mitigate as a hazard to human health. BMPs can reduce this possibility to an insignificant level as a public health concern. The basis for the significant contamination of drinking water sources without the presence of BMPs was a hypothetical worst-case scenario involving the direct defecation into a stream immediately upstream of a drinking water intake by 300 infectious calves resulting in a concentration of 75 oocysts/L in drinking water after treatment meeting Health Canada guidelines and a potential upstream concentration of 7.5 x 10^6 oocysts/L.

In conducting a field study (Chapter 3) to determine the effectiveness of the six BMPs being piloted to determine their effectiveness in mitigating the Chapter 3, the analysis of water and field samples collected during the grazing seasons from 2013 to 2105 revealed dramatically lower concentrations of *Cryptosporidium oocysts* than what the literature suggested might be expected. Furthermore, when successfully speciated, the detected samples were subsequently identified as *C. andersoni,* and not *C. parvum*. Oocyst concentrations even in the BMP control area, the Crescent Creek tributary to Duteau Creek, were several orders of magnitude lower than might be expected from the literature.

In addition to the field study to look at BMPs and determine their impacts on the presence of *C. parvum* oocysts in source water, cryptosporidiosis incident data was acquired from the BCCDC for each of the nine LHAs within the Okanagan HSDA from 2005 to 2014. This data was statistically correlated with the community drinking water systems and the pastures present in those systems that contained gazing cattle to determine if the presence of grazing cattle could be correlated with incidents of cryptosporidiosis. In contrast to the expected outcome, LHAs with exposure to the hazard actually revealed a lower incident rate of cryptosporidiosis.

Though it could not be concluded as definitive proof, results of the field study suggest the possibility that access scheduling, the practice of not allowing the young calves most likely to carry and shed *C. parvum* oocysts in their faeces, onto range in areas with vulnerable surface water sources, is a highly effective BMP. As discussed in Chapter 3, cattle ranchers target their breeding so that all calves should be born by the end of March in each year to satisfy market incentives. This is two and a half months in advance of when ranchers can place their cattle on crown pastures and a significant portion of the calves can be expected to be at least three months of age by this point in time. Furthermore, any cattle exhibiting symptoms of illness at that time are not turned out on crown range as a matter of normal practice. This complicated the ability to determine the effectiveness of the access scheduling BMP due to the inability to establish a control to test it.

If it is assumed that access scheduling by default significantly mitigates the potential exposure of the vulnerable surface water sources in the study area from *C. parvum* contamination, then the actual worst-case scenario is significantly different from that envisioned in Chapter 2. This prompts the consideration of an alternative worst-case scenario to determine the magnitude of the threat posed by grazing cattle in community watersheds and which BMPs might be most appropriate to mitigate this hazard.

In this chapter, an alternative worst-case scenario will first be explored assuming access scheduling as effective by default. Then, given the results of that scenario, the literature will again be briefly reviewed along with an analysis of the available data for the study area to ascertain and explain the differences between what the amended worst-case scenario indicates and the findings from the BMP verification study. The focus of this chapter is to use the available data for the study area and other watersheds within Local Health Reporting Areas (LHAs) of the Okanagan Health Services Delivery Area to further explore the relationship between incidences of reported cryptosporidiosis and the presence of crown pastures and grazing cattle in community watersheds. In analyzing the gap between theory (Chapter 2), the field results (Chapter 3), and analyzing the relationship between incident data provided by the BCCDC for the Okanagan HSDA, insights should be gleaned as to true extent to which grazing cattle in BC's interior community watersheds is a threat to human health.

5.1.1 Confounding Factors

Previous chapters raise several questions with respect to the actual level of risk and concern that grazing cattle and *Cryptosporidium* pose to human health in populations served by BC's interior community watersheds. Are grazing cattle truly problematic for contamination of drinking water with *C. parvum*, or are there other factors at play in mitigating contamination?

One factor confounding the correlation between cryptosporidiosis incidents and surface water source exposure to grazing cattle is the age of introduction of calves to pastures with sensitive streams (Chapter 3). Two different ranching operations leased the pastures in the study area, and in each instance, it was confirmed that calving is complete by the last day of March each spring (Chapter 3). This is a common practice on Canadian ranches. A survey of 270 Canadian beef ranching operations from British Columbia to Ontario found that calving typically starts late February at the earliest and ends by early May at the latest (Duckworth 2014). The survey also indicated that earlier calving is preferred to avoid bovine respiratory disease, and to improve uniformity in calves for marketing purposes.

Table 5.1 provides a summary of the pastures and watersheds in the study area, the location of site specific BMPs within pastures, and when cattle are present within each pasture. The earliest instance of cattle introduction within the study area is in Horse Lake pasture within Oyama Creek watershed on May 18th, seven weeks from the end of March. This is followed by Postill Lake Pasture in Vernon Creek Community Watershed on June 1st of each year, nine weeks after the end of March.

Both ranching operations in the study area also hold back calves identified with scours (watery stools), and/or any other health condition from introduction to crown pastures within community watersheds until their health has been restored. Ranching operations are also conscious of potential losses to predators on crown pastures, and hence avoid releasing small or ill calves onto the pastures. Consequently, even the youngest calves released onto crown pastures into the Horse Lake pasture can be expected to be at least two months in age and in good health.

Detailed studies of cryptosporidiosis in dairy calves (Zambrinski et al. 2013, O'Handley et al. 1999) have also demonstrated that calves typically take from 5 to 8 days from the time of exposure to the onset of symptoms such as diarrhea. Oocyst shedding in their faeces peaks about two weeks after exposure, and after a subsequent two weeks, oocysts become almost nondetectable in their faeces.

Table 5.1 Cattle presence in study area relative to sampling sites and pastures.

Community Watershed	BMPs Present	Sampling Site	Pasture	Dates Cattle Present
Vernon Creek	Off-stream watering. Silvopasture	Beaver Lake outflow	Fir Valley Pasture	June 6 to 30 October 1 to 15
		Vernon Creek tributary	Fir Valley Pasture	June 6 to 30 October 1 to 15
		Vernon Creek intake	Postil Lake Pasture	June 1 to 30 October 8 to 15
Oyama Creek	Exclusion Fencing Nose hole	Oyama Lake outflow	Riparian Pasture	September 1 to 15
		Damer Lake outflow	Round Lake Pasture	June 16 to September 15
			Streak Lake Pasture	June 16 to September 15
	Off-stream watering Key area management	Nosehole at North Fork Oyama Creek	Round Lake Pasture	June 16 to July 15 September 1 to 15
		Oyama Creek intake	Horse Lake Pasture	May 18 to June 15 September 16 - October 15
King Edward (Deer) Creek	Key area management Exclusion Fencing	King Edward Lake outflow	CJ Express Pasture	July 1 to 15
		CJ Meadow (Deer Creek)	CJ Express Pasture	July 1 to 15
		Below CJ Meadow (Deer Creek)	CJ Express Pasture	July 1 to 15
Duteau Creek	Exclusion Fencing Off-stream watering	Haddo Lake outflow	Buffer Management Pasture	No scheduled use.
		Haddo bridge	Buffer Management Pasture	No scheduled use.
		Duteau intake	No pasture	No use.
		Crescent Creek (Upper)	King Eddie Pasture	September 1 to October 15
		Crescent Creek (Below)	King Eddie Pasture	September 1 to October 15
		Tributary at 13 km. on Aberdeen road	King Eddie Pasture	September 1 to October 15

Olson et al. (2004) also established that beef calves in Canada typically experience cryptosporidiosis between week 1 and week 4 of age. This implies that during the seven week period from March 31st to May 18th, it is feasible for a calf to become infected, experience the full onslaught of cryptosporidiosis and then recover before they enter a crown pasture thus not shedding detectable *C. parvum* oocysts during defecation. The results of the research by McAllister et al. (2005) on the incidence of *C. parvum* in calf faeces in two Okanagan herds from March to May of 1998 indicated no detectable *C. parvum* oocysts (n=39) for calves averaging 16.6 days of age.

In reviewing Table 5.1 and the study area (Figures 3.3 to 3.6) It should also be noted that other pastures in the study are not exposed to calves until at least 10 weeks (2.5 months) of age, and in several instances, not until after September 1st when the youngest calves would already be five months of age. The implications being that despite the formal establishment of the access scheduling BMP, normal practices within the ranching operations in the study area has effectively resulted in this BMP being post factum for the entire study area and potentially explains why *C. parvum* was not identified in positive water and faeces samples. The final implication being that to better understand the fate of any *C.parvum* oocysts present in water, faeces, and sediment samples from the study area, the worst-case scenario needs to be reconsidered.

5.1.2 Alternative Worst-Case Scenario

In the previous worst-case scenario, it was assumed that all 300 calves were infectious for *C. parvum* via their faeces at the maximum daily load. Upon reconsideration of the i) literature with respect to the prevalence of *C. parvum* in beef calves in western Canada, ii) the results of the BMP verification study, and iii) what is known with respect to both normal practices of the ranching operations in the study area and the dates on which grazing cattle are permitted access to crown land pastures in community watersheds, an alternative worst-case scenario is proposed that assumes only 1% of calves are infectious and at their peak for shedding (10^6 oocysts/day).

Figure 5.1 summarizes a revised worst-case scenario (Scenario 1a). In this instance only 3 calves (1%) have been assumed infectious, shedding a load of 3×10^8 oocysts/day within a pasture in a community watershed.

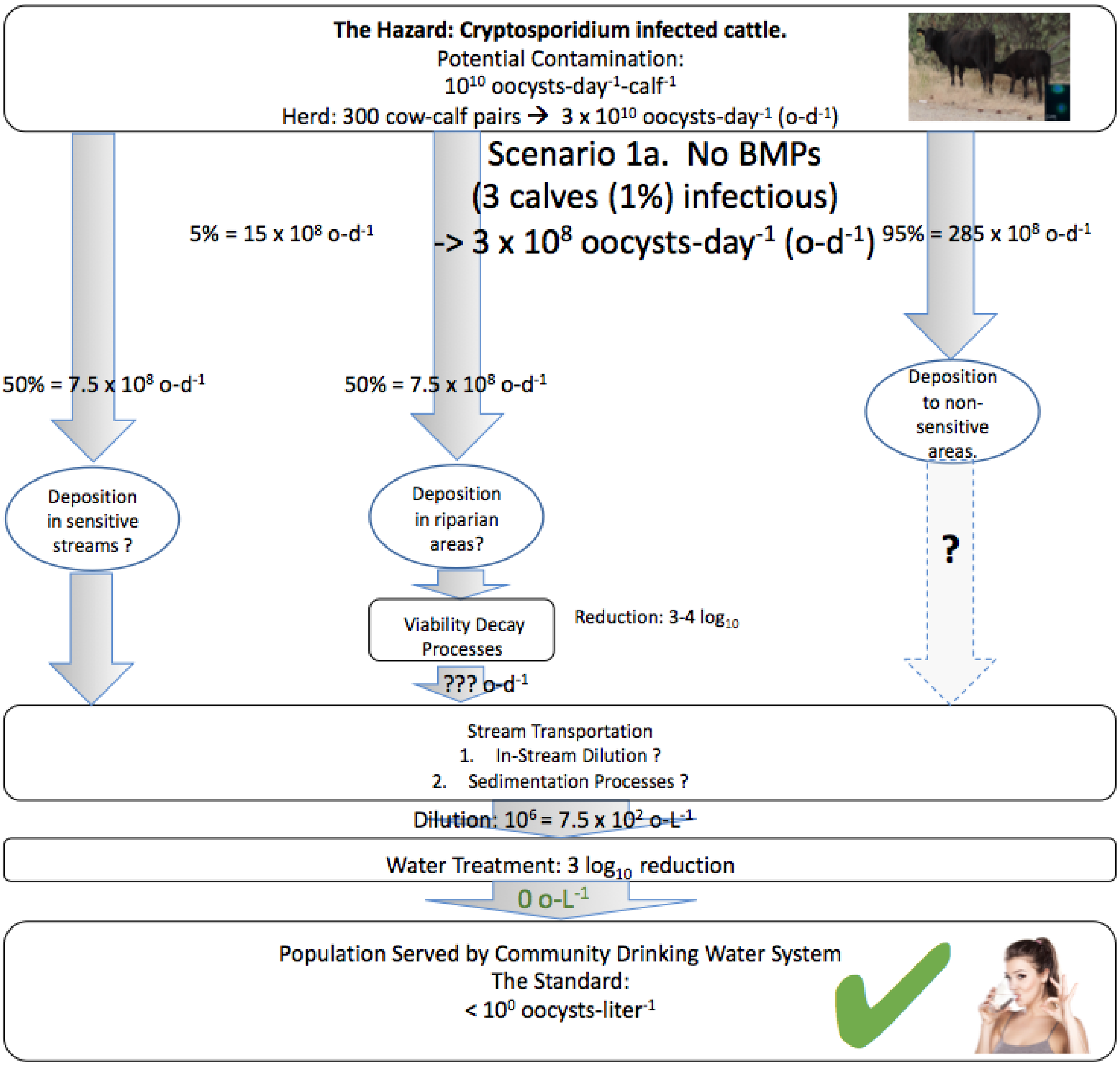


Figure 5.1 An alternative worst-case scenario.

Using the same analysis as in Chapter 2 and Duhaime & Roberts (2018), this implies a potential concentration of 750 oocysts/litre at the drinking water intake. If the water treatment facility meets current Health Canada guidelines resulting in a 3 $\log_{10}$ reduction in Cryptosporidium concentration, then effectively the water should meet the desired standard and have no infectious oocysts still present. This result indicates the value of access scheduling as both a BMP to assure water safety, and in its efficiency and convenience from the operational standpoint of ranchers, who effectively have been practicing the BMP post factum.

5.1.3 Implications of Alternative Worst-Case Scenario

Even under the revised worst-case scenario, there are still questions to be answered. Again in reviewing field results from the BMP verification study, oocyst concentrations upstream of the drinking water intake do not reflect this scenario. Under the scenario depicted in Figure 5.1, oocyst concentrations in field samples should have been at least two to three orders of magnitude higher than detected in the samples collected. There are two possible explanations for this outcome:

1. The scenario is still biased towards an unrealistic worst-case scenario with respect to either the number of *C. parvum* shedding calves present in crown lease pastures with access to sensitive riparian areas, or the concentration of oocysts being shed is lower than 10^{10} per day per calf as previous research has indicated.
2. Grazing cattle are not spending time and defecating in sensitive riparian areas to the extent that would result in oocyst concentrations even in the order of magnitude that the revised worst-case scenario would indicate.

In the first instance, as previously discussed, no evidence is available to ascertain the actual level of infection within the cattle herds released into pastures within the study area during the BMP verification study, and in the instances where oocysts were identified in water and faeces samples, they were never subsequently identified as *C. parvum* by DNA sequencing.

In the second instance, an understanding of the behaviour of grazing cattle while present on pastures in community watersheds is necessary, in particular, how and where they spend their time, and how they move about their landscape, and in particular, the spatial distribution pattern of their defecation.

5.2 Grazing Cattle Behaviour and Movement on Rangeland.

Research suggests that grazing cattle movement, like all animal movement is complex and driven by both random and deterministic processes (Zhao & Jurdak 2006), and that it is a function of a number of factors, including evolved strategies to optimize foraging efficiency, responses to external stimuli, environmental conditions, and landscape features.

The ideal solution to determining the amount of time cattle spend in vulnerable riparian areas posing a threat to surface drinking water sources would be to release cattle into the study area with GPS tracking and recording technology which could be subsequently analyzed. Without this data, the only alternative available is to analyze what has been revealed about grazing cattle under similar circumstances with respect to their need and preferences, and when and how they satisfy them in relation to the available resources and landscape of the study are. In particular, this means gaining an understanding of:

1. The daily routines of cattle.
2. Their needs and preferences, including foraging for sustenance, water, and shelter, and specifically how they are met by the resources available within the landscapes of the grazing pastures available to them.
3. The elements within a landscape that are attractants to cattle, including not just those that meet their needs, but those that facilitate access to resources such as corridors and landscape conditions that allow for ease of movement within the landscape.
4. The elements within a landscape that are barriers to cattle movement and prevent them from accessing areas within their pastures, including vulnerable riparian areas.
5. And finally, those elements within a landscape that repel cattle, or motivate them to avoid areas within a pasture.

The province of BC has compiled comprehensive datasets providing the opportunity to analyze the topography, ground cover, hydrological features, road networks, and other elements present in watersheds and pastures within the study area. Integration and analysis of these datasets, might provide insights on how cattle spend their time within crown pastures and in particular, the amount of time they might spend within vulnerable riparian areas as a hazard to surface drinking water sources. This may contribute to explaining the discrepancy between alternative worst-case scenario and the results of the analysis water and faeces samples collected during the BMP verification study.

5.2.1 Daily Routines and Relevant Scales of Grazing Cattle Behaviour, Movement, and Distribution on Rangeland.

As previously discussed (Chapter 2), Bailey et al. (1996) built on previous work by Senft et al. (1987) to propose a formal hierarchy (see Figure 2.1) defining both spatial and temporal scales for cattle movement, behaviour, and distribution.

More recent work (Zhao et al. 2016), based on the analysis of data collected with GPS technology has not only confirmed previous theories, but also suggests that finer scales of movement by cattle are dictated by stochastic and spontaneous mechanisms, whereas movement at coarser levels in the landscape are more deterministic, and more probably driven by memory or herding.

It is in their coarser levels of movement and behaviour that grazing cattle potentially threaten surface water sources. Larsen (1996) identified the need to keep cattle from defecating in streams and in riparian areas in close proximity to streams as a primary objective to mitigating adverse impacts on water quality and especially to mitigate its contamination by faecal pathogens from cattle. Ganskopp et al. (2007) also recognized a strong correlation between the amount of time cattle spend in close proximity to vulnerable surface water drinking sources and their potential contamination. Hence, though Bailey et al. (1996) (see Figure 5.2) defined temporal and spatial scales at very fine levels of behaviour and movement, the concern in addressing the challenge of quantifying the exposure of sensitive streams and riparian areas to grazing cattle is at the scale of movement from food patch to food patch and in daily range movement to satisfy water, shade, resting and rumination needs.

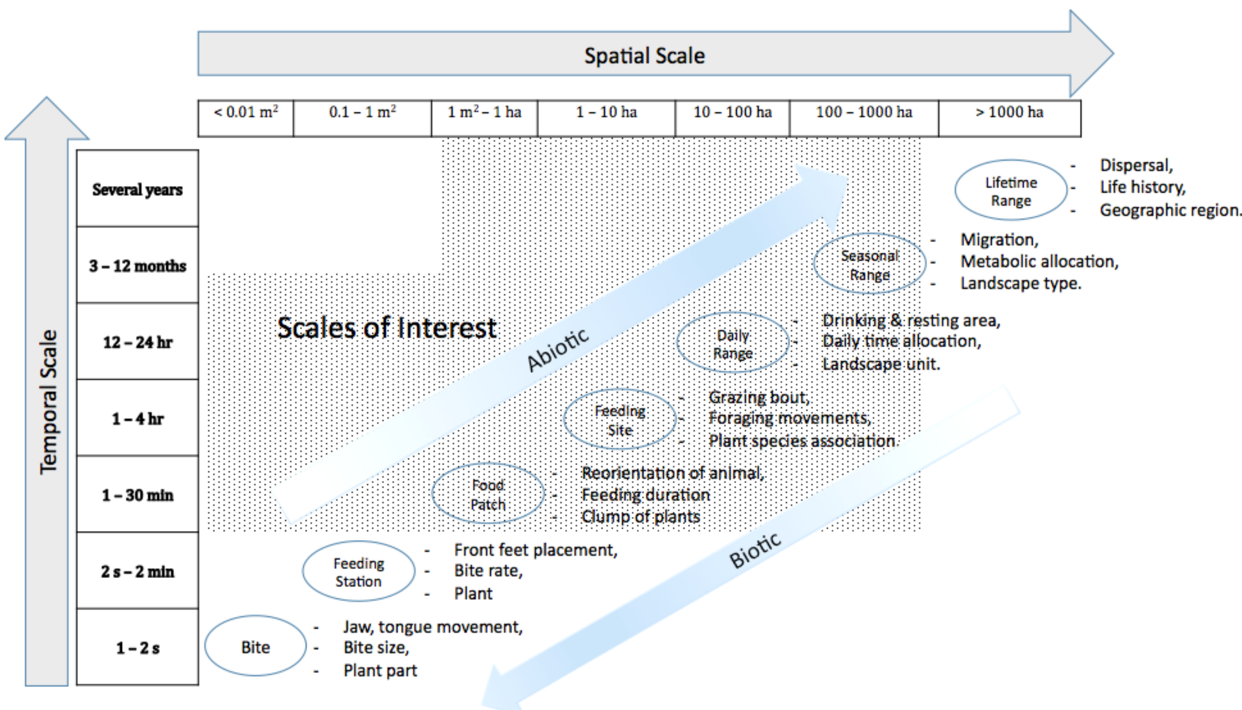


Figure 5.2 Cattle behaviour scales of interest in space and time (after Bailey et al. 1996).

At the coarsest levels, seasonal range and lifetime range, decisions about cattle movement and behaviour is a function of the permitted access to the pastures in the lease agreements and the management decisions of ranchers. Since cattle are not present in crown pastures outside of the specific periods for which the pastures are leased, they are not a threat to surface water sources other than during the lease periods, and as illustrated in Figure 5.2, this constrains the scales of interest in managing cattle movement and their impacts on water quality to those that define decisions an animal is going to make from scales of several minutes in movement from patch to patch or patch to water, rest or ruminating site within its daily routine to a scale defining its movement as constrained within the few weeks it is on pasture under the lease agreement. Understanding what happens during the daily routines of grazing cattle within these scales of behaviour and movement provides insight to their potential to contaminate surface water sources.

5.2.2 Time Allocations of Grazing Cattle Daily Routines.

The daily routine dictates where and when cattle choose to spend time during foraging bouts, retreat to for water, rest and rumination, and in shelter from sun and extreme weather conditions. This behaviour ultimately defines their potential impacts on water sources.

A primary component of grazing cattles' daily routine (24 hours) is the acquisition of sustenance in the form of forages. This usually consumes 7 to 12 hours of an animal's day and takes place in bouts. Extensive research has been done on grazing cattle feeding bouts (Bailey et al., 2008, Lyons et al., 2000, Gregorini et al., 2006) with consistent results:

- They are typically four hours in length and focused on feed patches and sites.
- A typical day usually consists of two major foraging bouts, and two minor bouts.
- The first major bout takes place in the morning and usually begins just before or at sunrise (3 – 4 am) and lasts from three to five hours.
- The second major bout typically takes place in the late afternoon (6 pm) and lasts for three hours.
- Two minor bouts of one to two hours often occur during the mid-day (noon) and during the night (midnight to 2 am).
- Major bouts are usually followed by periods of rest and rumination.
- Cattle adjust their foraging bouts with daylength.
- During mid-day, cattle can be expected to seek out water as well.

- During a foraging bout, cattle may visit diverse feeding sites to meet their nutritional requirements.
- The amount of time cattle can expect to forage varies depending on available forage and ambient temperature, ideally 15 to 25°C (National Research Council 2000).

The drivers for foraging behaviour in bouts are not fully understood yet (Gregorini et al. 2006). The current theory is the behaviour is a result of evolved defensive mechanisms against predation. Foraging ideally takes place in open meadows but it also distracts cattle (and other ruminants) from paying attention to what is happening in their environment, including the presence of potential predators. As a protective measure, cattle have evolved a strategy that quickly 'loads up' the rumen so they can then retreat to less open ground for mastication during rumination. For rumination and rest, cattle are also driven to seek out sites on the terrain that help them regulate their temperature via shade, however if bothered by pests, they may show a preference for open spaces.

5.2.3 Implications of Cattle Behaviour on Potential Contamination of Vulnerable Streams.

In reviewing the literature again, what is noteworthy in the context of all the previous research done on cattle the implication is that within the period they are on a given pasture for a period of time as defined by the lease from the province, their behaviour does not contain them to one particular site or area of the pasture. They are free to roam according to the behaviour as described in the literature to satisfy their needs. Hence when consideration is given to all streams and waterbodies in all pastures in community watershed, a possible explanation for why field results (Chapter 3) are revealing lower concentrations than might be expected is that over the course of time in the pasture, cattle have the opportunity to use areas of the pasture where streams exist that are not vulnerable to contamination of surface water for drinking purposes directly above drinking water intakes. Hence, examining the vulnerable stream length and riparian areas that cattle have access relative to total stream and lakefront that cattle have access to satisfy water requirements might correlate with the incidence rate of cryptosporidiosis in a LHA.

Table 5.2 provides a summary by watershed and LHA the length of stream in each watershed within active pastures potentially hazardous to human health. A total of 103 crown pastures present in 18 watersheds have been identified as potentially hazardous due to the location of grazing cattle access on vulnerable streams.

Table 5.2 Cattle presence in study area relative to sampling sites and pastures.

Local Health Reporting Area (LHA)	Community Watershed	Vuln. Stream (m)	Non-Vuln. Stream (m)	Lake shore (m)	Total Non-vuln. (m)	Total (m)	% Vuln.
Armstrong-Spallumcheen	Fortune	9376	142	173	315	9692	97
	Glanzier	2456	14	383	397	2853	86
	Meighan	2791			0	2791	100
Subtotal		14623	156	556	712	15336	95
Central Okanagan	Hydraulic	51686	38784	15673	54457	106143	49
	Kelowna	34757	27370	21953	49323	84081	41
	Lambly	152973	10078	16491	26569	179543	85
	Mission	375556	64518	44900	109418	484974	77
	Oyama	12982	9992	16121	26113	39095	33
	Peachland	78779	8521	12289	20810	99589	79
	Powers	63691	20546	25295	45841	109532	58
	Trepanier	35737	22902	10357	33258	68996	52
	Vernon	8026	8277	16146	24423	32448	25
Subtotal		814188	210988	179225	390213	1204401	68
Penticton	Penticton	8100	23563	14210	37774	45874	18
	Shingle	32132		175	175	32307	99
Subtotal		40232	23563	14385	37948	78181	51
Vernon	B.X.	4834			0	4834	100
	Duteau	34468	29466	81035	110501	144969	24
Subtotal		39302	29466	81035	110501	149803	26
Princeton	Dillard	25247	1875	5688	7563	32810	77
Summerland	Trout	392598	33605	53835	87440	480038	82
other	other watersheds	9	1482796	381026	1863822	1863831	0.1
Total		1326199	1782449	715750	2498199	3824398	35

Vulnerable stream reaches have been previously defined as those immediately above the drinking water intake in a watershed upstream to the first lake that provides a barrier for oocyst transportation due to sedimentation. Streams above these lakes have been deemed non-vulnerable. Shore line has also been deemed non-vulnerable in all instances as a result of the BMP verification study (Chapter 3) and the literature (Chapter 2).

In reviewing the results of Table 5.2, it is initially noteworthy that a total of 3824 kms. exists between stream length and lakeshore in pastures within community watersheds from which cattle can access water or potentially contaminate water by direct defecation. Of this 3824 kms, only 1326 kms (35%) is vulnerable within the Okanagan HSDA. This implies on a whole that over 65% of the time, their contact might be with surface water sources of low concern for *C. parvum* oocyst contamination.

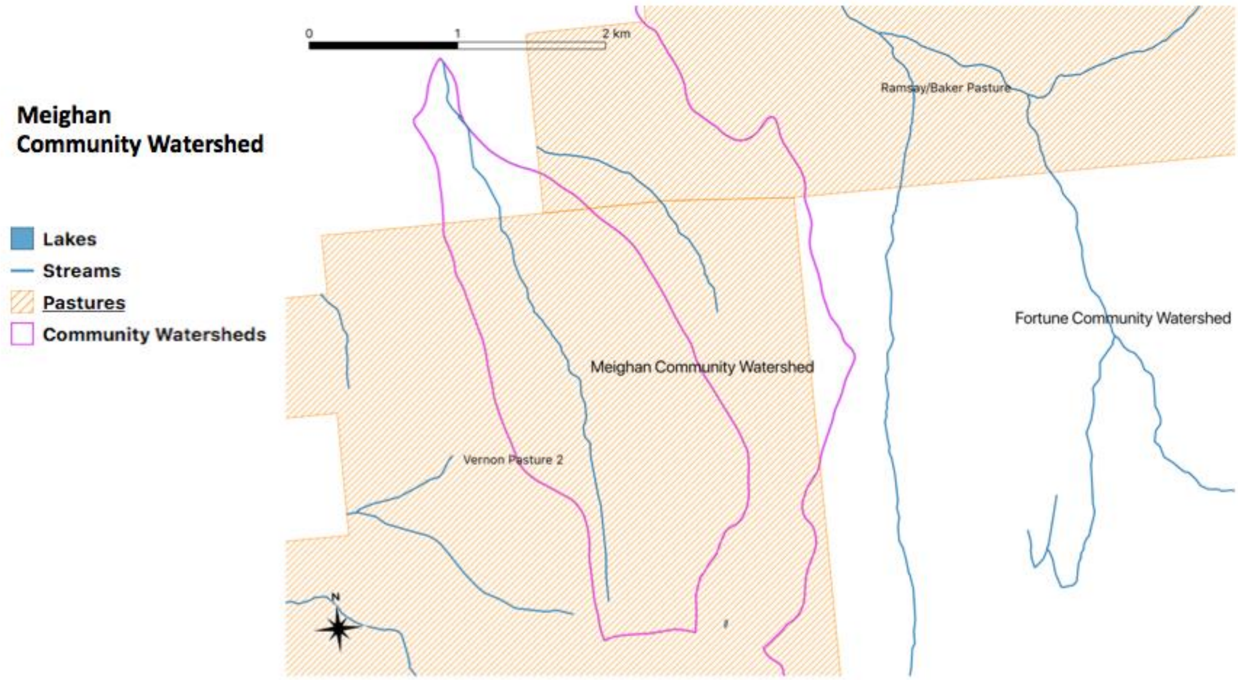


Figure 5.3 Meighan Community Watershed, Pastures, and Streams

On a watershed by watershed basis, vulnerability ranges from 18% (Penticton) to 100% (Meighan and BX), and on an LHA, however, in a number of instances this does not fully reveal the actual situation. Figure 5.3 illustrates the situation with Meighan Community Watershed. In this instance, the complete stream network within the watershed and pasture is vulnerable, but Vernon Pasture 2 extends well beyond the watershed and has other streams and water resources available within it, including a small lake. Vernon Pasture 2 also overlaps with Fortune Community Watershed as well. The resulting overlap of stream networks, community watersheds, pastures, and Local Health Reporting Authorities (LHAs) effectively renders the incidence of cryptosporidiosis within any given LHA a function of a portfolio of stream and lake shore exposed to cattle both within community watersheds in vulnerable areas and outside of the those areas. Alternatively, it may also be a function of the land areas within each watershed and each pasture available to cattle, and finally a function of the stream length from drinking water system intakes to the pastures overlaying community watersheds. In this chapter, each of these relationships will be explored with the available BCCDC data and BC government GIS data to determine if these relationships impacts the frequency of reported incidences of cryptosporidiosis within the LHAs of the Okanagan HSDa.

5.3 Methods

To analyze the first relationship, all stream segments from the province's stream centre-line network within the Okanagan HSDA have been analyzed using QGIS intersections to classify each section of each reach for the following;

1. Residence within a lake.
2. The community watershed and crown pasture within which each resides.
3. Whether the stream segment is vulnerable for contaminating water upstream of a drinking water intake.
4. The length of each resulting stream segment from all intersections.
5. The length of lake shore within each watershed and pasture.
6. The LHA within which each watershed's drinking water intake exists.

In the instance that a stream segment falls outside of a watershed and/or pasture, the segment is flagged as being in an 'other watershed' or 'other pasture'. The resulting attribute table was transferred to a relational database in Microsoft Access. Stream lengths and lake shore line lengths were then summarized across watersheds and LHAs. The length of vulnerable stream as a portion of total stream length and shoreline within each LHA was then calculated. Figure 5.4 illustrates the categorization of stream segments within the Oyama Community Watershed as an example.

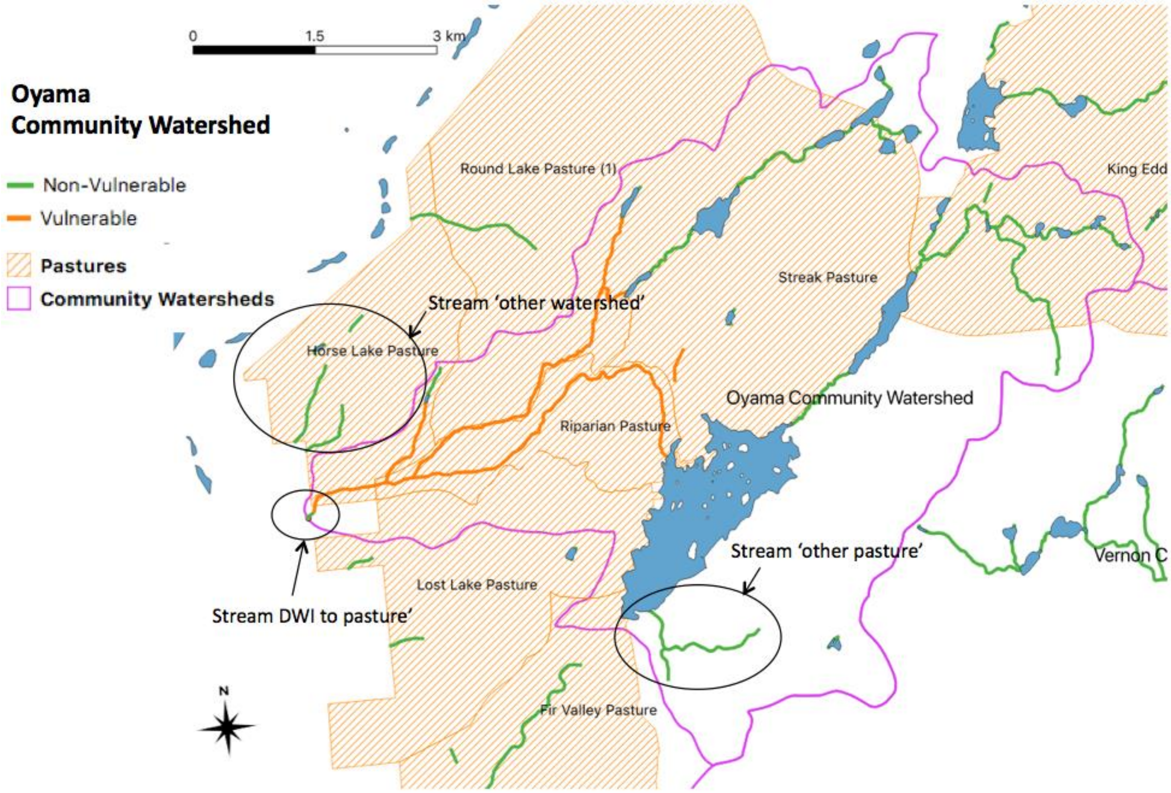


Figure 5.4 Oyama Community Watershed and stream segment classification.

Finally, the results were joined with the incidence data provided by BCCDC and the population estimates for each year and LHA as estimated in Chapter 4. The results of the join were then imported into R for analysis using a binomial regression. The first model to test was:

$$\text{Incidences/Population} = \alpha + \beta P + \varepsilon$$

Where:

α = the background incidences of cryptosporidiosis in LHA.

P = the proportion of stream length within an LHA in pastures exposed to grazing cattle within an LHA.

B = an estimate of the slope of the relationship between the proportion of stream exposure to grazing cattle and the incidence rate of cryptosporidiosis.

As previously discussed, this P is defined as:

$P = SL\_vul/(SL\_tot+LS)$ where:

SL_vul is the length of vulnerable stream in pastures within the LHA.

SL_tot is the length of all streams in pastures within the LHA, and

LS is the length of lakeshore within pastures within the LHA.

The second model to test considers the area of pastures within a watershed. A question to consider is whether the background level constant of Cryptosporidium in a watershed is constant, or do other animals that shed oocysts get crowded out by the presence of cattle? If cows are crowding out other animals, then maybe the relevant comparison is related to that crowding out.

In this model the share of time spent by a cow within a pasture is calculated as a proportion of the area in a pasture within a watershed (P_shed) relative to the entire area of the pasture (P_tot). Furthermore, the model assumes that there is some contribution to the background that comes from the length of vulnerable stream above the intake and below the lowest pasture boundary. Upstream of the pasture boundary, it is assumed that the sources of this background contamination are crowded out by cows, so that there is a different contribution in that part of the watershed where cows access the stream. This results in the following model to test:

$$\text{Incidence/population} = \alpha + \text{NoCows} * (1 - \text{SL\_vul\_past} / \text{SL\_vul}) * \text{SL\_vul}$$
$$+ \text{Cows} * (\text{SL\_vul\_past} / \text{SL\_past}) * (\text{PA\_shed} / \text{PA\_tot}) * \text{SL\_vul} + \varepsilon$$

Where:

NoCows = the probability of a cow not being present along a vulnerable stream.

Cows = the probability of a cow being present along a vulnerable stream.

SL_tot = total length of all streams in the watershed.

SL_past = total length of streams in a pasture in a watershed

PA_tot = total pasture area

PA_shed = pasture area in watershed

SL_vul = vulnerable length of streams in the watershed

SL_vul_past = vulnerable length of streams in a watershed that are in a pasture

SL_vul_past / SL_vul = share of vulnerable stream where pasture (cows) crowd out whatever other source of pathogens may be there

(SL_vul_past / SL_past) * (PA_shed / PA_tot) = probability a random cow in the pasture is going to drink from the vulnerable part of a stream in the watershed.

Pastures areas were calculated using QGIS and added to the MS Access database to summarize by watershed and LHA and then joined with the BCCDC incident data and population estimates from Chapter 4. The binomial regression was then performed using R.

5.4 Results & Discussion

As discussed, both models were analyzed using a binomial regression in R with the annual rates of cryptosporidiosis as the dependent variable. The dataset spanned ten years across nine LHAs for a total of 90 observations. In the case of three LHAs (Enderby, Keremeos, and Southern Okanagan), water systems were not exposed to source water from vulnerable streams in community watersheds with pastures for cattle grazing, and yet incidences of cryptosporidiosis were still reported. These potentially represent the incidence of baseline cases of cryptosporidiosis in the Okanagan HSDA if cattle were not present in any of the watersheds being surface sourced for drinking water.

5.4.1 Incidences as a Function of Vulnerable Stream Presence.

Table 5.3 summarizes the results of the first regression analyzing the impact of proportion of stream exposure within a crown pasture relative to all available stream and lakeshore (VulnPortion) for cattle to access within a pasture. The results indicate with strong siginificance that there is a nonzero background incidence of cryptosporidiosis in the Okanagan HSDA, but what is equally significant is negative slope of the relationship between the occurrence rate of cryptosporidiosis in the Okanagan HSDA and the exposure of vulnerable streams to grazing cattle. In other words, in the lack of other explanations, increasing exposure of vulnerable streams in a community watershed to grazing cattle actually seems to lower the incidence of cryptosporidiosis in the human population served by the watershed.

Table 5.3 Influence of Stream Exposure to Grazing Cattle on Incidences of Cryptosporidiosis

Stat.	Intercept	VulnPortion
Est.	10.2899	-1.9462
Std. Error	0.1924	0.4748
z-value	-53.475	-4.099
Pr(>|z|)	< 2e-16 ***	4.15e-05 ***
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1		

5.4.2 Incidences as a Function of Stream Lengths and Pasture Areas.

Table 5.4 summarizes the results of the second regression analyzing the impact of proportion of stream exposure within a crown pasture relative to all available stream and lakeshore (VulnPortion) for cattle to access within a pasture, and the area of pasture within and outside the bounds of a watershed. Other than again supporting with strong significance that there is a background incidence of cryptosporidiosis within the Okanagan HSDA, the results imdicated no significant relationship between the amount of pasture and streams within in a pasture within a watershed relative to pasture and streams accessible to cattle outside a watershed.

Table 5.4 Influence of Stream Exposure to Grazing Cattle on Incidences of Cryptosporidiosis

Stat.	Intercept	NoCows	Cows
Est.	-1.062e+01	-3.526e-06	7.583e-06
Std. Error	2.579e-01	8.569e-06	5.279e-06
z-value	-41.187	-0.412	-1.436
Pr(>|z|)	<2e-16 ***	0.681	0.151
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1			

5.5 Summary

The results of the analysis of available stream and pasture resources available in a community watersheds in the Okanagan HSDA indicate that counterintuitively, the presence of cattle on pasture in sensitive areas of a community watershed that are surface sourced for drinking water actually decreases the potential for cryptosporidiosis in the human population served by the watershed. There are three possible explanations that might warrant further investigation and/or confound these results.

1. In reviewing the provincial statistics on reported cases of cryptosporidiosis by year and Health Services Area, the Vancouver HSDA reported among the highest rate of incidences. This is despite there being allowed no anthropogenic access to the watersheds that supply Vancouver’s water system, including the ability for ranchers to place cattle on them. Hence this suggests the incidence of cryptosporidiosis in the human population is resulting from other sources, possibly from result travel to locations outside BC where water safety and quality is not assured, and the same may be occurring within the human population of the Okanagan HSDA.
2. A second factor that might explain why the increased presence of cattle reduces incidences of cryptosporidiosis is that cattle may be displacing wildlife and other sources of

Cryptosporidium within a community watershed that are more likely to be carriers of *C.parvum*.

Finally, another potentially confounding factor might be best described as watershed stewardship by ranchers. As discussed in Chapter 1, ranching on crown pastures within community watersheds has a significant history behind it and hence the ranching industry has a stake in managing and providing strong and responsible stewardship to protect its social licence with the public that ultimately own the land and have need for other resources from the land base, including drinking water. In watersheds without grazing cattle, there are no real substitutes for the ranchers that provide this service to the same level.

Chapter 6.0 Major Findings, Conclusions, Limitations, and Recommendations.

6.1 Review of Objectives

In the summer of 2010, the District of Lake Country noted spikes in faecal coliforms at their drinking water intakes in the Vernon Creek and Oyama Creek community watersheds. As briefly discussed in Chapter 1, the Forest Practices Board (FPB) of BC responded by conducting an audit of forestry and range activities in the two watersheds providing water to the District of Lake Country municipal water systems. Faeces samples collected near North Fork Creek in the Oyama Community Watershed tested positive *Cryptosporidium*, however it was not speciated to determine whether it was *C. parvum*, *C. andersoni* or another type.

As discussed in Chapter 1 and Chapter 2, there is a history of cryptosporidiosis outbreaks and incidents which has created a perception by public health professionals, water purveyors, and members of the general public that the presence of grazing cattle in watersheds sourced for community drinking water systems is linked to these outbreaks. In response to this perception, FLNRORD in partnership with local cattle ranching operations initiated a pilot project employing BMPs as a means to mitigate this potential threat to human health.

The original purpose of the research for this thesis was to explore the effectiveness of BMPs to mitigate the perceived threat that grazing cattle presented to water quality and safety, but as the research evolved, so did the purpose of this thesis to one challenging the very perception that grazing cattle in community watersheds in the interior of BC is truly a potential hazard to human health and if so, the need for formal management interventions including BMPs to mitigate the hazard and their effectiveness. Therefore, the major objectives of this research evolved to:

1. Review the current literature on the state of grazing cattle as a potential source of Cryptosporidium contamination problematic to human health.
2. Validate to the effectiveness of the six BMPs employed in the pilot study in four community watersheds in the BC interior.
3. Determine the relationship between the presence of cattle and BMPs in community watersheds in the Okanagan HSDA and the reported incidence of cryptosporidiosis.

4. Determine the relationship between the exposure of vulnerable streams and pastures in community watersheds to grazing cattle as a predictor of the incidence of cryptosporidiosis in human populations served by the watersheds.

6.2 Summary of Major Findings

In conducting the research necessary to achieve these objectives, a number of findings and conclusions were reached with respect to the relationship between grazing cattle and community drinking water systems and the populations they served.

1. The literature (Chapter 2) has verified that cattle can be a significant source of *Cryptosporidium* in the environment, but they are only one potential source and there are potential over 30 different species of *Cryptosporidium* that might be found in the natural environment being shed by not only cattle, but a range of other fauna within a community watershed. Cattle themselves are primarily responsible for shedding two species of *Cryptosporidium*, *andersoni* and *parvum* but it is more so dairy cattle and cattle in concentrated feeding operations which might be problematic due to chains of infection. In contrast, with beef cattle it is predominantly during spring calving that they are a potentially problematic source of *Cryptosporidium parvum*, and it is young calves less than 3 months of age that shed *C.parvum* which can be a hazard to human health whereas older animals tend to shed *C.andersoni* which is seldom a problem to humans.
2. The literature also showed that in the context of the leases of crown pasture land in BC's interior community watersheds that there is the potential for calves from beef cattle operations to contaminate surface water sources to a concentration of *C.parvum* oocysts sufficient to infect human populations. However, the literature also revealed that with the proposed and piloted BMPs, contamination could be sufficiently mitigated to negate cryptosporidiosis in human populations served by BC's interior watersheds where cattle also graze.
3. In the BMP verification study (Chapter 3), field samples of water, faeces, and sediments revealed that the incidence of *Cryptosporidium* oocysts in community watersheds in the BC interior is extremely low to non-existent. When detected, concentration of *Cryptosporidium* oocysts were found to be at least 3 to 4 orders of magnitude below what literature suggested might be expected.

4. Furthermore, of all field samples testing positive for the presence of *Cryptosporidium* oocysts in the field study, none were subsequently sequenced and identified to be *C. parvum*. All successfully sequenced oocysts were identified as *C. andersoni*, which are usually excreted by more mature animals. This evidence suggests that the normal management practice within the beef industry in BC to complete their calving operations by the end of the month of March each year may in itself mitigate the hazard posed by the presence of grazing cattle in community watersheds. This practice is driven by incentives that reward ranchers for uniformity of calves when marketed, good management for herd health, and assures calves are less subject to predation when they are turned onto rangeland. The reason for the hazard to drinking water being mitigated is that calves born by the end of March are very likely to have passed the period during which they are most likely to shed *C. parvum* into the environment in their faeces.
5. The one exceptional finding from the BMP verification study (Chapter 3) is the failing of the controlled access to water BMP ('nose hole'). As implemented, the nose hole provides a poor example of BMP location and also exemplifies the problem with pasture fencing in close proximity to sensitive surface water features in heavily forested areas where they can become preferred corridors for cattle resulting in their potential to aggravate the hazard that grazing cattle defecation can pose to water sources and human health. In addition to concentrating cattle into a sensitive riparian area, the forest cover can inhibit the penetration of UV light which deactivates *Cryptosporidium* oocysts and moderated temperatures under shade also contribute to the persistence of viable *Cryptosporidium* oocysts.
6. The field study also revealed some evidence that there are other potential sources of *Cryptosporidium* in Okanagan watersheds that may contribute to the cause of disease in a human population. This is the result of samples testing positive for *Cryptosporidium* from an area which did not contain cattle during the study. These samples were not successfully sequenced, indicating a mixture of *Cryptosporidium* species potentially present.
7. Of the four other BMPs being tested, the results suggest that due to its ubiquity in the study area, fencing to limit the ability of cattle to access sensitive areas is effective. Likewise stubble height management in key management areas such as meadow with vulnerable streams also proved effective. With respect to off-stream watering and silvo-pasture as an alternative source of forage to attract cattle to high locations in a watershed away from

vulnerable streams, it was not possible to collect enough field data to draw definitive conclusions with respect to these two BMPs.

8. It was also found in the BMP verification study (Chapter 3) that there exists no discernable relationship between the presence of *Cryptosporidium* oocysts in water, faecal and sediment samples, and *E.coli*. In other words, the presence and concentration or lack of presence of *E.coli* in water samples is not an indicator of the presence and/or concentration of *Cryptosporidium* in water.
9. In reviewing the relationship between reported incidences of cryptosporidiosis in LHAs within the Okanagan HSDA and watersheds that contribute to the water supplies within those LHAs (Chapter 4), it was found that there is no evidence of higher rates of incidences LHAs where cattle are in community watersheds. As a matter of fact, it seems those LHAs experience lower rates of incidence. In examining the relationship between LHAs where BMPs are employed versus those where BMPs are not employed, there appears to be some evidence that the BMPs do moderate the incidence of cryptosporidiosis, but without statistical significance.
10. In Chapter 5, two relationships were explored between the incidence rates of cryptosporidiosis in LHAs and community watersheds. In the first instance, the rate of reported incidences were explored as a function of the proportion of the length of stream vulnerable to the hazard in community watersheds within LHA relative to all the streams and lakeshore in the watersheds that cattle may have access to. Contrary to what might be expected, it was found with very strong statistical significance that as the proportion of vulnerable stream increased, the rate of rate of reported incidences of cryptosporidiosis declined. In the second instance, the rate of reported incidences of cryptosporidiosis was explored as a function of the proportion of crown pasture land overlapping a community watershed relative to the total crown pasture available. No statistically significant correlation was found. In both instances, a strong statistically significant background incidence of cryptosporidiosis was found to be present whether or not community watersheds in LHA were exposed to the grazing cattle.

6.2 Conclusions and Discussion

The primary and overarching conclusion after reviewing the literature, findings of the field samples taken in the BMP pilot project study area, complementary research on *C. parvum* persistence (Story et al. 2016), and analysis of BCCDC cryptosporidiosis incidences in the BC interior is that grazing cattle presence on crown lease pastures in community watersheds in the province of British Columbia is not a threat to human health, at least in regards to *C. parvum*. Historical incidences both globally and locally may contribute to the public perception that they are a threat, but evidence does not support this perception given the geography and current practices within the BC beef cattle industry and the constraints placed on the industry within the contexts of crown pasture leasing agreements.

The primary factor contributing to this overarching conclusion is timing of access to crown pasture by young calves. Since current market conditions for weaned calves provides incentives for cattle ranchers to complete calving each year by the end of March and also encourages them to hold back ill and/or smaller calves from access to crown pasture to prevent their loss from disease and/or predation, there is a very low probability of infectious cattle being on crown pasture in the first place.

However, the maturity of calves by the time they are allowed on crown pastures does not seem to be the only factor in mitigating the hazard they pose to surface water sources. The statistically strong relationship vulnerable stream exposure to grazing cattle, and the mitigation of cryptosporidiosis incidents suggests that there is an interaction between the intensity of use of crown pastures containing these vulnerable streams and potentially the management of these pastures. As discussed in Chapter 1, cattle ranching has taken place for many decades within the community watersheds of the BC interior. Leases for each of the crown pastures with land in community watersheds are often renewed with the same cattle ranching operation repeatedly for decades. To assure the success of their operations, cattle ranchers regularly survey what is happening within their cattle while on crown pastures. FLNRORD meet with them on an annual basis prior to the grazing season to discuss the state of the watersheds and operations taking place within them over the coming year. The cattle ranchers both need access to crown pastures as a valuable resource for their operations, and understand the necessity of good stewardship of the resources within these pastures to sustain the social licence they have with those downstream of their operations and with FLNRORD. As noted in the annual pre-grazing season meetings, the cattle ranchers are the best eyes and ears to other uses and mis-uses of the resources in the watershed.

One of the primary outcomes of the research on which this thesis is based is that FLNRORD has moved on to investigating other activities of concern to water quality and safety. In particular, they have subsequently engaged UBC Okanagan researchers to explore the impacts of off highway vehicles for recreational purposes and their impacts on water quality and safety. In contrast to cattle ranchers with their long history and ongoing use of crown pastures in community watersheds, recreational users tend to often not be resident to the Okanagan or BC, and are transitory in their use of BC's interior watersheds for their activities. They are usually only here for a few days each year, and may explore other regions in BC and beyond for their activities, potential limiting their concern for the impacts of their activities. They are also never directly present in pre-grazing season meetings attended by not only cattle ranchers but other stakeholders with historical and ongoing interests in good stewardship of these publicly owned resources.

Alternatively, cattle are not the only potential source of *Cryptosporidium* oocysts in the natural environment of BC's interior watersheds. Wildlife present in these watersheds are also a potential source. Is it possible that the presence of cattle displaces wildlife that might pose this hazard? It should be considered as discussed that by the time cattle are allowed on crown pastures, there is a very low probability of them shedding *Cryptosporidium* oocysts, whereas wildlife such as deer and other ruminants are present in the watershed even during peak periods of shedding. It might also be that the presence of cattle ranchers accompanying their livestock might dissuade other species problematic for shedding *Cryptosporidium* to remain resident.

6.3 Limitations to Findings and Conclusions.

Just because grazing cattle do not currently pose a threat to human health by contaminating drinking water sources with *C.parvum* does not mean that the may not pose a threat to human health in the future under different circumstances. The findings and the conclusions of this thesis are based on the following limitations:

1. The market for weaned calves from BC cattle operations continues to provide incentives that encourage ranchers to breed their cattle such that calving ends by the end of March each year, and that calving operations continue to be restricted to privately held property by ranching operations not within immediate vicinity of vulnerable streams.

2. That there continues to be an atmosphere of on-going dialogue and mutual respect among all stakeholders in a community watershed to assure the safety and quality of surface water sources within a watershed.
3. That the current state of the community watersheds and pastures continues to reflect the GIS and other data provided by the government of BC. Natural processes such as the annual spring freshet can in extreme instances alter the course of streams within a watershed, and do significant damage to infrastructure such as fences. Anthropogenic activities such as logging and silvo-pasture, and recreational activities such as the use of off-highway vehicles (OHVs) can also impact the landscape within community watersheds and pastures.
4. The limitations of the data provided by the BCCDC. These reported incidences do not necessarily reflect the actual incidence of cryptosporidiosis within the Okanagan HSDA. A number of these incidences may have resulted from travel experiences where infection resulted from drinking water not subject to Canadian guidelines, or conversely a number of incidences may have not been reported to health authorities. In the case of rural residents that work with cattle, immunity may have developed to the point that cryptosporidiosis infection may have also become asymptomatic.

6.4 Further Research Recommendations

The research conducted in the completion of this thesis was sufficient to lead to several high level findings and an overarching conclusion with respect to the threat posed by grazing cattle in community watersheds as a potential source of *Cryptosporidium parvum* problematic to human health, but it does leave several unanswered questions.

1. The data provided by the BCCDC control indicated that there were incidences of cryptosporidiosis reported in LHAs in the Okanagan HSDA in which the water supplies were not exposed to grazing cattle in crown pastures in the community watersheds providing the residents with water. This raises the question of the sources of these incidents. Unfortunately, the data collected by the BCCDC incident reporting system is extremely limited. In the absence of more specific data, there are several alternatives to cattle that might be deemed of benefit to shedding light on these occurrences and might be worth research:
    a. Is it possible these incidents are the result of wildlife defecating in sensitive streams in community watersheds? The four watersheds used in the BMP pilot study all

contained cattle. Ideally, future research would incorporate at least one community watershed without the presence of cattle for water sampling and analysis. Ideally this would take the form of a paired watershed study in which one watershed has cattle and the other doesn't and with as many other factors controlled as possible, for example the length of stream vulnerable to cattle and wildlife and the make up of land cover within the two watersheds. Detected *Cryptosporidium* oocysts from wildlife could then be enumerated as the background or baseline for comparison with watersheds with cattle and with BMPs being tested.

   b. Is it possible that these incidences are the result recent travel events by residents of the Okanagan to locations not subject to Health Canada drinking water guidelines and treatment recommendations? This would require that the BCCDC incident reporting system be upgraded to collect more information in the future to ascertain whether recent travel beyond the Okanagan and BC is a plausible means by which a person has become ill with cryptosporidiosis.
   c. Another check to be performed is the incidence of cryptosporidiosis in cattle, especially calves at the time of tune out onto crown pastures. Previous studies in western Canadian cattle herd were performed in advance of turn out onto summer range, but what is the actual incidence at that time?

2. What role does governance and stakeholder engagement and collaboration play in assuring the sustainable and safe use of resources in a community watershed? Could further work be done by social scientists to determine the extent to which stakeholder ownership of potential adverse outcomes to both themselves (e.g. loss of grazing privileges) or other stakeholders (e.g. cryptosporidiosis incidents and outbreaks) affect due care in the management and use of publicly held resources to mitigate and prevent these outcomes?

6.5 Concluding Note and Reflection.

The specific concern that gave genesis to the research documented within this thesis was the threat that grazing cattle potentially posed a hazard to human health by defecating into surface water sources for drinking water. The overarching conclusion is that grazing cattle in community watersheds is not a concern to human health, and that other activities may be of greater concern. This thesis has given light to some of the reasons that might be so, but it possibly also gives rise to a greater explanation and lesson to the sustainable management of both water and other resources in general, and that is importance of stakeholder engagement, recognition, and involvement in providing stewardship to assure long-term sustainability. As evidenced prior to the research upon which this thesis is based, cattle ranchers, FLNRORD, health officials, and water purveyors have participated in annual meetings to discuss the state of the resources in community watersheds and changes to their management. It is this dialogue among engaged stakeholders, and their commitment to working together as they did in the BMP pilot study that may be the best management practice of all in assuring the continued, safe, and wise use of these resources.

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Appendix A – BC Provincial Datasets.

The government of BC collects, organizes, and maintains a diverse set of spatial and non-spatial datasets. Many of these datasets are available for public use and research through BC Geographic Data and Services (BCGDS n.d.). In conducting the research within this thesis, a number of spatial datasets were downloaded and used as for analytical, mapping, and communications purposes.

1. Crown Range Pastures (https://catalogue.data.gov.bc.ca/dataset/range-pastures).
2. Community Watersheds (https://catalogue.data.gov.bc.ca/dataset/community-watersheds-current).
3. Municipal Boundaries (https://catalogue.data.gov.bc.ca/dataset/municipalities-legally-defined-administrative-areas-of-bc).
4. Health Authority Boundaries (https://catalogue.data.gov.bc.ca/dataset/health-authority-boundaries).
5. Health Service Delivery Area Boundaries (https://catalogue.data.gov.bc.ca/dataset/health-service-delivery-area-boundaries).
6. Vegetation Resources Inventory (https://catalogue.data.gov.bc.ca/dataset/vri-forest-vegetation-composite-polygons-and-layer-1/resource/8fb918dc-2546-4eba-8bd5-a1823a24b813).
7. Stream centre line network (https://catalogue.data.gov.bc.ca/dataset/wsa-stream-centreline-network-50-000).
8. Points of Diversion (BC Water Licences Query: http://a100.gov.bc.ca/pub/wtrwhse/water_licences.input).

Appendix B – GIS Landscape Development Methods.

B.1 Triangulated Irregular Network Development

Slope and aspect have been identified as important factors in grazing cattle behaviour with cattle showing preferences for south facing slopes while limiting their activities and willing to travel across slopes as they become steeper. To model these attributes, a Triangulated Irregular Network (TIN) surface was developed from the provincial 25 m. gridded Digital Elevation Model (DEM) (see Appendix A). Since the landscape within close proximity to critically vulnerable riparian areas is of greatest interest, the model was developed with a much higher degree of detail near these areas than for land at greater distance from them.

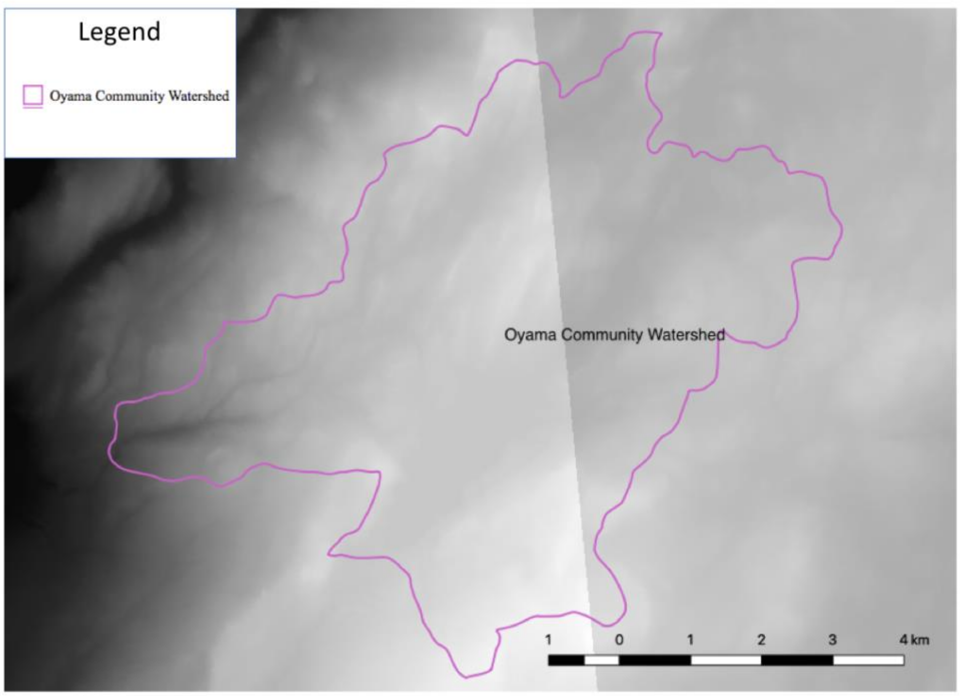

Figure B.1 Digital Elevation Model (Oyama Community Watershed).

In the first step of the process, contour line datasets were extracted from the DEM at 10, 30, 60, 90, and 120 m of elevation change (Figure B.2). All critically vulnerable streams were also identified from the provincial stream centre-line network.

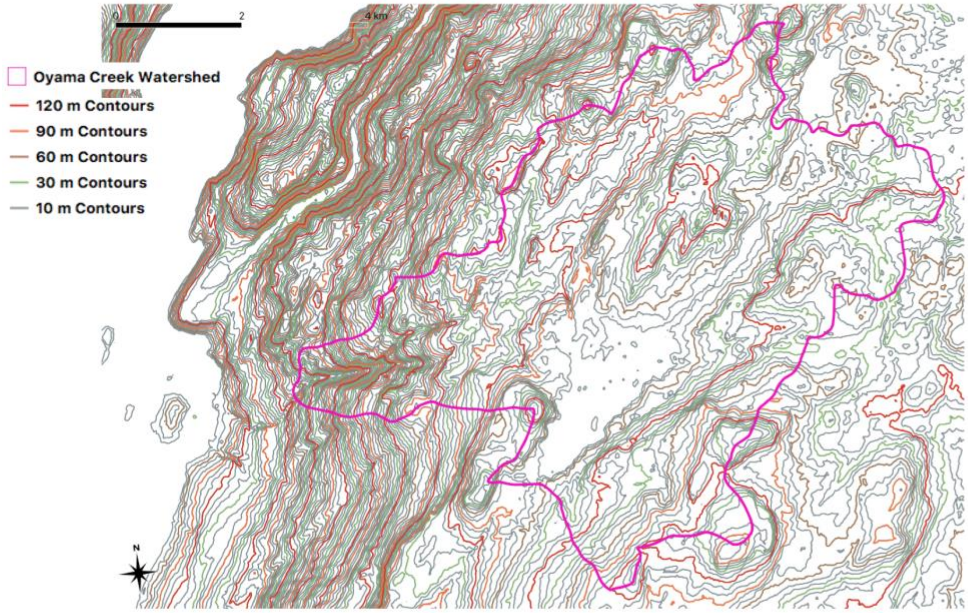

Figure B.2 Contour lines extracted from the DEM.

The stream centre-line dataset was used to develop a stream polygon dataset. Consistent with the assumptions in Section 4.3.4 based on field operations, in the case of all named streams within the provincial dataset, a 5 m buffer was applied to effectively create a 10 m wide stream. In the instance of streams without a gazetted name in the provincial dataset, a 1 m buffer was created to effectively create a 2 m wide stream.

Buffers were created at 120, 240, 480, and 960 m from the banks of critically vulnerable streams (Figure B.3 and B.4). The contour lines were then clipped using these buffers such that the 10 m contours were clipped with the 120 m buffer, the 30 m contours with the difference between the 120 m and 240 m buffers, the 60 m contours between the 240 m and 480 m buffers, the 90 m contour lines between the 480 m and the 960 m buffers. Finally, all remaining land was clipped with the 120 m contours. The clipped contours were then merged into a mixed interval contour dataset.

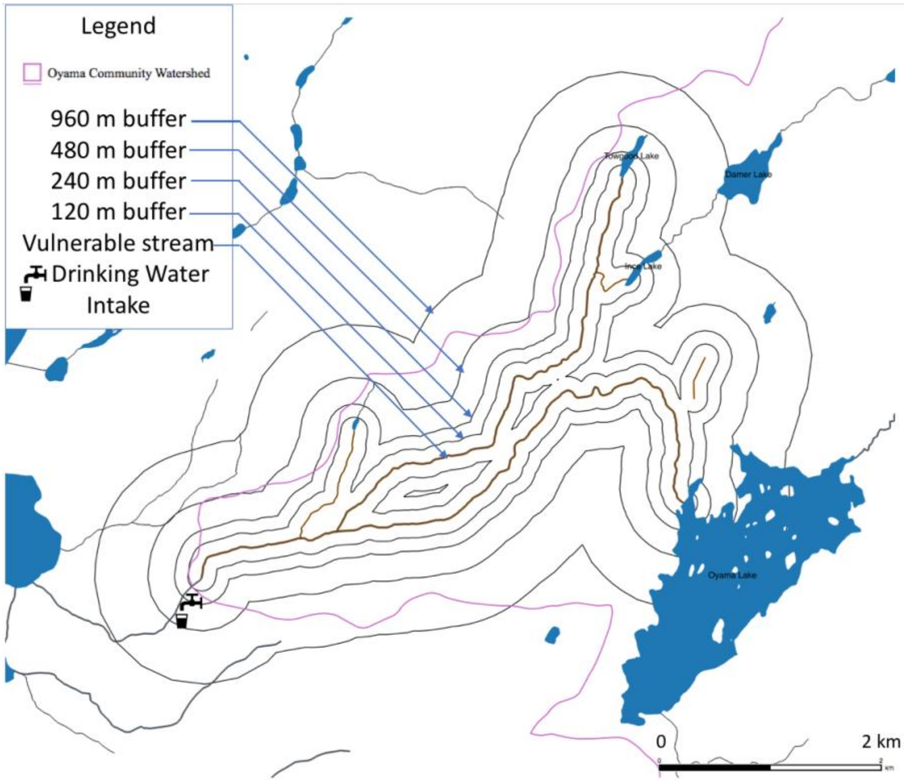

Figure B.3 Buffer zones for mixed-interval contours dataset.

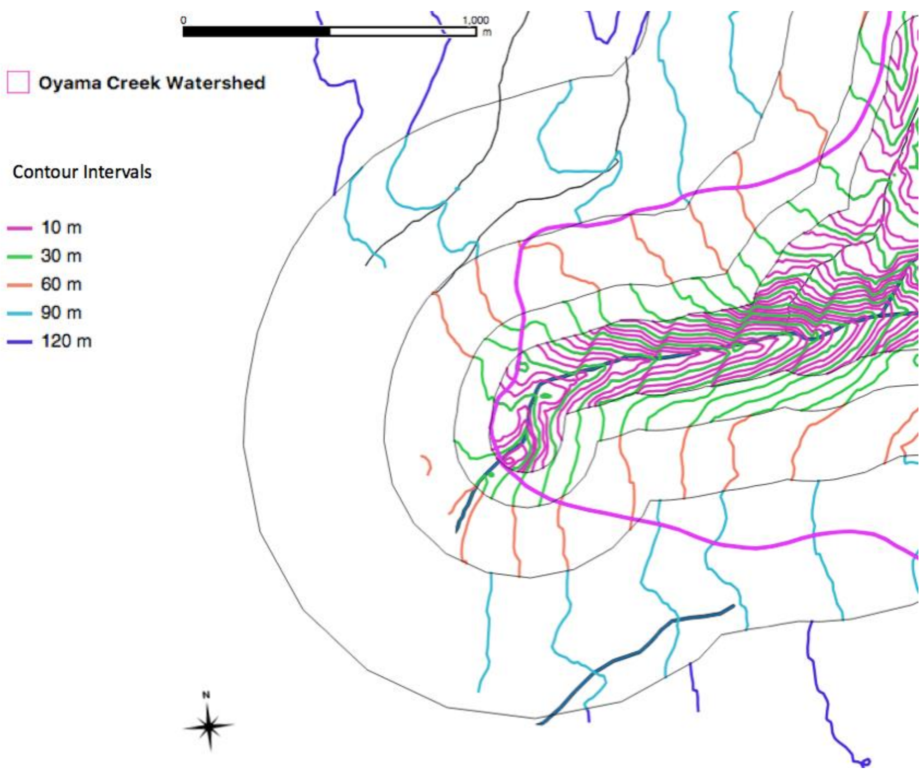

Figure B.4 Contours clipped by buffer zones.

The mixed interval contour dataset was then combined with the stream polygon dataset, the provincial lakes and water bodies dataset, and the watershed boundaries to create a TIN surface with ArcGIS. All stream polygons, lakes and water bodies, and watershed boundaries were set as hard edges in the creation of the TIN. The resulting surface was then converted to a triangle polygon layer with the slope calculated as percent grade and aspect as degrees clockwise from true north for each polygon. These were stored as attributes of the triangle polygon layer and classified as per figures B.5 and B.6 respectively. Subsequently, both calculated slopes and aspects were also classified.

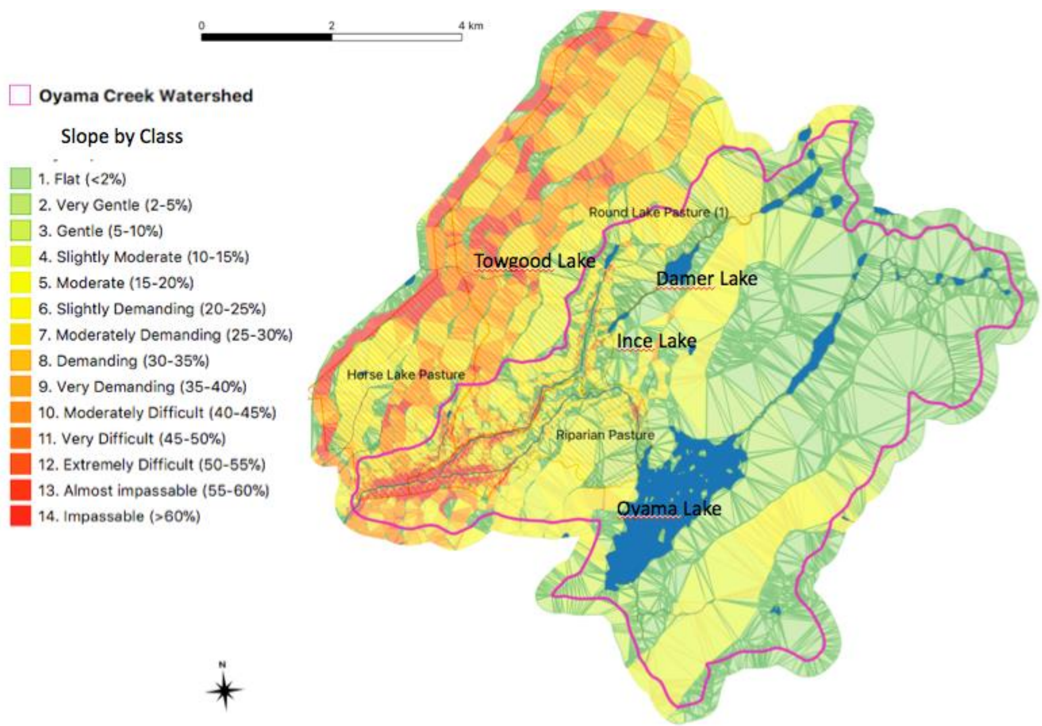

Figure B.5 Slope classification for Oyama Creek watershed and pastures.

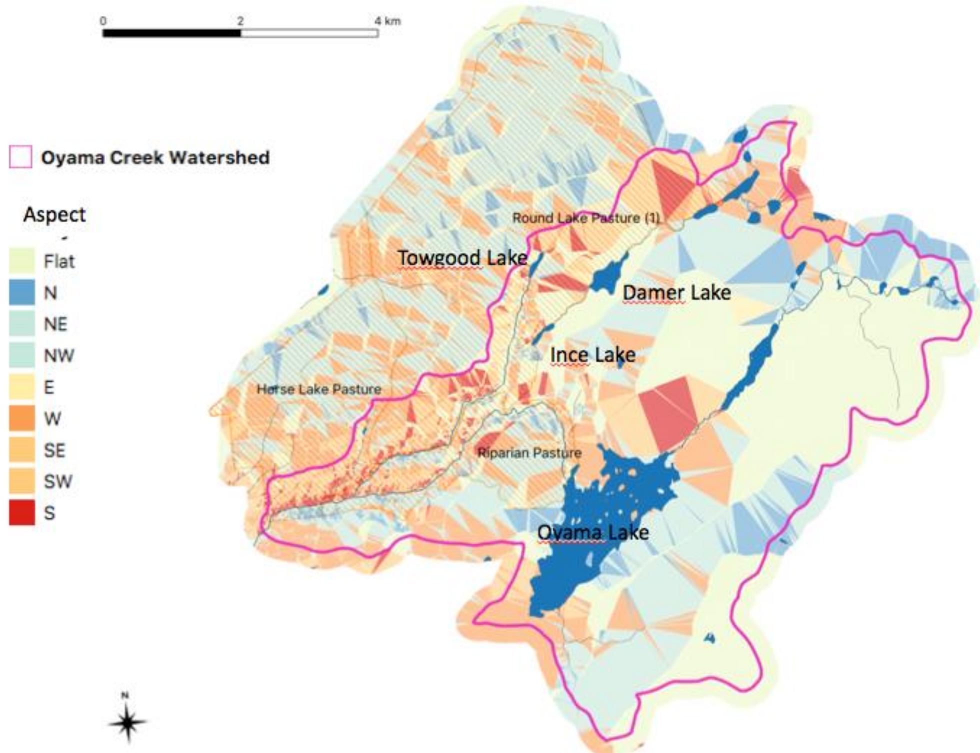

Figure B.6 Aspect classification for Oyama Creek watershed and pastures.

Appendix C – BMP Verification Study Results.

C.1 Vernon Creek Community Watershed

Vernon Creek Community Watershed (*Cryptosporidium* oocysts/litre)				
Date	**Sampling Site (see Figure 3.3)**			
	Swalwell Lake Outflow	**Tributary 1**	**Tributary 3**	**Vernon Creek Intake**
2013-09-23		1.1	17.1	
2013-10-21	0	0.4	10	0.7
2014-08-12	0		0	0
2014-08-19	0		0.5	0
2014-10-07	0	0.2		0
2014-10-21	0.4			0

C.2 Oyama Creek Community Watershed

Oyama Creek Community Watershed (Cryptosporidium oocysts/litre)						
Date	Sampling Site (see Figure 3.4)					
	Oyama Lake Outflow	Damer Lake Outflow	Above Nosehole	Nosehole	Below Nosehole	Oyama Creek Intake
2013-08-22	0.2	0.6	0.8	0.7		0.4
2013-10-28			11.9			12.9
2014-07-29	0	0		2		0.5
2014-08-19	0.6	0.1	0		0.8	0
2014-09-10		0	0.3		0	0.5
2014-10-07		0	0.8	0.3		0
2014-10-15						
2014-10-21						1.6

C.3 King Edward (Deer Creek) Community Watershed

King Edward Community Watershed (*Cryptosporidium* oocysts/litre)		
Date	Sampling Site (see Figure 3.5)	
	King Edward Lake Outflow	Meadow Outlet
2013-07-17	0	0
2014-07-29	0	1.1
2014-09-10	0	0

C.4 Duteau Creek Community Watershed

Duteau Creek Community Watershed (*Cryptosporidium* oocysts/litre)						
Date	Sampling Site (see Figure 3.6)					
	Haddo Lake Outflow	Upper Crescent Creek	Lower Crescent Creek	13 km Tributary	Haddo Bridge	Duteau Creek Intake
2013-09-18	0.4	0.1	0.4		0	
2013-09-30		3.2				
2013-10-21	0	6.3	10.6			
2013-10-28					3	
2014-08-05	0.3		0.6		1.3	0.6
2014-08-26	0		0		0	0
2014-09-02	0				0	0
2014-09-16			1.7			
2014-09-30	0		0			0.5
2014-10-14	0				0	0
2015-05-05			0	0		
2015-05-19	0	3	0	0.4		0.6
2015-06-02	0	1.7	0.6	1.6		0
2015-06-16	0	0.3	0	0		0
2015-06-30	0.6	4	0.2	0		1.3
2015-07-28			0			0
2015-08-25	0		0			0
2015-09-08	0		0			0
2015-09-29	0		0			0
2015-10-13			0			0

Duteau Creek Community Watershed (*E.coli/100 ml.*)						
Date	Sampling Site (see Figure 3.6)					
	Haddo Lake Outflow	Upper Crescent Creek	Lower Crescent Creek	13 km Tributary	Haddo Bridge	Duteau Creek Intake
2014-09-16			0			
2014-09-30	0		0			0
2014-10-14	0				22.5	0.69
2015-05-05		0	0	0		0
2015-05-19	0	0	0	0		0
2015-06-02	0.15	3	1.48	4.74		1.51
2015-06-16	0.26	0.28	0.16	0.56		15.72
2015-06-30	169.1	52.13	1.24	47.9		22.54
2015-07-28			21.92			16.4
2015-08-25	0.58					0.85

Appendix D: Current Status and Exposed Populations (2016) to Community Watersheds with Crown Pastures

CWID#	WATERSHED	AREA (ha)	POD	Population	Status
D.1 Health Services Delivery Area: East Kootenay					
	Local Health Reporting Area: Cranbrook				
61	Joseph Community Watershed	5812.8	PD230	19319	In service
309	Gold Community Watershed	9326.2	PD234	19319	Diverted (Joseph Community Watershed)
	Local Health Reporting Area: Creston				
214	Sanca Community Watershed	10879.4	PD263	0	Borderline pasture only
356	La France Community Watershed	5583.6	PD258	0	Borderline pasture only
414	Lockhart Community Watershed	3735.3	PD258	0	Borderline pasture only
426	Russell Community Watershed (2)	2350.2	PD728	0	Borderline pasture only
461	Floyd Community Watershed	1782.5	PD261	0	Borderline pasture only
	Local Health Reporting Area: Fernie				
224	Boivin Community Watershed	5864.0	PD233	0	Abandoned - alternate source
311	Miller Creek Community Watershed	730.5	PD239	10	In service
312	Reserve Community Watershed	1077.4	PD234	0	Abandoned - alternate source
324	Fairy Community Watershed	2369.5	PD561	0	Abandoned - alternate source
391	Boardman Community Watershed	215.1	PD235	0	Borderline pasture only
445	Cummings Community Watershed	12287.2	PD237	0	Abandoned - alternate source
	Local Health Reporting Area: Kimberley				
13	Kimberley Community Watershed	1019.5	PD231	0	Abandoned - alternate source
154	Matthew Community Watershed	15359.9	PD231	0	Lake intake
416	Mark Community Watershed	11201.1	PD654	0	Lake intake
	Local Health Reporting Area: Windermere				
64	Luxor Community Watershed	9287.6	PD244	0	Abandoned - alternate source
109	Madias Community Watershed	2434.6	PD248	0	Abandoned - alternate source
110	Abel Community Watershed	3489.3	PD247	2955	Lake intake
129	Dry Gulch Community Watershed	447.7	PD245	0	Borderline pasture only
185	Tatley Community Watershed	1913.6	PD248	0	Abandoned - alternate source

CWID#	WATERSHED	AREA (ha)	POD	Population	Status
189	Palmer Community Watershed	339.7	PD245	0	Borderline pasture only
319	Sophy Community Watershed	890.2	PD247	0	Abandoned - alternate source
383	Taynton Community Watershed	1454.9	PD249	0	Borderline pasture only
390	Forster Community Watershed	16616.4	PD242	777	In service
431	Cold Spring Community Watershed	975.2	PD240	0	Abandoned - alternate source
432	Pye Community Watershed	18.6	PD240	0	Lake intake

D.2 Health Services Delivery Area: Kootenay Boundary

Local Health Reporting Area: Grand Forks

139	Moody Community Watershed	2039.1	PD549	0	Lake intake
168	Sutherland Community Watershed	9185.8	PD549	0	Abandoned - alternate source
328	Overton Community Watershed	371.9	PD556	0	Abandoned - alternate source

Local Health Reporting Area: Kettle Valley

44	Skiing Brook Community Watershed	121.9	PD559	0	No cattle
177	Affleck Community Watershed	372.7	PD563	0	Integrated
178	McKinney Community Watershed	813.5	PD543	0	Abandoned - alternate source
182	Trapping Creek Community	37.5	PD559	0	No cattle
183	Brides Community Watershed	279.4	PD558	0	Abandoned - alternate source

D.3 Health Services Delivery Area: North Shore/Coast Garibaldi

Local Health Reporting Area: Howe Sound

291	D'Arcy Community Watershed	837.4	PD478	0	Abandoned - alternate source

Local Health Reporting Area: Lillooet

290	Mellott Creek Community	547.0	PD470	0	Seasonal (bottled water)

Local Health Reporting Area: Armstrong-Spallumcheen

3	Fortune Community Watershed	4276.6	PD593	500	In service
118	Meighan Community Watershed	389.5	PD616	45	In service
119	Glanzier Community Watershed	849.5	PD602	130	In service
393	Maid Community Watershed	486.3	PD571	0	Abandoned - alternate source
394	Kendry Community Watershed	429.5	PD602	0	Abandoned - alternate source

CWID#	WATERSHED	AREA (ha)	POD	Population	Status

D.4 Health Services Delivery Area: Okanagan

Local Health Reporting Area: Armstrong-Spallumcheen

CWID#	WATERSHED	AREA (ha)	POD	Population	Status
3	Fortune Community Watershed	4276.6	PD593	500	In service
118	Meighan Community Watershed	389.5	PD616	45	In service
119	Glanzier Community Watershed	849.5	PD602	130	In service
393	Maid Community Watershed	486.3	PD571	0	Abandoned - alternate source
394	Kendry Community Watershed	429.5	PD602	0	Abandoned - alternate source

Local Health Reporting Area: Central Okanagan

CWID#	WATERSHED	AREA (ha)	POD	Population	Status
12	Hope Community Watershed	153.1	PD593	0	Abandoned - alternate source
26	Kelowna Community Watershed	7656.6	PD581	18000	In service
56	Oyama Community Watershed	4222.6	PD582	1782	In service
73	Mission Community Watershed	60152.5	PD572	22500	In service
85	Vernon Community Watershed	8567.9	PD586	4000	In service
120	KLO Community Watershed	4973.8	PD575	0	Diverted (Hydraulic Community Watershed)
153	Norris Community Watershed	170.0	PD593	0	Abandoned - alternate source
163	Pooley Community Watershed	1868.6	PD582	0	Diverted (Hydraulic Community Watershed)
204	Hydraulic Community Watershed	9379.3	PD573	6000	Integrated
246	Lambly Community Watershed	22411.9	PD591	11000	In service
247	Peachland Community Watershed	12470.3	PD586	2600	In service
352	Powers Community Watershed	13596.3	PD588	13000	In service
377	Trepanier Community Watershed	23436.8	PD587	2080	In service

Local Health Reporting Area: Enderby

CWID#	WATERSHED	AREA (ha)	POD	Population	Status
403	Brash Community Watershed	3093.0	PD600	0	Abandoned - alternate source

Local Health Reporting Area: Keremeos

CWID#	WATERSHED	AREA (ha)	POD	Population	Status
47	Olalla Community Watershed	2665.7	PD568	0	Abandoned - alternate source
423	Keremeos Community Watershed	121.1	PD563	0	Abandoned - alternate source

Local Health Reporting Area: Penticton

CWID#	WATERSHED	AREA (ha)	POD	Population	Status
15	Farleigh Community Watershed	2154.1	PD548	0	Abandoned - alternate source
89	Shingle Community Watershed	4559.9	PD549	501	In service
98	Chute Community Watershed	1888.8	PD555	0	Diverted (Robinson Creek Watershed)
99	Robinson Community Watershed	1941.6	PD553	0	Abandoned - alternate source
161	Ellis Community Watershed	15291.8	PD545	0	Abandoned - alternate source
364	Penticton Community Watershed	17391.5	PD547	35000	In service
365	Naramata Community Watershed	3386.6	PD549	0	Abandoned - alternate source

CWID#	WATERSHED	AREA (ha)	POD	Population	Status

Local Health Reporting Area: Princeton

140	Dillard Community Watershed	3872.5	PD567	384	In service
166	Thomas Community Watershed	44.3	PD565	0	Abandoned - alternate source
242	Anderson Community Watershed	274.8	PD569	0	Abandoned - alternate source
271	Lee Community Watershed	464.9	PD566	0	Abandoned - alternate source
466	Hackett Community Watershed	163.6	PD569	0	Abandoned - alternate source

Local Health Reporting Area: Southern Okanagan

60	Rancher Community Watershed	443.6	PD539	0	Abandoned - alternate source

Local Health Reporting Area: Summerland

251	Trout Community Watershed	71616.1	PD547	12000	In service

Local Health Reporting Area: Vernon

55	Coldstream Community Watershed	6679.6	PD579	0	Abandoned - alternate source
68	Duteau Community Watershed	21275.4	PD576	53000	In service
86	King Edward (Deer) Community	2030.9	PD580	0	Abandoned - alternate source
194	B.X. Community Watershed	7077.7	PD598	0	Integrated
443	Irish Community Watershed	865.0	PD592	0	Abandoned - alternate source

CWID#	WATERSHED	AREA (ha)	POD	Population	Status

D.5 Health Services Delivery Area: Thompson Cariboo Shuswap

Local Health Reporting Area: Cariboo-Chilcotin

83	Weetman Community Watershed	359.3	PD401	0	Abandoned - alternate source

Local Health Reporting Area: Central Okanagan

357	Alocin Community Watershed	387.5	PD504	0	Abandoned - alternate source

Local Health Reporting Area: Kamloops

4	Tranquille Community Watershed	43758.5	PD528	0	Abandoned - alternate source
25	Paul Lake Community Watershed	15164.2	PD519	0	Lake intake
27	Nelson Community Watershed	1200.3	PD486	3	In service
58	Rosen Community Watershed	279.5	PD486	7	In service
66	Hudson Community Watershed	438.2	PD490	0	Abandoned - alternate source
74	Leonie Community Watershed	3010.4	PD486	0	Abandoned - alternate source
106	Toops Community Watershed	3.3	PD482	49	In service
121	Peterson Community Watershed	8200.7	PD486	52.5	In service
132	Kruly Community Watershed	385.1	PD698	0	Boil water advisory
150	Currie Community Watershed	17.7	PD653	35	In service
219	Corning Community Watershed	3061.8	PD708	0	Cattle grazing discontinued.
261	Anglemont Community Watershed	132.6	PD528	300	In service
292	Skowootum Community Watershed	1110.3	PD486	0	Abandoned - alternate source
430	Bass Community Watershed	258.3	PD529	668.5	In service
457	Paul Community Watershed	12459.7	PD517	0	Abandoned - alternate source

Local Health Reporting Area: Lillooet

45	Countless Community Watershed	66.4	PD478	0	Abandoned - alternate source
152	Fountain Community Watershed	7410.0	PD472	0	Abandoned - alternate source
167	Omin Community Watershed	187.4	PD471	0	Abandoned - alternate source
187	President Community Watershed	111.6	PD478	0	Abandoned - alternate source
252	Fergusson Community Watershed	3228.2	PD476	0	Abandoned - alternate source
385	Blackbird Community Watershed	28.8	PD478	0	Abandoned - alternate source

Local Health Reporting Area: Merritt

133	Skuagam Community Watershed	452.3	PD533	0	Cattle grazing discontinued.
134	Kwinshatin Community Watershed	2726.5	PD532	0	Cattle grazing discontinued.
209	Brook Community Watershed	3009.5	PD535	0	Cattle grazing discontinued.

CWID#	WATERSHED	AREA (ha)	POD	Population	Status
	Local Health Reporting Area: North Thompson				
262	Hascheak Community Watershed	654.8	PD512	0	Abandoned - alternate source
293	McDougall Community Watershed	1601.3	PD512	0	Abandoned - alternate source
326	Russell Community Watershed (1)	1768.7	PD512	2400	In service
369	Avola Community Watershed	307.0	PD514	0	Abandoned - alternate source
	Local Health Reporting Area: Salmon Arm				
67	Bastion Community Watershed	1134.6	PD528	100	In service
141	East Canoe Community Watershed	1988.3	PD492	2100	Cattle grazing discontinued.
208	Wiseman Community Watershed	529.3	PD528	0	Abandoned - alternate source
272	Wade Community Watershed	8.2	PD498	0	Abandoned - alternate source
353	Silver Community Watershed	1739.3	PD500	100	In service
374	Hobson Community Watershed	322.6	PD496	0	Abandoned - alternate source
399	White Cliff Community Watershed	223.6	PD493	0	Abandoned - alternate source
400	Gordon Community Watershed	2013.1	PD498	0	Abandoned - alternate source
449	Newsome Community Watershed	1810.2	PD504	0	Abandoned - alternate source
458	Sicamous Community Watershed	6487.1	PD633	0	Abandoned - alternate source
	Local Health Reporting Area: South Cariboo				
116	Nikaia Community Watershed	2063.2	PD478	0	Abandoned - alternate source
186	Jimmies Community Watershed	1358.4	PD457	0	Abandoned - alternate source
302	Murray Community Watershed	14945.4	PD457	0	Abandoned - alternate source
435	Intlpam Community Watershed	5698.4	PD480	0	Abandoned - alternate source
438	Cornwall Community Watershed	6150.7	PD472	0	Abandoned - alternate source

Appendix E: BC Population Estimates by Local Health Reporting Area (Okanagan Health Services Delivery Area)

Year	Age: 0 -10 years	Age: 11-64 years	Age: 65-99+ years	Total
E.1: Local Health Reporting Area: Armstrong – Spallumcheen LHA#: 21				
2005	1071	6803	1553	9427
2006	1034	6643	1599	9276
2007	1040	6678	1629	9347
2008	1047	6852	1729	9628
2009	1067	7022	1807	9896
2010	1054	7057	1854	9965
2011	1108	6938	1937	9983
2012	1105	6946	2036	10087
2013	1108	6829	2125	10062
2014	1120	6734	2247	10101
2015	1222	6684	2278	10184
2016	1224	6521	2319	10064
E.2: Local Health Reporting Area: Central Okanagan LHA#: 23				
2005	17579	115415	30067	163061
2006	17740	118834	30657	167231
2007	17807	123096	31615	172518
2008	18317	127321	32595	178233
2009	18583	129906	33372	181861
2010	18989	129493	33409	181891
2011	18741	130153	34287	183181
2012	18802	130741	35447	184990
2013	18666	130793	36617	186076
2014	18703	133195	37855	189753
2015	18719	135671	39205	193595
2016	19019	137045	40618	196682

Year	Age: 0 -10 years	Age: 11-64 years	Age: 65-99+ years	Total

E.3: Local Health Reporting Area: Enderby LHA#: 78

2005	786	5149	1325	7260
2006	788	5205	1366	7359
2007	819	5208	1391	7418
2008	837	5149	1398	7384
2009	795	5164	1462	7421
2010	808	5101	1480	7389
2011	775	5039	1517	7331
2012	766	4963	1563	7292
2013	791	4905	1639	7335
2014	827	4851	1677	7355
2015	806	4716	1651	7173
2016	831	4593	1650	7074

E.4: Local Health Reporting Area: Keremeos LHA#: 16

2005	493	3052	1331	4876
2006	478	3055	1374	4907
2007	515	3024	1429	4968
2008	519	3100	1499	5118
2009	521	3165	1503	5189
2010	488	3207	1432	5127
2011	456	3127	1524	5107
2012	437	3052	1580	5069
2013	401	3012	1650	5063
2014	399	3010	1747	5156
2015	392	2960	1797	5149
2016	374	2853	1864	5091

Year	Age: 0 -10 years	Age: 11-64 years	Age: 65-99+ years	Total

E.5: Local Health Reporting Area: Penticton LHA#: 15

2005	3723	25622	9798	39143
2006	3741	26956	9832	40529
2007	3682	27285	9962	40929
2008	3675	27542	10020	41237
2009	3677	27913	10112	41702
2010	3692	27701	10046	41439
2011	3666	27833	10351	41850
2012	3669	27864	10684	42217
2013	3591	27481	10907	41979
2014	3515	27707	11350	42572
2015	3422	27023	11479	41924
2016	3319	26360	11614	41293

E.6: Local Health Reporting Area: Princeton LHA#: 17

2005	430	3373	1082	4885
2006	409	3321	1168	4898
2007	361	3328	1075	4764
2008	352	3228	1072	4652
2009	331	3139	1082	4552
2010	314	3160	1119	4593
2011	313	2968	1235	4516
2012	301	2917	1311	4529
2013	301	2845	1375	4521
2014	326	2786	1449	4561
2015	349	2716	1500	4565
2016	337	2664	1534	4535

Year	Age: 0 -10 years	Age: 11-64 years	Age: 65-99+ years	Total

E.7: Local Health Reporting Area: Southern Okanagan LHA#: 14

2005	1610	11533	5461	18604
2006	1557	11574	5534	18665
2007	1548	11576	5704	18828
2008	1572	11689	5806	19067
2009	1537	11836	5933	19306
2010	1490	11486	5834	18810
2011	1386	11304	5926	18616
2012	1347	11085	6079	18511
2013	1263	10816	6398	18477
2014	1232	10565	6600	18397
2015	1246	10294	6831	18371
2016	1232	10123	6858	18213

E.8: Local Health Reporting Area: Summerland LHA#: 77

2005	1068	7476	2809	11353
2006	1028	7482	2830	11340
2007	1068	7581	2873	11522
2008	1073	7734	2939	11746
2009	1088	7897	2973	11958
2010	1043	7754	2995	11792
2011	1060	7702	3128	11890
2012	990	7519	3180	11689
2013	944	7412	3263	11619
2014	978	7362	3361	11701
2015	1017	7332	3447	11796
2016	1034	7287	3563	11884

Year	Age: 0 -10 years	Age: 11-64 years	Age: 65-99+ years	Total

E.9: Local Health Reporting Area: Vernon LHA#: 22

Year	Age: 0 -10 years	Age: 11-64 years	Age: 65-99+ years	Total
2005	6710	42848	11456	61014
2006	6751	43618	11808	62177
2007	6619	44180	12197	62996
2008	6689	44952	12573	64214
2009	6743	45452	12984	65179
2010	6755	44882	13188	64825
2011	6677	44858	13547	65082
2012	6649	44397	14098	65144
2013	6576	44086	14639	65301
2014	6593	44267	15393	66253
2015	6656	44786	16071	67513
2016	6829	44615	16588	68032