Understanding the risk of unpaved roads on drinking water treatability by assessing sediment erosion across Canada

by

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Abstract

Forest harvesting, wildfire suppression, energy resource exploration, and recreation all require unpaved roads. As a result, many roads in drinking watersheds are potential sources of fine (<63 μm) sediment. Erosion of fine sediment threatens drinking water treatability as can be a source of increased nutrients and sediment, creating issues in reservoirs and treatment infrastructure. However, there is a lack of research regarding sediment yields and erosion models on unpaved roads in Canada. The objectives of this study were 1) to understand the variability and predominant factors that contribute to increased road erosion risk in Canadian drinking watersheds, 2) evaluate the Forest and Range Evaluation Program (FREP) used to categorize risk, 3) evaluate erosion and runoff dynamics from representative unpaved roads and trails within the Ghost and Elbow River Watershed, near Calgary, Alberta, and 4) to validate the runoff and sediment production predictions of the Road Erosion and Delivery Index (READI) model using UAV data and rainfall simulations on the representative road segments.

The first two objectives were addressed in chapter 2 with 107 site surveys and 22 small-plot (1.5m^2) rainfall simulations. Unpaved road erosion risk was influenced by road surface conditions, road slope, and traffic. Furthermore, traffic and poor road surface conditions increased fine sediment yields. Risk was found to be highest in the Montane Cordillera which had poor road surfacing conditions, steep slopes, and high traffic. Rainfall simulations and the FREP model could not be directly compared because of sediment yield units, but when plot sediment yields were ranked from lest to highest sediment there was a positive linear relationship.

The final 2 objectives were addressed in chapter 3 with 6 site surveys, 6 large (60-150m^2) and small rainfall (1.5m^2) simulations, and 5 UAV flights. Site surveys gave insight to road construction, road sweep samples provided details on available sediment, runoff and erosion rates were assessed from the rainfall simulations, and UAV flights produced digital surface models that gave an understanding to road roughness. Rainfall simulations showed that large and small plots preferentially (>70%) eroded fine particles. The rainfall simulations erosion rates followed three patterns: a steady-state of erosion, an increasing rate of erosion, and a decreasing rate of erosion. Similarly, runoff followed three patterns; a gradual increase to a steady state, increase with no steady state, and a steady state throughout the simulation. Runoff started at different time intervals based on scale; large-scale experiments started between 8-16 minutes and small simulations started between 2-4 minutes. Lastly, the READI model did not accurately predict time-to-concentrations or sediment yields compared to rainfall simulations, expect when site specific roughness values from digital surface models and erosivity (K) values were applied.

The assessment of road erosion is valuable for understanding the impacts of road management practices on water quality. In Canada, sediment yields predominantly consists of particles ≤ 63 μm which poses a larger threat to drinking water treatability. Results showed fine sediment yields are related to traffic volume and road surface conditions. The Forest and Range Evaluation Program (FREP) and Road Erosion and Drainage Index (READI) models are tools to understand road erosion risk. These models assist in assessing sediment yields, providing useful insights for road managers. The appropriate method depends on the objectives and the available information to effectively address road erosion challenges.

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Chapter 1 : Introduction

Forestry management, oil and gas development, and recreational activities all require unpaved roads in forested watersheds. However, roads can cause sedimentation in nearby water bodies and managers have adopted best management practices (BMP) to minimize the potential of sedimentation. These practices include reduced road slope and segment lengths, and special road surface treatments when roads are in close proximity to water bodies (Macdonald & Coe, 2008; Vaidya et al., 2008). These practices can reduce surface erosion from unpaved road surfaces and disconnected road networks from streams, thus reducing sediment reaching streams. However, sediment contamination of surface drinking water remains a considerable concern for water quality and treatability (Emelko et al., 2011, 2015; Sthiannopkao et al., 2007). The sediment particles carried downstream can produce water contaminants, which may increase the cost and efficiency of water treatment processes (Holmes, 1988). If there is a change in raw water quality from streams, treatment plants must adjust the amount of chemicals used to flocculate and remove these particles, which can be time consuming and expensive (Dearmont et al., 1998).

Fine sediment is made more readily available by road maintenance and traffic, which breaks up larger particles into finer particles (Macdonald & Coe, 2008). These fine sediment particles ≤ 63 µm are of greatest concern, as they are more readily transported downstream. MacDonald & Coe (2007) showed that fine particles have a low to moderate likelihood of storage and moderate to high risk of delivery in all stream flows. These particles also carry nutrients such as phosphorus, which can impact reservoirs by influencing nutrient balance (Emelko et al., 2015; L. H. MacDonald & Coe, 2007). Many of these nutrients can promote algae growth, creating blooms and the potential for neurotoxins to be released (Emelko et al., 2015).

Sediment impacts on water quality have been observed and researched across the world. Rainfall is one major mechanism that influences sediment erosion. The attributes of precipitation including rain drop size, velocity, rainfall intensity, and wind, all greatly affect the amount of soil loss (Wischmeier & Smith, 1958). In addition to rainfall, road characteristics also influence total soil loss, including total contributing area, road slope, traffic levels, and surfacing material, which have varying impacts on sediment production (Bilby et al., 1989; Dangle et al., 2019; Lane & Sheridan, 2002; Megahan et al., 2001). Large contributing areas increase sediment yields by expanding the potential supply or source that sediment can erode from (Dangle et al., 2019). Steep slopes cause higher erosion by influencing runoff rates and providing the energy to move particles (Bilby et al., 1989). Road traffic can cause increased sediment yields by breaking down the gravel surface and creating poor road surfaces (Bilby et al., 1989; Reid & Dunne, 1984). Poor road surfaces that are not crowned properly affect fine sediment erosion and runoff rates (Bilby et al., 1989). This causes finer sediment to be eroded and runoff to pool on roads. Fine sediment (≤ 63 µm) makes up the majority (80%) of eroded sediment, which has the highest risk of sedimentation and greatest impact on water quality and treatability (Bilby et al., 1989; Lane & Sheridan, 2002; Sthiannopkao et al., 2007).

The threat of sedimentation can be reduced by limiting the connection of roads to streams. Approaches that have proven effective include vegetating cutslopes and ditches, reducing contributing areas and slope gradient, improving stream crossings, and locating roads away from streams reducing a roads proximity to watercourses. However, these latter approaches are best applied during the road planning phase. Vegetation and other organic or geotextile material reduces runoff velocity and sediment erosion rates (Bilby et al., 1989; Jordán & Martínez-Zavala, 2008; Liu et al., 2014; Sidle et al., 2004; Turton et al., 2009). One study examining cutslope and fillslope erosion, found that as vegetation on these slopes increased, soil detachment and runoff coefficients decreased (Liu et al., 2014). Older stream crossing designs can be problematic where they are steep, or direct runoff into streams because of short runoff travel distance (Sugden, 2018; Thomaz & Peretto, 2016), whereas lower slope gradients can increase infiltration, decrease runoff, and road-stream connectivity (Darboux et al., 2002; Sidle et al., 2004). As a consequence, streams with road crossings have been found to have up to 79% higher suspended sediment concentrations than streams without road crossings (Thomaz & Peretto, 2016). Similar to stream crossings, older road designs often located roads close to streams which can drain directly into water courses. Best Management Practices (BMPs) now recommend roads be built and moved, if possible, to 10 meters away from a stream (Maloney et al., 2009; Sugden, 2018) which can limit road-stream connectivity.

Erosion models can provide insight into sedimentation issues within a watershed. Generally, models can use data on road and watershed attributes to predict sediment yield. Studies have focused on evaluating erosion model performance against direct measurements of erosion such as rainfall simulations, plume surveys, sweep samples, sediment collection tanks, and road surveys (Bilby et al., 1989; Corrigan, 2017; de Vente & Poesen, 2005; Howard, 2018; Wade et al., 2012). Generally, most erosion models are either physically or empirically based. Physical models use event-based hydrological inputs to predict detailed sediment yields and delivery at various scales (Fu et al., 2010; Pandey et al., 2016). These models require a large amount of data and are favoured for watersheds with more historical data or strong field programs to obtain the data needed (Pandey et al., 2016). Alternatively, GIS can provide some input data needed for modelling sediment production, but model outputs are contingent on accurate input data. Empirical models use statistical relationships between independent and dependent variables governing erosion and are generally continuous models, meaning sediment yields are estimated from multiple rainfall events (Fu et al., 2010). These models require less data but are not as accurate as physical models (de Vente & Poesen, 2005). However, they are useful for watersheds with less background data and are more user friendly as they are generally less complicated. Depending on the application, either type of model is valid and can assist road and watershed managers when making decisions. Popular models include the Universal Soil Loss Equations and its revisions (USLE, RUSLE), the Washington Road Surface Erosion Model (WARSEM), the Watershed Erosion Prediction Project (WEPP), and the Geomorphic Road Analysis and Inventory Package (GRAIP). Additionally, new models such as the Road Erosion and Delivery Index (READI) and the Forest and Range Evaluation Program (FREP) have been developed and implemented for erosion modeling.

USLE was initially developed for agricultural purposes in the early 1950s (Fu et al., 2010), but has since been applied for various uses (Renard et al., 1991). The model predicts annual sediment yield using a function of road construction features such as slope length and steepness as well as the erosivity (Renard et al., 1991). Developments of this equation include the Revised soil loss equation (RUSLE) and Modified soil loss equation (MUSLE), and many other models use it as the base or component for analysis. USLE is an empirical method with a simple equation to estimate erosion. This method has been most popular as it is very user-friendly and does not require large amounts of data. However, this method has a range of limitations, such as not predicting sediment yield at a specific location. Also, USLE does not consider all erosion pathways such as ephemeral gully or concave surfaces, which are important erosion features and can be necessary in water quality studies (Wade et al., 2012). Gully erosion can be difficult to model as it is threedimensional and develops rapidly but is important to consider as it is a crucial sediment producing process and increases connectivity to surface water (Valentin et al., 2005).

WARSEM is an empirical model that can be considered a modification of USLE as it has similar equations (Fu et al., 2010; Jaafari et al., 2015). It predicts long term sediment delivery from roads. It can be used at large watershed scales and considers multiple road features (Jaafari et al., 2015; Sugden, 2018). WARSEM assumes roads more than 60 m away from a stream are not connected, fill-slope erosion is not significant, and road surfaces and ditches respond similarly to the same input factors (Jaafari et al., 2015). While these assumptions make the model more user-friendly, the model does not work well on roads with vegetated ditches or exposed fill-slopes that may contribute to sediment yields. This model has a lower data demand and has a maximum of 15 data inputs, which ranges based on the model's desired outcome (Fu et al., 2010). These inputs include, but are not limited to, road construction attributes (road surface material, slope, maintenance, and contributing area), annual rainfall, vegetation cover, among others (Fu et al., 2010; Sugden, 2018).

WEPP is a widely used, physically-based model that works for hillslopes or small watersheds. This model has multiple modules that can consider road construction, climate, and disturbances to predict sediment erosion and delivery (Fu et al., 2010). WEPP has a broad application range and can be used in both lumped and distributed space domains, single and continuous-time events, field to watershed scales, and accounts for hillslope sediment as well as channel sediment (Fu et al., 2010). This model has been applied to management problems from agricultural nutrient management to management of erosion from roads (Lang et al., 2017; Wade et al., 2012). The model has higher data demands, which may be challenging to obtain, requiring field measurements if data is missing. However, the WEPP: Road version does simplify some inputs (Fu et al., 2010), allowing users to select items, such as climate, which can help alleviate these high data demands.

GRAIP focuses on inventorying sediment sources within watersheds and how they connect to water bodies. GRAIP’s primary purposes are to 1) inventory watersheds to predict the locations of high road erosion, and 2) serve as a monitoring tool to examine the potential consequences of upgrades and changes to the configuration of road networks (Cissel et al., 2012). The model subdivides roads into road segments and defines their contributing features such as ditches, and classifies road conditions that promote concentrated runoff (Cabrera et al., 2015; Cissel et al., 2012). To do this, the model combines field inventory procedures with GIS analysis to predict sediment yields and delivery (Elliot et al., 2010). This physically-based model has high data demands, but the model can use estimated inputs from road inventories. However, using an inventory can produce less accurate results, making field derived data more desirable.

Many of these models incorporate some form of remote sensing data to collect or visual data. However, new erosion model, the Road Erosion and Delivery Index (READI) model, is an ArcGIS based model that uses a version of the kinematic wave formula to predict erosion and its delivery to streams (Benda et al., 2019). This model uses GIS and Digital Elevation Models (DEM) to estimate runoff, erosion rates, and sediment delivery. It can operate in both data-rich and data-limited environments as it has default values for missing inputs. The model analyzes roads to create hydrologically distinct segments that can be classified by their erosion and delivery yields (Benda et al., 2019). READI also enables users to identify and evaluate road segments that deliver runoff to stream networks so road drainage systems can be updated to reduce delivery. Lastly, READI enables evaluating the comparative control by watershed topography, soil infiltration, road, and stream characteristics and disturbances on the magnitude of sediment yield and delivery to determine road maintenance and upgrade requirements (Benda et al., 2019). The model first estimates peak sediment runoff times (referred to as time-to-concentration (tcr)) using rainfall intensity, contributing area, slopes, and Manning's roughness coefficient (Benda et al., 2019). Tcr then assists in describing erosion rates and sediment delivery.

Other assessment procedures also offer initial insight into road construction and their associated erosion risk. Procedures similar to the Forest and Range Evaluation Program (FREP) help a surveyor collect data, such as contributing structure (i.e. road surface, cutslope, ditch) length, width, slope, and distance from a water source. FREP uses these input measurements, with surface and traffic conditions, to estimate the potential erosion amount (m^3/year) (Maloney et al., 2009). The assessment procedure assists in assessing the connectivity between roads and surface water features by evaluating the distance and surface materials over which sediment must travel prior to delivery to a water body. FREP then ranks the road from a low to high-risk based on both the potential erosion and connectivity. Connectivity plays a crucial role in risk. For example, a road with high erosion but low connectivity has little impact on water quality (Corrigan, 2017; Maloney et al., 2009; Ziegler et al., 2001). However, a road with low to moderate erosion but is highly connected will have a more considerable impact on surface water.

Field methods are commonly used to supplement modelling results by either collecting input data, or to validate models. Input data is most commonly collected through field-based measurements and GIS analysis of terrain data. Model validation methods include rainfall simulations, monitoring erosion using sediment tanks, and surveys documenting the location and characteristics of sediment plumes, and erosional features such as gully and rill development. The most common of these methods is rainfall simulations, which measures runoff and erosion rates. These rainfall simulators are often mobile, which allow multiple sites to be evaluated. Depending on the set-up, users can also control the rainfall intensity and drop size. Rainfall drop size and intensity are important factors when assessing erosion and should be set to local or forecasted conditions to predict sediment yields accurately (Meshesha et al., 2014). Rainfall simulations can also provide information on road infiltration, sediment yields (mass/area/time), and runoff rates. Sediment tanks can collect similar information when a tipping bucket mechanism is used to measure runoff along with a local rainfall gauge. This method measures runoff and sediment delivery produced by erosion from natural rainfall from a fixed plot to characterize runoff rates and sediment yield (mass/area/time). These tank systems are not very mobile; therefore, they are best suited for detailed studies on specific road segments.

This project is part of an extensive research network focusing on water treatability within Canada. It is essential to understand the erosion risks of unpaved roads within Canada and how that risk varies across the country to manage our roads better and protect our water sources. There has been extensive research on road erosion risk, prediction, and modeling. However, the risk of unpaved roads within drinking water supply watersheds in Canada has not been evaluated. Thus, understanding the risks from unpaved roads on drinking water supplies has not been evaluated at larger scales.

Research Goals

The goals of this thesis are to,

1. Compare the risk of runoff and erosion from unpaved roads across Canada, and evaluate FREP's ability to predict sediment export (volume/time) compared to measured rainfall simulation results, and

2. Assess sediment yields (mass/area/time) from different road types using rainfall simulations and calibrate and validate the Road Erosion and Delivery Index (READI) within the City of Calgary's watersheds.

Research Objectives and Organization of Thesis Chapters

Chapter 2 describes unpaved road erosion risks across Canada using rainfall simulations and surveys from the Forest and Range Evaluation Program (FREP) developed by the Government of British Columbia. The specific objectives include using a water quality survey method to characterize and identify the main factors that impact the erosion risk of unpaved roads across Canada. Along with validating erosion rates produced by the FREP survey method using rainfall simulations a subset of surveyed sites to determine what factors (slope, contributing area, and traffic) affect sediment yields.

Chapter 3 is a case study within the City of Calgary's watersheds to qualify the potential impact of unpaved roads on potential sediment inputs to key source water streams that would impact water treatability in Calgary. In this chapter, the FREP method, along with digital surface models (DSM) derived from unmanned aircraft vehicles, are used to assess roads construction. This chapter calibrates the READI model using rainfall simulations and DSM's, explicitly focusing on surface roughness and manning's n. The specific objectives include determining the key factors regulating erosion and runoff yields from the representative sites within the Ghost and Elbow River Watershed. Additionally, this chapter evaluates the READI model using large-scale rainfall simulation data and digital surface models to evaluate predicted time-to-concentration (tcr) accuracy, and the role surface roughness has on tcr and sediment yield predictions.

Chapter 4 synthesizes the results and conclusions from Chapters two and three in the context of risks from unpaved roads and potential impacts on water treatability and management in Canada and in the City of Calgary.

Chapter 2 : Risk of erosion from unpaved roads on Canadian drinking water

Introduction

Forest management, agriculture, oil and gas exploration, and outdoor recreation all require unpaved forest roads to access resources. However, these roads are a source of fine sediment (particles < 63µm) which impacts the receiving waterbodies (Lane & Sheridan, 2002). Increased turbidity and total suspended solids (TSS) are common impacts of unpaved roads on water quality (Bilby et al., 1989; Lane & Sheridan, 2002; Tremblay et al., 2009). To manage this impact, many road managers adhere to the most stringent best management practices (BMPs), such as, entirely restricting assess to minimize traffic, operational shutdowns during bad weather, and improved surfacing material. However, implementing these measures is not possible for all watersheds. The inability to implement BMPs increases the risk of sedimentation and impacts drinking water supply (Holmes, 1988).

Fine sediment impacts water storage, treatment, and the cost of providing clean drinking water (Holmes, 1988). When treatment facilities are overwhelmed by changes in raw water quality, it can cause treatment difficulties; in extreme cases triggering boil water advisories. To upgrade a treatment facility to include or improve filtration can be extremely expensive and has prompted management of source watersheds (Holmes, 1988; Robinne et al., 2019). Occasionally, treatment costs out-weigh forest and land management costs and utilities will obtain long-term leases on source watersheds (e.g. Halifax Water, Victoria, Vancouver) (CRD Integrated Water Services, 2016; Vaidya et al., 2008). However, increased operational costs can be significant enough that many utilities are concerned about managing source watersheds.

The ability to obtain a long-term lease for land and water quality management is dependant on the size of the utility and the source watershed. Purchasing land or leases is not always possible for smaller utilities, where the watersheds are vast with expensive property, or where the political environment favours multiple uses for forest lands. As a result, road management in Canadian watersheds is remarkably diverse. In addition to road use and ownership, forests, topography, geology, and climate vary across Canada. This diversity causes more variability in the watersheds and the forest roads they contain.

Road Erosion

Erosion is the process of detachment and movement of soil particles, and surface erosion is common on most unpaved road surfaces. Erosion yields from a road surface are related to the erodibility of the material, traffic, road slope, bulk density, rainfall intensity and duration, road maintenance, and infiltration (Jaafari et al., 2015; Jordán & Martínez-Zavala, 2008; Reid & Dunne, 1984; Rummer et al., 1997). Management actions such as reducing the traffic, applying gravel, or crushed rocked capped surface, decreasing the contributing area, and revegetating exposed surfaces can reduce erosion. The sediment yield from a road surface can also be reduced by ensuring adequate drainage with proper road grading (maintaining road crowns and out-slope roads), and cross drain culverts reduce the contributing area (Black & Luce, 2013). If sediment does not enter a water body, it is often deposited on the forest floor as runoff infiltrates into the soil, creating a sediment plume. Sediment can connect to waterbodies if a large sediment plume develops, or a culvert drains near streams. The potential connection (or likelihood that sediment will reach a water body) is dependent on the rainfall intensity and, the conditions and length of the surface the sediment must travel to reach the watercourse (Bracken et al., 2015; Jaafari et al., 2015; Maloney et al., 2009). Therefore, water crossings are exceptionally high risk for sedimentation because of the proximity of road surfaces and water bodies. As a result, these areas have been the focus of many studies that have found increased amounts of fine sediment downstream of bridges and other road crossings (Brown et al., 2013; Lane & Sheridan, 2002; Thomaz et al., 2014).

Erosion Models and Assessment Procedures

Understanding erosion rates and sediment delivery from unpaved roads to streams is important to determine potential impacts and risk. To understand sedimentation rates, data can be obtained through field procedures such as rainfall simulations, sweep samples, settling ponds, and road surveys. Additionally, erosion and delivery rates can be estimated with erosion models using field data or default values within the models.

Field methods obtain site specific data that provide a more accurate understanding of erosion and sediment delivery rates. The suitability of a field method is dependant on the site conditions and research goals. Road plots instrumented with sediment collection tanks, surveys of sediment plumes, sweep samples, and rainfall simulation experiments can provide erosion data (Baird &

Schmidt, 2011; Covert & Jordan, 2009; Iserloh et al., 2012; McFero Grace, 2005; US-EPA, 1995). Sediment settling ponds provide detailed erosion and runoff data from sites. This method is dependent on natural rain events, is labour intensive, and not portable, so it is usually limited to a limited number of sampling locations (Black & Luce, 2013). Surveying sediment plumes is a simple field method used to assess plume size and the road characteristics that contribute to it (McFero Grace, 2005). This method evaluates erosion of road features but provides little detail on the hydrological processes. Sweep samples capture information on materials available for erosion and provides a general understanding of the road surface conditions at study sites (Corrigan, 2017; US-EPA, 1995). A common field method is small scale rainfall simulations which can be used to compare many different sites and understand erosion potential across a broad range of road surfaces. Many different types of portable rainfall simulators have been used to test runoff and erosion on a variety of surfaces (Brown et al., 2013; Covert & Jordan, 2009; Iserloh et al., 2012; van Meerveld et al., 2014). Small scale simulation plots (1 m^2) are preferred over large plots (≥ 5 m^2), as they are easily transported to different sites and have low water requirements (Iserloh et al., 2012). However, not all erosion processes are captured from a small scale and can only focus on specific surface characteristics (Seeger, 2007). Large rainfall simulation plots provide more insight into road erosion processes. The larger surface area allows for more interaction between runoff and the road, impacting flow transport (Chaplot & le Bissonnais, 2000). However, large scale rainfall simulations require more water, are difficult to transport, but are considered to be comparable to smaller-scale model simulations (Seeger, 2007).

Modelling erosion is useful when determining the potential threat of sediment delivery to streams. To understand erosion risks and make management decisions, road managers can use several methods to determine the amount of erosion and sediment that might enter a stream from a road network. There are detailed models such as the Water Erosion Prediction Project (WEPP) and the Road Erosion and Delivery Index (READI), which have high input data demands but produce comprehensive and accurate results (Benda et al., 2019; Croke & Nethery, 2006; Fu et al., 2010). These detailed models are physically based and use long-term watershed data to calculate erosion and connectivity (Fu et al., 2010). However, obtaining the data required for detailed models can pose a challenge and may lead managers to use other approaches. These other methods include field data assessment-based models or empirical models such as the Forest and Range Evaluation Program (FREP), Geomorphic Road Analysis Inventory Package (GRAIP), and the Universal Soil

Loss Equation (USLE). Within Canada, the BC government developed FREP as part of the Water Quality Effectiveness Evaluation (WQEE) procedures to promote informed decision-making and commitment to the environment (Maloney et al., 2009). FREP, GRAIP, and USLE require less information and are best used for ranking and comparing sites or assigning an erosion class to a type of road surface based on data from erosion studies (Fu et al., 2010; Wade et al., 2012).

Objectives

Although many studies have investigated the factors controlling the erosion and sedimentation hazard of forest roads, there is still little known about the threats of road sediment to drinking source water and the factors that affect these risks across regions and road types in Canada. This study uses the FREP survey methodology and simulated rainfall experiments on unpaved gravel roads to evaluate erosion risk in drinking water supply watersheds across the country. Specific objectives are to:

1. Use a water quality survey method (FREP) to characterize and identify the main factors that impact the erosion risk of unpaved roads across Canada.
2. Validate the survey method erosion rates with rainfall simulations on a subset of the survey sites.
3. Use the rainfall simulation and survey results to determine the dominant factors affecting sediment yield.

Methods

Drinking Watershed Selection

Canada is a large country with varying topography, climate, and forests. Therefore, for this study the country was broken down into ecozones to classify biogeographical borders for broad-scale assessment (Saad et al., 2011). Watersheds were then selected throughout ecozones that have forested watersheds that provide drinking water. The Pacific Maritimes, Montane Cordillera, Boreal Plains, Boreal Shield, and Atlantic Maritimes were the focus areas of this study (Figure 2-1). However, due to differences in available data on drinking water supply watersheds across Canada, it was challenging to apply a systematic approach for site selection. Nevertheless, government resources and local managers were able to provide information on location and characteristics of representative drinking water supply watersheds. Additionally, managers provided advice on representative watersheds, roads, and sample locations. In some cases, managers were able to provide information on watersheds that were not readily available in public records. Table 2-1 provides an overview of the forest ecozones, watersheds, provinces, and towns included in this study.

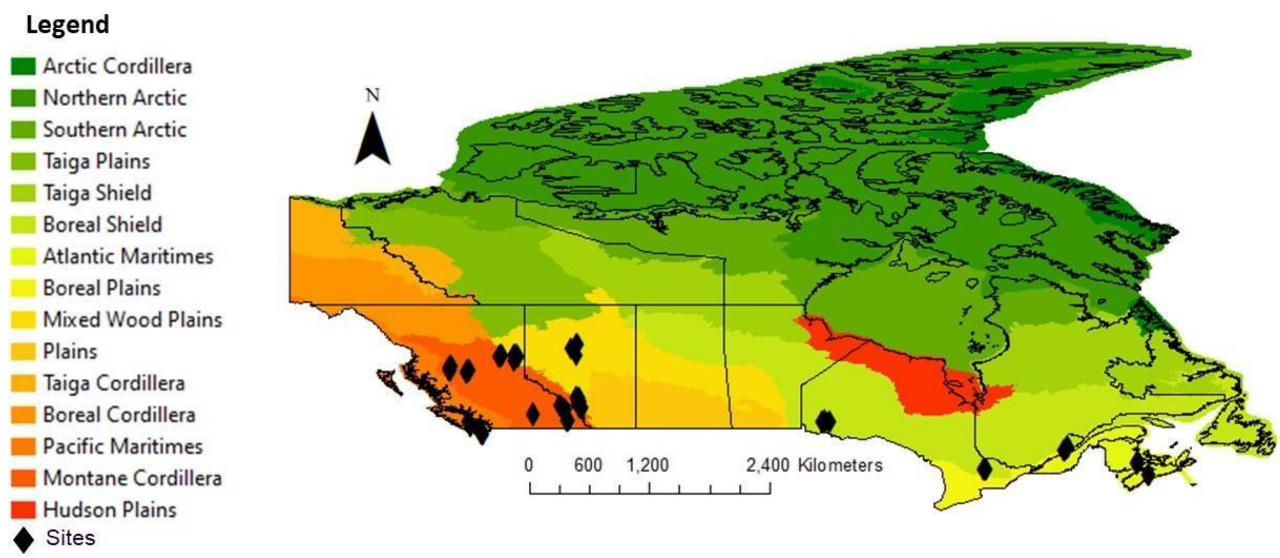

Figure 2-1 The 107 study sites across Canada that incorporated a variety of ecozones.

Study Regions

Table 2-1 Summary of studied watersheds, describing size, topography, and climate.

Forest Ecozone	Watershed	Watershed Size (km^2)	Elevation Gain* (m)	Average Temperature (°C)	Average Precipitation (mm/year)
Pacific Maritimes	Goldstream	23.1	740	9.9	1207
	Leech	96.2	740	9.9	1207
Montane Cordillera	Billy Goat	5.6	865	4.1	615
	Elbow	1,238	1,000	4.6	419
	Forster	167	1,730	5.1	505
	Ghost	1,046	1,975	4.6	419
	Kimberley & Lois	141.2	730	4.2	557
Boreal Plains	Utikuma	2,70	55	1.4	413
Boreal Shield	Wabigoon Lake	6,788	120	2.7	706
	Haliburton Forest	238	115	4.6	997
	Lac St. Charles	198	150	5.7	1,171
	Montmorency Forest	397	400	4.9	1,186
Atlantic Maritimes	Pockwock	566	140	6.7	1,367
	Turtle Creek	204	180	5.8	1,170

* Elevation gain is the difference in vertical distance from the lowest to highest point in elevation

Pacific Maritimes

Goldstream & Leech Watersheds – Victoria, British Columbia

The Great Victoria Water Supply Area (GVWSA) includes the Sooke, Goldstream and Leech watersheds, which are gated watersheds with no public access. The watersheds are dominated by winter rainfall, with large storms occurring in November. The average annual temperature is 8.8°C, with an average yearly precipitation of 1640 mm (Environment and Climate Change Canada, 2020). Since 1993, the area has not had any harvesting (CRD Integrated Water Services, 2016) and has had an extensive monitoring program in place since 1996 (Werner et al., 2015). The roads are primarily used for security, watershed management, and water sampling. Prevention of erosion and sediment delivery is a primary concern and aspect of managing the roads in the watershed.

Montane Cordillera

Billy Goat Watershed – Parsons, British Columbia

The Billy Goat watershed supplies the small town of Parsons, British Columbia, with additional households that use untreated water from the stream. The dominant uses of the forest are the forest industry, with some agricultural and residential land use. The watershed is 5.6 km^2 in size, with elevation ranging from 785 m to 1650 m above sea level (MacDonald Hydrology Consultants LTD., 2016). The area is snowmelt dominated with an average of 615 mm annual precipitation and temperatures averaging 4.1°C (Environment and Climate Change Canada, 2020). A primary concern for the forest industry is the increase of sediment in streams from unpaved road crossings (MacDonald Hydrology Consultants LTD., 2016).

Forster Watershed – Radium, British Columbia

This community watershed is a multi-use forest, primarily used for forestry development, grazing, and recreation. The Forster watershed has an area of 167 km^2 with an elevation gain of 1,730 m. It has provided water to the town of Radium since 1981 (Dobson & Cook, 2013). Forster Creek is glacier-fed, with annual average temperatures reaching 5.1°C and 505 mm of annual precipitation (Environment and Climate Change Canada, 2020). According to the local forest manager, the main threats to this watershed are the pine beetle and forest fires. The water treatment plant has a settling pond allowing significant sediment load events to settle out before treatment. The only impact seen from high sediment influxes is that the pond will fill faster and needs increased maintenance (Apex Geoscience Consultants Ltd., 2012).

Kimberley and Lois Watershed – Kimberley, British Columbia

The Kimberley and Lois Creek Watersheds are designated community watersheds that supply the Meadowbrook Waterwork District. The watersheds combined are approximately 141.2 km^2 in size, with 3.2 km^2 used for harvesting (Apex Geoscience Consultants Ltd, 2012). Forest harvesting was started to combat the pine beetle, but the pine beetle threat has grown since 2002 (Apex Geoscience Consultants Ltd, 2012). Elevation ranges from 1130 m to 1860 m, with annual temperatures averaging 4.2°C and 557 mm of annual precipitation (Environment and Climate Change Canada, 2020), and streams are mainly snowmelt dominated. The water is chlorinated at the time of treatment; however, the utility has failed to meet drinking water quality parameters several times and boil water advisories were issued in the past (Apex Geoscience Consultants Ltd, 2012).

Elbow Watershed – Calgary, Alberta

Located in southern Alberta, the Elbow watershed provides 40% of the City of Calgary drinking water (Wijesekara et al., 2012). It covers an area of 1,238 km^2, with the majority of land forested with some agricultural, parkland, and urban uses (Wijesekara et al., 2012). The elevation ranges from 1000 m to 2000 m, with the lowest height being where the Elbow meets the Bow River (Wijesekara et al., 2012). Annually, temperatures average 4.6°C, with precipitation averaging 419 mm (Environment and Climate Change Canada, 2020). This watershed faces a variety of source water impacts as land use varies over the stream course.

Ghost Watershed – Calgary, Alberta

The Ghost River is a tributary to the Bow River, providing water for the City of Calgary. This watershed is a public land-use zone, dominantly used for forestry operations, recreation, grazing, oil and gas exploration, and hunting. Mountains encompass most of the land, with the Eastern slopes connecting to the foothills. Elevations range from 1,190 m at the river to 3,163 m in the mountain ranges (ALCES Landscape and Land Use Ltd., 2011). The steep slopes are the main concern for erosion, as this reduces infiltration rates. Heavy snowfall with cold temperatures dominates the winter and melts during warm chinooks, with warm wet springs and summers. Annual temperatures average 4.6°C, and the mean annual precipitation is 416 mm (Environment and Climate Change Canada, 2020). The main concern in this area is the use of Off-Highway Vehicles (OHV’s) and camping that can impact water quality (R. MacDonald & ALCES Landscape and Land Use Ltd., 2018).

Boreal Plains

Utikima Watershed – Red Earth, Alberta

This wetland dominated watershed is 2,170 km^2 in size, with oil and gas development, forestry, and recreation uses (Devito et al., 2016; Environment and Climate Change Canada, 2020). The basin is relatively flat, with elevation gains of 55 m. The mean annual precipitation is 413 mm, and the average yearly temperature is 1.4°C (Environment and Climate Change Canada, 2020). The small streams and wetlands in the area store most of the drinking water. However, providing enough clean water for the community is a primary concern.

Boreal Shield

Wabigoon Lake Watershed – Dryden, Ontario

Wabigoon Lake is a water source for both Dryden and neighbouring Indigenous communities. The forest is owned by the crown and leased to private companies for resource development, who are responsible for maintaining the roads and having a forest management plan. The managed land is 6,788.7 km^2 in size, with 5,332.2 km^2 available for harvesting (Domtar, 2019). Temperatures average 2.7°C, with mean annual precipitation of 706 mm (Environment and Climate Change Canada, 2020). Nutrients are more problematic than sediment load; however, forest management plans still incorporate road erosion concerns.

Haliburton Forest Watershed – Haliburton, Ontario

The Haliburton Forest Watershed is part of the Great Lakes region, covering 238 km^2 (Mrosek, 2001). As a common location for summer getaways, the forest has high recreational uses with some forestry and research activities. Forest managers regulate entry, and users must have a pass to gain access. Approximately 80% of the landmass is forested, with temperatures averaging 4.6°C yearly and precipitation averaging 997 mm/year (Environment and Climate Change Canada, 2020). This watershed is relatively separate from the drinking water facility intake area, but water quality is still a focus of this watershed.

Lac St. Charles Watershed – Quebec City, Quebec

Lac St Charles is located north of Quebec City and has a drainage area of 198 km^2. Water is stored in a 3.6 km^2 reservoir and has two other smaller basins up and downstream of the main reservoir

(Narancic et al., 2019). Located in the Canadian Shield, dense forest dominates this landscape with hills reaching 750 m above sea level. The climate is mild, with temperatures averaging 5.7°C yearly and higher precipitation levels averaging 1171mm, which is dominantly rain (Environment and Climate Change Canada, 2020). Since the 1960s, the population has increased, with many homes on the shoreline, each having a septic tank system (Narancic et al., 2019). This population increase raises concern for water treatability as there is a higher risk of urban contamination.

Montmorency Forest Watershed – Quebec

This forest lies north of Quebec City, located in the Canadian Shield ecozone, covering 397 km^2 (University of Laval, 2020). This watershed is a research watershed with recreational and forestry activities. Elevation reaches 1000 m above sea level, with moderate temperatures of 4.9°C, and precipitation split between snow and rain, 1186 mm falling annually (Environment and Climate Change Canada, 2020). Water quality concerns in this area are mostly nutrient-based, as sediment levels don't increase long enough to cause concern (Tremblay et al., 2009).

Atlantic Maritimes

Turtle Creek Watershed – Moncton, New Brunswick

Turtle Creek is the primary water source for the Moncton area, mostly forested with small parts used for agriculture. The 204 km^2 basin provides water to over 100,000 people (St-Hilaire et al., 2001). Regionally, annual temperatures average 5.8°C, and precipitation averages 1170 mm (Environment and Climate Change Canada, 2020). The watershed is partially owned by residents however, some recreational and industrial uses cause concern for water quality. According to local watershed managers, the main concern in this community is algae and sediment.

Pockwock Watershed – Halifax, Nova Scotia

This watershed is 566.1 km^2 in size and is one of two primary water sources for the City of Halifax (Halifax Water, 2020). Gates are used to regulate access, and large 50 mm gravel (2-inch crushed rock) is used to surface the roads and deters unwanted recreational users. Traffic is mostly 4x4 trucks, with occasional forestry vehicles for harvesting. Mean annual temperatures sit around 6.7°C, with yearly precipitation around 1367 mm, primarily as rain during the winter season (Environment and Climate Change Canada, 2020). Sediment concerns in this watershed are low as they have measures to reduce sediment erosion and connection.

Field Data Collection

In each selected watershed, multiple roads were surveyed using the FREP methodology to collect road characteristics and estimate sediment yields. As this study was focused on drinking water impacts, all surveyed road sections had a drainage feature, such as a culvert, bridge, or low point on the road at which the water left the road surface near (< 30 m) a stream. Additionally, road surface material and exposed soil samples were collected for particle size and chemical lab analysis in a companion study. For each watershed, a representative road section was selected for a 30-minute rainfall simulation to collect runoff samples, and measure sediment yields and runoff rates (erosion plots).

Survey Method: Forests and Range Evaluation Program (FREP)

Road sediment yields were estimated using the Forest and Range Evaluation Program (FREP) survey method (Maloney et al., 2009). The FREP method was selected because it provides a simple assessment tool allowing relatively inexperienced users to assess road erosion within 30-minutes (Maloney et al., 2009), which could be an asset for road managers across Canada if proved to be accurate. The method characterizes key road features governing sediment production (contributing area, slope, surfacing material quality) and road use, which are then used to estimate sediment yield (m^3) and the proportion of the yield composed by fine particles ≤63 μm (Maloney et al., 2009). It then provides a general evaluation of connectivity, ultimately influencing the risk of a road. Within FREP, predicted sediments yields are a product of erosion depth and contributing area. Erosion depth is classified from slope, traffic, and surface quality measurements taken in the field (Table 2-2). The total predicted sediment yield for surveyed surfaces are then multiplied by the percent of fines (< 2 mm) found on the surface. For road surfaces, the percent of fines is assumed to be 100%, which was identified to be the main factor that could potentially affect drinking water treatment. The FREP sediment yield results can then be used to rank multiple road segments on the risk they pose to nearby water bodies and can then be used to inform decision making processes for road maintenance and upgrades. To collect the data required for the FREP model, including contributing area, slope, surface quality, and traffic volume, a survey was created in ArcGIS Survey 123 that encompassed the FREP requirements. Survey 123 allows the user to create a set of questions through Microsoft Excel that are uploaded to the Survey 123 interface. It creates a customized form-based survey that can be used to collect data through the web or mobile device and uploaded to the server. The data can then be downloaded and reviewed in Microsoft Excel or on the ArcGIS web-based platform.

Within the FREP Survey 123 method, each drainage point was categorized as natural (rut or hillslope) or engineered (culvert, bridge, or ford). The areas contributing runoff (e.g., road surfaces, cutslopes, and ditches) (Figure 2-2) to a drain were measured and entered into the Survey 123 form. The length, width, and slope were measured with a rangefinder (Nikon, Forestry Pro). Supplemental elements, such as percent erodible area and canopy cover, were estimated. Other FREP requirements, such as traffic level and surface quality, were assigned a category based on the FREP guidelines. This process is somewhat subjective, but the FREP method provides descriptions to maintain consistency. For example, specifications for traffic level include; 1) low use seasonal roads are only accessible by 4x4 vehicles and the occasional hauling truck, 2) moderate use are all-season use roads with 1.5 lane width and pickup and industrial traffic, 3) and high use all-season roads have double lanes with pickup and hauling trucks (Maloney et al., 2009). The FREP process also categorizes sediment connection, which uses the distance from a waterbody and describes the flow path of runoff to the waterbody (Maloney et al., 2009). Features were classified as connected if there was a clear, unobstructed path for sediment to move to a waterbody. Partially connected features have some displacement; for example, cut-slope erosion travels down a partially vegetated ditch, which reduces transport. Lastly, drains that have no connection either have no water body nearby or go a substantial distance (>10 m) over the forest floor (Maloney et al., 2009).

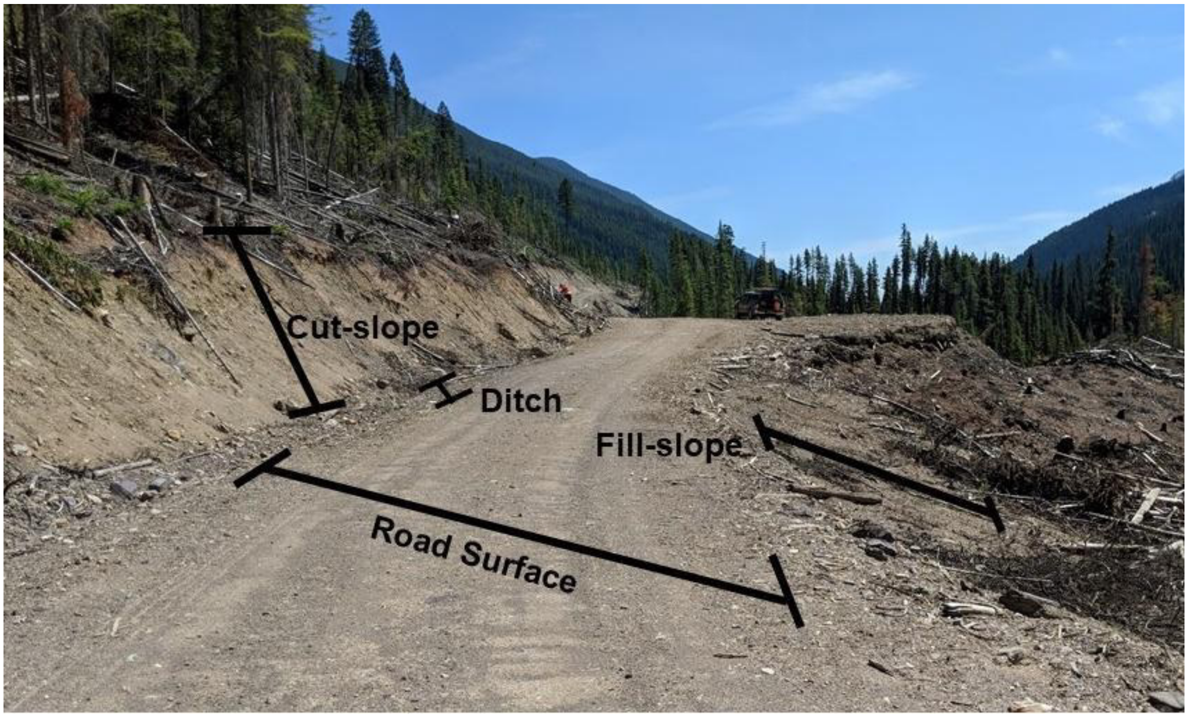

Figure 2-2 Road build diagram. An unpaved road generally consists of a road surface that can be crowned and a ditch. Roads on hillslopes will have cut and fill slopes.

Rainfall simulations

The rainfall simulator

The design presented by Covert and Jordan (2009) was used as a guide for building a rainfall simulator to measure erosion from a 1x1.5 m plot. Longer plots allow the development of sheet or rill runoff, substantially affecting erosion (Moreno-De Las Heras et al., 2010). Therefore, a larger frame length of 1.5-meters was used which was the maximum length that would fit in the field vehicle. The metal plot frame was sealed to the road surface using foam refrigerator sealant, modelling clay, and Petroleum jelly where needed (Lane et al., 2004) (Figure 2-3b). A hole was excavated in the road at the end of the pan to allow clearance for sample bottles to collect runoff, and the pan was clamped onto the metal plot frame to keep it secure during rainfall simulation. Modelling clay and Petroleum jelly were used to seal the pan to the road surface (Lane et al., 2004). The simulator frame was made of steel and had a height of 3 metres to ensure simulated rain reached the terminal velocity (Covert & Jordan, 2009). Tarps were fastened to the frame for wind guards (Figure 2-3a), and if there was a chance of rain, a top cover was attached to the frame's top to protect the plot from natural rainfall.

The simulator employed a spray nozzle (¼ inch HH-WSQ, Spraying Systems Co., Wheaton, IL, USA) to produce a controlled rate of rainfall which was fixed vertically and centred on the plot. This nozzle was previously used by Howard (2018) and produced a 22.5 mm/hr rainfall intensity with acceptable drop sizes. Polyethylene (PEX) plumbing connected the nozzle to a 12V pump (SHURflo, 2083-343-135BX) powered by two deep-cycle lead-acid batteries connected to a 300-watt solar panel. Water was pumped from a nearby water source (stream, lake) and stored in a tank or water bladder. A 1µm filter (Rainfresh, HP1) was installed between the pump and the valves that controlled the pressure and flow rate (Figure 2-3c). A 30-PSI pressure valve (Princess Auto, glycerine gauge) and the 2-GPM flow metre (OMEGA Acrylic Rotameter, FL7302) controlled the pressure and flow rate with a bypass valve system to help regulate flow (Figure 2-3c). The bypass system was similar in design to a hydraulic system and proved a reliable way to control pressure and flow rate (Figure 2-4).

Figure 2-3 Small Rainfall Simulator set up including the a) frame with wind guards, plot frame, and collection pan, b) the plot frame connected to the pan with modelling clay and petroleum jelly, and c) the pump and filtration system.

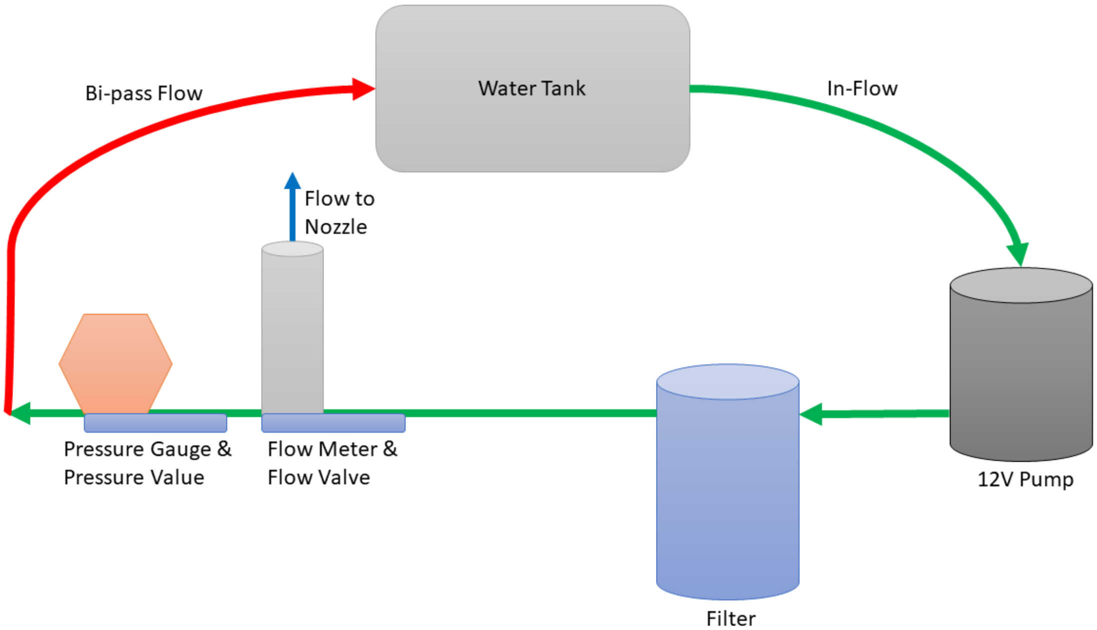

Figure 2-4 Bypass system to control pressure and flow rate during simulated rainfall. Green arrows show the water flow into the system, the red arrow shows the bi-pass flow from the pump back to the tank, and the blue arrow shows the flow to the nozzle to produce rain

Rainfall simulation intensity

The calibrated intensity for all data presented here was 36 mm/hr (+/-0.9mm) with 82% of uniformity. This represents a 10-25 year return period for the Canadian average rainfall intensity (Simonovic et al., 2018). The initial objective was to use two rainfall intensities for each road section; 1) first an intensity that represented the regional average (5-yr return period) and 2) second a consistent average intensity for all of Canada (26 mm/hr) to allow more direct comparison between experimental results. Two rainfall simulations were used in 2018, but they produced similar erosion yield results (ANOVA p-value = 0.22), so in 2019 only one rainfall simulation was conducted on each road.

To calibrate the rainfall intensities, a grid of 6.5 cm diameter collection containers was evenly distributed across the runoff plot frame (Figure 2-3b) (33 x 37.5 cm) (Howard, 2018). The resulting data was used to calculate the mean, standard error, and Christiansen-Uniformity-Coefficient of the simulated rainfall (Equations 2-1 and 2-2). The pressure and flow rate for the nozzle was set before field experiments and checked after field experiments, to ensure consistency. Before the 2018 field season, 135 containers where used for ten 5-minute calibration runs, which resulted in a mean intensity of 26 mm/hr (+/- 0.37 mm) with 100% uniformity. However, after the first field season some plots produced more runoff than the calibrated intensity. Therefore, after the first field season, 12 containers were used to check the intensity with three 10-minute and one 15-minute calibration runs, which produced an average intensity of 36 mm/hr (+/-0.9 mm) with 82% of uniformity. Although the reason for the discrepancy in rainfall intensity is not known, the short run time for intensity measurements may have affected the results.

Equation 2-1 Rainfall Intensity

$$Rainfall\ \left(\frac{mm}{hr}\right) = Volume\ \left(\frac{cm^3}{min}\right) \times \frac{1}{Area(cm^2)} \times (\frac{10mm}{cm})(\frac{60min}{hr})$$

Equation 2-2 Christiansen Uniformity Coefficient

$$UC = 100\%(1 - \frac{Average\ Deviation\ from\ the\ Average\ Depth}{Overall\ Average\ Depth})$$

Raindrop size

Rainfall drop size was determined using the staining method (Kathiravelu et al., 2016). An absorbent paper (Artist’s Loft Watercolor Pad, 10.1cm x 15.2cm) was lightly stained with potassium permanganate and placed under the simulator. As rain drops hit the paper, potassium permanganate oxidized and changed colour outlining the drop size. Papers were placed in a 3x4 grid to capture the range of drops over the plot frame area. Drops were captured in one section of the plot frame grid at a time. Three papers were placed on the ground and covered with a stiff plastic board. The simulator was then turned on and set to the target intensity, the board was removed, and the simulator was operated for 3 seconds. The board was then held above the papers, and the simulator turned off. The papers were photographed (Google Pixel 2) with a ruler for scale and then allowed to dry before storing them for later analysis. To determine the spread ratio of the raindrop absorbing into the paper, a known drop size, determined by the photograph method (Kathiravelu et al., 2016) was used to drop onto potassium permanganate-stained absorbent paper and measured. The difference between the photographed falling drop size and the paper drop size was assumed to be the spread ratio. Both the measurements of raindrops were cross analyzed to ensure accuracy. The simulator produced an average drop size of 0.3 mm ± 0.26 mm, with over 3600 drops counted. The cross analyses of these drops show that measurements were accurate, with the cross-analysis showing a mean of 0.33 mm ± 0.22 mm and ranging from 0.08-2.24 mm (Humeny, E). Drops size ranged from 0.05 -2.4 mm, which is at the lower end of drop sizes compared to other studies at 0.3-6.2 mm (Kathiravelu et al., 2016; Lu et al., 2008; Meshesha et al., 2014). Within the configuration of drop sheets, the top and bottom rows and left column produced larger drops, which were 0.5 to 2 times larger in size. Although, this method has drawbacks when raindrops overlap and cannot be separated from each other, affecting accurate size count, it has been shown to be a reliable method for application outside of a lab environment. Different techniques were attempted, including the oil method (Eigel & Moore, 1983) and the photograph method (Kathiravelu et al., 2016), which are more accurate (Kathiravelu et al., 2016). However, results were inconclusive as drop size could not be adequately measured or photographed for analysis.

Sampling and lab analysis protocols

Rainfall simulations and runoff samples

Rainfall simulations were performed for 30-minute durations, collecting a maximum of 14 runoff samples in 500 ml bottles (ULINE, Natural round wide-mouth plastic jars – 32 oz) in 2-minute intervals, starting 2 minutes into the simulation or when runoff started if it was after the 2-minute mark. The time to fill each sample bottle was recorded and used to calculate the runoff rate. Sample bottles were sealed and stored in light-blocking containers. In between the 2-minute samples, all the runoff was collected in 500 ml bottles and transferred to 19 L buckets. The bucket volume was measured with a graduated cylinder at the end of the simulation to determine the total runoff volume.

Runoff samples were processed for sediment concentrations using the ATSM D3977-97, 2013 Suspended Sediment Concentration (SSC) method, and Particle Size Analysis (PSA) using the laser particle analysis at the Natural Resources Analytical Laboratory (NRAL) (Beckman Coulter LS 13320) (University of Alberta, 2020). In the lab, runoff samples were left to settle in the sample bottle for one day. A large pipette was used to syphon off the water at the top of the sample bottles. After syphoning, the remaining sediment volume was marked with a permanent marker, and the sediment-water mixture was rinsed into a weight-boat. Sediment-water mixtures were then evaporated in the oven or on a drying rack (if the laboratory oven was unavailable). Samples were evaporated in an oven at 80℃ for 2-3 hours or left to dry on a dry rack at room temperature for 8-

72 hours depending on the sample volume. Samples were then oven-dried at 104°C for 2 hours and allowed to cool before final weighing (Mettler Toledo, New Classic MF). Dried sediment from each site was composited using a clay mortar and pestle and stored in a soil bag (Systems Plus, Poly Bags) until particle size processing. The soil was passed through a 2 mm ASTM sieve, and then sub-samples were obtained with a riffler (Gilson SP 230 Spinning Riffler) to prepare samples for PSA. The sub-samples were analyzed at the NRAL using a Beckman Coulter LS 13320 system. Duplicate PSA analyses were performed on each sample to confirm accuracy.

Soil Moisture

Soil moisture samples were collected near rainfall simulation plots prior to the simulation. A pickaxe was used to collect a sample from a volume of approx. 3 cm deep and 2 cm wide. The sample was collected and stored in a soil bag until analysis. The ASTM D2216, 1995 method was used to determine the soil moisture content in the laboratory. Samples were weighed and then dried at 104°C for 24 hours and allowed to cool before weighing again. Gravimetric soil moisture content (%) was determined as sample (wet weight - dry weight) / dry weight.

Results

Road Survey

A total of 107 road surfaces were surveyed in 15 watersheds, within 5 ecozones across Canada (Table 2-2). Most surveys were focused on the Montane Cordillera because sites were more accessible whereas east coast surveys were required to be completed in 3 weeks of travel. In total, 70 surveys were completed western Canada, while 37 were completed in eastern Canada (Table 2-2). As expected, there were some noticeable regional differences between the ecozones. The Red Earth watershed in the Boreal Plain ecozone had the largest and greatest range for contributing area. The smallest contributing area was in the Wabigoon Lake watershed, in the Boreal Shield, at 63 m^2. Slopes were steepest in the mountains of the Montane Cordillera, and public industrial roads of the Atlantic Maritimes. Gentle sloping roads were found in the Boreal Plain (Table 2-2). The Pacific Maritimes watersheds were the only watersheds that had all gated access road, the rest of the ecozones had a mixture of open and gated access. The Atlantic Maritimes region had the only watershed with ‘good’ surface quality roads. ‘Poor’ surface quality roads were only found in the Montane Cordillera and Boreal Plain ecozones (Table 2-2). Erosion depth was shallowest and had the largest range in the Pacific Maritime ecozone, and deepest in the Boreal Plains and Atlantic Maritimes. FREP predicted sediment yields were highest in the Montane Cordillera ecozone, and lowest in the Atlantic Maritimes ecozone (Table 2-2). The Montane Cordillera also had the largest range in predicted sediment yields between watersheds, and the Boreal Shield has least variation (Table 2-2).

Table 2-2 Summary of FREP results from surveyed watersheds in Canada, including watershed and road characteristics, and number of surveys in each watershed.

Ecozone	**Watershed** Number of (Surveys, Simulations)	**Road Contributing Area (m^2)**	**Avg Road Slope (%)**	**Traffic**	**Avg Surface Quality Rating**	**Avg Erosion Depth (m)**	**Avg Predicted Sediment Yield (m^3)**	**Avg Predicted Fine Sediment Yield (m^3)**
Pacific Maritimes	Goldstream (6,0)	900 – 2,600	3.8	Low - Moderate	Average	0.002	2.7	2.3
	Leech (5,0)	300 - 600	3.8	Low	Average	0.0007	2.1	0.8
Montane Cordillera	Billy Goat (3,1)	250 – 1,500	6.5	Low	Average	0.001	1.8	1.0
	Elbow (16,1)	250 – 2,900	6.7	Low - High	Poor - Average	0.003	7.1	4.5
	Forster (9,1)	120 – 1,765	6.5	Low - Moderate	Average	0.003	7.5	4.0
	Ghost (16,6)	164 – 2,500	7.5	Low - High	Poor	0.005	5.8	2.9
	Kimberley (4,1)	200 - 750	8.6	Moderate - High	Average	0.004	2.9	0.8
	Louis (4,1)	200 – 1,250	8.6	Low - Moderate	Average	0.002	5.3	2.3

Ecozone	**Watershed** Number of (Surveys, Simulations)	**Road Contributing Area (m^2)**	**Avg Road Slope (%)**	**Traffic**	**Avg Surface Quality Rating**	**Avg Erosion Depth (m)**	**Avg Predicted Sediment Yield (m^3)**	**Avg Predicted Fine Sediment Yield (m^3)**
Boreal Plains	Red Earth (6,1)	600 – 3,700	1.6	Moderate - High	Poor - Average	0.002	2.4	1.4
Boreal Shield	Wabigoon Lake (8,1)	63 – 1,150	4.9	Moderate - High	Average	0.003	1.4	0.8
	Haliburton Forest (7,1)	255 - 840	6.6	Low - High	Average	0.003	1.2	0.6
	Lac St Charles (3,0)	825 – 1,320	3.7	Moderate	Average	0.002	2.0	1.7
	Montmorency (6,1)	150 - 900	6.0	Moderate - High	Average	0.004	2.1	1.3
Atlantic Maritimes	Pockwock (6,2)	120 - 420	3.2	Low - Moderate	Good	0.001	0.12	0.04
	Turtle Creek (7,1)	100 - 360	8.6	Low - High	Average	0.004	2.7	1.0

Rainfall Simulations

Rainfall simulations were completed on 18 roads across 4 of the surveyed ecozones. Table 2-3 shows the road characteristics and rainfall simulation sediment yield results. From the rainfall simulation locations, the steepest slope was in the Montane Cordillera, and the gentlest slope was in the Boreal Plains. Across Canada, sediment yields ranged from 0 to 2464.5g/m^2. The simulation on the Tomahawk Road in the Atlantic Maritimes, and Road 103 in the Boreal Shield did not yield any erosion. The site that had the lowest sediment yield was Fire Tower Road, in the Montane Cordillera. The site with the highest amount of erosion was in the Atlantic Maritimes with about 54% of the sediment yield made up of fines. Waiparous Trail in the Montane Cordillera had the highest amount of fine sediment eroded at almost 86%, while the least percentage of fines eroded was in the Boreal Shield at Rainbow Trail (Table 2-3).

Table 2-3 Summary of rainfall simulation sites, including site names and locations, the road slope, and general traffic conditions from surveys, and rainfall simulation total sediment yields and the percent fines of that yield.

Ecozone	Road, Province	Road Contributing Area (m^2)	Slope (%)	Traffic	Sediment Yield (g/m^2)	Particles <63 µm Eroded (%)
Montane Cordillera	Bridgeland, AB	300	13.2	Low	130.1	36.3
	Fire Tower, AB	165	10.0	Low	8.91	61.1
	Forster, BC	775	11.6	High	578.4	39.8
	K Rd, BC	1500	10.5	Low	429.9	47.9
	Mark North, BC	720	9.2	Moderate	189.5	9.6
	Mclean Creek, AB	400	9.3	High	25.8	83.9
	Sutton Rd, AB	440	6.0	Moderate	92.4	76.2

Ecozone	Road, Province	Road Contributing Area (m^2)	Slope (%)	Traffic	Sediment Yield (g/m^2)	Particles <63 µm Eroded (%)
	Sutton Trail, AB	164	21.2	Low	101.8	38.5
	TransAlta, AB	1500	10.5	Moderate	849.5	21.0
	Waiparous Trail, AB	183	18.0	Moderate	73.5	85.7
	Waiparous Viewpoint, AB	900	5.1	Moderate	25.9	82.2
Boreal Plains	Industrial Rd, AB	420	3.5	Moderate	1004.9	67.6
Boreal Shield	Bear Narrows, ON	750	4.9	Moderate	188.5	20.1
	Rainbow Trail, ON	300	11.6	Moderate	31.1	7.0
	Road 103, QC	210	7.7	Low	0	0
Atlantic Maritimes	Hardscrabble, NB	360	13.9	High	2464.5	54.2
	Pockwock, NS	420	4.4	Low	69.0	7.1
	Tomahawk, NS	330	5.2	Low	0	0

FREP and Rainfall Simulations

Of the 107 roads surveyed across Canada a subset of 18 had successful rainfall simulations. The categorical descriptors in the FREP process, traffic, surface quality, slope, and erosion depth, had the strongest relationship with the measured percent of fine sediment from rainfall simulation measurements (Figure 2-5). All three sediment variables (total sediment eroded, fine sediment eroded, and percent fine sediment) were strongly affected traffic intensity where sediment production was greater at higher traffic intensities (Figure 2-5 a, b, c). The mass of both total and fine sediment erosion were not strongly affected by road surface quality, though decreasing road surface quality did increase the percent of fine sediments eroded (Figure 2-5 d, e, f). Rainfall simulation sites only fell into two of the three slope categories. Across the measured road sections, greater slopes were associated with greater percent fines eroded (Figure 2-5 g, h, i). Lastly, erosion depth was only strongly correlated with percent fines eroded (Figure 2-5 j, k, l).

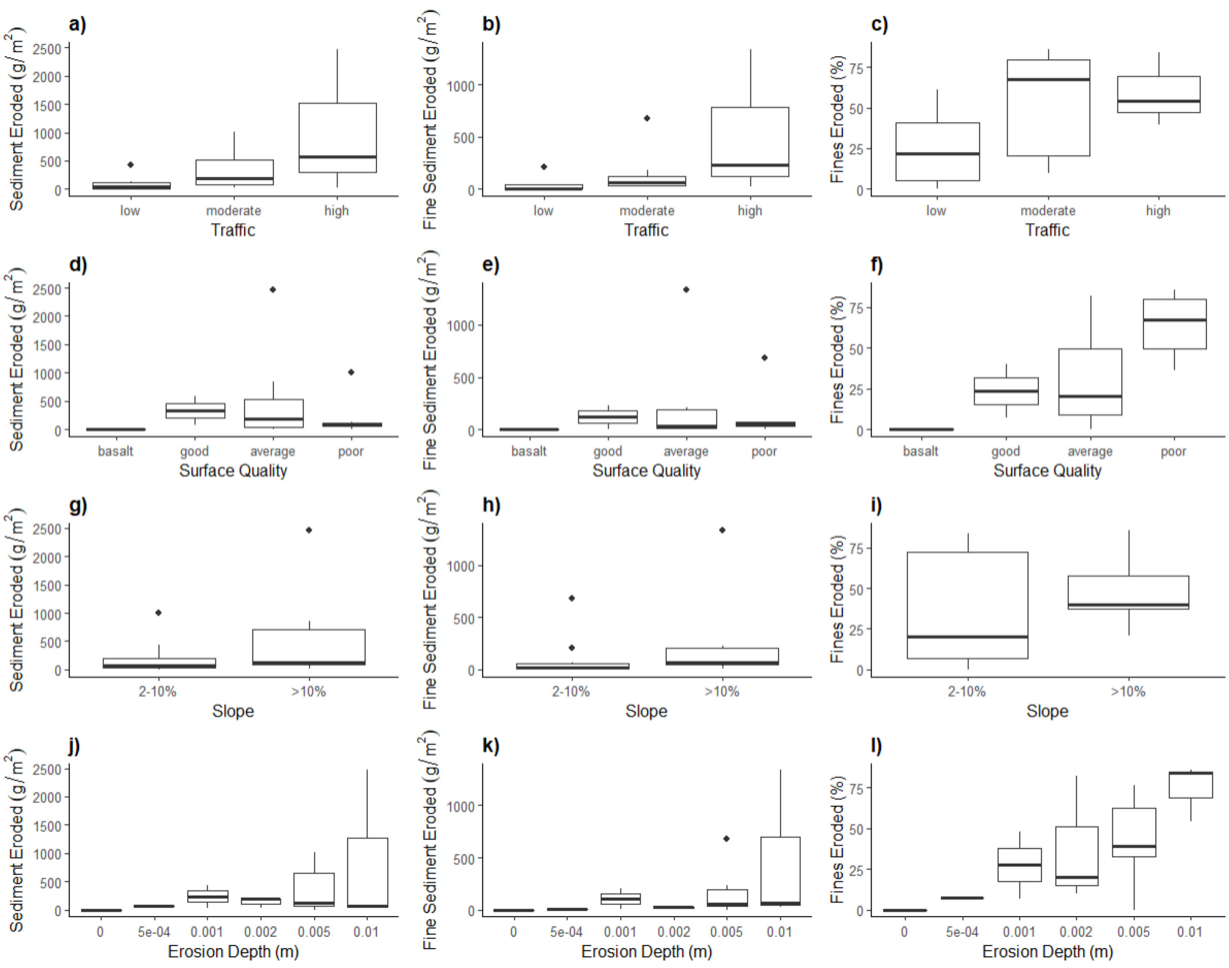

Figure 2-5 The relationship between FREP factors including traffic, surface quality, slope, and erosion depth and total sediment yields, fine sediment yields, and percent fines eroded.

Erosion risk in drinking water supply watersheds across Canada

Erosion risk ranged across the studied ecozones. The FREP surveys predicted greater erosion in western Canada (BC, Alta), specifically in the Montane Cordillera region (Figure 2-6). A Kruskal-

Wallis test confirmed that predicted sediment erosion varied across the five ecozones ($p < 0.001$) which was largely driven by greater erosion in the Montane Cordillera compared (Dunn's multiple range tests) to both Atlantic Maritimes (adjusted $p < 0.001$) and the Boreal Shield (adjusted $p = 0.01$) ecozones. The erosion from the remaining ecozones also differed from each other ($\alpha = 0.05$) however, most ecozones had a large range in the sediment erosion predicted by FREP (Figure 2-6). Regional differences were evident for the FREP elements (Table 2-4). Mean contributing area was larger in the Pacific Maritimes, Montane Cordillera, and Boreal Plains. Slopes varied across Canada but was steepest in the mountainous roads of the Montane Cordillera. Similarly, high traffic roads and poor road surfaces were most common in the Montane Cordillera (Table 2-4).

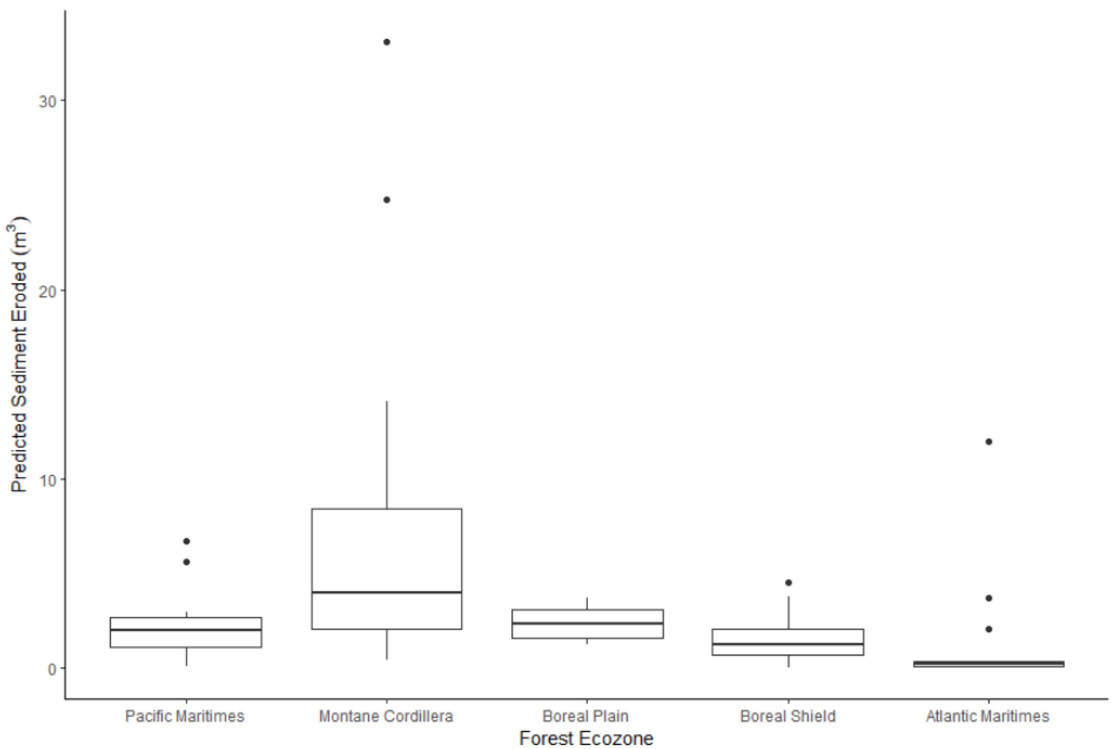

Figure 2-6 Volume of erosion estimated by the 107 FREP surveys grouped by the Forest Ecozone.

Table 2-4 Summary of factors significantly influencing FREP erosion risk from Canadas east and west coasts.

Forest Ecozone	Sample Count	Mean Area (m^2)	Mean Slope (%)	High Traffic Count	Poor Surface Condition Count
Pacific Maritimes	11	1189	3.8	0	0
Montane Cordillera	53	1042	7.1	12	22
Boreal Plain	6	1840	1.5	2	2
Boreal Shield	24	533	5.4	6	0
Atlantic Maritimes	13	437	6.1	2	2

Discussion

Survey methods for assessing erosion potential

Survey methods, such as FREP, are a cost-effective way to assess potential sediment inputs to water bodies from high-risk areas, such as road crossings (Maloney et al., 2009; Robinson et al., 2010). However, the accuracy of survey methods depends on the ability to capture and quantify the dominant processes affecting erosion. Most modeling methods use contributing area, slope, surface material, and traffic to predict sediment yields (Cissel et al., 2012; Hartanto et al., 2003; Jaafari et al., 2015; Macdonald & Coe, 2008). Similarly, the FREP method predicts erosion depth for individual sites of variable slope, traffic, and surface quality. Traffic was found to be the best FREP predictor of total and fine sediment yields measured with rainfall simulation, which is consistent with other studies that have shown a strong relationship between sediment availability and traffic level (Fu et al., 2010; Howard, 2018; G. J. Sheridan et al., 2006; Sosa-Pérez & MacDonald, 2017). Sediment production has been shown to triple with traffic and increase fine sediment availability by 2.4 times (Sosa-Pérez & MacDonald, 2017). Reducing traffic volume by controlling access not only maintains the quality of roads but also reduces maintenance frequency and the risk of sedimentation (Howard, 2018; G. J. Sheridan et al., 2006; Sosa-Pérez & MacDonald, 2017). In this study, results showed a poor relationship between road surface quality categories and measured sediment yields, which might be an artifact of the rainfall simulation method, as plots were only 1.5 m in length. Different erosion processes could dominate over longer slope lengths, potentially producing different results (Chaplot & le Bissonnais, 2000; Moreno-De Las Heras et al., 2010) (see chapter 3). Nevertheless, exceptional gravel surfacing can significantly reduce erosion from road surfaces but its effectiveness is temporary when exposed to high amounts of traffic (Bilby et al., 1989; Brown et al., 2015; G. Sheridan & Noske, 2007). This was apparent in rainfall simulations conducted near Halifax, NS, which had basalt surfacing with little to no erosion (Table 2-3). Road slope increases runoff velocity and can reduce storage capacity, providing additional energy for erosion (Darboux et al., 2002; Fox & Bryan, 1999; Howard, 2018; Ramos-Scharrón & Macdonald, 2005), thereby influencing sediment yield. However, the FREP slope categories did not strongly correlate with measured sediment yields. While slopes in Canada are dictated by topography to a certain degree, most slopes are driven by the design and implementation of BMP (Dangle et al., 2019; Edwards et al., 2016). However, when all the parameters were combined (slope, traffic, road surface quality) for the estimated depths of erosion, it did not have a relationship with total and fine sediment yields (g/m^2) (Figure 2-5). Overall, FREP parameters related well to the percentage of fines eroded, and the studied sites had a higher percentage of fine sediment eroded when roads were steeper, had high traffic, and little gravel surfacing.

In examining the effectiveness of different erosion models previous studies have found varying outcomes when comparing modeled results to field method findings. For example r^2 values of 0.5 to 0.92 were reported for WEPP, USLE, and USLE modifications (Brown et al., 2015; Mahmoodabadi & Cerdà, 2013; G. Sheridan & Noske, 2007; Wade et al., 2012). Although the FREP method did not have a clear relationship between predicted and measured sediment yields from rainfall simulations, it provides a simple but effective technique for establishing site risk. With the disclaimer that the method does not claim to be accurate but to provide an estimate of erosion within one magnitude (Maloney et al., 2009). To provide consistency in data collection, additional training is recommended if this procedure is implemented outside of British Columbia, given the subjective guidelines in the FREP method. In summary, each parameter (Figure 2-5) showed a strong trend with the percent of fines in the eroded material. Furthermore, the results suggest that best management practices related to FREP factors reduce total sediment yields (traffic) and the percentage of fines eroded (traffic, surface quality, and slope).

Road erosion in Canadian drinking watersheds

The changes in landscape, topography, and geology across Canada, influence road construction and road location within watersheds. Regional differences were observed for average slope and the road surfacing quality. For example, the mountainous region of the Montane Cordillera was found to have some of the steepest slopes (Table 2-4). Similarly, surface quality conditions changed significantly across the country, and good quality surfacing were relative based on access to materials. In regions with smaller watersheds, it was more common to have limited access and better surfaced roads. However, the regional differences were less impactful than road construction, use, and maintenance practices, as each region had a wide range in predicted sediment (Figure 2-6). For example, in the Atlantic Maritimes the lowest risk site was in Halifax, with a 2-inch gravel surfacing, low traffic, and a shallow slope. The rainfall simulations produced no runoff as the water infiltrated and dispersed without being captured in the plot. The highest predicted sediment site for the Atlantic Maritimes was in Moncton, with fine-textured surfacing, high traffic, and a steep slope, which also had a high sediment yield in the rainfall simulation. In general, roads that had limited access and were designed and maintained with strict practices to minimise water quality impacts, had low predicted and measured sediment yields.

Previous studies researching the effectiveness of BMP on gravel roads have reported reduced (modelled) sediment yields regardless of region (Dangle et al., 2019; Sugden, 2018). Research has found that BMP such as decreasing the contributing area, regulating traffic, and increasing ditch infiltration with vegetation reduces sediment delivery (Sugden, 2018). Additionally, researchers have found that high traffic on gravel roads poses a risk to sedimentation across Canada (Benda et al., 2019; Howard, 2018; van Meerveld et al., 2014). This is reflected in Figure 2-6, as each ecozone had a range in sediment yields which is most prominent in the ecozones that had varying management practices. The Montane Cordillera and Atlantic Maritimes best reflect the impact of BMP on sediment yields as predicted yields ranged from 0 to upwards of 15 and 30 m^3. Sites that had strict practices such as basalt surface quality, low traffic, and low slopes (ie: Pockwock Watersheds) produced substantially less sediment yields than those with open access, native soils, and steep slopes (ie: Moncton & Ghost Watersheds). However, there may be regional factors that limit the ability of road mangers to implement BMP (Dangle et al., 2019).

Summary and Conclusion

The FREP model produced by the British Columbia Government assists in assessing road risk and erosion potential. The FREP factors, slope, surface condition, and traffic, govern erosion depth, all of which corresponded well to the field measured percentage of fines eroded in rainfall simulations. However, traffic was the only factor that strongly correlated to total and fine sediment yields from rainfall simulations. FREP predicted sediment yields were highest when sites had steep slopes, poor surface quality, and high traffic levels, regardless of ecozone.

Each ecozone ranged in predicted sediment yields, which was driven by regional implementation of traffic controls, good road surface quality, and reduced road slopes during construction. The Montane Cordillera and Atlantic Maritimes had predicted sediment yields that were significantly different than the other ecozones. This outcome is a result of road management practices. In general, the Atlantic Maritimes had implemented more BMPs compared to other ecozones, such as regulated traffic and good road surfacing. On the other hand, the Montane Cordillera had less BMPs implemented and therefore, had more high-risk roads. The practicality and ability to implement BMPs can be impacted by watershed size, ownership, and land use. Therefore, knowing where erosion risks lie within watershed can assist managers in developing action plans to reduce road erosion risks. In summary, sediment yields, and the percentage of fine sediments eroded, are impacted by road management practices such as road surface quality and traffic. When possible, roads should be gated to regulate traffic and preserve good road surfacing to reduce road erosion potential.

Chapter 3 : Drivers of erosion on forestry roads and recreational trails in an Alberta Eastern Slopes Watershed.

Introduction

Unpaved roads are necessary for industrial development, environmental monitoring, and recreational activities in most Canadian forest regions. However, unpaved roads are known to change hydrology and impact surrounding and downstream water quality (Bilby et al., 1989; Lane & Sheridan, 2002; L. H. MacDonald & Coe, 2007). These roads have been shown to increase contributing runoff and sediment to streams (Bilby et al., 1989; Fannin & Sigurdsson, 1996; Zemke, 2016). Sedimentation is the process of sediment deposition into streams, which is dependant on road hydrology, the rainfall depth and runoff pathway characteristics including, surface roughness, vegetation, and length (Macdonald & Coe, 2008; Moreno-De Las Heras et al., 2010). Road hydrology can be categorized into two processes, overland flow, and shallow subsurface flow into ditches (Benda et al., 2019). Downstream impacts are apparent when sediment connects to waterbodies and is carried downriver. This connection is common at water crossing or from large sediment plumes connecting to streams (Thomaz & Peretto, 2016). Furthermore, fine particles less than 63 µm are of particular concern because they increase stream turbidity levels, indicating a rise in suspended sediment, and becomes a concern for water treatability (Sthiannopkao et al., 2007). Increased turbidity can affect the normal operations of a treatment facility because fine particles are less likely to settle out and travel further downstream, carrying nutrients, bacteria, pathogens, and other microorganisms (Bilby et al., 1989; Emelko et al., 2015; Reid & Dunne, 1984; Sthiannopkao et al., 2007).

The majority of Albertans, up to 92%, get their drinking water from surface water originating from forested areas (Robinne et al., 2019). Therefore, monitoring of these sediment sources is crucial to ensure clean drinking water (Sthiannopkao et al., 2007). To characterize erosion from unpaved roads and its impact on drinking water sources, researchers and industry have used erosion models and assessment procedures to predict erosion rates and sediment delivery to water bodies (Fu et al., 2010; Maloney et al., 2009; Pandey et al., 2016; Renard et al., 1991).

Erosion Models and Assessment Procedures

Models can be defined as physically or empirically based. Empirical models rely on an equation to predict sediment yields. A common empirical model is the Universal Soil Loss Equation (USLE) developed in the 1960s on farmland in the United States (Renard et al., 1991). This model incorporates area, slope length, vegetation coverage, and surface roughness to predict sediment yields (tons/hectare). Since its creation, many researchers and managers have adopted this method for road erosion (Renard et al., 1991). There have been updates to improve its accuracy, including the Revised Universal Soil Loss Equation (RUSLE), which improves the description of the erosion and hydraulic process at work (Renard et al., 1991). Other models have taken the basics of USLE and developed it into more complex models, such as the Washington Road Surface Erosion Model (WARSEM) and the ROADMOD (Fu et al., 2010). Physically based models, such as the Water Erosion Prediction Project (WEPP), use specific site features to predict sediment yields. Physically based methods typically require more data and are suitable for areas with more background knowledge on their watershed or a strong field program to obtain the necessary data (Fu et al., 2010). There are also assessment-based methods, including the Forest and Range Evaluation Program (FREP) developed by the British Columbia government, the Geomorphic Road Analysis and Inventory Package (GRAIP), and the Road Erosion and Delivery Index (READI). These assessment-based methods use basic field measurements to calculate results (Cissel et al., 2012).

Measurement techniques

Sedimentation risk is related to connectivity, which is a function of rainfall intensity, total sediment yield, and total runoff, as higher sediment yields and runoff amounts will increase the likelihood of connection (Macdonald & Coe, 2008; Maloney et al., 2009). Rainfall simulations have been a popular method of assessing road runoff, sediment erosion, and their connection to water bodies (Covert & Jordan, 2009; Iserloh et al., 2012; Jordán & Martínez-Zavala, 2008; Wischmeier & Smith, 1958). Additionally, small and large plot rainfall simulations are commonly used field methods to understand road runoff (Corrigan, 2017; Covert & Jordan, 2009; Iserloh et al., 2012). Site-specific runoff times, runoff volumes, and sediment yields are often measured by simulating rainfall conditions on unpaved roads. However, small-scale rainfall simulations are generally favoured as equipment is easier to transport and use in remote locations. Yet, there are concerns with small-scale simulations (1-1.5 m^2) as they potentially leave out crucial erosion processes such as rill erosion and re-infiltration, the process of surface water moving downslope to areas that are not fully saturated (Moreno-De Las Heras et al., 2010). Large-scale rainfall simulations (5+ m long) encompass these erosion processes but are logistically difficult to coordinate. Large plots are harder to establish, transport, require much more water, and roads may have to be temporarily closed. However, both methods are accepted for understanding the processes that contribute to erosion yield from a road segment (Covert & Jordan, 2009; Croke & Nethery, 2006; Lane et al., 2004).

Field studies have paired rainfall simulations with sweep samples to understand sediment availability (Sosa-Pérez & MacDonald, 2017). Sweep samples are taken by brushing the loose top layer of sediment into a collection pan, which are then processed for particle size analysis (Corrigan, 2017; Sosa-Pérez & MacDonald, 2017). These samples could provide insight into materials available for erosion during rainfall and potentially indicate if there should be road surface maintenance (Sosa-Pérez & MacDonald, 2017).

Unmanned Aerial Vehicles (UAVs) and remote sensing have become popular methods to obtain data about the earth’s surface, including data input for erosion models. UVAs are prevalent for forest inventories, understanding surface conditions, and topography (Baath et al., 2002; Reutebuch et al., 2005). Old or a lack of remote sensing data can become an issue, and UAVs provide a sensible solution to acquire new data. They offer an easy way to photograph and develop digital models of roads. However, understanding unpaved road details has not been a major focus with this technology. Many tools within digital surface models (DSM’s) can provide insight to road conditions, runoff patterns, how a road may erode, and support erosion model requirements. These tools include information on flow direction, surface roughness, and other necessary construction details such as length, width, and slope (Ozcan et al., 2008).

Objectives

The goal of this study was to provide new insights on hydrology and road-associated sediment production in the Ghost and Elbow Watersheds of Alberta, two sources of drinking water for the City of Calgary. Additionally, this study intentioned to validate the READI model using UAV data and two scales of rainfall simulations. Local Alberta practitioners were using READI to determine erosion risk within the Ghost and Elbow Watersheds and these objectives support the application of READI near Calgary, Alberta. The specific objectives are:

1) Directly evaluate erosion and runoff dynamics from representative unpaved roads and trails within the Ghost and Elbow River Watershed, near Calgary, Alberta.
2) Validate the runoff and sediment production predictions of the READI model using UAV data and rainfall simulations for representative road segments within the Ghost and Elbow River Watershed, near Calgary, Alberta.

Methods

Study Sites

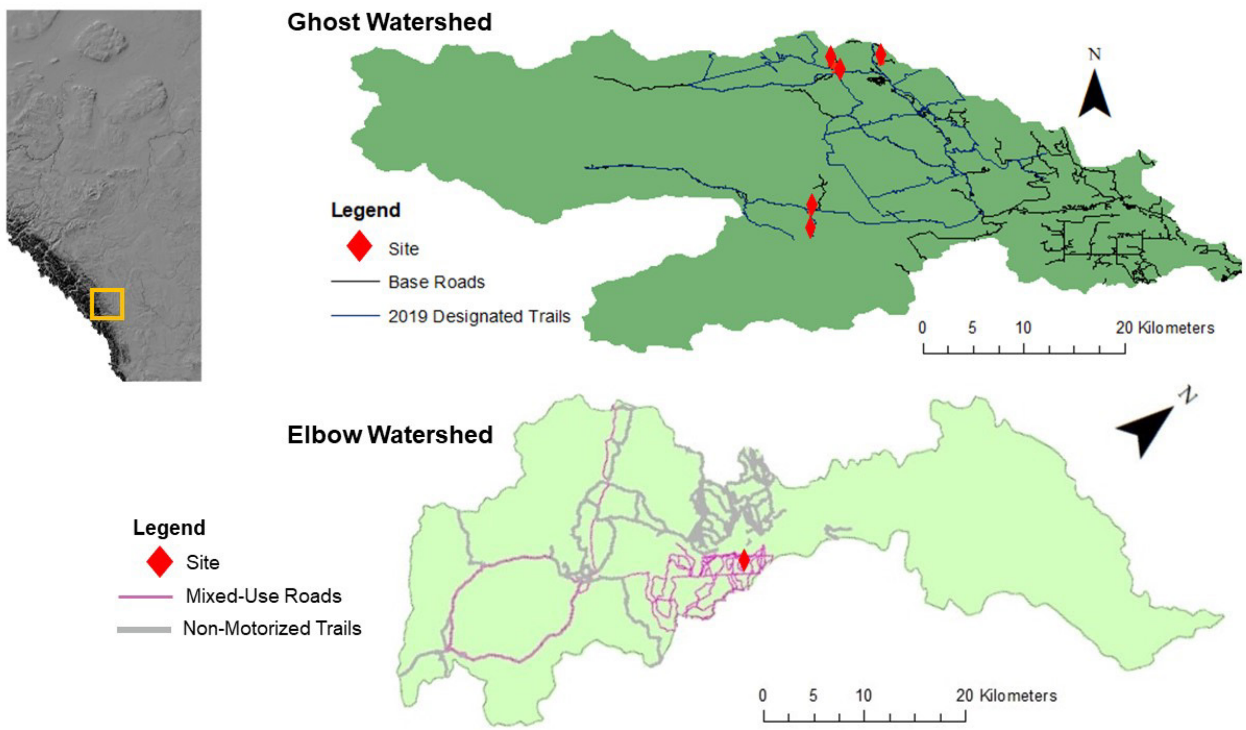

Figure 3-3-1 Map of the sites located in the Ghost Watershed, with a reference map of the general location of the watershed

The Ghost Watershed (the Ghost) is located on the Eastern Slopes of the Rocky Mountains, west of the City of Calgary. The Ghost has a drainage area of 953 km^2 and is a tributary to the Bow River, the primary water source for Calgary (ALCES Landscape and Land Use Ltd., 2011; Andrews, 2006; Bow River Basin Council, 2008). The basin transitions from the Rocky Mountains into rolling foothills then to grasslands. In 1910 the government formed the Rocky Mountain Forest Reserve covering 340 km^2 for the continued supply of timber and water for the prairie region (Andrews, 2006). The water quality in this region is relatively good, with most water quality parameters within the 'natural' to 'good' status. Excluding *Escherichia coli* (E.*coli*) and clarity, which had a 'poor' rating (Andrews, 2006; Bow River Basin Council, 2008; R. MacDonald & ALCES Landscape and Land Use Ltd., 2018). Concerns over land use impacts to water quality include potential impacts from recreation, tree harvesting, cattle grazing, and residential ownership. The remaining 613 km^2 drainage area is a heavily used Off-Highway vehicle and camping Public Land Use Zone (ALCES Landscape and Land Use Ltd., 2011; Andrews, 2006; Bow River Basin Council, 2008; R. MacDonald & ALCES Landscape and Land Use Ltd., 2018).

The Elbow Watershed (the Elbow) is located in Southwestern Alberta and supplies 40% of Calgary's drinking water. The Elbow is forested (44%) and primarily used for agricultural (16.7%) and rangeland (6.2%) purposes (Wijesekara et al., 2012). The drainage area is 1,238 $km^{2,}$ with the majority of the area within the Kananaskis Improvement District (Wijesekara et al., 2012, 2014). The Elbow River is approximately 120 km long and joins the Bow River in downtown Calgary. The Elbow River decreases in elevation from 2,000 m in the mountains to 1,000 m within the city limits, where it fills the Glenmore Reservoir (Sosiak & Dixon, 2006; Wijesekara et al., 2012). Water sampling has shown that nitrates, phosphorous, and total suspended sediment (TSS) increase within the city limits (Sosiak & Dixon, 2006). *E. Coli* sources are primarily from the forested region of the watershed, with little to no urban contribution (Sosiak & Dixon, 2006). The Elbow is also a popular spot for camping, which is regulated by permit from the Provincial Parks.

The Ghosts and Elbow watersheds have similar weather, hydrology, and geology. The Bedrock geology for the Ghost is dominantly sedimentary, including carbonates such as limestone and dolomites, and clastics including shales and sandstones (Andrews, 2006; Bow River Basin Council, 2008; R. MacDonald & ALCES Landscape and Land Use Ltd., 2018). While the Elbow watershed is underlain primarily by shale and sandstone (Manwell & Ryan, 2006). The surficial geology has been dramatically influenced by receding glaciers in both watersheds, which have alluvial formations, deposited till moraines, and kames (Bow River Basin Council, 2008; R. MacDonald & ALCES Landscape and Land Use Ltd., 2018; Manwell & Ryan, 2006). These deposits range from carbonates and quartzites to glaciofluvial gravels, sands, and silts.

Local weather stations have shown that rain is the dominant form of precipitation, at 68%, with 75-80 mm falling each month from June to August (Andrews, 2006; Bow River Basin Council, 2008; R. MacDonald & ALCES Landscape and Land Use Ltd., 2018), and accumulating 500-600 mm/year of mixed precipitation (Manwell & Ryan, 2006). The rivers are snowmelt-dominant, with large contributions from groundwater throughout the year (R. MacDonald & ALCES Landscape and Land Use Ltd., 2018; Manwell & Ryan, 2006). On average, temperatures range from -10°C in the winter to +13°C during the summer (Andrews, 2006; Bow River Basin Council, 2008; R. MacDonald & ALCES Landscape and Land Use Ltd., 2018). These areas are also prone to chinooks, where strong winds can bring in above-average temperatures during the winter months.

Site Selection

Surveys were conducted in the Spring of 2019 to determine the road types in the Ghost (surveyed in April) and the Elbow (May) watersheds (Figure 3-1). There were three types of unpaved roads identified in these watersheds, 1) permanent 4x4 trails, 2) conventional gravel roads (ungated and gated), and 3) temporary forestry roads (Figure 3-2). The road characteristics considered when selecting sites included road slope, surface material, road type and access. Roads must have a slope of 5% or higher for a successful simulation. Surfacing material ranged from native material to some form of gravel capping. Native material roads are built with local soils or subsoils and generally do not have a capped surface. Within these watersheds, native materials are most common on trails but are also seen on some unmaintained roads. Unmaintained roads receive little to no grading or gravel surfacing, leading to tire ruts, potholes, and rills, impacting road drainage.

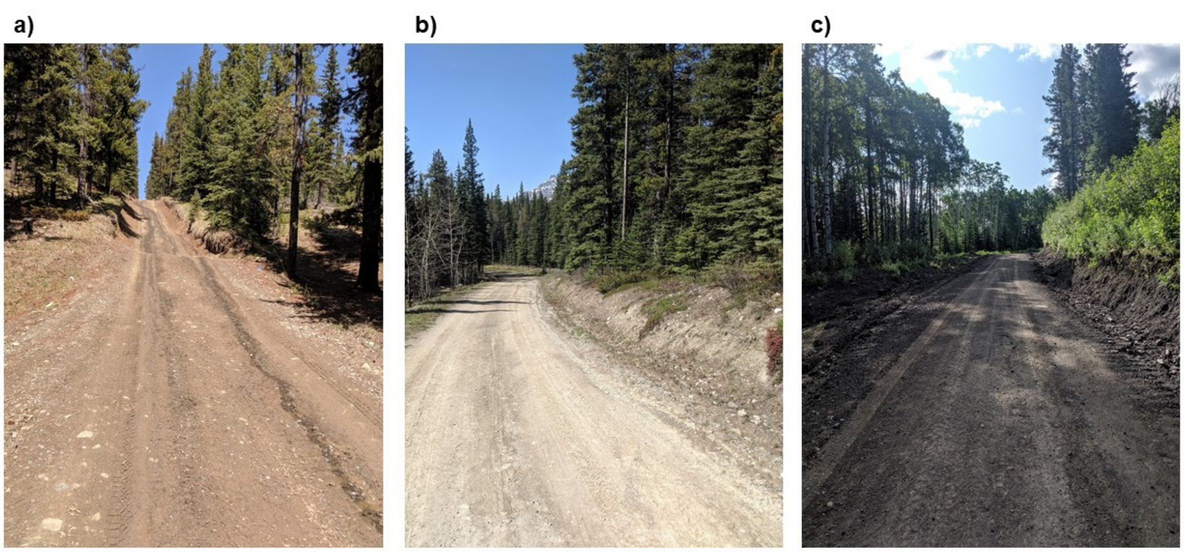

Figure 3-2 Road types with the studied watersheds. a) Permanent 4x4 trail - Waiparous Trail b) Ungated gravel road - Sutton Road c) Temporary gated gravel road - Mclean Creek Road

This study used six road segments representing the characteristics of typical road and trail types in the two watersheds that provide drinking water to Calgary (Figure 3-1). Where possible, road sections in the Ghost were selected for study sites because airspace was not UAV restricted whereas the airspace the Elbow Watershed was restricted. This study paired sites, a trail and a road within close vicinity each other. Generally, road sites had better surfacing conditions, lower slopes, varied traffic conditions and mixed access. In contrast, trails generally had poor quality surfacing, steep slopes, and higher traffic conditions from unrestricted, public access. Therefore, 4x4 trail characteristics are assumed to lead to higher erosion risks.

This study categorized sites as a road or a trail, which either had open (ungated) or gated access (Table 3-1). The slope of all plots ranged from 5 to 21%, with steeper slopes found on trails (Table 3-1). Sites ranged in width from 2 to 5 m with trails having narrower sites. Total contributing lengths ranged from 55 to 180 m (Table 3-1). Mean bulk density for these sites was 1.96, ranging from 1.33 to 2.7. Bulk density was lower for both trails and open-access sites, which also had higher erosion rates. All plots had some form of gravel surfacing ranging from average to poor quality. Road moisture conditions before rainfall simulations averaged 3.7% with a range of 1.2 to 8.3% for large plots, and 1.7% ranging from 0.7 to 2.4% for small scale plots (Table 3-1). Lastly, roughness and erodibility did not vary much between access and site type.

Table 3-1 Overview of road features for sites within the Elbow and Ghost Watersheds from surveys and rainfall simulations

Site ID	Site Type	Traffic	Access	Width (m)	Length (m)	Surface Quality	Bulk Density (g/mL)	Plot Slope (%)		Moisture (%)	
								Small	Large	Small	Large
Fire Tower	Road	Low	Gated	3	55	Poor	1.49	60	10	2.4	2.5
Mclean Creek	Road	Moderate	Gated	4	100	Poor	2.7	34	9	1.6	1.4
Sutton Road	Road	Moderate	Open	4	109	Poor	2.1	25	6	0.7	4.3
Sutton Trail	Trail	Low	Open	2	82	Poor	1.95	119	21	2.4	2.4
Waiparous Viewpoint	Road	Moderate	Open	5	180	Average	1.33	33	5	1.1	1.2
Waiparous Trail	Trail	Moderate	Open	3	61	Poor	2.21	154	18	1.9	8.3

Fire Tower Road

This unmaintained road was primarily used for fire patrol and forest management. The road had mixed access, with a gate located halfway up the hill restricting access. The study site was immediately behind a gate and had a steeper slope of 10%. The road surface material primarily consisted of gravel and organic material. Based on sweep samples, the dominant fine particle size was 0.63-2 mm. Additionally, Fire Tower Road had the lowest bulk density. The road is relatively narrow with a width of 3-meters that meanders up the hill to the wildfire lookout tower. This site has a cut slope on one side and no defined ditches. Most of the runoff pools on the road by the gate or drains onto the forest floor. The area with the highest sedimentation risk was at the bottom of the hill, where there was open access and connection to a stream.

Mclean Creek Road

A temporary forestry road was not available in the Ghost Watersheds so a road in Mclean Creek in the Elbow watershed was used. This road was once an OHV trail and has been developed into an industrial use road. Mclean Creek Road was typical of a gated temporary forest road, restricting access while it was industrially active. Once the road is no longer needed the road will be restored to its original purpose or reclaimed. In general, the road had poor drainage as it was in a low-lying area. The study site was approximately 500 m from the gate, with a 6.9% slope. The road measured 4-meters wide and had a cut slope with well-defined ditches. The surface material was a mixture of natural material and gravel, with a relatively even distribution of fine particles available. It also has the highest bulk density out of all sites.

Sutton Road

This road was primarily used for recreational and industrial purposes. An oil and gas site was located at the end of the road, and had an old cutline that became an unofficial OHV trail (Sutton Trail). Sutton Road had a range of slopes and surfacing material. The surface material varied from gravel to sand-based, which notably affected the drainage after storms. At the study site, the dominant fine surface material available was less than 63 µm. The studied segment had a 6.0% slope, a length of 109-meters, and a width of 4-meters. The road had an open canopy, partially vegetated ditching, and no contributing cut or fill slopes. Lastly, it had a moderate bulk density in relation to the other sites.

Sutton Trail

This site was representative of a low traffic non-designated trail. This trail was once a cut line for seismic exploration that intersected with Sutton Road and then used by OHV traffic. The road was surfaced with a mixture of large woody debris, gravel, and fine sediment. The sweep samples indicated that the dominant available fine particle size was ≤63 µm. Sutton Trail had a steep slope of 21.2% that flattens out in a valley. The trail was narrow, with a width of 2-meters and a length of 82-meters. The trail had canopy cover as it entered the valley, where the trail stayed saturated as there was poor drainage and little sunlight to dry it out. There was also no cut or fill slopes that could contribute to sedimentation.

Waiparous Viewpoint

This site provided insight into mixed road uses with moderate to high traffic. The Waiparous Viewpoint Road had both industrial oil and gas, and recreational users. The study segment was on the open access section before a gate for regulated oil and gas use. The slope was the least steep of all the study sites, at 5.14%. The road had a width of 5-meters, and the longest segment length of 180-meters (Table 2-1). Waiparous Viewpoint Road had no canopy cover or contributing cut slopes, and ditches were not vegetated. The dominant fine particle size available was ≤63 µm, and the site had the lowest bulk density. This road had no maintenance throughout the summer and developed tire ruts and rills as time went on, creating more accessible runoff paths.

Waiparous Trail

Waiparous Trail was a heavy use OHV trail. The trail was steep with an 18% slope and had partial canopy cover. The long hill was broken into little steps which drained runoff into the forest. The study area was at the bottom of the hill, where runoff flowed towards the main road and river, increasing the sediment delivery risk. This trail had a width of 3-meters and a length of 61-meters. The surface material was local material with fine particles between 0.63-2mm. However, this site had one of the highest bulk densities. Waiparous Trail had some recent maintenance, including a new bridge to cross the river as it had been a significant source of sediment contamination in the past.

Field Sampling

FREP Surveys

FREP surveys, road features, and measurements followed the survey method protocol as Chapter 2 Methods. The FREP procedure calculates sediment yield (m^3) as a product of surface area (m^2) and erosion depth (m), which is determined with road slope, road surfacing conditions, and traffic levels.

Sweep Samples

Sweep samples were obtained following the method presented by the United States Environmental Protection Agency (US-EPA, 1995). Sweep plots were measured with a ruler, the top layer of road material was swept into a collection pan for 30-seconds (US-EPA, 1995). Samples were taken at each rainfall simulation site. One sample was collected at the small-scale plots, and three samples were collected for large scales simulations. For large scale simulations 30 cm^2 sweep samples were taken at 5-metre spacing (5, 15 and 25 m) to incorporate any road surface changes across the plots. All sweep samples were stored in soil bags, labelled with their site name and meter, until further analysis in the lab. These samples were analyzed for physical parameters and, therefore, were not stored in a fridge. The brush and collection pan were cleaned with water and Palmolive dish soap and air-dried between sites to prevent contamination**.**

Small Rainfall Plots

Road Hydrology and Erosion Yields

The small rainfall simulation design, calibrations, distributions, drop sizes, and sample collection followed the sampling protocol as Chapter 2 Methods.

Large Rainfall Plots

Design and Sample Collection

The design presented by van Meerveld et al. (2014) was used with minor modifications to simulate rain on roads in the Ghost and Elbow watersheds. A pump pulled water from a holding tank and travelled through fire hosing to five I-WOB nozzles. The nozzles were an inverted rotating-plate, typical for agriculture irrigation. They allow for low-intensity rainfall with larger drop sizes. The I-WOB nozzles were hung 3-meters up using metal poles, tripods, and PVC tubing, placed every 5-meters down the plot (Figure 3-3, Figure 3-4). The plots spanned 30-meters in length, and the width of the roads, which ranged from 2 to 5 meters wide. Adjustments made to this simulator included water being pumped from holding tanks instead of a river, as most sites were not close enough to a stream. The nozzles were also plumbed in a loop system to reduce pressure build-up and the chance of overloading the nozzles. This study also used the whole road as the roads were narrower, and the nozzles spray covered the road's width. Lastly, the collection method was modified as most of the roads were not crowned and did not direct runoff to the ditch. Instead, a berm was constructed at the roadside to reduce water loss and directed runoff towards the collection system at the bottom of the plot. A small channel was dug out at the bottom of the plot and lined with PVC pipe and plastic carpet underlay. The plastic carpet underlay was sealed to the road using modelling clay and liquid petroleum jelly (Lane et al., 2004). The runoff was directed to a spout in the ditch where samples were collected. A 19-litre bucket was at the end of the spout to collect runoff in-between sample bottles. Once the simulator was set up, simulations rained for 30-minutes, with 1-litre sediment sub-samples collected every 2-minutes.

Runoff ratios in these experiments did not equal 1, indicating that there was some form of water loss. Water loss was mitigated as best possible at both plot scales. For small-scale simulations, the plot frame was sealed to the road with refrigerator foam. In large-scale experiments, a berm was made on each side of the road. For both scales, the collection system was sealed to the road. With these measures in place, the assumption is that water loss within the system is minimal, and most of the water loss is infiltration and some evaporation.

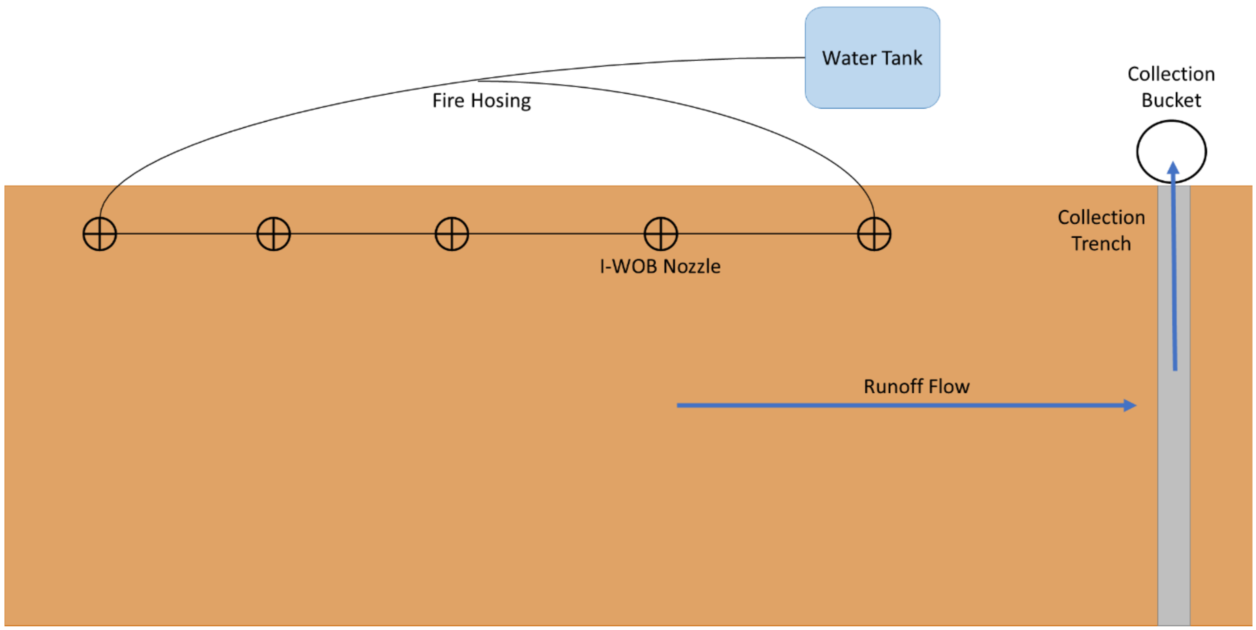

Figure 3-3 Large rainfall simulation diagram (plan view) illustrating the setup and flow of the simulator. Water is drawn from the tank with a pump to the fire hose, which is looped to prevent pressure build-up. The five nozzles are spaced 5-meters apart, connected by a fire hose. The runoff flows down the road to the trench and into the collection bucket.

a) b)

Figure 3-4 Large rainfall simulation setup with I-WOB nozzles attached to PVC pipe that rests on 3m tall steel rods supported by survey tripods spaced 5m apart. a) Trail setup b) Road setup

Intensity and Distribution

The methods for intensity and distribution were similar to the Chapter 2 small-plot methods. To document the intensity, distribution, and spatial uniformity of the large-scale plots, large buckets (RONA, 18.93 L bucket) captured rainfall at 1,3 and 5 meters away from each nozzle and between nozzles (a total of 36 buckets). The simulator was run for 5-minutes, and after shutting off the simulator, each bucket volume was measured using a graduated cylinder and recorded. This process was repeated five times at each meter for accuracy and to understand the possible range of simulated rainfall. Results showed the intensity to be 12 mm/hr (+/- 0.1 mm/min), which approximated a 2-5-year return period storm for the Calgary and Kananaskis area (Simonovic et al., 2018). In contrast to the small simulator, this setup had a pressure regulator in the nozzles but had no flow regulator. Therefore, the pump was set to full throttle and power to ensure consistent flow between experiments. The Christian-Uniformity-Coefficient-Equation (Equation 2-1) described how normal the rainfall was over the plot (Iserloh et al., 2012; van Meerveld et al., 2014). The large rainfall simulator had a spatial uniformity of 101 Cu, which falls within acceptable ranges for rainfall simulations (Iserloh et al., 2012).

Drop Size

Drop size for Large-scale experiment was determined using the staining method (Eigel & Moore, 1983; Kathiravelu et al., 2016). For this experiment, paper dusted in potassium permanganate captured raindrops from the same locations as the intensity buckets, one at each nozzle at 1, 3, and 5 meters away, to capture the potential range across the plot. While the simulator ran, the paper was exposed to simulated rain one location at a time. The paper was exposed to rainfall for 3-seconds and then covered again to stop the capture of more raindrops. The drops were then photographed, measured, and recorded. The sheets were sectioned horizontally in two and labelled 1 or 2 to measure the drops, similar to the measuring method in Chapter 2.

The average drop size was 1.1 mm ±0.6, ranging from 0.1 to 4.2 mm with a sample size of 1527 drops, obtaining the crucial minimum natural raindrop size of 0.1mm (Lu et al., 2008). This range is at the lower end of other studies, which found drops of 0.3-2.0 mm (Kathiravelu et al., 2016), 1.9-5.5 mm (Meshesha et al., 2014) and 2.4-6.2 mm (Lu et al., 2008). There were two new nozzles to cover the plot area. The new nozzles produced a smaller drop, averaging 0.4mm ± 0.2mm (n=940), while the old nozzles averaged 0.8 mm ± 0.3 mm (n=587). Drop sizes also varied based on their distance from the nozzle head. Drop sizes increased the further they were from the nozzle head. Drops 1-meter away had the most and smallest drops, averaging 0.4mm ± 0.1mm (n=1038), 3-meters away averaged 0.8mm ± 0.3mm (n=335), and drops at 5-meters away averaged 1.0mm ± 0.7mm (n=154).

Bulk Density

A standard metal ring bulk density method was used to obtain measurements at each site (Soil Quality Pty Ltd. et al., 2020). For this study, the sample area was saturated with water to help extract the sample from the road. A metal cylinder (5 cm diameter) was then hammered 5 cm deep into the road. The area around the pole was cleared using a trowel to assist in a smooth transfer of the sample to a soil bag (Systems Plus, Poly Bags). The pole was then lifted and emptied into the bag and cleared using the trowel if needed.

Remote Sensing

UAV equipment, pilot, and flight paths were all provided by the University of Calgary, Department of Geography (McDermid, G., Rahman, M., Perry, I). A drone (Ebee Classic UAV) was flown over each road and captured multiple photos (RGB Camera, Sensefly SODA). Which created a digital surface model (DSM) with a 2 cm resolution, a point cloud, and orthomosaic photos of the sites using structure-from-motion workflow inPix4D (Version 4.3.1). The accuracy of the DSMs and roughness results are reliant on the quality of data taken by the drone. Results of which can be affected if there are pools of water on the road as it will give a no-data result. Therefore, flights were completed after multiple sunny dry days to ensure dry road conditions. From the DSM, plots were extracted from the model using ArcGIS (extract tool) (ESRI, 2019). The road plots were then sent for analysis on flow patterns, using ArcGIS at the University of Calgary (Rahman, M.). The DSM was used to determine other road characteristics measurements, including width, slope related to elevation change in the DSM, and road length. There were some restrictions for UAV equipment and derived DSMs. These restrictions included no fly zones, such as the Mclean Creek area, as well as wet roads, puddles, and canopy-covered roads, as they impede the model accuracy and can cause non-data points.

Lab Analysis

The runoff samples, sweep samples, and moisture samples were processed following the ATSM D3977-97 suspended sediment concentration method (ASTM, 2013), US-EPA Appendix C-1 surface sampling method (US-EPA, 1995), and the ASTM D2216 moisture content method (ASTM, 1995), respectively. Particle size analysis was also completed on suspended sediment concentration samples. Refer to Chapter 2 for detailed methods.

Bulk Density

Field samples were oven-dried at 104°C for 24 hours in large weigh boats. The sample was then removed from the oven, cooled, and weighed (Mettler Toledo, New Classic M.F.) to the nearest decimal place. This weight was then used for the bulk density calculations (Equation 3-1).

Equation 3-1 Bulk Density

$$BD\left(\frac{g}{cm^3}\right) = \frac{Dry\ Soil\ Weight(g)}{Soil\ Volume\ (cm^3)}$$

Calculations

READI model parameters

The READI model is based off the kinematic wave formula, where time-to-concentration (tcr) is calculated with Equation 3-2.

Equation 3-2 Time-to-concentration (tcr) with infiltration

$$tcr = (nL)^{0.6} \div (I - i_s)^{0.4} \times S^{0.3}$$

Where; *n* is Manning's roughness, *L* is road segment length (m), *I* is average intensity rate (mm/hr), i_s is soil infiltration rate, and *S* is slope (%).

Equation 3-2 can be rearranged to calculate roughness for the large-scale steady-state experiment (Equation 3-3).

Equation 3-3 Roughness 'n'

$$n = [(tcr \times I^{0.4} \times S^{0.3}) \div L]^{0.6}$$

The READI model uses Manning's n as a roughness value to predict runoff. Alternatively, roughness can be calculated with Equation 3-3 from site-specific data, including percent slope (*S*), road segment length (*L*), as well as simulation, derived information including the average intensity rate (*I*), infiltration rate (i_s), and time-to-concentration (*tcr*). Runoff curves were generated from simulations, from which a steady-state runoff time was extrapolated, giving *tcr*. In this experiment, water loss is the difference between total rainfall depth and total runoff, which is assumed to be the infiltration amount.

The maximum discharge from a drain can be predicted with the equation below (Equation 3-4). Maximum discharge occurs when the time since the start of the rainfall exceeds tcr of a road segment.

Equation 3-4 Maximum Runoff (Q_{max})

$$Q_{max} = Min(v_R D, L_R)(W_R(1 - P_o)I$$

Where; v_R is the average flow velocity over the road length (length/tcr), D is storm duration, L_R road segment length, W_R is road segment width, and P_o is the portion of the road that is out-sloped, Sediment production in the READI model is a product of road surface area, slope, geology, surface material, rainfall intensity, and traffic. The model then estimates an erosion rate in mass unit per time.

Equation 3-5 Predicted Sediment Eroded (P_{SED})

$$P_{SED} = A_R S_R^n y(t,I)$$

Where; A_R is contributing road area, S_R is the slope of the road segment, which is to the exponent of n, an empirical constant between 1 and 2, and y(t,I) is the mass of sediment/road unit area/time unit.

Equation 3-6 Erosion Rate y(t,I)

$$y(t,I) = c(a + bI)$$

Where; c reflects the accumulation of erodible sediment or initial pulse of erosion, a and b are empirical constants, where a is the erosivity factor K from the USLE, and I is rainfall intensity. The erosivity factor *a* was calculated from USLE using rainfall data to solve for erosivity K and obtained from the water erosion potential of Alberta soils handbook (Agriculture Canada, 1985) to compare and validate the READI model soil production results.

Remote sensing surface roughness calculations

Surface Roughness Index was calculated using the Digital Surface Model derived from the UAV data and the Focal statistics tool within the Arc toolbox (Interreg Alpine Space NEWFOR, 2014). The Focal statistics tool calculated the standard deviation of the surface height variability. Previously, this method has been used in soil roughness and to describe topography in relation to storage capacity on gravel roads (Darboux et al., 2002; Interreg Alpine Space NEWFOR, 2014). The focal statistic tool classifies the DSM through a histogram and colours the model in coordination with the bins. The standard deviation value is then considered the roughness index (Interreg Alpine Space NEWFOR, 2014). The Mclean Creek site is excluded from DSM analysis as its location was in a no-fly zone for UAV's and requires extensive permits.

Results

Road Erosion and Hydrology in the Ghost and Elbow Watersheds

Table 3-2 Measured and predicted sediment yields, and erodibility estimates for rainfall simulation plots. Sediment Yield and Fine Sediment Yield (g/m^2) were obtained through rainfall simulations. Erodibility (k) was calculated using USLE and collected field data. Estimated FREP Erosion (m^3) and FREP Rating was determined using the FREP method. Predicted READI (g/hr) Sediment Yield, was calculated using the default local soils erodibility value and the USLE calibrated erodibility presented in column 7 (Erodibility k, Large).

	Sediment Yield (g/m^2)		**Fine Sediment Yield (g/m^2)**		**Erodibility (k)**		**Estimated FREP Erosion (m^3)**	**FREP Rating**	**READI (g/hr)**	
Site	**Small**	**Large**	**Small**	**Large**	**Small**	**Large**			**Default Erodibility**	**Calibrated Erodibility (k)**
Fire Tower	8.91	2.97	6.60	2.50	0.01	0.14	0.83	Low	45.0	126.0
Mclean Creek	25.76	1.07	15.70	0.40	0.03	0.06	4.00	Moderate	41.4	49.7
Sutton Road	92.40	46.75	61.00	31.80	0.47	4.55	2.18	Moderate	35.9	3270.5
Sutton Trail	101.7	7.50	81.70	4.20	0.03	0.10	0.82	Low	63.5	127.0
Waiparous Viewpoint	25.94	4.00	21.90	1.50	0.08	0.49	1.80	Moderate	23.1	226.7
Waiparous Trail	73.54	10.80	38.50	6.70	0.01	0.20	3.66	Moderate	134.9	539.7

Sediment yields consisted of three main particle sizes, coarse sand and gravel (>2 mm), fine sand (2-0.63 mm), and silt and clay (<0.63 mm). Fine silt-clay particles were the dominant particle size eroded, followed by fine sands for both scales of rainfall simulations. Larger particles were eroded the least, but a higher percentage of large particle were transported in the small-scale simulations. The road sweep samples were dominantly particles larger than 2 mm (59% of large-scale sweep samples and 29% of small-scale plots), followed by particles less than 63 μm. Sweep samples showed there was no relationship between the weight of sediment swept and the sediment yield. Sutton Trail produced the highest sediment yield and fine sediment yield for the small-scale experiments (Table 3-2). Sutton Road had the high sediment yield and fine sediment yield for large-scale experiments. Fire Tower Road had the lowest total and fine sediment yields for small-scale rainfall simulations. Lastly Mclean Creek had the smallest total and fine sediment yields for large-scale experiments (Table 3-2). Due to differences in sediment yield units, results are compared by rank from lowest sediment yield to highest sediment yield. Estimated FREP sediment yields did not relate measured sediment yield from either small or large scale rainfall simulations. Furthermore, FREP estimated that Mclean Creek would have the most erosion, and Sutton Trail would have the least (Table 3-2). Similarly, READI predicted sediment yields did not align with rainfall simulations when the default erosivity factor (K) was used (Agriculture and Agri-food Canada, 2016; Agriculture Canada, 1985). However, READI produced results that corresponded to rainfall simulation results when K was calculated with rainfall simulation data and the USLE equation. For example, Mclean Creek had the lowest sediment yield and READI predicted it would have the lowest production when a site-specific K was calculated.

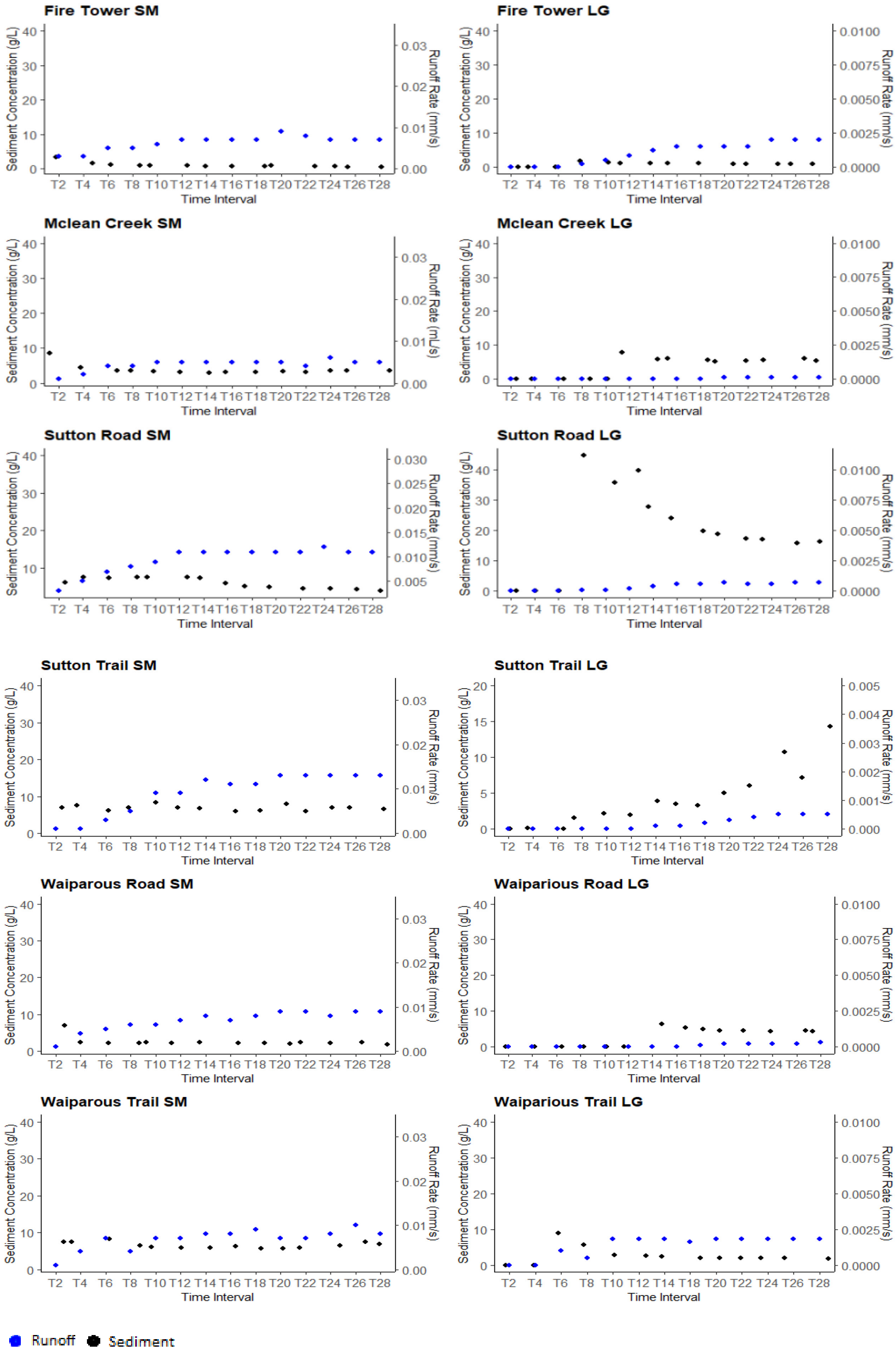

Figure 3-5 Measured runoff rates (blue) and sediment concentrations (black) for samples collected during small (SM) and large (LG) rainfall simulations.

Erosion rates followed three patterns: a steady-state of erosion for the full rainfall simulation, an increasing rate of erosion, and a decreasing rate of erosion (Figure 3-6). A steady-state of erosion occurred at both rainfall simulation scales for Fire Tower Road, Mclean Creek, Waiparious Road, and for small plots at Waiparious Trial, Sutton Road, and Sutton Trail. An increasing erosion rate was observed at the large scale for Sutton Trail. Lastly, erosion rates that started at a peak and decreased to a steady-state was observed at the large scale for Sutton Road, Waiparious Trail, and Waiparious Road. Runoff started at different time intervals based on scale. Large-scale experiments started between 8-16 minutes into the simulation, whereas small simulations started between 2-4 minutes. Runoff followed three patterns; a gradual increase to a steady state, increase with no steady state, and a steady state throughout the simulation (Figure 3-7). The first pattern was an increase to a steady state of runoff which was observed at four of the twelve plots including Fire Tower Road (small), Sutton Road (small), Sutton Trail (small & large), Waiparous Trail (large). The second pattern was an increase in runoff that did not reach a steady state, observed at five plots including Fire Tower Road (large), Mclean Creek (small), Waiparous Road (small), Waiparous Trail (small), and Sutton Road (large). The third pattern was a steady runoff for the entire simulation, observed at two plots: Waiparous Road (large) and Mclean Creek (large).

Validating the READI Model

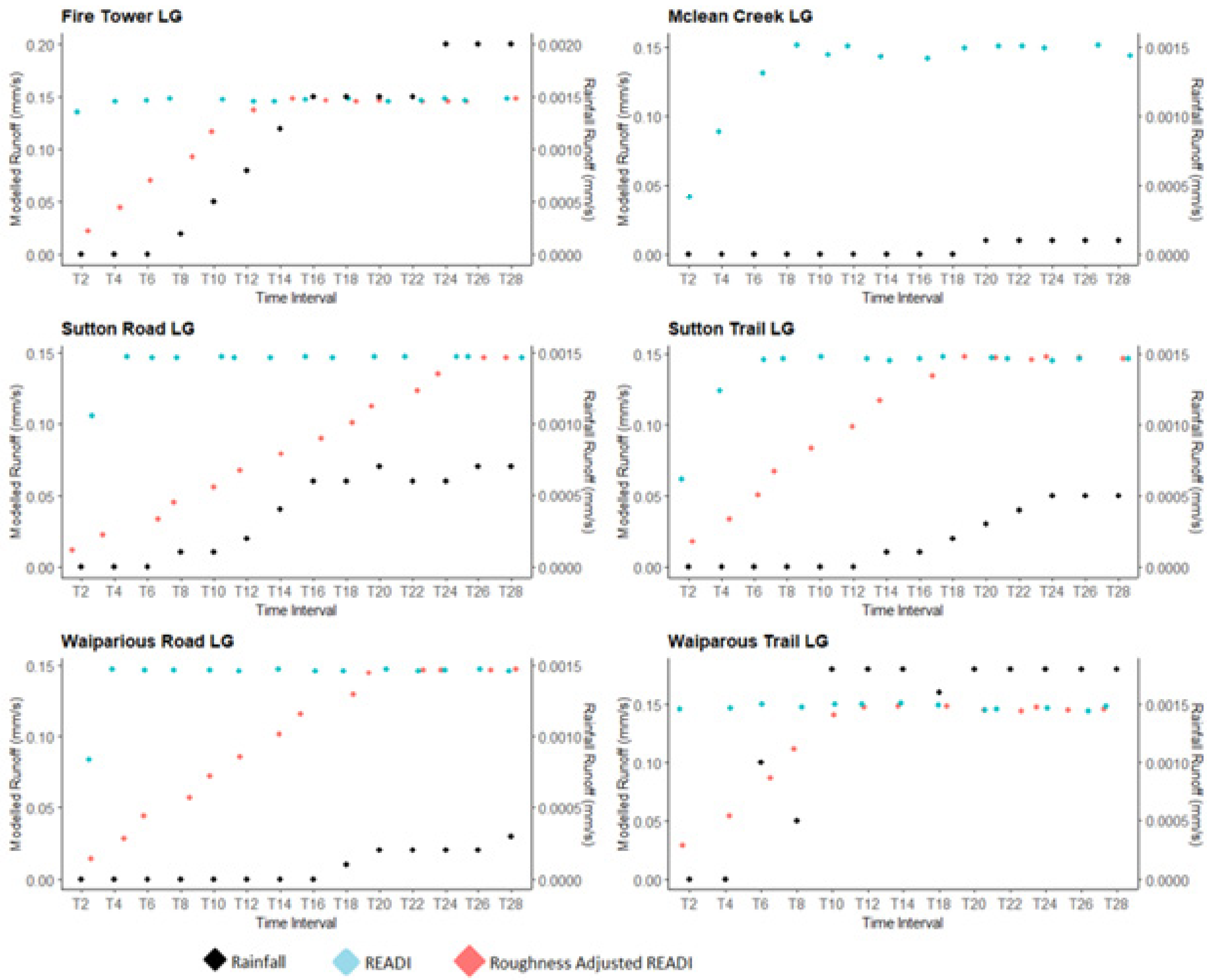

Figure 3-6 Measured and modeled runoff from rainfall simulations (black), predicted READI (blue), and READI resulted with adjusted roughness values from DSM models (red).

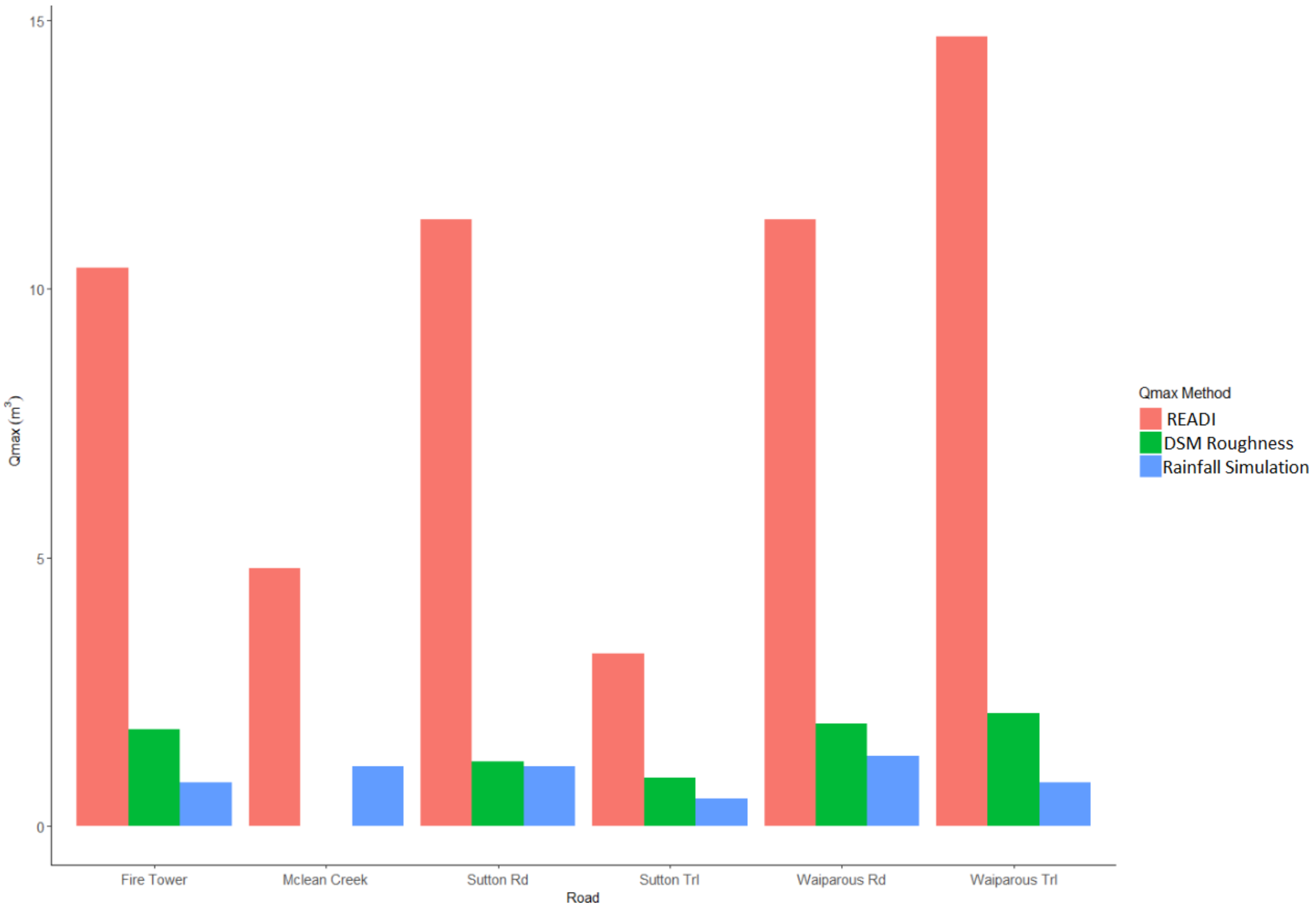

Figure 3-7 Measured and modeled maximum runoff values for; rainfall simulations (blue), READI with default roughness values (red), and READI with adjusted roughness values from DSM models (green).

Overall default roughness values in READI did a poor job at predicting time-to-concentration (tcr) and the max runoff rate (Qmax) (Figure 3-7 and Figure 3-8). On average READI predicted tcrs were 15- minutes greater than those measured from large rainfall simulation. Similarly, READI over estimated Qmax by a minimum factor of 10. However, tcr and Qmax predictions were improved when the site-specific roughness value, derived from the DSMs, were used. When site specific roughness values were used, Tcr curves followed a similar pattern as the rainfall simulations. However, the overall rate of runoff (mm/s) is about 100 times large than what was measured (Figure 3-7). Similarly, Qmax predictions were improved and within $2m^3$ of measured rainfall simulation results (Figure 3-8).

Discussion

Road Erosion and Hydrology in the Ghost and Elbow Watersheds

Road hydrology has been shown to influence sediment yields and provide insight on unpaved road connection to surface water (Baird & Schmidt, 2011; Jordán & Martínez-Zavala, 2008; Jordán-López et al., 2009; Moore & Wondzell, 2005; Seeger, 2007; Thomaz et al., 2014). For example, lower infiltration rates increase runoff which increases erosion, creating higher erosion potential. Changes in roughness either by increased vegetation or gravel, have shown to influence runoff results (Darboux et al., 2002; Hartanto et al., 2003; Helming et al., 1998). However, roughness usually reduces runoff, where results from this study showed increased runoff with increased DSM roughness. This discrepancy is likely due to the type of roughness measured, as this study focused on changes in road surface elevation (i.e. potholes) whereas previous studies have measured roughness with vegetation. The majority of the study plots followed a typical runoff pattern of increasing runoff until steady-state runoff was observed (Figure 3-6 and 3-8). Runoff typically slowly increases until infiltration capacity is reached and the runoff rate levels off (Jordán & Martínez-Zavala, 2008; Zemke, 2016). The only study plot that produced a different pattern was Fire Tower Road (large). Fire Tower Road had an increasing runoff that plateaued at different levels of steady-state, potential due to the surface roughness and storage capacity of the degraded road surfacing. This runoff pattern is not commonly observed in the literature, as most studies show one steady-state achieved or a continuously increasing rate (Jordán & Martínez-Zavala, 2008; Ramos-Scharrón & MacDonald, 2007; Sosa-Pérez & MacDonald, 2017; Zemke, 2016).

All sites and scales showed sediment concentrations decreased, and runoff rates increased during simulations, suggesting that the road plots were sediment limited supply scenario (Baird & Schmidt, 2011; Bilby et al., 1989). It is common for sediment loss to peak at the beginning of a rainfall event and decrease to a steady state (Benda et al., 2019; Costantini et al., 1999; Reid & Dunne, 1984; van Meerveld et al., 2014). In this study, sediment pulses occurred at the beginning of select simulations, and steady-state sediment concentrations were reached at 6-10 minutes and 12-16 minutes for small and large plots, respectively; aligning with other studies at 8-20 minute for steady states (Jordán & Martínez-Zavala, 2008; Jordán-López et al., 2009; Sosa-Pérez & MacDonald, 2017). Peak soil loss has been observed at 8-10 minutes into a rainfall simulation for road segments with slopes greater than 11% (Fox & Bryan, 1999; Jordán & Martínez-Zavala, 2008), similar to the results here for Sutton Road, Waiparous Road, and Waiparous Trail. The lag in time for erosion to occur is due to the time is takes for the road surface to saturate and particles to detach (Jordán & Martínez-Zavala, 2008). However, many of the other study plots did not follow this common peak to steady-state sediment curve. Plots that had a steady erosion rate throughout the rainfall simulations, including both plot scales at Fire Tower Road, Mclean Creek, Waiparious Road, and for small plots at Waiparious Trial, Sutton Road, and Sutton Trail (Figure 3-6). These were likely more influenced by the lack of traffic and grading, as reduced traffic and grading conditions has been shown to decrease sediment yields (Ramos-Scharrón & Macdonald, 2005; Reid & Dunne, 1984; Sosa-Pérez & MacDonald, 2017; van Meerveld et al., 2014). Sutton Road Large had an increasing erosion rate throughout the rainfall simulation (Figure 3-6), this is likely an outcome of the rainfall simulation time which did not last long enough to reach steady-state. Notably, fine sediment (<63 µm) consistently dominated sediment yields up to 69% at both plot scales. This is similar to other studies where fines (≤ 20 µm) contributed up to 80% of sediment yields (Bilby et al., 1989; Costantini et al., 1999). These silt-clay particles are a threat to water treatability due to their ability to stay suspended in waterbodies and disrupt the treatment process (Dearmont et al., 1998; Holmes, 1988; Sthiannopkao et al., 2007). A small increase in turbidity has the potential to raise treatment costs by affecting the amount of chemicals used, and reduce storage capacity in reservoirs (Dearmont et al., 1998; Sthiannopkao et al., 2007).

Overall, the small-scale rainfall simulations produced sediment yields similar to other studies on gravel road with a comparable plot size (Table 3-4). Although this study had steeper slopes compared to the studies presented in Table 3-4, peak flows were within a similar range (Howard, 2018; Jordán & Martínez-Zavala, 2008). Minimal large-scale rainfall simulations have been published on unpaved roads. Based on the few studies, the sediment yields from large plots measured were on the lower end of reported values (Table 3-4) (Baird & Schmidt, 2011; Costantini et al., 1999). Similarly, runoff ratios were lower than those reported by Baird & Schmidt (2011), despite using a rainfall simulator based on the methods presented in that study.

Table 3-3 Rainfall simulation sediment yields and runoff rates compared to other rainfall studies completed on unpaved roads

Small Scale Rainfall Simulations

Study	Intensity (mm/hr)	Plot Size (m^2)	Plot Slope (%)	Sediment Yield (g/m^2)	Hydrology (mm/hr)
Alberta, Canada Howard	22.5	1.0	5.2 - 32	1.2 – 636.5	*Peak Flow:* 10.26-56.09
Colorado, USA Sosa-Perez & MacDonald	44	1.0	4 - 10	43 - 103	*Infiltration:* 2-8
Sierra de Luna Mountains, Spain Jordan &Martinez-Zavala	72	0.625	0.68 - 2.5	20.1 - 22.2	*Peak Flow:* 77.8 – 135.4
Elbow/ Ghost Watershed	37.2	1.5	25- 154	8.9 – 101.8	*Peak Flow:* 30.72 – 47.28

Large Scale Rainfall Simulations

Study	Intensity (mm/hr)	Plot Size (m^2)	Slope (%)	Sediment Yield (g/m^2)	Runoff Ratio
British Columbia, Canada Baird. E et al.	*Nozzle 6*: 4.7-7.3	150	3-5	11.9 - 26.5	0.8-1.2
	Nozzle 11: 16.6-18.1			60.8 – 82.8	0.9-1.0
Queensland, Australia Costantini, A et al.	81.1 - 109.2	6	4.8-12.45	44.5 - 287.6	N/A
Elbow/ Ghost Watershed	*Nozzle 11:* 8.8	60 - 150	5-21	4.0 - 46.75	0.04-0.9

Validating the READI Model

Modelling road erosion has been popularized because of its low labour costs and the ability to predict sediment yields in various conditions and scales (Mhangara et al., 2012; Seutloali & Reinhard Beckedahl, 2015; Wade et al., 2012). Coupling the models with rainfall simulations has proven to validate methods and provide more details on the erosion processes (Mahmoodabadi & Cerdà, 2013; Seeger, 2007; Wade et al., 2012). Previously in Alberta, the READI model has been used to estimate erosion and sediment delivery from the Simonette River, Oldman, Bow River, Upper Saskatchewan, and Red Deer River Watersheds (Fath & Anderson, 2020; TerrainWorks Inc. & Foothills Research Institute, 2018b, 2018a). Overall, the READI sediment production results (Equation 3-6) using the USLE calculated erosivity factor in the Elbow and Ghost Watersheds are within the previously modelled ranges 0.00 – 4775.00 (Fath & Anderson, 2020; TerrainWorks Inc. & Foothills Research Institute, 2018b, 2018a). READI predicted sediment production using a default soil erosivity value based on the native soil in the area showed to be substantially lower than predictions using the calculated K value (Equation 3-6, 3-7), but still within the previously modeled sediment product range. Additionally, the READI model had a positive relationship with rainfall simulation sediment yields when ULSE K value were used. For example, Mclean Creek produced the lowest sediment yield in rainfall simulations, followed by Fire Tower and Waiparous Viewpoint. This was similar for sediment yields predicted by the READI Model (Table 3-2). This difference in predicted sediment production was expected because unpaved roads are usually capped with gravel which will have a different erosivity factor than native soils. However, it should be noted that the READI model did not perform as good under default roughness parameters.

The READI modeled and rainfall simulation measured tcr's did not fully align (Figure 3-7) (Equation 3-2). It is hypothesized that this difference is because the type of flow that occurs on these roads, the amount of water loss, and the roughness coefficients. Manning's roughness coefficient 'n' used in READI, is most suited for sheet flow (Equation 3-2, 3-4) (Natural Resources Conservation Services, 2010), where rill flow was more commonly observed for these sites. DSM derived roughness values showed potential in replacing manning's n within the READI model, as the predicted tcr's were much closer to measured rainfall simulation tcr's. By replacing manning's n, Equation 3-2 can be tailored for a specific site and potentially give more accurate runoff results and sediment yields based on that location's roughness. The DSM roughness was not substantially different from roughness values derived from rearranging the READI model (Equation 3-3). Suggesting that the DSM model is accurate in analyzing the road roughness when using the standard deviation method. UAV data paired with the READI model showed an excellent alternative to field methods such (Chaplot & Le Bissonnais, 2000). Although the time of runoff became more accurate, runoff volumes were still different between measured and modeled results with READI runoff volumes 100 times higher than measured volumes (Figure 3-7). This suggests that there is some form of water loss in the rainfall simulation system that is not captured in the tcr modeling. Tcr does include infiltration into the road, yet this is not fully capturing what is happening on the road. Runoff could be retained on the road segment in potholes on the road stopping the runoff from reaching the discharge location and small amounts could be evaporating off the road.

Summary and Conclusions

This study aimed to understand (1) road erosion and road hydrology within the Ghost and Elbow watersheds, and (2) calibrate and validate the READI model with UAV data and rainfall simulations, respectively. (1) In general, most road plots had runoff rates that increased to a steady-state over the course of a 30-minute rainfall simulation. Runoff started between 1-4 minutes for small rainfall simulations, and 8-10 minutes for large scale plots. Additionally, peak flows, runoff ratios, and sediment yields were within the range of results presented by other rainfall simulation studies. Most sediment yield curves followed the common sediment pulse at the beginning of a rainfall events, that decreased to a steady-state of erosion. These sediment yields were dominated by fine particles less than 63 µm, which poses a threat to drinking water treatability. (2) The READI model did a poor job at predicting, time-to-concentration, maximum runoff, and sediment production with default values when compared to rainfall simulations on roads within the Calgary Watersheds. However, UAV data showed to be successful at obtaining site specific roughness values through DSM's and improved runoff predictions from the READI model. Additionally, when site specific erodibility values were substituted for default values, sediment predictions had a positive relationship with sediment yields produced by rainfall simulations. Overall, the READI model performed poorly within the Ghost and Elbow watersheds without site specific roughness and erosivity values, potentially making the model less viable for road managers is these values cannot be easily obtained.

Chapter 4 : Synthesis

Unpaved roads are essential for industrial development, watershed monitoring, and recreational purposes. However, these roads pose a threat to water quality, notably in watersheds that provide drinking water to downstream populations. Unpaved roads become a problem when they erode during rainfall events and connect to water bodies, contaminating surface water with sediment and other contaminants it may carry. Water treatment facilities downstream face a significant challenge when sediment yields are predominantly composed of particles ≤ 63 μm, as these particles have a lower likelihood of settling out. Contamination can further increase the cost and complications of water treatment. These issues impact areas where heavy rainfall and high turbidity have increased fine sediment transport and, therefore, sludge removal from reservoirs (Sthiannopkao et al., 2007). Increased turbidity also increases the use of chemicals to treat the water, every 1% increase in turbidity chemicals, costs increase by 0.25% (Dearmont et al., 1998). Large pulses of sediment during rainfall events can cause facility shutdowns and boil water advisories. While upgrading the treatment facilities is an option, it is expensive and is not always within a water provider's budget. Therefore, municipalities and watershed managers have turned to managing their source watersheds and putting effort into protecting source water (ie: Vancouver, Victoria CRD, and Halifax). With sedimentation impacts seen across the globe (Braune & Looser, 1989; Corrigan, 2017; Rummer et al., 1997; Schleiss et al., 2016), it is evident that we need to understand, assess, and manage our source watersheds to help predict and reduce these impacts.

Assessment procedures and models assist watershed and road managers understand the risk roads pose on water quality by quantifying erosion and sediment delivery rates. Field procedures such as rainfall simulations, sweep samples, settling ponds, and road surveys provide erosion and sediment delivery data (Black & Luce, 2013; Brown et al., 2013; Covert & Jordan, 2009; McFero Grace, 2005; US-EPA, 1995). These procedures provide a range of detail from contributing area characteristics to hydrological and erosion information. Furthermore, erosion models using field data or default values within the models can estimate erosion and delivery rates. These models include the Universal Soil Loss Equation (USLE), and its revisions, the Water Erosion Prediction Project (WEPP), Road Erosion and Delivery Index (READI, and the Forest and Range Evaluation Program (FREP), and others (Benda et al., 2019; Croke & Nethery, 2006; Fu et al., 2010; Maloney et al., 2009). All which range in complexity of input data and the type of results they produce. The objectives, the historical data one has, and the ability to run a field program to get missing data, drive the suitability of each method.

This study aimed to assess and understand the risk unpaved roads have on Canada's surface waters. With the knowledge that headwater systems are critical for drinking water supply and fine particles from road erosion impact the quality of surrounding waters. This study explored unpaved road erosion and the factors controlling erosion in Canada using the FREP method and rainfall simulations and compared the two methods (Chapter 2). Additionally, small- and large-scale rainfall simulations, the READI model, and Digital Surface Models (DSMs) were used to validate and compare method results and understand erosion and hydrology in source watersheds of Calgary, Alberta (Chapter 3).

Assessment of Erosion Risk across Canada

The impact of road sediment on drinking water sources in Canada is not fully understood, therefore, this study aimed to characterize the main factors affecting erosion risk of unpaved roads in Canada using the FREP method and rainfall simulations. The study's objectives were to (1) evaluate erosion risk using FREP, (2) validate the results with rainfall simulations, and (3) determine what factors impact sediment yield. 107 FREP survey assessments along with 22 small scale rainfall simulations were completed across Canada in forested watersheds that were a source for drinking water.

This study used FREP surveys and rainfall simulations to identify and characterize the main FREP factors impacting erosion risk and validate FREP with rainfall simulation results. Additionally, the relationship between rainfall simulations and the FREP factors (contributing area, slope, traffic, and surface quality) was also explored. To determine the accuracy of the FREP model small-scale rainfall simulations were completed on selected survey sites that met the slope, traffic, and water supply requirements. The rainfall simulator had a calibrated intensity of 36 mm/hr with 82% of uniformity, representing an avaerage 10–25-year return period for Canada. Rainfall simulations lasted 30 minutes, with runoff samples collected every 2-minutes. Samples were analyzed in the lab for suspended sediment concentration and particle size distributions.

Regional differences were observed for FREP factors such as contributing area, slope, road surface quality, and traffic. A Kruskal-Wallis test showed that the Montane Cordillera was significantly different from the Atlantic Maritimes and the Boreal Shield in terms of predicted sediment erosion, while the other ecozones did not have significant differences. The FREP surveys showed that the site with the highest predicted erosion was in the Montane Cordillera region. The Montane Cordillera had the largest contributing area, steepest slopes, poor road surfaces, and high traffic roads.

Rainfall simulations occurred on 18 roads in 4 ecozones across Canada. The simulations showed sediment yields ranged from 0 to 1004.9 g/m2. One in the Atlantic Maritimes and one in the Boreal Shield, showed no signs of erosion. The site with the highest erosion was in the Atlantic Maritimes with 54% of the sediment yield consisting of fines. The site with the highest amount of fine sediment eroded (86%) was on a trail the Montane Cordillera, while the road with the least amount of fines eroded was in the Boreal Shield.

FREP assessments and rainfall simulations proved that sediment yields predicted by FREP did not correspond with small-scale rainfall simulations sediment yields. However, the FREP factors, slope, traffic, surface quality, and erosion depth aligned well with the percentage of fines eroded. In summary, the FREP model is straight-forward and provides a simple, cost-effective way to determine site risk. Allowing road and watershed managers to make more informed decisions on road maintenance and upgrades.

Evaluation of Factors Influencing Road Erosion near Calgary, Alberta

This study aimed to characterize the main factors affecting erosion risk of unpaved roads in the Ghost and Elbow watersheds using the FREP survey method, rainfall simulations, and the READI model. The local government has utilized the READI model, thus this study aimed to validate the use of this model within these watersheds.

This study used small- and large-scale rainfall simulations, Unmanned Aerial Vehicles (UAVs), and the FREP method to collect field data. Small- and large-scale rainfall simulations are common methods for model validation and understanding sediment yields (Jordán-López et al., 2009; Lane et al., 2004; Sosa-Pérez & MacDonald, 2017; van Meerveld et al., 2014). UAVs and remote sensing have become popular methods to obtain data surface and spatial data and values for models, including flow direction, surface roughness, and other construction details such as length, width, and slope (Akay et al., 2008; Bartsch et al., 2002; Bhattarai & Dutta, 2007; Chen et al., 2011).

This study completed six small- and large-scale rainfall simulations and five UAV flights within the Ghost and Elbow watersheds, to characterize runoff and erosion within Calgary's watersheds and determine what factors influenced sediment yields. UAV data informed the Digital Surface Models (DSMs), used to obtain site-specific roughness values. The substitution of default values for site-specific roughness values in the READI model allowed for the assessment of their affect on time-to-concentration (tcr) and sediment yield predictions. Lastly, this study compared rainfall simulation runoff results to READI model tcr predictions, both original and roughness adjusted tcr's.

Rainfall simulation results showed that runoff reached steady sediment concentrations by 10-18 minutes for small plots and 16-24 minutes for large plots. The READI predicted that rainfall would steady-state would start (tcr) at 2 minutes with default roughness values. However, when applying UAV roughness values, predictions became more align with rainfall simulation results, predicting tcr's at 12-26 minutes. Similarly, READI predicted sediment results with default erodibility were lower than measured sediment yields. However, substituting USLE erosivity (K) with site specific factors, results were similar to rainfall simulations. Although sediment yield units from READI and rainfall simulations were not directly comparable, arranging sites from least to highest sediment yields showed results aligned.

Overall, tcr and sediment yields results from rainfall simulations and READI modelled did not align, unless site specific roughness and erosivity values replaced default values. However, this could be a phenomenon within the Ghost and Elbow watersheds based on road construction and maintenance. Site specific values may not be necessary on roads with sheet flow, conditions that are ideal for manning's n roughness.

Management Implications

The assessment of road erosion is valuable for understanding the impacts of road management practices on water quality. Sediment yields vary across Canada and within watersheds, highlighting the importance of considering local conditions when assessing road erosion impacts. In Canada, sediment yields predominantly consists of particles ≤ 63 μm and results showed it related to traffic volume and road surface conditions. Areas with higher erosion risk typically showed steep slopes, heavy traffic, and poor road surfacing. The Forest and Range Evaluation Program (FREP) and Road Erosion and Drainage Index (READI) models offer valuable tools to understand road erosion risk. These models assist in assessing sediment yields, providing useful insights for decision-making by road managers. The selection of the appropriate method depends on the objectives and the available information to effectively address road erosion challenges.

The FREP road erosion model is an efficient and simple assessment procedure which can be beneficial for road managers. FREP allows users to promptly evaluate sediment yields and make initial comparisons between selected sites, providing valuable insights for prioritizing erosion management efforts. Overall, while the road erosion model offers a rapid assessment approach, road managers should consider its limitations when seeking detailed erosion predictions.

The READI model aims to provide detailed results regarding hydrology and sediment dynamics (Benda et al., 2019). However, when applied to the specific road conditions studied, the model did not perform as expected in predicting tcr and sediment production. It became evident that the model's accuracy relies on site-specific values to yield more accurate results when roads do not conform to the sheet flow assumptions. Nevertheless, using site-specific road roughness values from UAV data, the model demonstrated a good correlation with rainfall simulations. Suggesting the model has potential for providing reliable predictions when calibrated appropriately. The READI model, despite its high data demands, holds potential benefits for road managers as it offers valuable insights into the hydrological processes and sediment dynamics occurring on roads, aiding in the development of effective erosion control strategies and maintenance plans.

Future Research

While this study answered broad research objectives regarding unpaved road risk within Canada, the controlling factors on road erosion within Calgary's source watersheds, and how sampling methods and models compare. Knowledge gaps remain concerning:

- Detailed studies within watersheds to observe sediment impacts and road contributions,
- The applicability of FREP in other Provinces related to road management such as maintenance and upgrades,

- Assessment of the READI model’s ability to accurately predict sediment delivery, and if site-specific values impact the model’s accuracy in other watersheds.

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Appendix A: FREP results from all sites

Ecozone	Road Name, Province	Surface Quality	Slope (%)	Traffic	FREP Predicted Sediment (m^3)
Pacific Maritimes	15S, BC	Average	7.0	Low	2.15
	Deception Bridge, BC	Average	3.5	Moderate	0.51
	Goldstream Bridge, BC	Average	3.5	Moderate	1.55
	Goldstream G1067, BC	Good	1.7	Moderate	2.39
	Goldstream G2494, BC	Average	7.0	Low	2.01
	Goldstream G2495, BC	Average	3.5	Low	2.98
	Horton Creek, BC	Average	5.2	Low	5.64
	Leechtown Beesting Creek, BC	Average	1.7	Low	1.85
	Leechtown Clear Creek, BC	Average	1.7	Low	0.10
	Leechtown S145, BC	Average	1.7	Low	0.65
	Rithet Bridge, BC	Average	5.2	Moderate	6.70
Montane Cordillera	734 & Stud Creek Intersection, AB	Average	3.7	High	3.70
	Baltic Branch A Culvert, BC	Average	2.4	Low	2.40
	Baltic KM 30, BC	Average	13.2	Moderate	13.20
	Benjamin Creek Branch Bridge, AB	Poor	7.0	Low	7.00

Ecozone	Road Name, Province	Surface Quality	Slope (%)	Traffic	FREP Predicted Sediment (m^3)
	Benjamin Creek Branch Culvert, AB	Poor	2.6	Low	2.60
	Benjamin Creek Fallen Timber Bridge, AB	Average	2.6	Moderate	2.60
	Branch E Culvert, BC	Poor	10.3	Moderate	10.30
	Bridgeland Bridge, AB	Average	10.5	Low	10.50
	Bridgeland KM 1, AB	Poor	13.2	Low	13.20
	Bridgeland KM 2, AB	Poor	2.3	Low	2.30
	Bridgeland KM 3, AB	Poor	5.8	Low	5.80
	Bridgeland KM 4.5, AB	Poor	7.3	Low	7.30
	Bridgeland KM 6, AB	Average	7.7	Low	7.70
	BT-22 Bridge, BC	Poor	3.5	Moderate	3.50
	Coldstream Cross Drain KM 3, BC	Average	8.7	High	6.13
	Creek Rd Bridge, AB	Average	8.9	Low	2.05
	Creek Rd Cross Ditch, AB	Average	6.3	Moderate	1.05
	Fire Tower Rd, AB	Poor	10	Moderate	0.83

Ecozone	Road Name, Province	Surface Quality	Slope (%)	Traffic	FREP Predicted Sediment (m^3)
	Forster KM 20, BC	Average	2.7	Moderate	6.95
	Forster KM 36, BC	Poor	2.3	Low	1.45
	Forster KM 38, BC	Poor	0.8	Low	0.41
	Forster North Bridge, BC	Average	12.3	Low	12.72
	Forster North Culvert, BC	Average	1.4	Moderate	3.68
	Forster KM 22 Bridge, BC	Good	11.6	High	9.60
	Harold Creek Branch, BC	Average	4.7	Moderate	1.79
	Harold Creek Culvert, BC	Good	0.8	High	2.28
	Houle Bridge, BC	Average	12.3	Low	2.00
	Houle Rd Culvert 1, BC	Average	10.5	Low	6.90
	Houle Rd Culvert 2, BC	Average	11.6	Moderate	8.90
	Houle Rd Culvert 3, BC	Average	5.3	Low	3.30
	Husky Rd KM 3, AB	Poor	3.5	Moderate	6.43
	Husky Rd KM 6, AB	Poor	3.4	Moderate	11.00
	Jumping Pound Rd Culverts 1, AB	Good	3.8	High	11.12

Ecozone	Road Name, Province	Surface Quality	Slope (%)	Traffic	FREP Predicted Sediment (m^3)
	Jumping Pound Rd KM 4, AB	Average	6.8	High	13.55
	Jumping RD Bridge KM 20, AB	Good	12.3	High	5.17
	K Rd KM 14, BC	Average	6.1	Low	1.90
	K Rd KM 13, BC	Average	3.8	Low	1.28
	Mark Crk North KM 17, BC	Average	9.3	Moderate	2.30
	Mark Crk North Bridge, BC	Average	4.7	Moderate	3.24
	Mark Main KM 16, BC	Poor	6.9	High	4.48
	Matthew Rd, BC	Average	2.3	Moderate	1.45
	Mclean Creek, AB	Poor	8.4	High	4.00
	Shortcut Billy goat crossing, BC	Average	9.6	Low	2.13
	Sutton Rd, AB	Poor	6.0	Moderate	2.18
	Sutton Rd Culvert, AB	Poor	0.5	Moderate	0.55
	Sutton Rd Natural Drainage 1, AB	Poor	15.1	Low	2.60
	Sutton Trail, AB	Poor	21.2	Low	0.82
	Trans Alta Bridge, AB	Poor	4.0	High	7.15
	Trans Alta Natural Drainage 1, AB	Poor	5.9	Moderate	9.00

Ecozone	Road Name, Province	Surface Quality	Slope (%)	Traffic	FREP Predicted Sediment (m^3)
	Trans Alta Natural Drainage 2, AB	Average	10.5	High	8.45
	Trans Alta RD Ford, AB	Average	5.6	Moderate	33.10
	Waiparous Trail, AB	Poor	18	High	3.66
	Waiparous Viewpoint, AB	Average	5.1	Moderate	1.80
Boreal Plains	Airport Rd, AB	Poor	1.0	Low	3.18
	Harmon Rd KM 21, AB	Average	4.2	High	1.25
	Harmon Rd KM 5, AB	Average	0.2	Moderate	2.88
	HWY 686, AB	Good	0.2	High	1.50
	Industrial Rd Bridge, AB	Poor	2.4	Moderate	1.80
	Powerline Trail, AB	Average	1.1	Moderate	3.70
Boreal Shield	103 Rd, QC	Average	5.6	Low	1.05
	108 Rd, QC	Average	4.8	Moderate	2.04
	33 Rd Bridge, QC	Average	7.2	High	3.75
	369 Rd Bridge, QC	Average	3.5	Moderate	0.68
	73 Rd Bridge, QC	Average	3.8	Moderate	1.80
	Bear Narrows Blk, ON	Average	3.8	Moderate	0.88
	Bear Narrows Branch, ON	Average	2.1	High	1.10

Ecozone	Road Name, Province	Surface Quality	Slope (%)	Traffic	FREP Predicted Sediment (m^3)
	Bear Narrows Bridge, ON	Average	4.1	High	3.75
	Cascades Branch, ON	Average	11.9	High	4.56
	Dore Lake Bridge, ON	Average	8	Moderate	1.37
	Dutton Rd, ON	Average	8.2	Moderate	2.04
	Havelock Rd, ON	Average	7.5	Moderate	2.00
	Holts Rd, ON	Average	5.2	High	0.86
	Lac St Charles Ave, QC	Average	2.6	Moderate	1.49
	Lac St Charles ND, QC	Average	4.7	Moderate	2.64
	Montmorency Secondary Rd, QC	Average	2.8	Moderate	0.30
	Nabish Rd, ON	Average	4.6	Moderate	0.73
	North Rd, ON	Average	5.2	High	1.38
	Pellet Lake, ON	Average	6.2	Low	0.56
	Rainbow Trail, ON	Average	8.6	Low	0.98
	Rainbow Trail Wetland, ON	Average	5.1	Low	0.23
	Rock Lake Main Rd, ON	Average	1.9	Moderate	2.30
	Rock Lake Rd, ON	Average	7.1	Moderate	0.65
	Shaky Rd, ON	Average	4.5	Deactive	0.03
Atlantic Maritimes	East Tomahawk 1, NS	Good	3.3	Low	0.04

Ecozone	Road Name, Province	Surface Quality	Slope (%)	Traffic	FREP Predicted Sediment (m^3)
	East Tomahawk 2, NS	Poor	0.7	Moderate	0.09
	Hardscrabble Rd, NB	Average	13.9	High	3.73
	Lemen Brk Branch, NB	Poor	3.3	Low	0.21
	Lemen Brk ND, NB	Average	10.5	Moderate	12.00
	Levy West, NB	Average	3.2	Low	0.32
	Pockwock Culvert 1, NS	Good	1.6	Moderate	0.33
	Pockwock Lacy Mills Bridge, NS	Good	8.2	Low	0.21
	Pockwock New build, NS	Good	3.2	Low	0.05
	Prosser Brk, NB	Good	12.8	High	2.10
	Stewart Mountain Rd, NB	Average	15.9	Low	0.24
	Tomahawk Rd, NS	Good	2.1	Low	0.00
	Tower Rd, NB	Average	0.7	Moderate	0.26