BEAVER DAM CAPACITY IN THE CANADIAN BOREAL PLAINS ECOZONE:

AN ANALYSIS OF RIDING MOUNTAIN NATIONAL PARK

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PERMISSION TO USE

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ABSTRACT

Beaver, and the dams they build, have a profound impact on aquatic ecosystem-forming processes in every landscape they occupy. Beaver dams increase surface water retention, sedimentation storage, enhance riparian plant composition and have been shown to attenuate floods and augment low flows. With expected warmer future climate in Canada's boreal region along with increasing development, understanding and monitoring beaver dam building under environmental change is critical. The purpose of this research is thus to better understand the capacity of the boreal plains ecozone of Western Canada to support beaver dams. I studied beaver dam capacity in Riding Mountain National Park, Manitoba. The Beaver Restoration Assessment Tool (BRAT) is a recently developed beaver dam building capacity model, tested thus far only along riverscapes such as in Utah. I applied BRAT in RMNP and modelled results indicate the maximum beaver dam density to be ~25,000 or 9 dams/km in 2016. Manual analysis of a subset of beaver ponds using aerial images was completed to determine water storage potential. The results indicate there is substantial water storage in beaver ponds within RMNP. Beaver pond storage for 120 km^2 (4%) of the park is ~5.2 million m^3 of water, which is comparable to that stored in some hydroelectric dam reservoirs in Manitoba. Post-hoc analysis on the distribution of beaver dams based on physiography type indicate that the maximum beaver dam capacity in the hummocky region within RMNP is higher than modelled predictions, owing to the presence of off-channel dams. Additionally, temporal changes in beaver dam density throughout RMNP were explored by modelling the beaver dam density for 1991, 2003 and 2016. Modelled capacity was ~29,000 in 1991, which subsequently decreased to ~25,000 dams in both 2003 and 2016. The results suggest that BRAT reasonably estimates beaver dam capacity in RMNP and should be useful in informing water management plans or policies. The study also demonstrates the value of the BRAT beyond use as a reintroduction tool - as a predictive tool to determine beaver dam density within the boreal forest and changing northern habitats.

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1. INTRODUCTION

Beaver (*Castor canadensis*) have a profound impact on aquatic ecosystem-forming processes in North America (Naiman et al., 1988). Dams are the structures that cause the most desired ecological feedbacks from beaver activity. These impacts include increased local biodiversity, enhanced stream complexity, surface water retention, channel and riparian sedimentation and diversified plant composition (Gibson and Olden, 2014). These ecosystem services are created by the regulation and restriction of stream flows by the dam (Westbrook et al., 2013).

In Canada, the boreal plains ecozone, which spans southwestern Manitoba to northern Alberta, has historically been important beaver habitat (Novakowski, 1965). Beaver populations were suppressed by widespread trapping in the late 1700s through the late 1800s. Beginning in the 1930s, resource management activities, such as re-introduction programs, have encouraged population growth (Whitfield et al. 2015). The generally warmer future climate in the boreal forest region of Canada is predicted to lead to further modest beaver range expansion and substantial increases in density (Jarema et al., 2009). Environmental change, beyond that driven by climate, is also expected to impact beaver occupation patterns and density in the boreal plains ecozone. Fire and logging, for example, produce rapid re-growth of aspen, a preferred beaver food. Thus, these types of disturbances provide quality habitat for beaver 5-30 years afterwards by increasing their food and dam building supply (Thompson, 1988). As well, the growing oil and gas extraction industry in the boreal plains ecozone (Creed et al., 2019), which has expanded the access road network in northern Alberta, has led to increased beaver damming of culverts (Flynn, 2006). Beaver are likely an important part of enhancing the resiliency of the boreal plains ecozone to environmental change owing to how they increase open water storage in ecosystems via dam and canal building (Hood and Larson, 2015; Morrison et al., 2015; Hood and Bayley, 2008b).

Given the considerable changes to aquatic ecosystems affected by beavers engineering capabilities, understanding and monitoring beaver occupancy and dam building activities under environmental change is critical. It is for these reasons that a variety of habitat models have been employed to predict beaver densities (e.g., Allen, 1983; Beck et al., 2008). However, few of these models directly identify beaver dam building capacity (Macfarlane et al., 2013), even though dams are the main hydrological signature of beaver activities (Westbrook et al., 2013). Macfarlane et al. (2017) recently developed the Beaver Restoration Assessment Tool (BRAT), which focuses on beaver dam building capacity. BRAT was created specifically for exploring beaver dam capacity across the diversity of riverscapes found in Utah so that potential beaver reintroduction sites along degraded streams could be identified. The model holds promise for assessing beaver dam building capacity elsewhere, including in the boreal plains ecozone, because it is based primarily on landscape parameters that are often ubiquitously available. What is needed is testing the utility of the BRAT model to predict beaver dam capacity in a diverse environment such as the boreal plains ecozone.

1.1 Research goal and objectives

The purpose of my thesis is to better understand beaver dam building capacity in the boreal plains ecozone. I use Riding Mountain National Park (RMNP) as a case study given that the park has an extensive beaver-monitoring program that started when they reintroduced beaver in 1947. The case study will allow the following objectives to be met:

1. Determine the utility of BRAT to estimate beaver dam capacity in the boreal plains;
2. Determine beaver dam abundance and associated water storage capacity;
3. Evaluate temporal changes in dam capacity; and
4. Explore factors influencing changes in dam capacity over time.

1.2 Literature review

This section reviews literature with respect to the research goal and study objectives. The following literature review is being written from a zoogeomorphology perspective, specifically focusing on beaver dams. The first part of the review includes historic information on beaver populations within Canada, which is followed by an analysis of the activities of beaver, particularly dam-building, and impacts in the boreal plains ecozone. The review concludes with a detailed discussion of modelling tools available for predicting beaver dam capacity and the gap of knowledge.

1.2.1 History and Distribution of Beaver

North American beaver (*Castor canadensis*) and European beaver (*Castor fiber*) are both known for their ability to modify the landscape. Historically, beaver occupied landscapes across North America and all throughout Europe. Presently, they are currently expanding back throughout their former range largely due to reintroduction efforts in North America and Europe, including introduction as an exotic, invasive species in South America (Lizarralde et al., 1993; Nolet and Rosell, 1997; Macfarlane et al., 2017).

1.2.2 Rebounding Canadian Beaver Population

Beaver are an integral part of Canadian history. The beaver population prior to European settlement has been estimated in the tens to hundreds of millions (Innis, 1956). Trapped for their pelts, beaver were popular with early European settlers when fur hats and coats were fashionable in Europe (Banci and Proulx, 1999). Trapping became a gateway for Indigenous people to interact with Europeans - pelts were used as currency for items such as manufactured goods and food from overseas (White et al., 2015). Through these relationships, trading posts were established throughout Canada, igniting the fur trade and motivating further European settlement of the Canadian North and West. As a result of fur trade activities starting in the early 1600s, Canadian beaver populations were overexploited in an expanding wave that originated in the east and spread west then north across the continent (Innis, 1956). By the early 1900s, beaver were extirpated in many areas across North America due to unregulated trapping and loss of habitat as the human population grew (White et al., 2015). During the height of the fur trade, Naiman et al. (1988) estimated that 195,000– 260,000 km^2 of wetlands, which were likely originally beaver habitat, were drained or altered for human use across North America.

Since the mid-1900s, the beaver population across North America has been rebounding, albeit at a lower density, due to a combined effort of stronger conservation laws (Butler and Malanson, 1995) and successful reintroductions (Baker and Hill, 2003). For example, beaver were reintroduced in the southeastern United States as well as in the Colorado River system in southern California in the 1940s (Baker and Hill, 2003). By 2000, the beaver population had sufficiently recovered for beaver to be considered a nuisance by the timber industry (Baker and Hill, 2003). In Canada, one place beaver were reintroduced was Riding Mountain National Park (RMNP) in southwestern Manitoba. Fourteen beaver were released in 1947; an additional 14 beavers were released in 1949, and another 19 beavers were released in the eastern part of RMNP in 1958 (Trottier, 1980). The reintroduction was successful and the beaver population has recovered due to a monitoring program and trapping regulations (Sinkins, 2008). This, however, was not the first attempt at beaver reintroduction for RMNP. Grey Owl, a naturalist working with RMNP went to the park to help establish beaver in 1931 but shortly after his arrival he deemed RMNP to not be suitable habitat due to low water levels from drier years and requested a transfer to Prince Albert National Park (Parks Canada, 1985). The 1940s had much wetter climatic conditions than the early 1930s. RMNP is now home to a well-established beaver population that has been near its carrying capacity since the mid-1970s (Trottier, 1980).

Beaver rapidly colonize suitable habitats as their population expands (Halley and Rosell, 2002). A study in Voyageurs National Park, Minnesota, for example, estimated that it would be possible for beaver to colonize as far as 736 km over a 46-year period (Johnston and Naiman, 1990). Another example of how quickly a beaver population can expand is that of southern South America. In 1946, twenty beaver from Canada (Pietrek and Fasola, 2014) were released as an exotic, invasive species to stimulate a fur trade in Tierra del Fuego, Argentina (Lizarralde, 1993). The absence of predators and hunting regulations, and an abundance of habitat led to the rapid expansion of the population. Lizarralde (1993) estimated to be just over 60,000 in the year 2000 (Skewes et al., 2006). However, there is uncertainty in the population size. Whitfield et al. (2015) estimated it reached 95,000 – 168,000 individuals by 2000. Reintroduction efforts have occurred in Europe after the same exploitation activities decimated the Eurasian beaver (*Castor fiber*) population in the late 1800s. For example, 80 beaver were released throughout Sweden between 1922 and 1939 (Hartman, 1994) and it is estimated that the population grew to 100,000 by 1998 (Nolet and Rosell, 1998). Additionally, increased air temperatures in the northern regions of the boreal and arctic are changing the arctic tundra biome as the permafrost is thawing and snow duration is decreasing (Tape et al., 2018). This thawing is allowing for the shrubification of the landscape, which is creating suitable habitat for beaver to expand (Jung et al., 2016). In Alaska, 56 new beaver pond complexes have been identified since 1999 by researchers studying tundra beaver colonization (Tape et al., 2018).

Land management practices, predation and competition for woody resources are recognized as factors impacting beaver populations. Morrison et al. (2015) found in the Canadian

Rocky Mountain foothills near Calgary, Alberta that the number of beaver impacted wetlands was significantly lower in municipalities compared to protected areas like improvement districts and provincial parks. Trapping and removal as part of regular road maintenance and in response to landowner complaints was identified as the most likely causes of a lower beaver population in municipalities. In addition to habitat loss and land management practices, beaver populations are susceptible to predation risk. Specifically, the grey wolf (*Canis lupus*) will prey on beaver when larger ungulates are not available (Müller-Schwarze and Sun, 2003; Latham et al. 2013). For example, a review reported wolf scats containing beaver remains ranging from 7 to 62.8% (Müller-Schwarze and Sun, 2003). Researchers analyzing wolf scats determined that beaver were most frequently consumed in the summer whereas ungulate species were consumed in the winter (Latham et al., 2013). When ungulate and beaver niches overlap, there is a direct competition for woody vegetation (Hood and Bayley, 2008a), which can, in some instances, precipitate ecosystem collapse. Within Yellowstone National Park, for example, prior to the reintroduction of a predator (the grey wolf), nearly all-deciduous woody species available to elk in the winter range were heavily browsed, which resulted in a significant decline in beaver colonies (Ripple and Beschta, 2003; Beschta and Ripple, 2012). In fact, there were no documented beaver colonies directly after wolves were reintroduced. However, in 2002, there were 4 colonies documented in Yellowstone National Park and then in 2009, the number of colonies grew to around 12 (Beschta and Ripple, 2012). The increase in beaver colonies appears to be linked with the willow communities that have been improving since the reintroduction of the wolf and subsequent decline in the elk population in the park (Ripple and Beschta, 2003). Within RMNP, Richards (1997) found beaver, moose and elk populations reacted negatively to severe winters and positively to mild winters. She also noted that beaver create favourable habitat for moose. Beaver have proved to be highly industrious and resilient. They now occupy most of their former range in North America (Naiman et al., 1988) and are estimated to number between 9.6 and 50.4 million in 2000 (Whitfield et al., 2015).

1.2.3 Ecological Impacts of Beaver Dams

Dams are one of the most recognizable structures associated with beavers. The construction of beaver dams impact the surrounding ecosystem immensely by altering riparian conditions by impounding water (Naiman et al., 1988). Dams are built to stop or reduce the flow of water with the intent to create a pond behind it. Beaver ponds provide protection from predators and increase food supply by modifying terrestrial habitat to aquatic conditions favorable to certain tree species growth (Naiman et al., 1986). Using woody vegetation such as felled trees, branches, leaves, stones and even human waste (Butler, 1995), beavers construct dams perpendicular to the flow of water in a river by pushing sediment, rocks and sticks against existing substrate (Baker and Hill, 2003). Trembling aspen (*Populus tremuloides*) is the preferred material in North America, where beaver will selectively choose this over other materials when it is available (Hood and Bayley, 2009). Beaver typically use mud from the stream bottom immediately upstream of the dam, making this area of the pond the deepest (Novak, 1987). The addition of mud acts as a glue to make the dam sturdier and less likely to breach. Frequently, several dams are built in succession, with water from each pond backed up to the base of the upstream dam. This creates a stair-step pattern of dams and ponds, which flattens the slope of the drainage basin (Baker and Hill, 2003). The size and number of dams in a colony and the surface area and volume of water in ponds vary greatly among sites, depending on the duration of occupancy, topography, substrate, flow levels and available vegetation (Naiman et al., 1986; 1988; Butler and Malanson, 1995; Gurnell, 1998).

Dam construction is the biggest influence of beaver on hydrogeomorphic processes and can alter large areas of the landscape (Rosell et al., 2005; Westbrook et al., 2013). Dams are typically 15-70 m long and 1-2 m tall (Butler, 1995), although the size, length and height of dams can vary depending on the topography (Gurnell, 1998). Dams act like low weirs in that they create water storage, which can elevate the water table, and impact both high and low flows (Johnston and Naiman, 1987; Woo and Waddington, 1990; Gurnell, 1998; Westbrook et al., 2006). Dugmore (1914) provided sketches illustrating how beaver dams highly altered the drainage pattern of a boreal landscape. He depicted how beaver diverted a stream that had been flowing in a southeastern direction, and with the addition of new dams, created two new streams flowing north and northwest over a watershed divide. Other hydrological processes are impacted by beaver ponds. For example, evapotranspiration is increased by changing the distribution of vegetation (Fairfax and Small, 2018), and stream suspended sediment load is reduced by retention behind dams (Gurnell, 1998; Westbrook et al., 2013). All of these factors have been shown to result in improved water quality (Rosell et al., 2005) and increased regional biodiversity (Wright et al., 2002). In some environments, the main effects of beaver on hydrologic processes occur downstream of dams rather than being confined to the near-pond area (Westbrook et al., 2006).

When beaver dams are not adequately maintained, they gradually lose their mud and finer debris, followed by the loss of stones and small twigs, until only some branches and sticks remain (Woo and Waddington, 1990). The type of materials used in construction can determine dam preservation stage. Woo and Waddington (1990) created a classification of beaver dams according to the construction materials present in their study of 50 dams in the Hudson Bay lowlands. Active dams had evidence of fresh mud, indicating that beaver have been maintaining the dam, while dams that only had small branches and no mud or debris remaining were classified as being relict and abandoned, and more prone to failure. As a dam decays, its capability to pond water declines causing four distinct flow pattern changes; overflow, gapflow, under flow and through flow. Overflow occurs when the dam is well maintained and no water is able to seep through it, so rising water levels cause water to overflow over top of the dam. If the dam is breached and water can flow through at certain points along the dam, this is known as a gapflow type. When the base of the dam is weakened, then water will flow from the bottom of the dam, termed under flow type. Finally, if the dam is abandoned, it will become porous over time and water will seep through the entire dam, termed through flow type (Woo and Waddington, 1990). Each dam flow type thus likely influences streamflow differently.

Studies confirm that beaver dams directly affect the stream power by creating a barrier that makes water flow power dissipate (Naiman et al., 1988; Gibson and Olden, 2014). Both beaver habitat abandonment and dam removal from streams can drastically reduce surface water storage while increasing stream power (Green and Westbrook, 2009). Dam failures and abandonment can be hydrologically important, and sometimes devastating. For example, in central Alberta, the failure of a dam on Rocky Creek released ~7500 m^3 of water with a flood wave of 3.5 times the maximum recorded for the creek over 23 years (Hillman, 1998). The beaver dam outburst flood destroyed five hydrometric stations. But, few of these circumstances are described in the peer-reviewed literature. Instead, reports usually document the occurrence of failures and abandonments (Butler and Malanson, 2005). Active dams can last for decades or even centuries (Burchsted et al., 2010; Westbrook et al., 2013) with older dams being more prone to through flow and even catastrophic failure (Butler, 1989; Woo and Waddington, 1990). A beaver dam built in peatland in Wood Buffalo National Park, Alberta, Canada, for example, reached 850 m in length and is estimated to have been around since the 1970s (Thie, 2007).

1.2.4 Role of beaver dams in ecological succession and landscape features

Beaver affect trees in riparian areas through both cutting and flooding, creating beaver ponds as water close to terrestrial landscape is critical to beaver survival as they forage on land but live in water (Novak, 1987). Beaver cut trees for both food and building material for dams and lodges (Ives, 1942; Novak, 1987). The activities of beaver and dam construction affect ecosystem structure and dynamics far beyond their immediate requirements for food and shelter (Naiman et al., 1986). Beavers require minimum water depths to build a lodge for protection from predators, overwintering and food caching, and will often engineer their environment to provide that habitat (Naiman et al., 1988). Beaver dams have been shown to greatly enhance the extent and duration of overbank floods with the ability to spread the water laterally and downstream from the dam (Westbrook et al., 2006). Beaver presence within North America and their impacts are still evident today in terrestrial vegetation of meadows centuries after dam abandonment is a testimony to their enduring influence on landscape ecology (Naiman et al., 1986).

Beaver dams are important as they play a large role in the ecological succession of a landscape. Beavers are known to dig canals to aid in the transfer of trees from land into water (Gurnell, 1998). Beaver dams and the subsequent ponds and canals built create a series of disturbance patches within the boreal landscape (Johnston and Naiman, 1987) that have relatively homogenous plant communities (Wright et al., 2002). These patches are a direct effect of the changed hydrological conditions from beaver dam construction (Gurnell, 1998; Westbrook et al., 2011). As such, long-term beaver occupancy influences landscape features because their dams may endure much longer the beaver's lifespan (Westbrook et al., 2013). Beaver meadow formation (BMF) theory explains that over time, beavers transform forested riparian areas to unforested meadows, termed beaver meadows, along small streams by flooding out and killing vegetation. In BMF theory, ponds eventually fill with sediment. As dams are abandoned and degrade, the ponds drain and leave behind nutrient rich soil (Ives, 1942; Terwilliger and Pastor, 1999; Westbrook et al., 2011). A breached dam, however, may end up depositing the sediment on the landscape creating a fertile environment for new vegetation growth (Westbrook et al., 2011).

The BMF theory, with reference to the wet meadows characterized by multi-thread channels that form in broad, low-gradient valleys from the presence of beaver dams (Polvi and Wohl, 2012), is not extensively tested in the peer-reviewed literature. However, sediment accumulation and deposition upstream of beaver dams is well substantiated within the literature (e.g., Polvi and Wohl, 2012).

Since beaver dams decrease stream velocity, their associated ponds and overbank flows allow sediment to accumulate in both the channel and on adjacent riparian areas (Westbrook et al., 2011). The rate and the amount of sediment buildup depends not on the size of the dam, but the size of the beaver pond that forms upstream of the dam (Naiman et al., 1986; 1988). In Quebec, for example, Naiman et al. (1986) determined the amount of sediment behind several dams. The sample ponds ranged in size from 100 to 14,650 m^2 and the sediment volumes ranged from 35 to 6500 m^3. The results demonstrated a positive correlation between pond size and sediment volume. Butler and Malanson (1995) corroborated this positive correlation, and also established that the age of the pond contributes to the amount of sediment that accumulates behind dams. For example, one pond that was ~30 years old had 5084 m^3 compared to ponds ~6 years which ranged from 11 to 31 m^3. The rate of sediment buildup within beaver ponds varies drastically by geographical location. Butler and Malanson (2005) report the range of sedimentation as <1 cm yr^{-1} in ponds located in Ontario to almost 40 cm yr^{-1} in northwestern Montana. Based on these findings, site specific measurements for sediment accumulation rates was recommended, and the amount of sediment accumulation within beaver ponds in North America was estimated at 750 million to 3.85 billion m^3.

1.2.5 Beaver Dam Densities

Beaver dams provide numerous ecological benefits, as described earlier in this review. These benefits are closely related to the frequency, density, and size of dams along a stream network (Johnston and Naiman, 1990). Beaver dam density along a stream network varies greatly depending on topography, available habitat, predator density, trapping regulations and land management activities (Gurnell, 2008). For example, Naiman and Melillo's (1984) study of areas of Quebec where the beaver population is largely unexploited, showed beaver can influence as much as 30–50% of the total length of 2nd to 4th order streams. Novak (1987) argued that as long as food and a water source are available, beaver continue to expand into all available habitats. As their populations expand, beaver will continue to dam. Several studies conducted in different habitat types have found varying densities (Table 1.1), which will dictate the intensity of impact on the surrounding landscape. Whitfield et al. (2015) estimated that the riparian interface at beaver ponds ranges between 204,000 and 908,000 km.

Table 1.1 - Beaver dam density reported in the literature (adapted from Gurnell, 1998)

Density (km/stream or wetland)	Location	Source
0.14/km	Eastern Oregon	McComb (1990)
1.1/km	Coastal Oregon	Leidholt-Bruner et al. (1992)
10.6/km (average) 2.5/km (average)	Quebec Minnesota	Naiman et al. (1986;1988)
14.3/km (wetland)(average)	North Ontario	Woo and Waddington (1990)
3.06/km	Alberta	Loates and Hvenegaard (2008)
0.83 dams/km	Utah	Macfarlane et al. (2017)

1.2.6 Dam Capacity Models

Researchers have been focusing on determining beaver habitat preferences and estimating population and density since beaver reintroduction programs began in North America. It has been a shared goal among researchers to create a model that will determine where beaver are likely to succeed while creating the most positive feedbacks (Pollock et al., 2007). Most often, habitat preference and historic presence are used as benchmarks (Baldwin, 2013). Several approaches to attain this goal have been utilized including habitat suitability index (HSI) models that involve inventorying current beaver landforms (i.e., caches, lodges, dams) to estimate population and beaver dam density.

The first generation of models focused on quantifying beaver habitat suitability. Allen (1983) was one of the first researchers to develop a quantitative beaver HSI model that evaluated the suitability of beaver habitat based on deterministic variables that affect beaver success. The model was grounded in the assumptions that: i) beaver habitat preferences are fairly similar in every type of habitat beaver occupy; ii) beaver require a water source, food, building materials and a lower gradient stream to build dams (McComb et al., 1990); and iii) beaver are generalists when it comes to food selection, however, they prefer aspen and willow (Baker and Hill, 2003).

HSI models thus include beaver preferences and study an area looking for positive correlation to beaver presence based on these preferences.

Allen's (1983) model included variables such as stream gradient, average stream level fluctuation, stream flow type (perennial or intermittent), percent tree and shrub canopy data, tree size, shrub canopy height, and vegetation composition. Considered unprecedented, his HSI model sparked a body of research (e.g., Howard and Larson, 1985; Broschart et al., 1989; Suzuki and McComb, 1998) evaluating relationships between beaver density and various physical, environmental and vegetative variables. For example, Slough and Sadleir (1977) evaluated the utility of regression analysis within their HSI model to determine preferable beaver habitat within interior British Columbia, with the goal of using the collected data to determine where reintroduction efforts should be focused. Although there were statistical issues of variable classification and correlation (Thompson, 1988), the HSI model suggested that the amount of aspen along the shores of ponds is an important habitat component. This body of literature suggested that HSI-based models can accurately distinguish between suitable beaver habitat and unsuitable habitat within a short temporal window (McComb et al., 1990). However, there are issues with the fact that HSI models tend to be system specific with limited potential to extrapolate results to other watersheds (Robel et al., 1993; Baldwin, 2013).

Researchers use aerial surveys to estimate beaver population size by counting caches, lodges and dams (e.g. Allen, 1983; Beck et al., 2008; Parks Canada, 2016). This is because it is relatively easy to identify beaver dams, lodges and even food caches from aerial photographs (e.g. Green and Westbrook, 2009; Morrison et al., 2015). However, where riparian vegetation is thick, ground census methods provide higher accuracy (Robel and Fox, 1993). The number of structures is then multiplied by an average of beaver family size (Novakowski, 1965) – usually 5 or 6 - to obtain the population of beavers. This method provides estimates, usually with a 95% confidence interval. Johnston and Windels (2015) used aerial photography and independently collected population data to confirm current beaver activity, as opposed to verifying evidence of 'beaver works'. The authors argue that the presence of beaver activity is not evidence of active beaver activity and stress the use of field surveys to verify that an area is actively used by beaver as it takes several years for the activity to be visible from an aerial photograph. The problem is that having an estimated population does not help quantify the impacts to the landscape from beavers, nor does it help with prediction of future number of beaver dams. Thus, there has been a desire to go beyond simple habitat population correlation models to understand the complex hydrological impacts beaver have on the landscape they occupy, specifically, through predicting their dam building activities (Macfarlane et al., 2017).

Habitat suitability models tend to use absence as a proxy for environmental inappropriateness and presence as validation for habitat variable preference, thereby ignoring anthropogenic factors causing absence (Baldwin, 2013). To overcome this challenge, Macfarlane et al. (2017) recently developed a new model, the Beaver Restoration Assessment Tool (BRAT) that focuses on beaver dam density rather than 'suitable beaver habitat', as dam building activity is identified as the keystone process in shaping lateral and longitudinal connectivity within ecosystems. BRAT has been successful at modelling the capacity for beaver dams on riverscapes in Utah (Macfarlane et al., 2017). The BRAT is GIS based, and unlike other models which combine habitat preference and landscape suitability and graph the regression between the two for the specific site, it produces a visually appealing map that has the beaver dam capacity indicated on each stream way. Unlike empirical HSI models, which are able to accurately distinguish suitable beaver habitat from unsuitable habitat within a temporal window (Macfarlane et al., 2017), the BRAT models beaver dam processes at a larger scale, allowing the quantification of the hydrological impacts of beaver dams at scales useful to water management. Additionally, the BRAT utilizes Fuzzy Inference Systems functions which allow scenarios from HSI models to be represented using categorical data (e.g. 'pervasive' or 'can probably build dam') and to assign values to each based on predetermined rules (or scenarios) using a sliding scale. One of the advantages of the BRAT is that it utilizes publicly available input data such as stream data available from the USGS National Hydrography Data (http://nhd.usgs.gov/) which would be useful for studies based in the United States. The BRAT programming components are freely available from http://brat.joewheaton.org/brat-data/utah-brat with the hope that researchers will modify the source code to include data that is specific to their study site. This should allow for evaluation of the transferability of BRAT, which is a shortcoming of traditional HSI models (Macfarlane et al., 2017).

1.2.7 Beaver in the Boreal Plains Ecozone of Canada

Beaver are abundant in the boreal forest, with its extensive areas of mixed woods and wetlands, and it is difficult to find small or medium streams that are not affected by them (Hillman, 1998). Within the boreal plains ecozone, researchers have reported that beaver are active in nearly all surface waters (Martell et al., 2006). Further, there is evidence that beaver populations are increasing across the region (Dinsmore et al., 2013; Whitfield et al., 2015). Changes in beaver populations are expected as the climate changes. Jarema et al. (2009), for example, studied the spatial variation in beaver abundance across Quebec, Canada using a species-climate envelope model to identify if climate variables were a determining factor in beaver abundance. They demonstrated several strong climate and non-climate predictors of variation in beaver density. However, 97% of the non-climate variables could be explained by climate variables. For example, increase of wildfires are expected in the future which may impact vegetation composition creating favourable conditions for beaver-preferred plant species to germinate (e.g. willow and aspen) (Chapin et al., 2004; Boulanger et al., 2016). The variability in beaver density demonstrated by Jarema et al. (2009) will have unpredictable consequences, which require further study. In the northern extent of the boreal forest, discontinuous permafrost is thawing (Vitt et al., 2000; Price et al., 2013). Permafrost is also thawing in tundra ecosystems (Tape et al., 2018). Permafrost loss is leading to shrubification of these ecosystems, which creates ideal conditions for beaver colonization (Jung et al., 2016; Tape et al. 2018). As beaver are recognized as ecosystem engineers, their presence in these new landscapes means that they will inevitably play a large role in shaping the hydrology of these regions.

With the addition of human-driven change (mining, logging, development), additional complexities in beaver population dynamics are expected to arise (Flynn, 2006; Martell et al., 2006; Jarema et al., 2009; Charron and Hermanutz, 2015; Whitfield et al., 2015). Fire and logging produce rapid re-growth of trembling aspen (*Populus tremuloides*) in the boreal forest, which provides quality habitat for beaver 5-30 years post-disturbance by increasing their food and dam building supply (Thompson, 1988). Beaver density may not even change in the first five years after disturbance if the riparian systems remain intact (Potvin et al., 2005). Boreal forests are disturbance-driven ecosystems with fire being an integral part of a healthy boreal ecosystem

(Johnstone et al., 2010). Riding Mountain National Park uses prescribed burning and selective logging as part of their park management plan, contributing to areas of rapid regrowth including a dominance of trembling aspen (Walker, 2002). A large portion of RMNP (the escarpment) is cooler and has higher precipitation than the surrounding lowlands and so experiences few extensive fires (Caners and Kenkel, 2003). Martell et al. (2006) observed beaver dam sites on low-order streams in Alberta over a 50-year period using aerial photography. Researchers observed that as the beaver population grew, so did the number of dams and the trees adjacent to the streams were felled within a 30-40 m radius of the pond. The Alberta Government requires forestry industrial development to leave 30-60 m unharvested buffer strips adjacent to streams. However, beaver are removing the forest cover from buffer strips, rendering the policy ineffective (Martell et al. 2006). Thus, larger buffer zones are needed to counteract the cumulative impact of logging and beaver. As well, exploitation of natural resources in the boreal plains ecozone (primarily oil and gas extraction) has allowed beaver to expand their habitat through enhancing the road network where beavers are increasingly damming culverts (Flynn, 2006).

Although there has been considerable research into beaver density and populations throughout North America, there is a lack of understanding of the capacity of the boreal plains ecozone to withstand the impacts that dams create. Given the recent growth in the beaver population in the boreal plains ecozone, the diversity of habitats available to beaver in the boreal plains ecozone, and the high degree of development activities throughout the region, it is useful to have a tool that can assess the future capacity of the boreal plains ecozone to support beaver dams.

2. METHODS

2.1 Study site description

The study was conducted in Riding Mountain National Park (RMNP), which is in southwestern Manitoba, Canada, approximately 225 km northwest of Winnipeg (Figure 2.1). Riding Mountain National Park covers an area of 2976 km^2 and is part of a larger biosphere reserve which encompasses the surrounding multi-use landscape. RMNP is situated within the southeastern limits of the boreal plains ecozone. The park has long cold winters and short warm summers. RMNP is bordered by the gradually sloping Assiniboine Valley to the west and south, the Wilson and Valley Rivers to the north, and the steep Manitoba Escarpment to the east. Land use surrounding the national park is primarily agriculture (Figure 1). The topographic boundary features, combined with the highly modified agricultural land surrounding the park, create an island-like effect for the park (Sinkins, 2008).

Riding Mountain National Park encompasses four ecological land districts: the escarpment, the lowlands, the hummocky, and the upland plateau (Trottier, 1980). The Manitoba escarpment is characterized by eroded shale bedrock dissected by deep ravines produced by streams draining the upland plateau. The lowlands is located at the base of the escarpment and is dominated by eastern deciduous forests where flooding is common and fire disturbances are rare. These two land districts occupy the least amount of land area within RMNP. The amount of beaver habitat in these districts is restricted by the relatively high stream velocities observed on and near the escarpment. Most of the park lies in the hummocky and the upland plateau land districts.

The hummocky land district occurs in the southern and western reaches of RMNP and is characterized by water-filled depressions created by melting blocks of ice left by the retreating glaciers. As a result, wetlands are expansive and drain slowly (Sinkins, 2008). This district is characterized by mixed wood boreal forests dominated by white spruce (*Picea glauca*) and trembling aspen (*P. tremuloides*) with open prairie habitat and black spruce (*Picea mariana*) bogs interspersed throughout. Fires in the early to mid-20th century (Parks Canada, 2002) have resulted in large, uninterrupted stands of trembling aspen and balsam poplar (*P. balsamifera*) throughout the park. A multi-strata shrub community is commonly seen in the hummocky district, primarily composed of beaked hazelnut (*Corylus cornuta*) and mountain maple (*Acer* *spicatum*) (Sinkins, 2008). The hummocky land district sustains a dense population of beaver (Frey and Avery, 2004).

Most of RMNP occurs within the upland plateau land district, a region dominated by boreal mixed wood forest. White spruce and trembling aspen are the major tree species, along with balsam poplar, paper birch (*Betula papyrifera*) and black spruce (Caners, 2001). Among the shrubs, beaked hazelnut dominates well-drained sites, while alders (*Alnus* spp.) occur frequently in moist lowlands (Walker, 2002). The landscape is characterized by rolling hills with an uneven distribution of glacial till, creating many poorly drained wetlands (Bailey, 1968). These wetlands are surrounded by boreal mixed wood forest, which provides ample habitat to support one of the highest density populations of beaver in North America (Parks Canada, 2002).

RMNP has a long-term interest in beaver. Beaver were extirpated by trapping from RMNP and the surrounding area by the 1930s (Sinkins, 2008). In 1947, 14 beaver from Prince Albert National Park, Saskatchewan were released within RMNP to repopulate it (Sinkins, 2008). Due to the unique location of the park, producers who own agricultural lands adjacent to RMNP expressed concerns over potential flooding impacts the park's beaver would have outside the park. In response, the Canadian Wildlife Service initiated systematic aerial surveys of food caches in 1973 within RMNP to track beaver population trends (Trottier, 1980; Town, 2016). Beaver population records within the park are thus reasonably extensive, and a reintroduction timeline is available. Twenty surveys have been completed since 1973, following the same methodology until 2004, when navigation and data collection were completed with a laptop linked to a GPS rather than hardcopy 1:10,000 scale air photo mosaics that were used previously (Frey and Avery, 2004). RMNP thus serves as an ideal place to study beaver dam building capacity in Canada as there are long-term records of beaver cache locations, information on plant community composition (i.e., food and dam building supplies) and extensive GIS imagery.

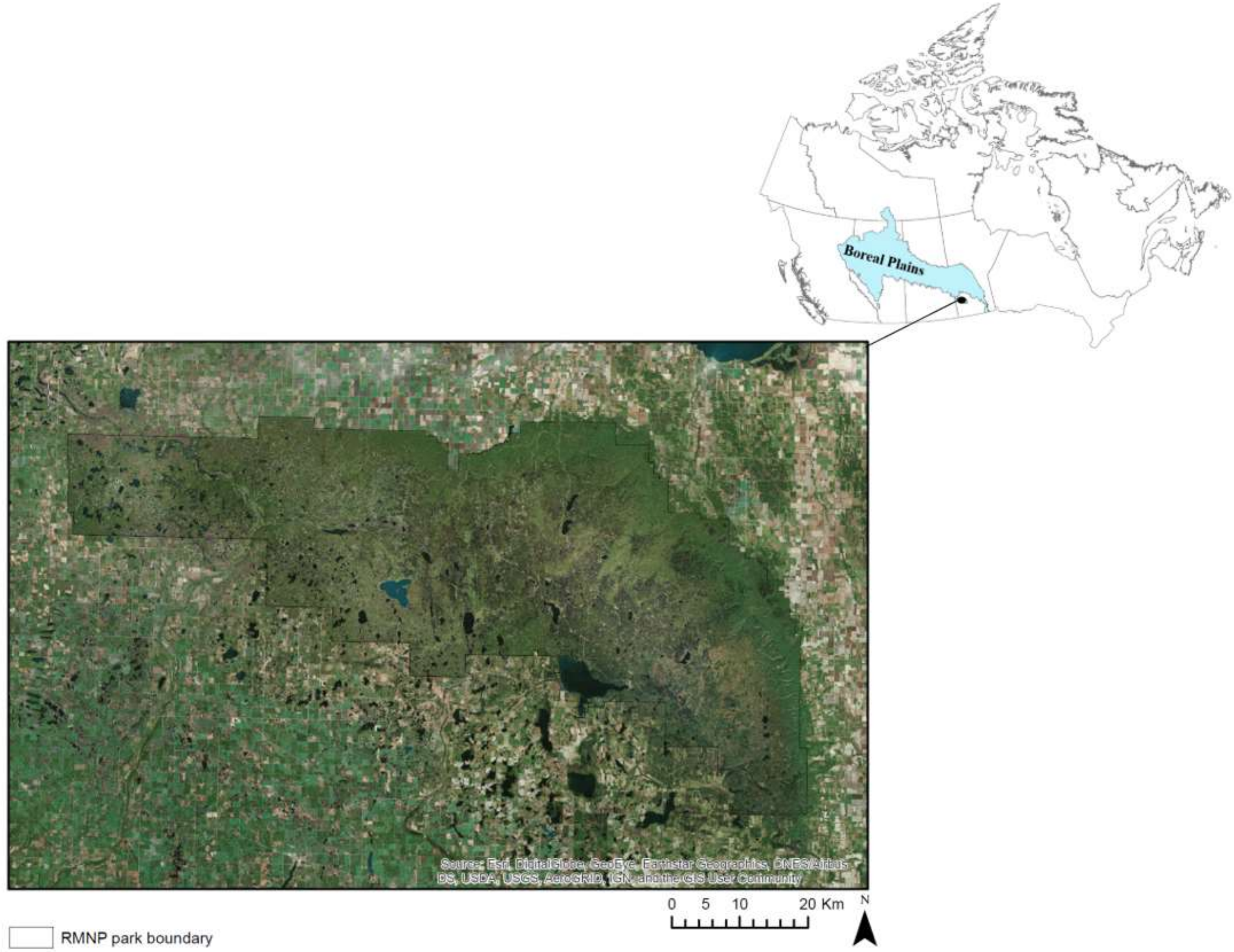

Figure 2.1 - Location of Riding Mountain National Park in the boreal plains ecozone (source: ESRI basemap).

2.2 Estimating beaver dam capacity in RMNP

The Beaver Restoration Assessment Tool (BRAT) utilizes publicly available datasets to predict the upper limits of riverscapes to support beaver dam-building activities. BRAT, (version PyBRAT 3.0.17) was used in this research and is available at: https://github.com/Riverscapes/pyBRAT/releases/. BRAT is a GIS based model that combines stream segment slope, beaver vegetation preferences and streamflow information to calculate maximum beaver dam capacity, and then projects the attribute data onto the stream network. BRAT has been updated extensively by its creators since its original conception in 2016 and is now a user-friendly, Python script toolbox extension in ESRI ArcMap. The requisite inputs to the beaver dam capacity model include a drainage network layer, vegetation type raster data of historic and existing conditions, a digital elevation model (DEM) raster, and streamflow (baseflow and peak flow) information throughout drainage network. The input data require preprocessing, as outlined in Figure 2.2.

Table 2.1 - Geographical data utilized in the BRAT for Riding Mountain National Park.

Image	Type	Resolution/ Scale	Source	Year
1991 Vegetation	Raster	30 m	Parks Canada	1991
2003 Vegetation	Raster	30 m	Parks Canada	2003
2016 Vegetation	Raster	10 m, 30 m	Parks Canada	2016
Drainage	Polyline Polyline	1:20,000 1:50,000	Manitoba Land Initiatives NRCAN (CanVec Data)	2008 2010
DEM	Raster	20 m	NRCAN	
Aerial Imagery	Raster	62.5 cm	Parks Canada	2004

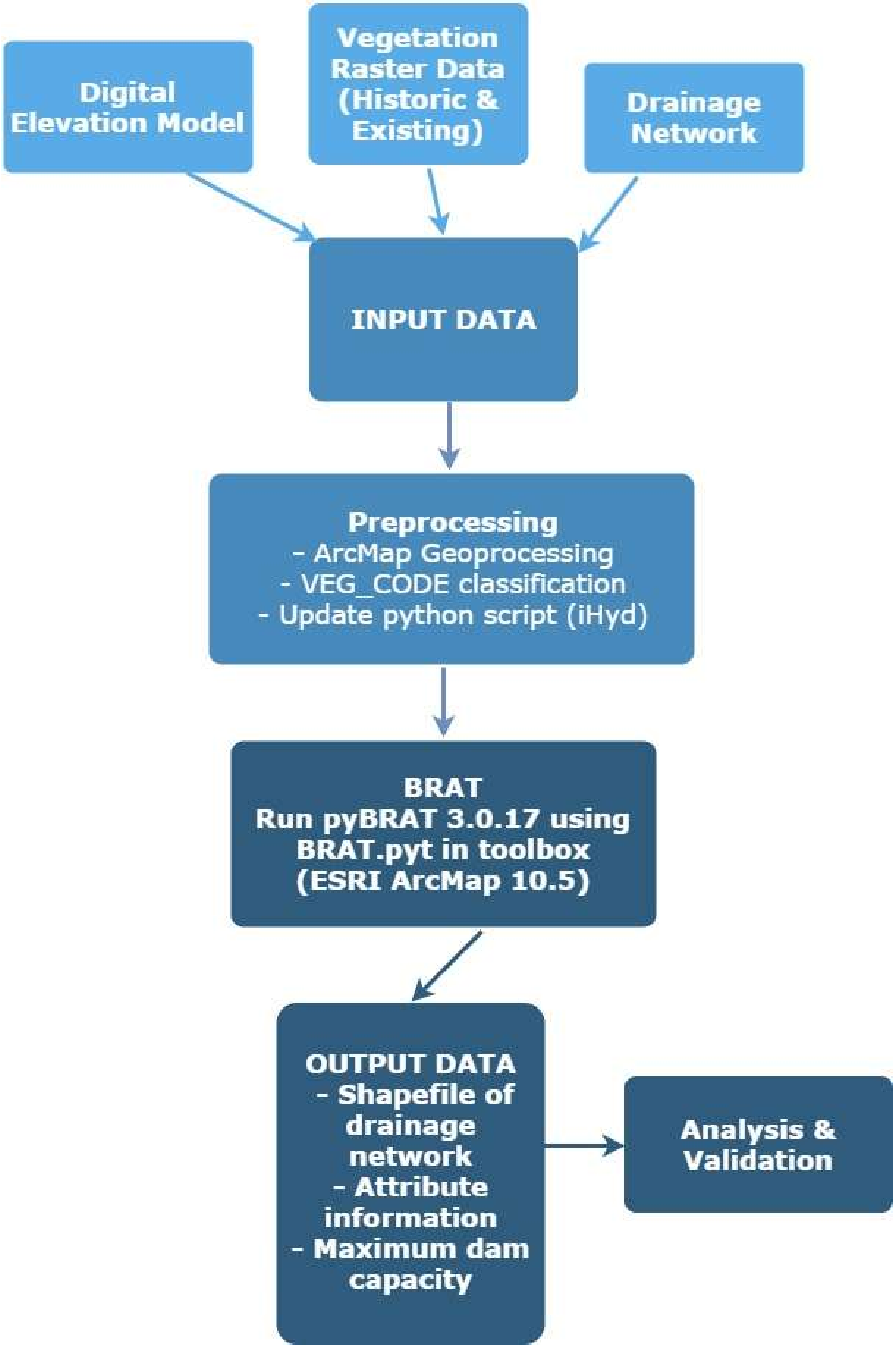

Figure 2.2 – Flowchart conceptual model of steps required to use BRAT to calculate maximum beaver dam capacity in RMNP.

2.2.1 Preprocessing of BRAT input data

Basic editing and knowledge of ESRI ArcMap was required to complete the following steps. All GIS layers (DEM, drainage network, vegetation rasters) were projected into the same coordinate system (NAD_1983_UTM_Zone_14N) using the projection tools in ESRI ArcMap 10.5. I clipped all GIS layers to the study area using a georeferenced park boundary polygon layer and extract to mask or the clip function.

2.2.1.1 *Drainage Network*

The input drainage network shapefile layer was a combination of layers acquired from the Manitoba Land Initiatives' (Government of Manitoba, May 12, 2008) website (at 1:20000 scale) and from RMNP (CanVec data at 1:50000 scale, 2010, unknown time of year). In ESRI ArcMap 10.5, I used an on-screen digitizing method to extend streams to create a continuous network, being careful to maintain the drainage patterns of each topography (i.e. not adding a stream channel in the digitization where the drainage network is actually deranged). This technique involves digitizing directly on top of an orthorectified image using the editor toolbar and the classic snapping feature to minimize errors. In the digitizing of the RMNP drainage network, a 62.5-cm resolution image from 2004 was used and additional segments were added to fill any gaps found throughout the stream network. The drainage network is the key element to projecting and analyzing the BRAT maximum dam capacity, so it was imperative that the network was checked for any obvious errors in its continuity. Once complete, the drainage network layer was segmented into 300-m reaches using the 'segmentNetwork' script which is a supporting tool within the pyBRAT 3.17 ArcMap tool box. This step is required for the BRAT model statistics to be calculated and is added onto the drainage network layer in ESRI ArcMap once the tool is run.

2.2.1.2 *Vegetation*

BRAT modelled output of dam capacity is primarily driven by the vegetation data, which is constrained by stream power and stream gradient. Historic and existing vegetation layers for a study site are required inputs to the BRAT model. In the United States where BRAT was developed, there is a nationwide LANDFIRE vegetation dataset, which is based on classification of 30 m resolution LANDSAT satellite imagery. It is comprised of detailed vegetation data from 2014 as well as a historic biophysical layer which represents the landscape prior to Euro-

American settlement. BRAT capitalizes on these excellent quality data. In Canada, however, readily available vegetation data, including for the province of Manitoba, is limited to generalized satellite-derived land cover data that must be classified by individual users as required. The exception that was found was land cover from NRCAN derived from LANDSAT images compiled over several years in the early 2000s. Manitoba data does not have specific vegetation species classified in a similar way to LANDFIRE. So, to get suitable vegetation raster data for RMNP for use in BRAT, data from secondary sources was used.

The imagery analysis for 1991 was created using a 30 m resolution LANDSAT 5 image acquired in August of 1991 (Walker, 2002). The image was classified using specific tree species and types of landscapes found within RMNP (Table 2.2). The vegetation layer from 2003 was created using LANDSAT 5 Thematic Mapper (TM) imagery at a 30 m resolution; the month of that imagery was acquired was not available. Vegetation cover was compiled and classified using classes shown in Table 2.2. Imagery from 2016 was derived from Sentinel 2 satellite imagery from June and July 2016 at a 10 m resolution. The 2016 image classification was completed in the QGIS mapping program using the 'dzetsaka' classification tool, following a similar classification scheme as the 2003 vegetation raster (Table 2.2). Since the vegetation raster for 2016 was at a 10 m resolution, the aggregate tool in ESRI ArcMap 10.5 was used with a cell factor of ‘3’ and the aggregation type kept as the default (‘SUM’). The output was a reduced-resolution version of 30 m. I added a “VEG_CODE” field in each of the three vegetation raster files by adding a field code to each layer’s attribute table within ESRI ArcMap.

Beaver are selective harvesters with a preference for aspen but are also known as generalists, making do with the building supplies that are available. BRAT vegetation preferences were originally classified based on what is prevalent in the literature and to suit the riverscape vegetation in Utah, based on detailed food preference studies there (Macfarlane et al. 2017). There is a wide array of food and building resources beaver are known to use in the boreal plains ecozone. RMNP’s hummocky landscape is known for its multi-strata shrub community cover approaching 100% in some places. (Sinkins, 2008). To tailor beaver vegetation selection and vegetation prevalence to RMNP, I took the suitability of vegetation classification created by Macfarlane et al. (2015) and modified it to suit the vegetation found in RMNP (Table 2.2) for all three years. As the raster data were classified at different times and by different people, creating seamless rules for how each category was coded based on beaver preference was a challenge. A value of 0 to 4 was assigned to each vegetation classification type based on its suitability as dam building material, with 0 being 'unsuitable' and 4 being 'preferred' (Table 2.2). Based on class metadata, the 1991vegetation raster has the highest percentage of the vegetation type classified as a 4 because the species type was originally finely classified, which allowed beaver preferred species to be identified in areas that are classified as 'deciduous' or 'mixed wood forest' in 2003 and 2016. It is because of this that some judgement calls were required to make layers comparable (Appendix A). The BRAT model calculates a 30 m and a 100 m buffer adjacent to each 300 m stream segment using the value of suitability (0-4) and the zonal statistics geoprocessing operation which calculates the mean of all categorical values for the suitable vegetation (Figure 2.3). Using the Fuzzy Inference System (driven by predetermined rules), these vegetation buffer scores are added to the attribute table to be combined to find the maximum beaver dam capacity.

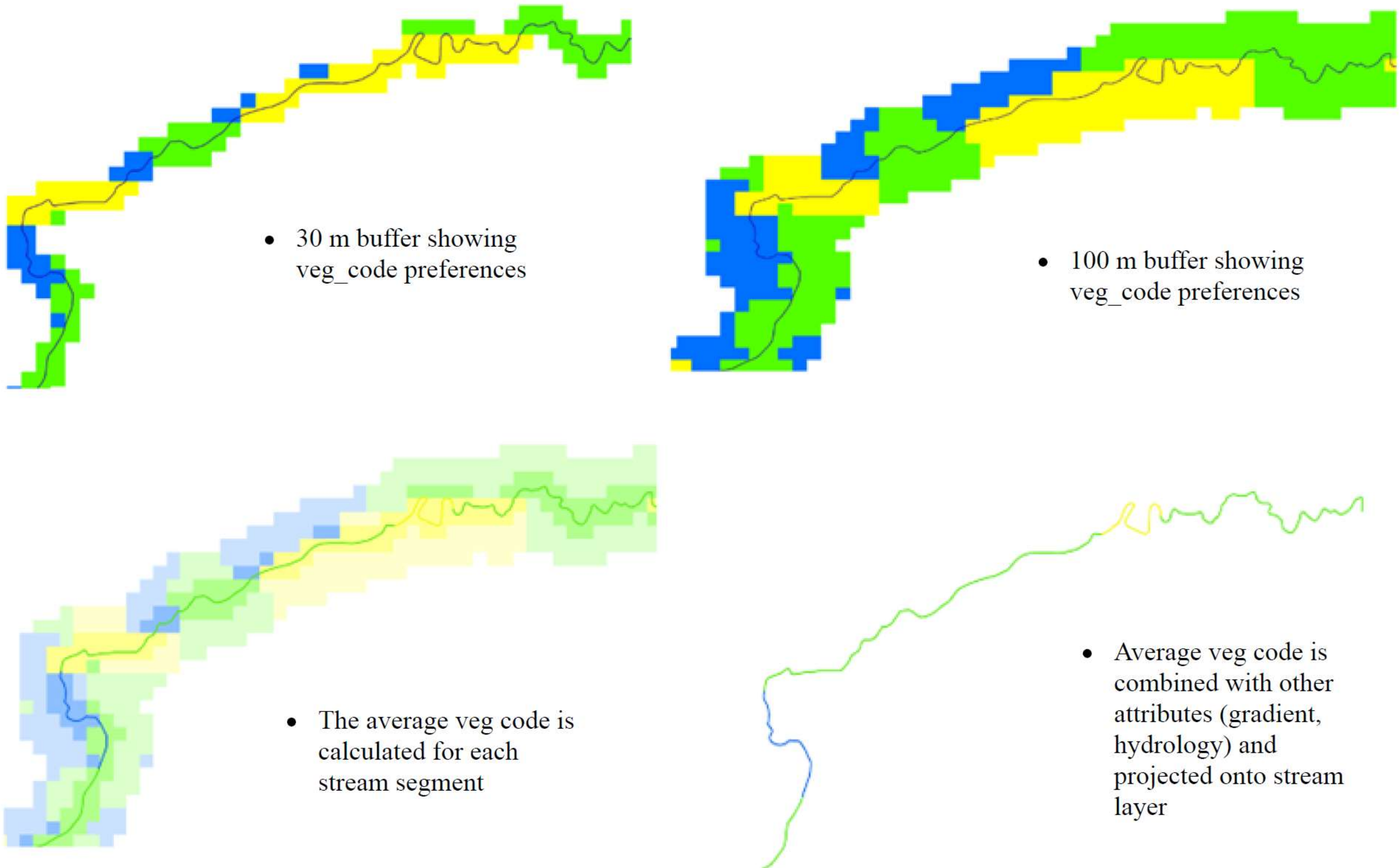

Figure 2.3 – Visual showing the 30 m and 100 m riparian buffers. Buffer coding is created from the veg_code variable used to calculate the quality of vegetation surrounding a stream. Blue = Preferred Material, Green = Suitable Material, Yellow = Moderately Suitable

To determine whether the vegetation changes from 1991 to 2016 were real or a result of classification differences, LANDSAT images from each year were analyzed in ArcMap 10.5 using the time series change detection method Landsat-based detection of Trends in Disturbance and Recovery ('Landtrendr') outlined in Kennedy et al. 2010. The normalized burn ratio (NBR) spectral index was used to determine the disturbance magnitude or cover percentage lost due to fire disturbance. This approach examines each pixel from year to year to see how it changes over time and highlights it if a substantial change is detected. Additional analysis was undertaken on the highlighted pixels to determine what type of cover change occurred, either a full cover change type or a shift in the spectral index value. Results were compiled into a database to calculate the total percentage of changes. Additionally, results were projected in ESRI ArcMap as shapefiles, to highlight areas of change.

Table 2.2– Classified raster data for 1991, 2003 and 2016 showing the percentage of each class cover and the vegetation code assigned. Colour coordinated based on material preference. Blue = Preferred Material, Green = Suitable Material, Yellow = Moderately Suitable, Orange = Barely Suitable, Red = Unsuitable Material

Vegetation Raster 1991 (30 m)			***Vegetation Raster 2003 (30 m)***			***Vegetation Raster 2016 (10 m & 30 m)***			
Class Name	**Veg Code**	**%**	**Class Name**	**Veg Code**	**%**	**Class Name**	**Veg Code**	**% 30 m**	**% 10 m**
Low Canopy Deciduous	4	6.23	Open Deciduous/Shrub	4	1.66	Open Deciduous Forest	4	3.27	4.73
Eastern Deciduous	4	12.48	Deciduous	3	41.17	Deciduous Forest	3	32.22	32.74
Shrubland	3	8.45	Mixed wood Forest	3	29.62	Mixed wood Forest	3	33.68	30.91
Deciduous Canopy/Coniferous subcanopy	3	12.25	Marsh	2	13.20	Marsh/Fens	2	6.06	5.24
Mixed Canopy (Deciduous/conifer)	3	11.49	Treed and open bogs	2	1.61	Bogs	2	4.42	4.35
Aspen Parkland	3	28.27	Coniferous	2	6.54	Conifer Forest	2	12.66	12.82
Regenerating Coniferous	2	0.73	Water	1	4.74	Water	1	3.19	3.21
Lowshrub Grassland	2	2.48	Grassland	1	1.10	Grassland	1	3.42	4.28
Bur Oak Forest	2	2.32	Wildfire Areas	1	0.0001	Burns	1	0.42	0.45
Closed Canopy Coniferous	2	5.56	Agriculture	0	0.008	Agriculture	0	0.01	0.004
Wetlands	2	1.48	Forage Crops	0	0.001	Forage Crops	0	0.12	0.27
Open Canopy Coniferous	2	2.95	Cultural	0	0.05	Cultural	0	0.54	1.01
Grassland	1	0.72	Forest Cutovers	0	0.0004				
Open Water	1	4.50	Bare Rock	0	0.01				
Agriculture	0	0.003	Roads and Trails	0	0.30				
Forested (outside RMNP)	0	0.08							

2.2.1.3 *Stream Power*

The BRAT model uses stream power to determine the likelihood of a beaver dam persisting along a stream reach during low flow (Qlow) and 2-year flood (Q2) conditions (Macfarlane et al., 2017). RMNP does not monitor long-term stream flow within the park boundary so it was necessary to use Environment and Climate Change Canada stream gauging stations. In order to calculate the Qlow and Q2 for streams in RMNP, the historical hydrometric data from the closest 13 stations were acquired (Figure 2.5) and analyzed for flood frequency. To construct the flood frequency curves to obtain the magnitude of Q2, I used the peak flow data which included the annual maximum instantaneous discharge (m^3/s) measurements (separately for all gauging stations) and ranked the discharges in descending order and calculated the recurrence interval using Weibull probability:

$$T = \frac{n+1}{m} \tag{2.1}$$

where T is the recurrence interval in years, n is the number of annual peak stream discharge values in the data series and m is the magnitude rank in descending order. The recurrence intervals were then plotted with the line of best fit (Figure 2.4).

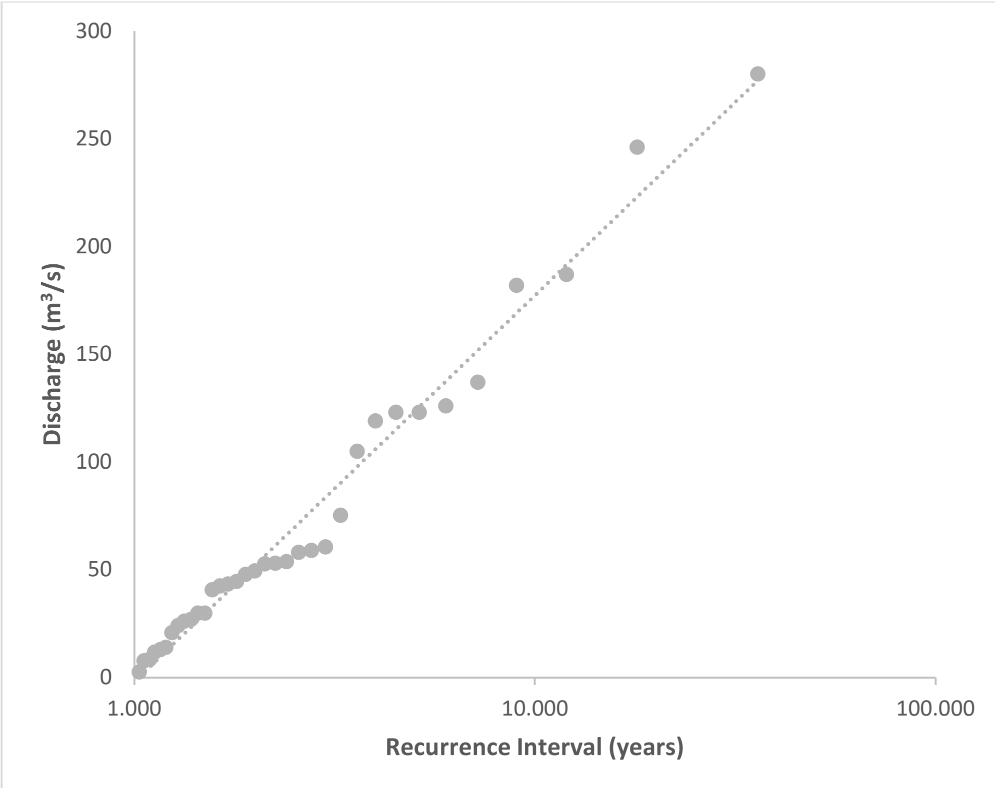

Figure 2.4 - Flood frequency curve analysis forthe period 1979 to 2015. For this curve, data from station 05LJ045 were used. See appendix C for the flood frequency curves for each gauging station shown in Figure 2.4. $y = 77.85\ln(x) - 1.9551$, $R^2 = 0.9795$, $n = 35$, p-value = 4.50×10^{-12}

Using the equations of the line of best fit from the Weibull probability plots, the maximum discharge rate during a 2-year flood for each station was calculated. For example, the equation for hydrometric station 05LJ045 (Figure 2.4) is $y = 77.85\ln(x) – 1.9551$ where y is the discharge rate (m^3/s) and x is equal to the flood year in question, in this case, $x = 2$. Q2 values for stations located around the park (Figure 2.5) were calculated and compiled in Appendix B.

To calculate Qlow, I used daily flow data and calculated 7-day flow for each year by taking the lowest discharge reading and the subsequent measurement for the next 6 days for each hydrologic year in each dataset and then calculated the mean. Those values were then ranked and plotted following the same method as the Q2 data. The definition of 7Q10 is, the lowest average discharge over a period of one week with a recurrence interval of 10 years. Since the value of N for the 7Q10 is 10 years, there is only a 10% probability that there will be a lower flow in any given year. There is a 90% probability that the flow will be greater than the 7Q10 value. In order to calculate Qlow for all stations, I used the R package 'Flowscreen'. All discharge values are compiled in Appendix B. Based on the Q2 and Qlow discharges and the location of the hydrometric stations around the park, station 05LJ045 was chosen to for use as the regional representative station. This station was chosen largely due to its location based on the interest in flooding by landowners to the north of the park. It was also chosen based on the number of years of records available.

BRAT is not a hydrologic model, meaning it does not include other variable inputs like precipitation or soil type, and simply uses regional regression curves to estimate a flow statistic for every reach using upstream drainage area from the DEM and the Qlow and Q2 discharges. What BRAT is set to do is determine whether a given stream reach has a suitable flow regime to support beaver dams. The metric used in the model to describe the suitability of the flow regime is stream power.

To create a regional curve for station 05LJ045 I took the discharge values for Qlow and Q2 and created an equation that related discharge to the drainage area (Appendix B). Using the Qlow and Q2 discharge values for 05LJ045, I edited the 'iHyd' python script which is a part of the BRAT toolbox in ESRI ArcMap 10.5 (Appendix C) in IDLE. The 'iHyd' tool prepares the hydrologic inputs to BRAT by taking the equations created for Qlow and Q2 and calculates the values using the drainage-discharge relationship. The tool adds on two additional fields in the attribute table called 'iHyd_SPLow' and 'iHyd_SP2'. Stream power was subsequently calculated as:

$$\Omega = \rho \cdot g \cdot Q \cdot S \tag{2.2}$$

where **Ω** is the total stream power (Watt/m), ρ is the density of water (1000 kg/m^3), g is acceleration due to gravity (9.8 m/s^2), Q is discharge (m^3/s) and S is steam bed slope which is calculated using the DEM to estimate the highest and lowest points along each segment.

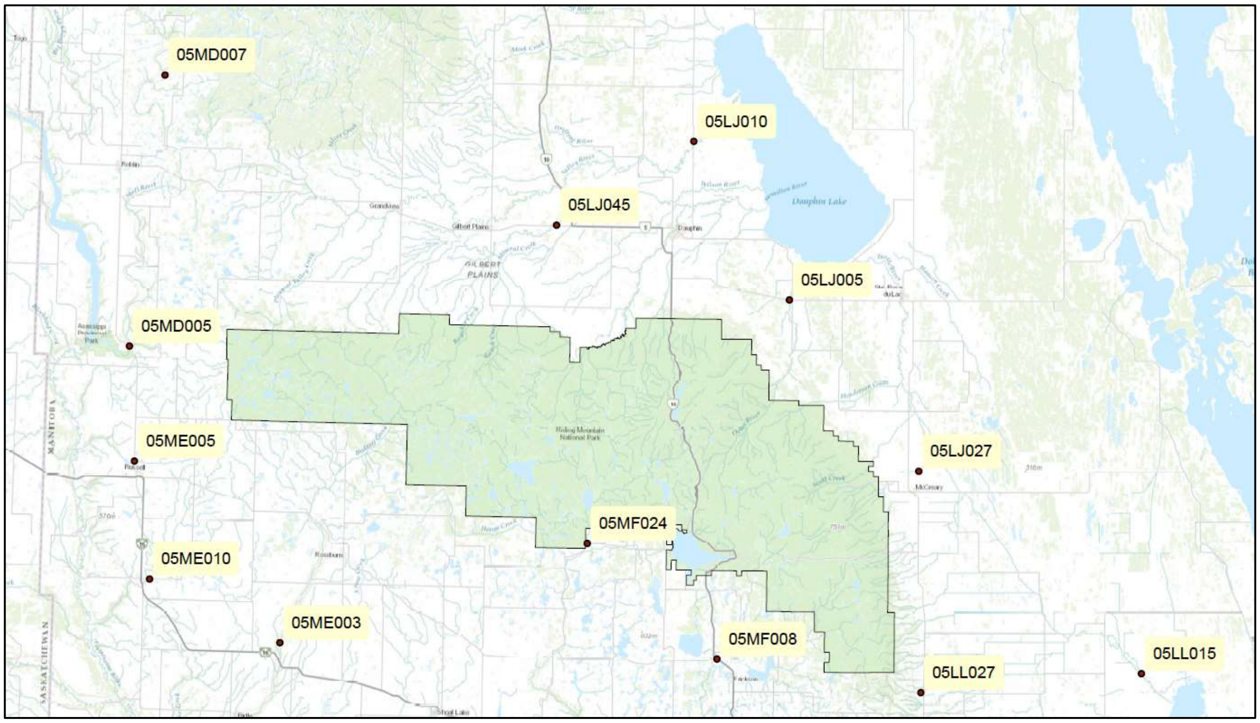

Figure 2.5 - Hydrometric stations located around RMNP (source: ESRI basemap)

2.3 Model outputs

2.3.1 Running the BRAT model

The input layers for the BRAT model were ready to use once the preprocessing steps had been completed. The first step of running the BRAT tool was to load 'BRAT Project Builder' from the BRAT.pyt toolbox in ESRI ArcMap 10.5. This first step gathers the input data and creates a folder structure for the project. The second step is ‘BRAT Table’, which calculates the attributes (e.g., segment slope, segment length, etc.) needed to run the rest of the tools and breaks it out for each stream segment of 300 m or less. The third step ‘iHyd Streamflow Attributes’ calculates discharge (in US units of cfs) and stream power for both baseflow and Q2 peak stream flows. The fourth step is ‘BRAT Vegetation Dam Capacity Model’ which calculates dam capacity based solely on vegetation type found in the 30 m and 100 m buffers it creates. This step calculates capacity for each stream segment and for both existing and historic vegetation covers. The fifth step I used is the ‘BRAT Combined Dam Capacity Model’ that calculates maximum dam capacity based on all input variables. It calculates total dam capacity for each stream segment, based on the stream power (Qlow and Q2), vegetation code, and stream segment slope, to determine the maximum number of beaver dams and creates new columns in the attribute table. The result was a polyline shapefile of the original drainage network with all of the above attribute data added to it and symbology layers to display the network in ESRI ArcMap. I exported the attribute data into a spreadsheet in order to explore it.

To determine if raster resolution has an impact on the results for modelled beaver dam capacity, BRAT was run using the original 10 m resolution vegetation raster for 2016. The modelled capacity was only ~2% different in overall results and it was determined to continue all further analysis using the aggregated 30 m resolution modelled results.

2.4 Model validation

Both field and digital data were used in model verification. The goal of the field validation was to ground truth 10% of the 193 km of total stream length within RMNP. In all, 13.7 km (~7%) of stream length was ground truthed between August 1 and August 14 in 2017. The specific stream reaches chosen for ground truthing were selected in part for ease of access owing to a lack of a well-developed trail network in the National Park. Using Google Earth overlaid with a trail and road shapefile, access points were chosen in the week prior to field work starting. RMNP is not overly developed so existing hiking trails/service roads were utilized to get as close to streams as possible. Also considered in site selection was park physiography, which influences stream gradient – an important constraining variable on beaver dam capacity. RMNP has four land districts with quite different physiography, described earlier. The ground truthing ended up occurring close to four main access points within the park, which balanced ease of site access while capturing of the diversity of park physiography.

Field data collected include beaver dam length, height, pond depth, descriptive characteristics, photographs and videos (Table 2.3). Beaver dams were located in the field by following the stream course and scouting for beaver dams in or near the stream channel. Lengths were measured along the crest of the dam across the stream from bank to bank using a cloth measuring tape. Pond depth was measured by standing at the foot of the dam on the upstream side using a stadia rod held vertically. Height was measured using both the measuring tape and stadia rod held downstream of each dam. Measurement error using this technique was < 0.05 m.

In addition to descriptive characteristics, geographic coordinates were recorded at each beaver dam location using a Garmin GPS Map 62s handheld GPS (± 3.7 m accuracy). All the above measurements were recorded in the field on the Fulcrum data collection application, run on an iPhone 6.

After returning from the field, all of the collected data were downloaded from the Fulcrum application to a database. The GPS coordinates of beaver dam locations were entered into ESRI ArcMap 10.5 using the 'Make XY Event Layer' function and saved as a point feature layer. All photos and videos were digitally archived for future use. The number of dams in each watershed was calculated and added to the database.

Table 2.3 -Variables collected during field verification activities and value options for each variable.

Variable	Description	Units
Dam height	Measured from the top of dam to the stream thalweg downstream of the dam	metres
Dam status	Assessed as active or inactive beaver activity	Categorical (active, inactive)
Dam length	Measured streambank width from spring growth line on both sides	metres
Dam classification	Structural status of the dam based on Woo & Waddington	Categorical (gap flow, through flow, blown, under flow; *sensu* Woo and Waddington, 1990)
Pond depth – upstream	Measured with a stadia rod	metre

2.4.1 Digitizing

Analysis of the spatial extent of open water was completed by using high resolution imagery (62.5 cm) from 2004 in ESRI ArcMap 10.5. Since RMNP is such a large park, it was decided to use the park's delineated 30 aerial survey blocks, each of which are ~24 km^2. These were divided into 6 equal quadrants of ~4 km^2 and one from each of the 30 blocks was randomly selected for further analysis. I manually delineated all detectable beaver ponds polygons in these blocks (Figure 2.6). Using the ‘calculate geometry’ feature in ArcMap, the total surface area (m^2) of the polygons and number of ponds were calculated and compiled in a database.

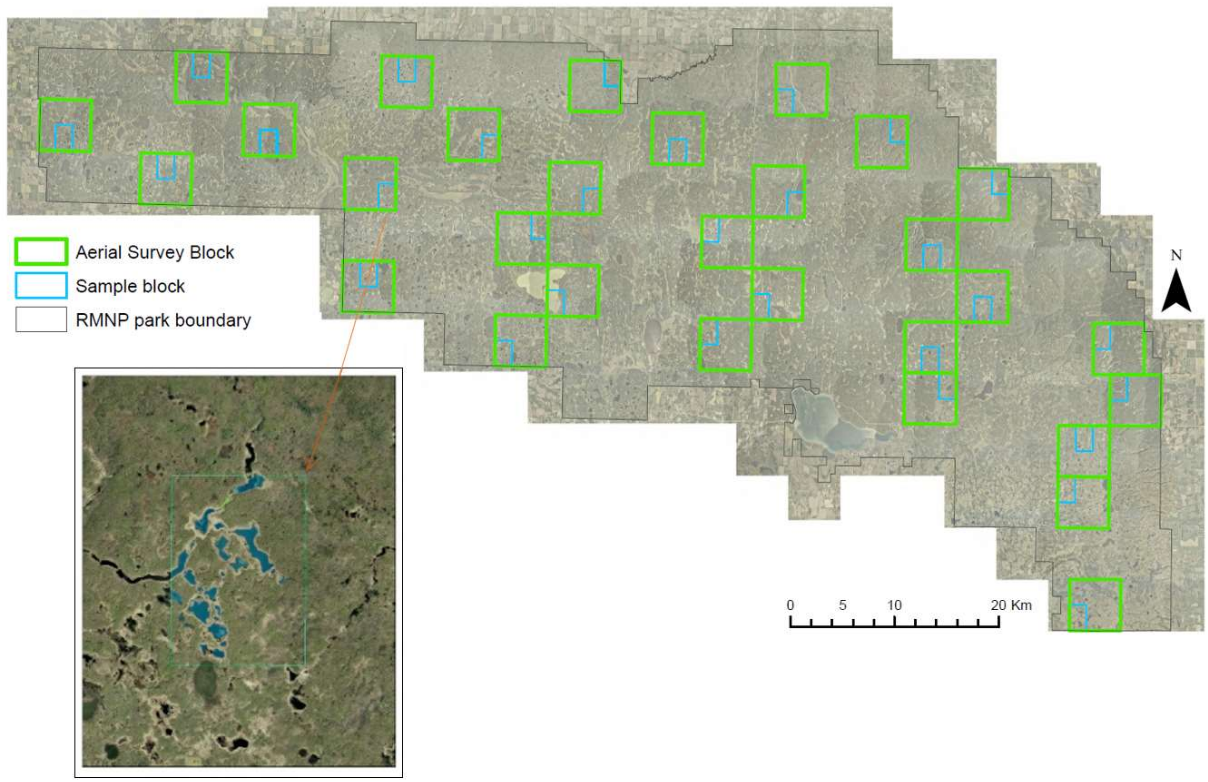

Figure 2.6 - Digitized beaver pond sampling grids in RMNP based on 62.5 cm resolution imagery with 4 km^2 sample blocks (blue blocks). Enlarged picture illustrates digitized beaver ponds and subsequent beaver dams. Green blocks show Parks Canada predetermined aerial survey blocks

2.5 Determining potential water storage

The methods of Karran et al. (2017) were used to calculate the water volume of the digitized ponds. Specifically, pond volume (V) was calculated using the power regression relationship between the maximum volume of the beaver ponds and the maximum surface area:

$$V = 0.0955x^{1.1562} \qquad (2.3)$$

where x is the surface area (m^2). The results were compiled into a database for further analysis.

2.6 Sensitivity analysis

Climate change modelling predicts significant stream flow changes in the boreal plains ecozone (Ireson et al., 2015, Price et al., 2017). To evaluate how climate-induced changes to the streamflow hydrological regime might impact beaver dam capacity, I manipulated the discharge (Qlow and Q2) values in BRAT (Table 5). Scenarios run included a Qlow increase of 25% and a decrease of 25%. Also, Q2 was increased by 10%, 25% and 100% to simulate the effects of larger two-year floods. To run the scenarios, I edited the 'iHyd' python script (Appendix C) in IDLE to include the new discharge rates and ran the BRAT model for each scenario. There were no differences in total dam capacity with the Qlow scenarios as all scenarios resulted in stream powers between 0 and 175 Watts/m, which BRAT designates as 'can build dam'. Meaning, decreasing Qlow does not impact the model results, and as a result, BRAT does not recognize any stream reaches being unable to support beaver dams. Thus, reported are only scenarios where Q2 was manipulated.

Table 2.4 – Variables used in discharge scenario analysis.

Flow	Variable	Discharge (m^3/s)
10 Year Average 7-day baseflow	Qlow	0.05
Qlow – 25%	$Qlow_{-25}$	0.04
Qlow +25%	$Qlow_{+25}$	0.07
2 Year Peak Flow	Q2	52.01
Q2 +10%	$Q2_{10}$	57.21
Q2 +25%	$Q2_{25}$	65.01
Q2 Double	Q2D	104.02

3. RESULTS

3.1 Beaver dam capacity

The capacity model results indicate that RMNP has the capacity to support a very large number of beaver dams. The estimated current (2016) maximum capacity is 24,690 dams or 9 dams/km (Figure 3.1; Table 3.1). Beaver dam density is unevenly distributed across the park. Stream reaches classified as 'frequent' damming are located throughout the park, accounting for over 70% of total stream length. However, stream reaches classified as 'occasional' damming, accounting for 23%, are clustered in the centre and southeast of the park. A total of 3.2% of the stream reaches are classified as 'pervasive' damming. These are located primarily in the western part of the park. Little of the park is unsuitable for beaver dams as evidenced by the 'rare' and 'none' damming categories accounting for <2.8% of the total stream length.

3.1.1 Beaver dam capacity over time

The BRAT model is underpinned by the hypothesis that beaver dam distributions are driven primarily by beaver vegetation preferences. To explore changes in predicted dam capacity over time, vegetation raster data inputs from 1991, 2003 and 2016 were used in the model and predicted dam capacities were compared (Table 3.1). Model results from 2003 and 2016 were similar, but different from 1991. Total maximum beaver dam capacity in 1991 was 28,440 and 13% lower (24,846 dams) in 2003 and 2016.

In 1991, ~17% of total predicted stream length falls within the 'occasional' damming category. Most stream reaches were classified as 'frequent' damming (~72%). Only 9% were classified as 'pervasive' damming (Figure 3.1c); these are located mostly in the northern escarpment, with a small cluster in the south. The distribution of dam capacity in 2003 is similar to that in 2016 (Table 3.1; Figure 3.1a and Figure 3.1b). Most stream reaches fall into the 'frequent' category (~70%), and both 2003 and 2016 have ~3% of the stream reaches predicted as 'pervasive'; ~60% lower than 1991. The differences in 'pervasive' damming stream reaches were greatest in the southeastern part of the park in 2003 and 2016.

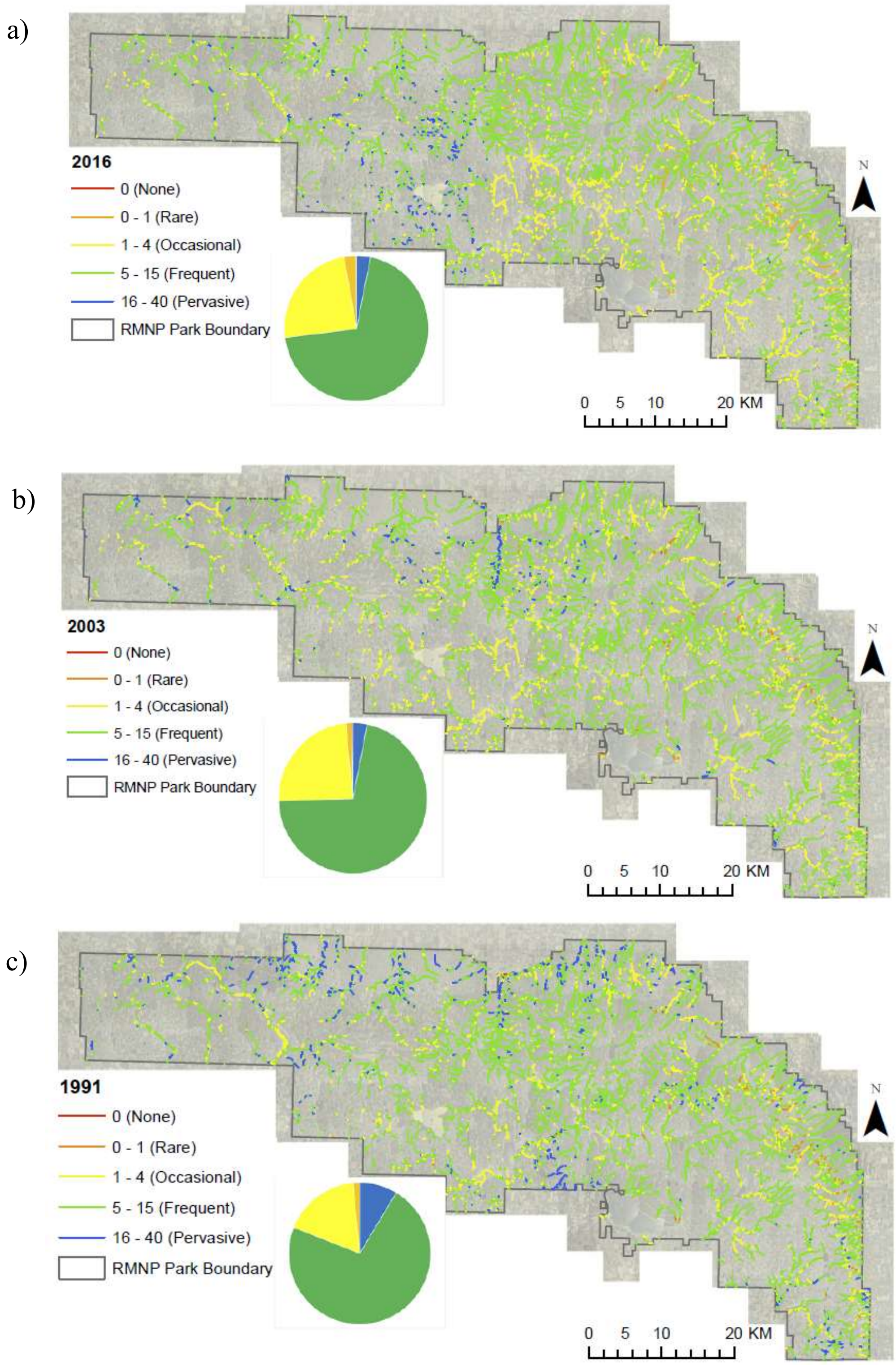

Figure 3.1 – BRAT maximum dam combined capacity model for a) 2016, b) 2003 and c) 1991 using 30 m resolution input vegetation raster data.

Table 3.1 - Distribution of beaver dam capacity by stream length and vegetation imagery year.

	Pervasive (16-40 dams/km)		**Frequent (5-15 dams/km)**		**Occasional (1-4 dams/km)**		**Rare (0-1 dams/km)**		**None (0 dams/km)**		**STREAM LENGTH**	**Total Beaver Dam Capacity**	
Vegetation Imagery Year	Length (km)	%	Length (km)	%	Length (km)	%	Length (km)	%	Length (km)	%	Length (km)	Dams/km	No.
1991	224.2	8.6	1883.5	72.3	455.7	17.5	40.2	1.5	0.6	0.02	2604	11	28,440
2003	80.6	3.1	1864.8	71.6	625.6	24	32.9	1.3	0.4	0.01	2604	10	24,846
2016	82.4	3.2	1832.9	70.4	618.1	23.7	70.6	2.7	0.3	0.01	2604	9	24,690

3.1.2 Spatial variation in beaver dam capacity

Stream length varies by physiographic land districts within RMNP (Table 3.2). The plateau has the highest stream length (~55% of total) and the escarpment has the second highest stream length (~28%). The hummocky (9%) and lowlands districts (8%) have relatively similar stream length (Figure 3.2; Table 3.2).

Table 3.2 - Maximum predicted beaver dam density in each physiographic land district

		1991	2003	2016
Physiography District	**Length (km)**	**Dam Density (No./km)**		
Escarpment	721	10	9	9
Hummocky	208	12	9	11
Lowlands	229	13	11	11
Plateau	1,446	11	9	9
Total	**2604**	**11**	**10**	**9**

There is considerable spatial variation in maximum beaver dam capacity among physiographic land districts within RMNP (Figure 3.2). The 2016 model results indicate the lowland and hummocky districts have the highest beaver dam capacity, at 11 dams/km (Table 3.2). Maximum beaver dam density in the plateau and escarpment is 9 dams/km. The plateau is predicted to be able to support the most beaver dams (13,105) while the lowlands are predicted to support an order of magnitude fewer dams (2,389) owing to its smaller area.

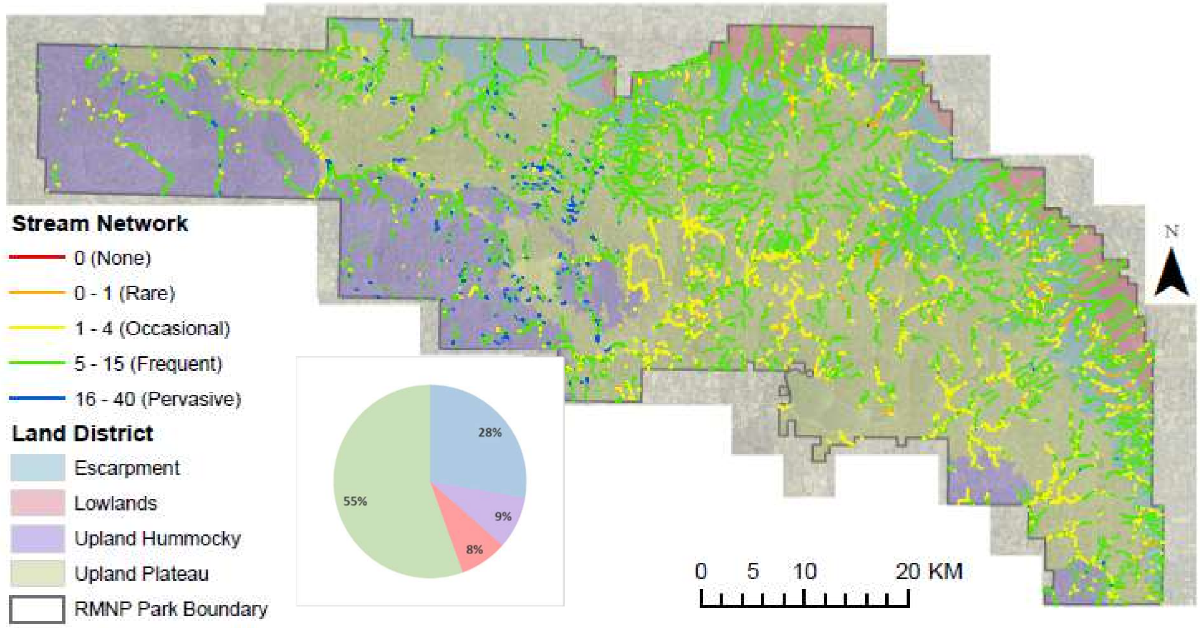

Figure 3.2 – Predicted beaver dam capacity for 2016 stream network overlay on physiographic land districts. Inset pie chart gives the percentage of stream length in each land district.

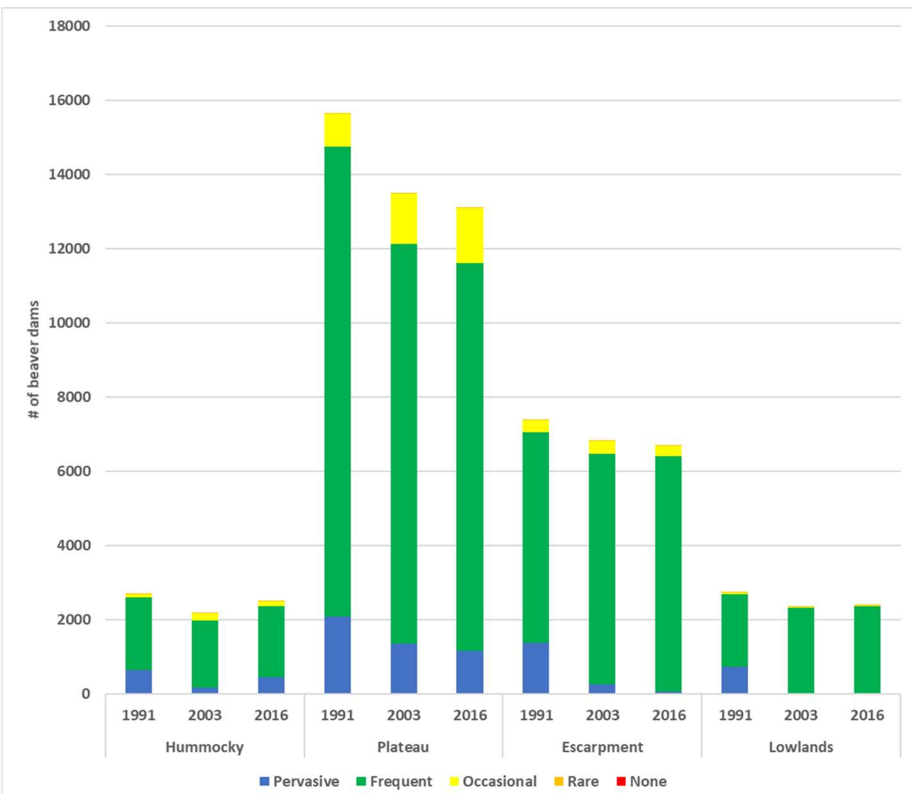

Figure 3.3 – Modelled maximum beaver dam capacity in each physiographic land district.

There is little difference in total maximum dam capacity between the studied years in the escarpment and lowlands (Figure 3.2). In the plateau, however, total dam capacity was highest in 1991 and was 14% lower in 2003 and 2016. The hummocky district dam capacity in 2003 was 19% lower than in 1991 but was then 14% higher in 2016.

The majority of stream reaches in each physiographic land district falls in the ‘frequent’ category (Figure 3.3). The ‘pervasive’ category has decreased in all districts except for the hummocky. The amount of ‘pervasive’ stream reaches in the hummocky district is 73% lower in 2003 than 1991, but is 160% higher in 2016 than 2003.The proportion of ‘pervasive’ stream reaches along the escarpment changed the most of any of the physiography land districts over time; it was 81% lower in 2003 and ~100% lower in 2016. Between 1991 to 2003, there was an extensive shift in the ‘pervasive’ category to the ‘frequent’ category in the lowland district going from 16% to 0%. The park does not have any noteworthy ‘none’ damming category stream reaches (Figure 3.4).

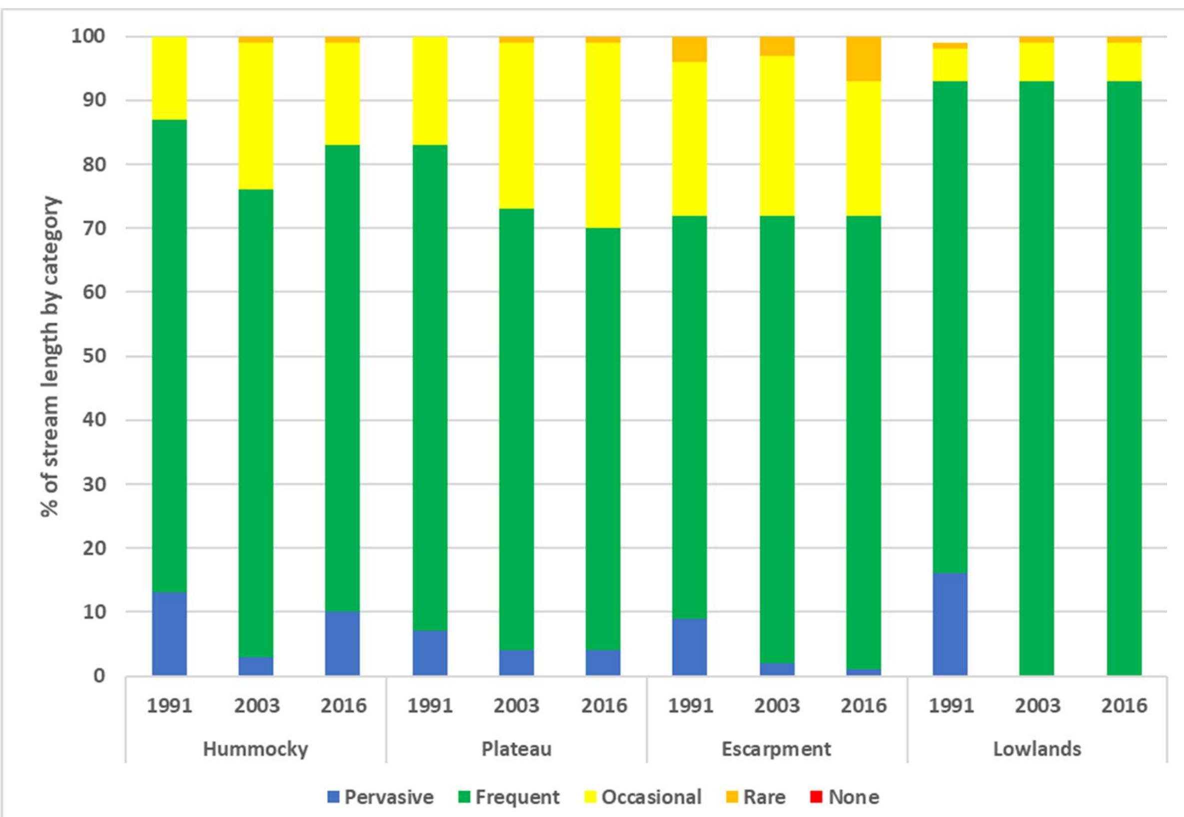

Figure 3.4 - Percentage of stream length in each damming category by year and physiography land district.

RMNP regularly performs a census of beaver caches. Cache numbers have fluctuated since the aerial surveys began in 1973 (Figure 3.5). Unfortunately, there were no cache counts in 1991 or 2003. In 1992, there were 3367 caches and in 2004 there were 1773 caches. There was a decline in the number of caches during 1995 to 2004 but an increase of ~50% in 2016 (Figure 3.5). There is considerable spatial variation in beaver caches across in the park (Figure 3.6; Figure 3.7), with most caches located in the plateau and hummocky physiographic land districts. In 1992, 53% of caches were in the plateau, 36% on the hummocky, and less that 15% in the lowlands and escarpment. In 2004, the cache count across the park decreased (Figure 3.5) but not in a spatially uniform way. The proportion of caches in the plateau fell to 37% but increased to 46% in the hummocky district. In 2016, the proportion of caches in the plateau increased to 45% of total, and the hummocky decreased to 39% (Figure 3.6).

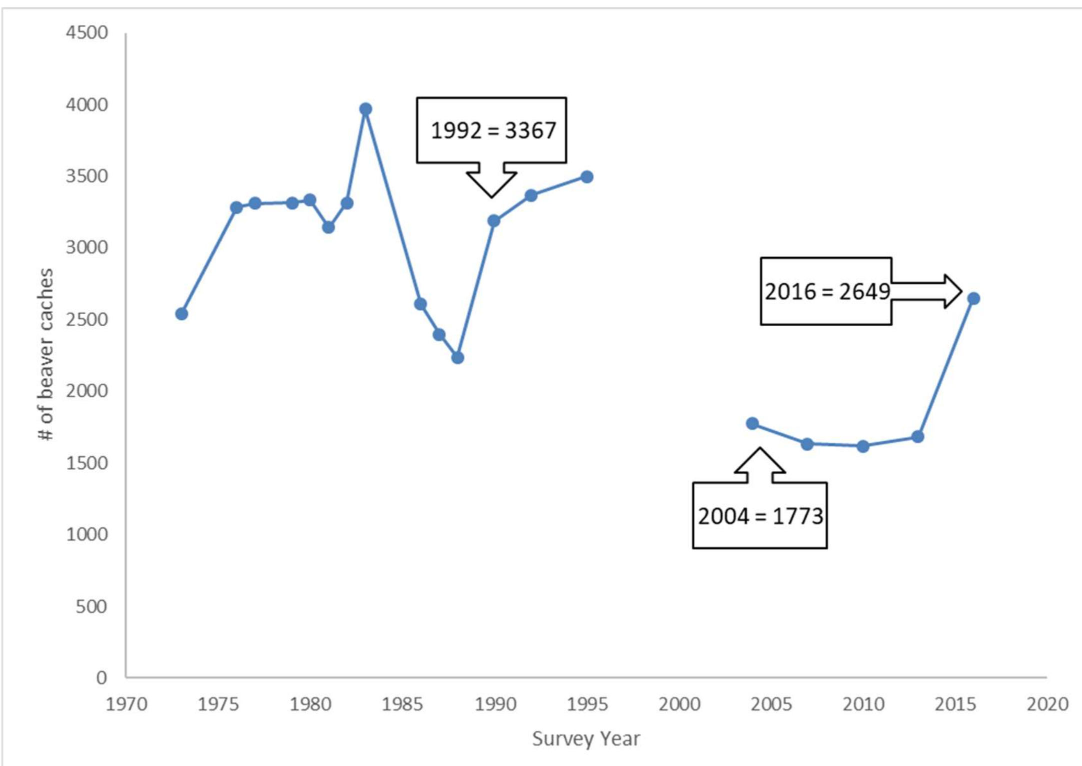

Figure 3.5 – Beaver cache count since 1973 in RMNP. Aerial surveys are flown every 3 – 5 years in 30 sample blocks and the total is estimated using a 95% confidence interval by Parks Canada. There were no aerial surveys between 1995 to 2004 (data provided by RMNP). Highlighted are cache counts for years closest to those used in the BRAT dam capacity modelling.

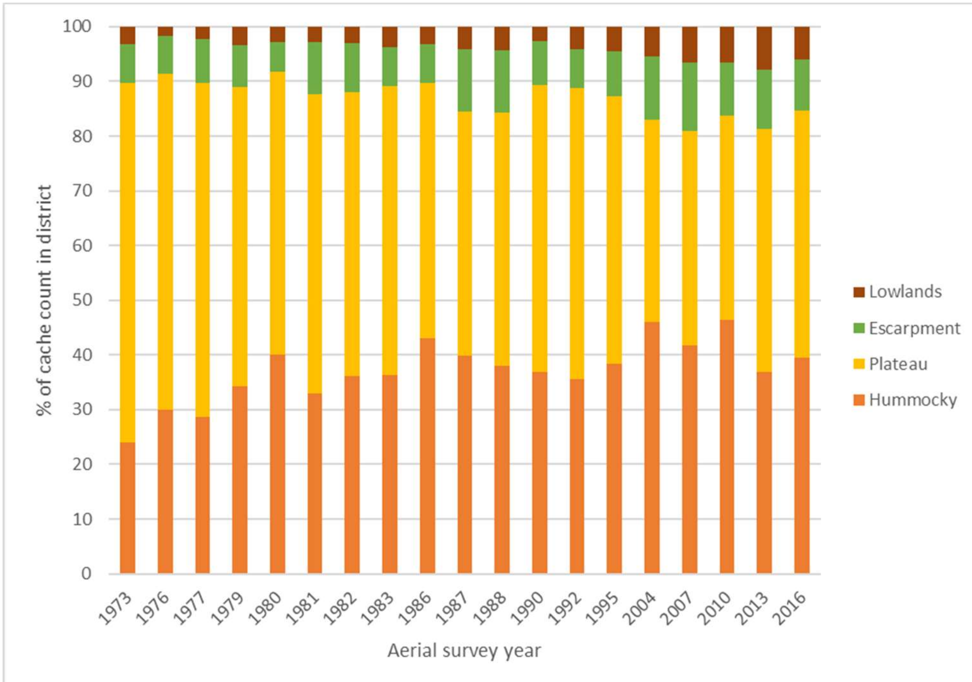

Figure 3.6 – Proportion of beaver caches occurring in each physiography land district.

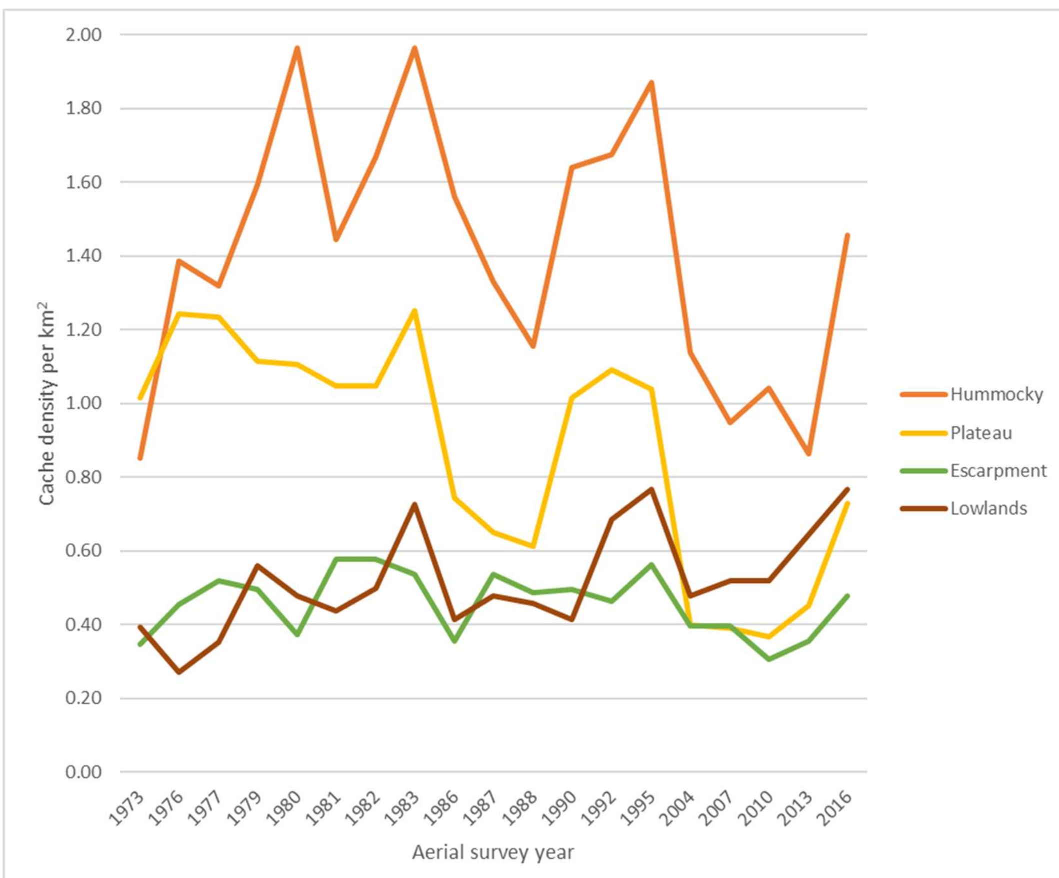

Figure 3.7 – Cache density (number/km^2) occurring in each physiography land district.

3.2 Changes to forest cover in RMNP

Vegetation composition changes have occurred within RMNP in the last 25 years (Figure 3.8). There has been an overall change of 2.8% between 1991 to 2003 (Table 3.3), and an additional 3.4% between 2003 to 2016 (Table 3.4). The primary changes that occurred are a shift in deciduous to coniferous species in the park. Much of the change between 1991 to 2003 was concentrated in the western part of the park in the hummocky and plateau districts (Figure 3.9a). The largest changes between 2003 to 2016 occurred in the central part of the park in the plateau district. There was one specific area in the southeastern region that has a large area of change (Figure 3.9b).

The largest major cover changes between 1991 to 2003 was an additional 23.2 km^2 of marsh; 11.8 km^2 of this area was previously deciduous cover while ~3 km^2 was previously mixed wood and shrub (Table 3.3a). During 2003 to 2016, the major cover change was that of mixed wood, which decreased by 28.2 km^2; this vegetation cover shifted to coniferous (12.7 km^2), grassland (5 km^2), bogs (~3 km^2) and burns (~3 km^2) (Table 3.4a). There was a significant spectral index change to deciduous vegetation (38.5 km^2), accounting for 1.3% of the total change between 1991 to 2003 (Table 3.3b). However, there was only a further spectral index change of just over 1 km^2 between 2003 to 2016 (Table 3.4b). During 2003 to 2016 there was ~11 km^2 of disturbance to coniferous cover type indicated by the change in spectral index, and ~10 km^2 of disturbance to marsh and mixed wood cover types (Table 3.4b).

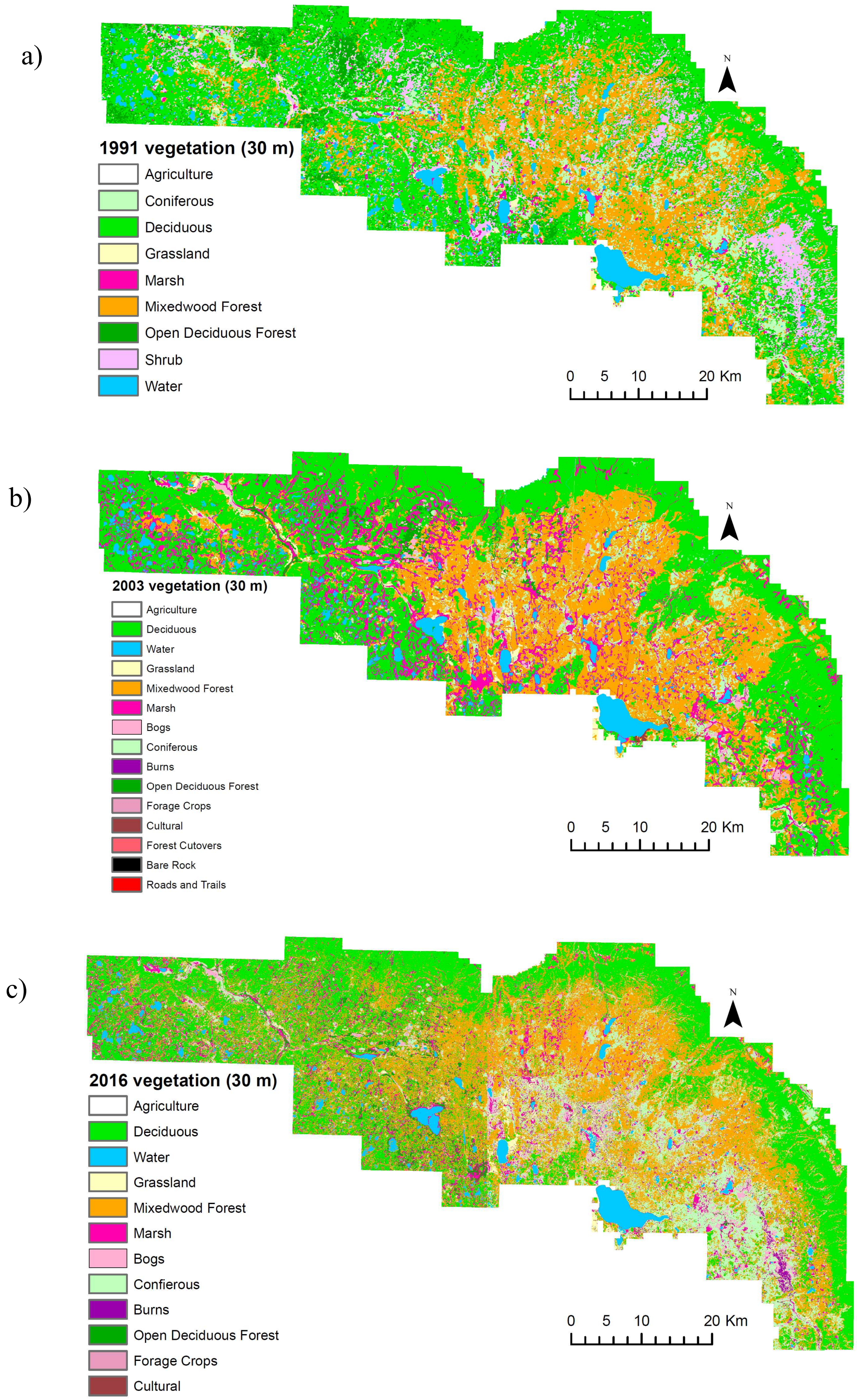

Figure 3.8 - Vegetation raster data (30 m) for a) 1991, b) 2003 and c) 2016.

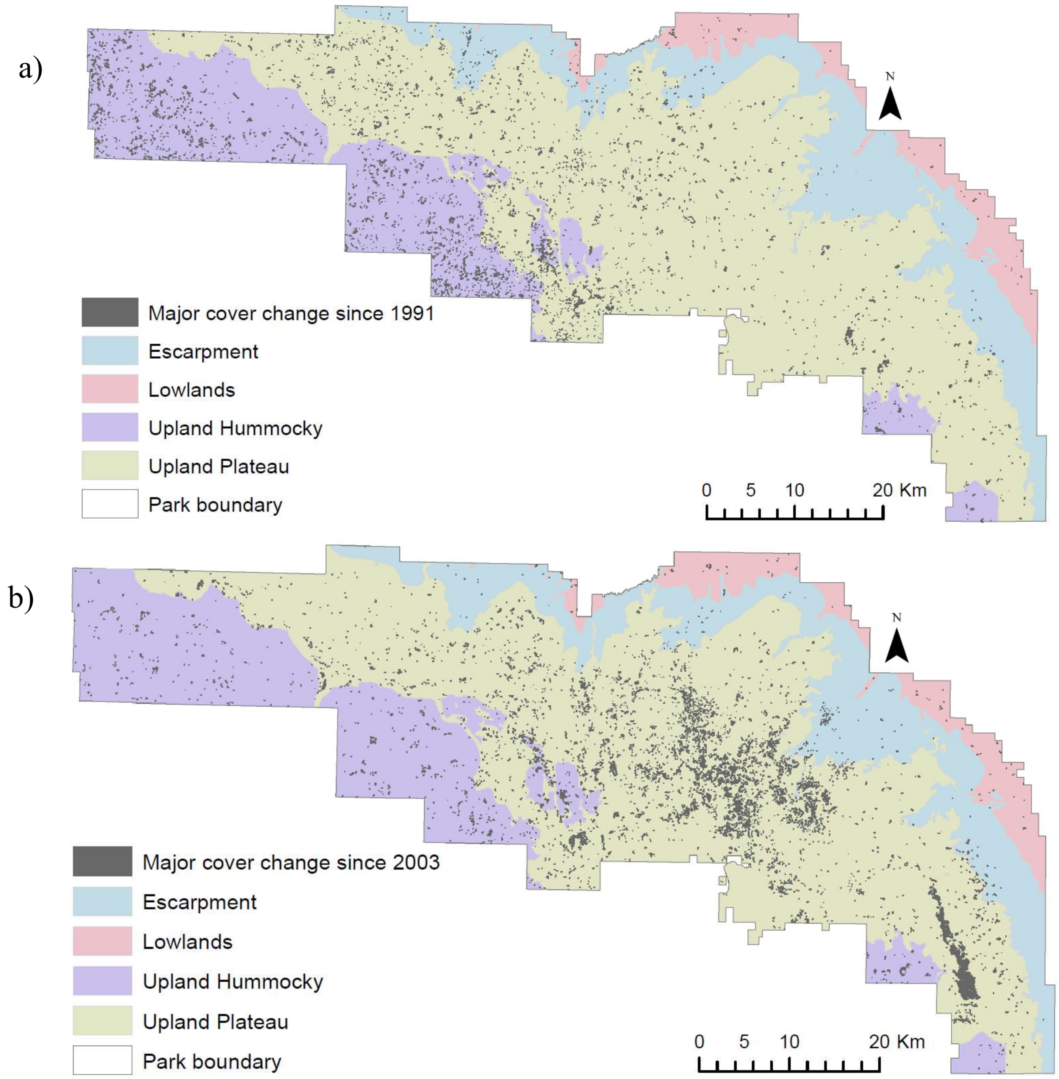

Figure 3.9 – Major vegetation cover change since a) 1991 and b) 2003 using Landsat-based detection of Trends in Disturbance and Recovery (Landtrendr) approach with a normalized burn ratio (NBR) spectral index.

Table 3.3 - Breakdown of vegetation changes during 1991 to 2003. Cover type change from one type to another (a) and vegetation quality change (b).

a)

		Major Cover change (km^2)									
		2003									
		Coniferous	Cultural	Deciduous	Grassland	Marsh	Mixed wood	Roads and Trails	Shrub	Water	Total (km^2)
1991	Coniferous			0.7	0.01	4.40	0.62	0.65	0.24	0.09	6.7
	Deciduous	0.03			0.13	11.80	4.14	0.25	1.16	0.22	17.7
	Grass	0.002		0.01	0.24	0.32	0.03				0.6
	Marsh	0.02		0.20	0.02		0.05	0.01	0.08	0.04	0.4
	Mixed wood	1.02	0.01	1.45	0.04	3.43		0.44	0.08	0.08	6.5
	Shrub	0.05		0.86	0.004	3.23	0.30	0.03		0.03	4.5
	Total (km^2)	1.1	0.01	3.1	0.4	23.2	5.1	1.4	1.6	0.5	36.4

b)

		Disturbance magnitude – change of spectral index (km^2)						
		2003						
		Coniferous	Deciduous	Grassland	Marsh	Mixed wood	Shrub	Total (km^2)
1991	Coniferous	1.6						1.6
	Deciduous		38.5					38.5
	Grassland			0.2				0.2
	Marsh				2.4			2.4
	Mixed wood					3.4		3.4
	Shrub						0.2	0.2
	Total (km^2)							46.4

Table 3.4– Breakdown of vegetation changes during 2003 to 2016. Cover type change from one type to another (a) and vegetation quality change (b).

a)

		Major Cover Change (km²)											
		2016											
2003		Bogs	Burns	Coniferous	Cultural	Deciduous	Forage Crops	Grassland	Marsh	Mixed wood	Open deciduous	Water	Total (km$^{2)}$
	Coniferous	2.374	0.710		0.032	0.392		2.407	0.500	4.434	0.549	0.005	11.4
	Deciduous	0.316	1.102	0.508	0.060		0.016	1.678	1.113	1.957	0.411	0.027	7.2
	Grassland	0.052	0.032	0.082	0.023	0.136	0.405		0.277	0.319	0.061	0.024	1.4
	Marsh	1.141	0.356	1.822	0.942	0.604	0.046	2.761		2.296	4.653	0.340	15.0
	Mixed wood	3.368	3.443	12.691	0.140	0.720	0.004	5.101	1.462		1.232	0.034	28.2
	Open deciduous	0.047	0.058	0.050	0.005	0.103	0.005	0.102	0.289	0.233			0.9
	Bog		0.821	0.135	0.013	0.096		0.203	0.347	0.053	0.065		1.7
	Total (km$^{2)}$	7.3	6.5	15.3	1.2	2.1	0.5	12.3	4.0	9.3	7.0	0.4	65.8

b)

		Disturbance magnitude – change of spectral index (km²)							
		2016							
2003		Agriculture	Bogs	Coniferous	Deciduous	Grassland	Marsh	Mixed wood	Open deciduous	Total (km$^{2)}$
	Coniferous			11.025						11.0
	Deciduous				1.268					1.3
	Grassland	0.012				1.336				1.3
	Marsh						10.129			10.1
	Mixed wood							10.972		11.0
	Open deciduous								0.226	0.2
	Bog		0.419							0.4
	Total (km²)									35.4

3.2.1 Fire impact on beaver dam capacity

Polygons of fires since 1999 indicate there are places in the park that are regularly burned, and other areas that are infrequently burned (Figure 3.10). For example, forest fires occurred during all three-time intervals near the centre of the park. In comparison, there were sizable fires in the southeast and west of the park during 2009-2015 that had not experienced recent burning. Post-hoc analysis to explore dam density differences pre- and post-fire was completed using modelled dam capacity of burned streams segments (Table 3.5). Results show that of the ~248 km of burned riparian vegetation, beaver dam density increased along half (110 km) and decreased along the other half (138 km). Approximately 51 km^2 was burned more than once over our study period and ~37 km^2 of it increased or stayed the same in beaver dam density.

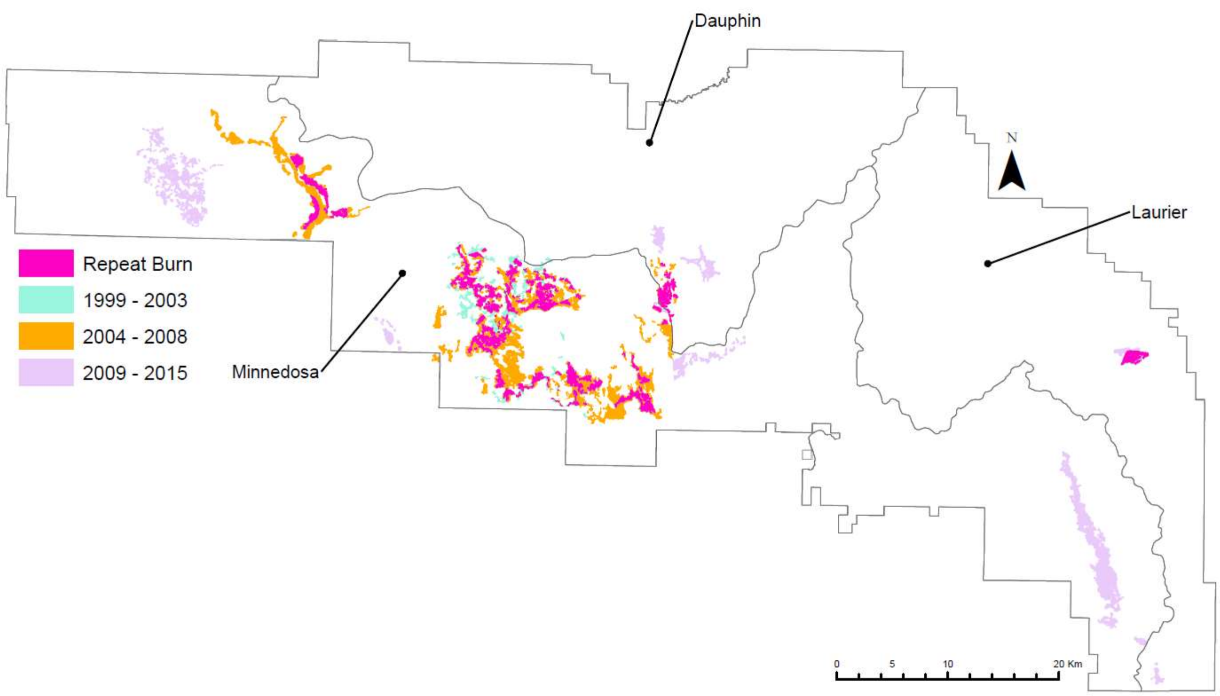

Figure 3.10 – Burned areas of RMNP from 1999-2003, 2004-2008 and 2009-2015. Call out text are the watersheds located in the park.

Table 3.5 - Predicted maximum dam capacity for each length (km) of riparian burn areas using 1991, 2003 and 2016 data. Red = decrease in dams; Green = increase in dams, Blue = no change.

	Length (km)	Dam Density (No./km)				
Burn Year		*1991*	*2003*	*2016*	*Second Burn*	Watershed
1999	1.4	2.7	4.1	10.2	*2006*	Minnedosa
2000	2.8	5.9	7.5	4.1	*2005*	Minnedosa
2001	2.4	6.8	10.3	8.1	*2006*	Minnedosa
2002a	5.6	14.1	10.4	10.3	*2010*	Laurier
2002b	7.5	7.5	7.1	10.4	*2005*	Minnedosa
2003	28.5	9.4	7.6	12.2	*2008*	Minnedosa
2004	3.0	9.8	4.3	3.4	*2010*	Minnedosa/ Dauphin
2005	32.1	7.4	6.5	8.1		Minnedosa
2006	46.7	7.8	9.5	8.4		Minnedosa
2008	39.0	9.6	7.8	12.7		Minnedosa
2009	18.2	8.9	6.5	5.4		Minnedosa
2010a	4.6	9.9	10.7	10.7		Laurier
2010b	22.5	9.3	6.5	5.9		Dauphin
2011a	4.03	11.6	8.3	6.8		Minnedosa/ Laurier
2011b	19.1	9.6	8.9	4.3		Minnedosa
2015	11.2	10.2	9.9	10.4		Minnedosa

3.3 Comparison of predicted beaver dam capacity to observed dam density

Predicted beaver dam capacity from 2003 in each land district was compared to the digitized dam data for the survey blocks from 2004 and results revealed RMNP is not at predicted maximum dam capacity (Figure 3.11). For the areas analyzed, beaver dams are at 39% (488 dams) of modelled capacity (1243 dams), although this varies by land district. The plateau physiographic land district has the highest predicted maximum dam capacity (48%) and the hummocky has the lowest at 8.6%. The observed capacity for the escarpment is 40 dams, only 10% of total modelled capacity. The lowlands are at ~23% of the modelled dam capacity. The blocks located in the lowlands and escarpment physiographic land districts are below maximum dam capacity with block 12 at 56% and block 56 at 5%, and the escarpment blocks range between 1% (block 108) to 21% (block 36) (Figure 3.11).

Some parts of the park though have more beaver dams than indicated by the modelling (Figure 3.11). This is the case for blocks 8, 20, 24, 40 and 72. Four of these (20, 22, 40, 72) occur in the hummocky land district and one (8) occurs in the plateau district (Figure 3.11). Specifically, block 20 had 35 dams in 2004 with a predicted maximum of 4. In the plateau, only block 8 is over the modelled maximum capacity (557%).

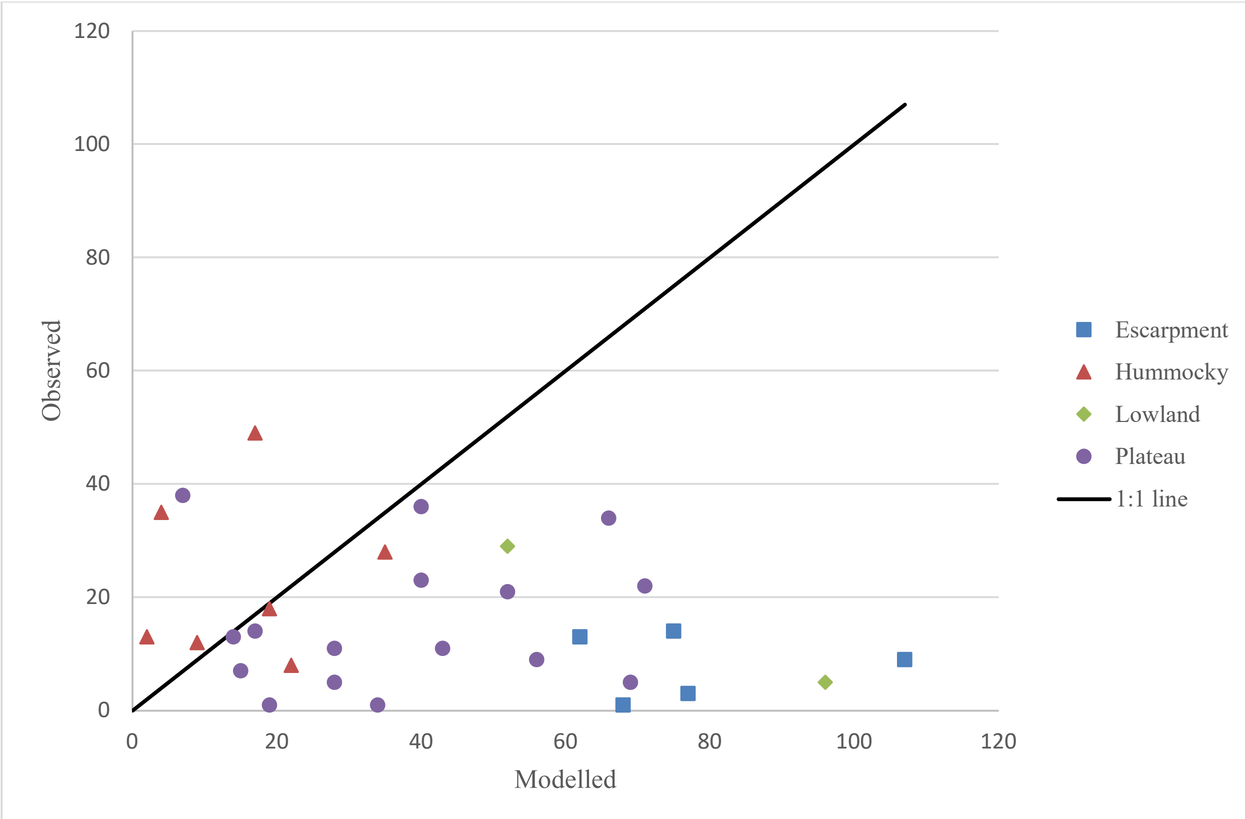

Figure 3.11 - Number of beaver dams observed in 2004 aerial imagery compared to the number of predicted maximum beaver dams in 2003 in each physiography type.

3.3.1 Ground Truthing

Field verification of beaver dam locations was carried out in August 2017. In total, field verifications were completed on 7 different streams (13.5 km of stream length) within RMNP (Figure 3.12). Thirty-one beaver dams were found. Most dams (13 dams) were found in the Rolling River watershed located in the southeastern part of the park (Figure 3.12). In contrast, no dams were found in the Jackfish watershed located in the central part of the park.

Similar to the survey block analysis, modelled dam capacity was different than that observed during the ground verification (Table 3.6). For example, modelled beaver dam density for the field verified stream reaches was 8.2 dams/km whereas the observed beaver dam density was 2.5 dams/km. None of the field verified stream reaches had a beaver dam density greater than the modelled maximum capacity. In the Rolling River watershed, the field verified beaver dam density was 4.2 dams/km, which is 81% of modelled maximum capacity. Interestingly, in

Jackfish watershed, modelled density is the highest of all stream reaches at 13 dams/km, however, no dams were observed during the field verification.

Post hoc analysis on beaver dam density by physiographic land district indicates that the highest number of observed dams (16 dams) occurs in the plateau and the least (0 dams) occurs in the lowlands (Table 3.7). The hummocky land district has the highest field verified density of 7.9 dams/km and the lowlands has the lowest at 0 dams/km. The escarpment's field verified density is 1.6 dams/km and the plateau's density is 2 dams/km. All field verified stream reaches have beaver dam densities below modelled maximum dam capacity, except for the hummocky land district. There, the field verified beaver dam density is 167% more than the modelled maximum.

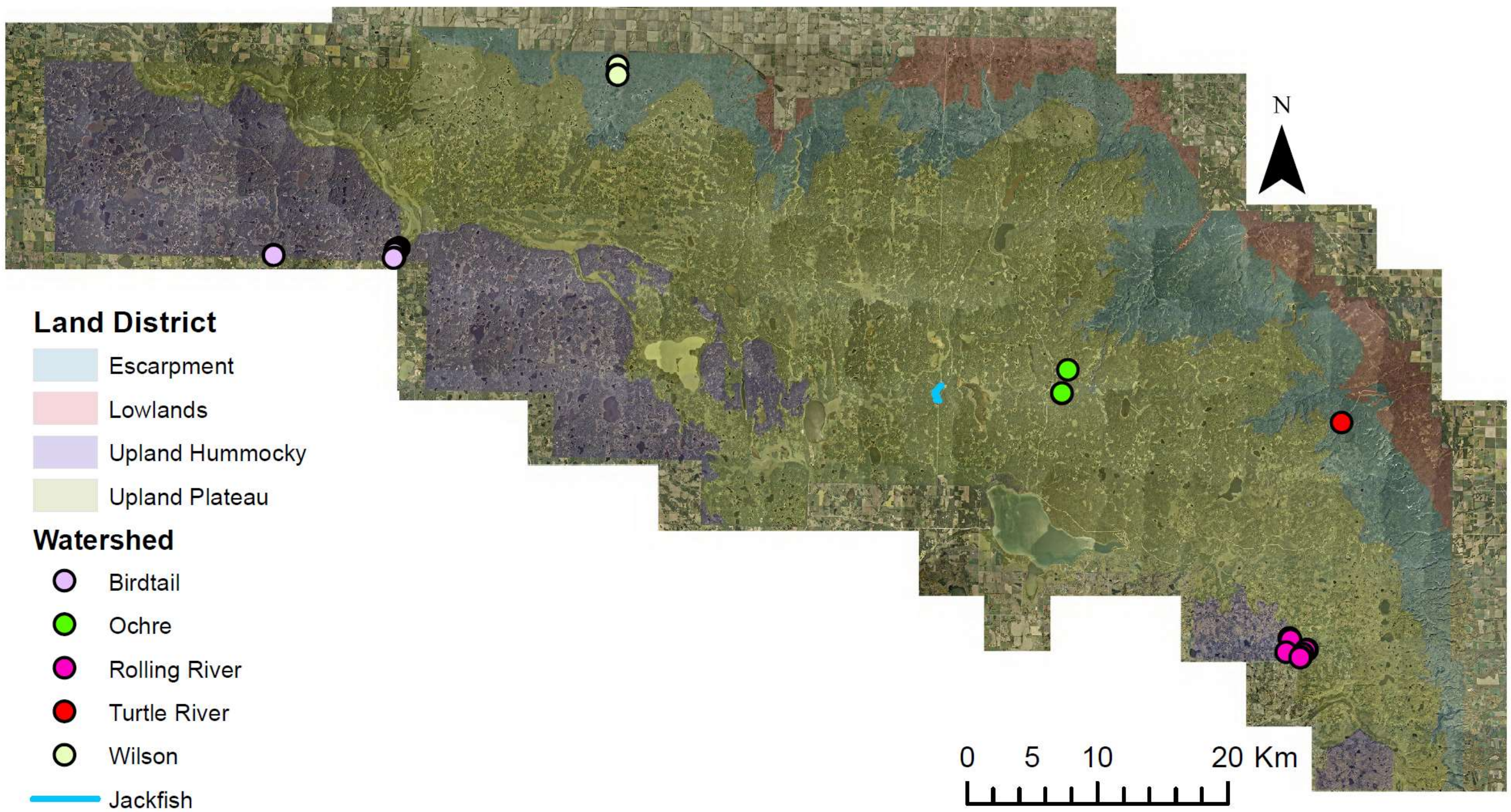

Figure 3.12 – Overview of RMNP showing locations of dam observations in watershed and physiographical district.

Table 3.6 - Observed and modelled beaver dam density. Field observations are from August 2017 and modelled results are from running BRAT with the 2016 30-m resolution vegetation cover.

	Observed			Modelled		
Watershed	**Total dams**	**Distance (km)**	**Dams/km**	**Max capacity**	**Distance (km)**	**Dams/km**
Rolling River	13	3.1	4.2	16.0	3.1	5.2
Birdtail	11	3.5	3.1	26.5	3.5	7.7
Ochre	3	1.4	2.1	10.5	1.4	7.9
Wilson	3	2.9	1.03	33.6	2.9	11.7
Turtle River	1	1.0	1.0	0.5	1.0	1.0
Jackfish	0	1.9	0	25	1.9	13.0

Table 3.7 – Observed and modelled beaver dam density displayed by physiography land district.

	Observed			Modelled		
Physiography	**Total dams**	**Distance (km)**	**Dams/km**	**Max capacity**	**Distance (km)**	**Dams/km**
Escarpment	4	2.5	1.6	19.9	2.5	8.0
Lowlands*	0	1.4	0	14.2	1.4	10.1
Hummocky	11	1.4	7.9	7.4	1.4	5.3
Plateau	16	8.4	2.0	45.6	8.4	5.8

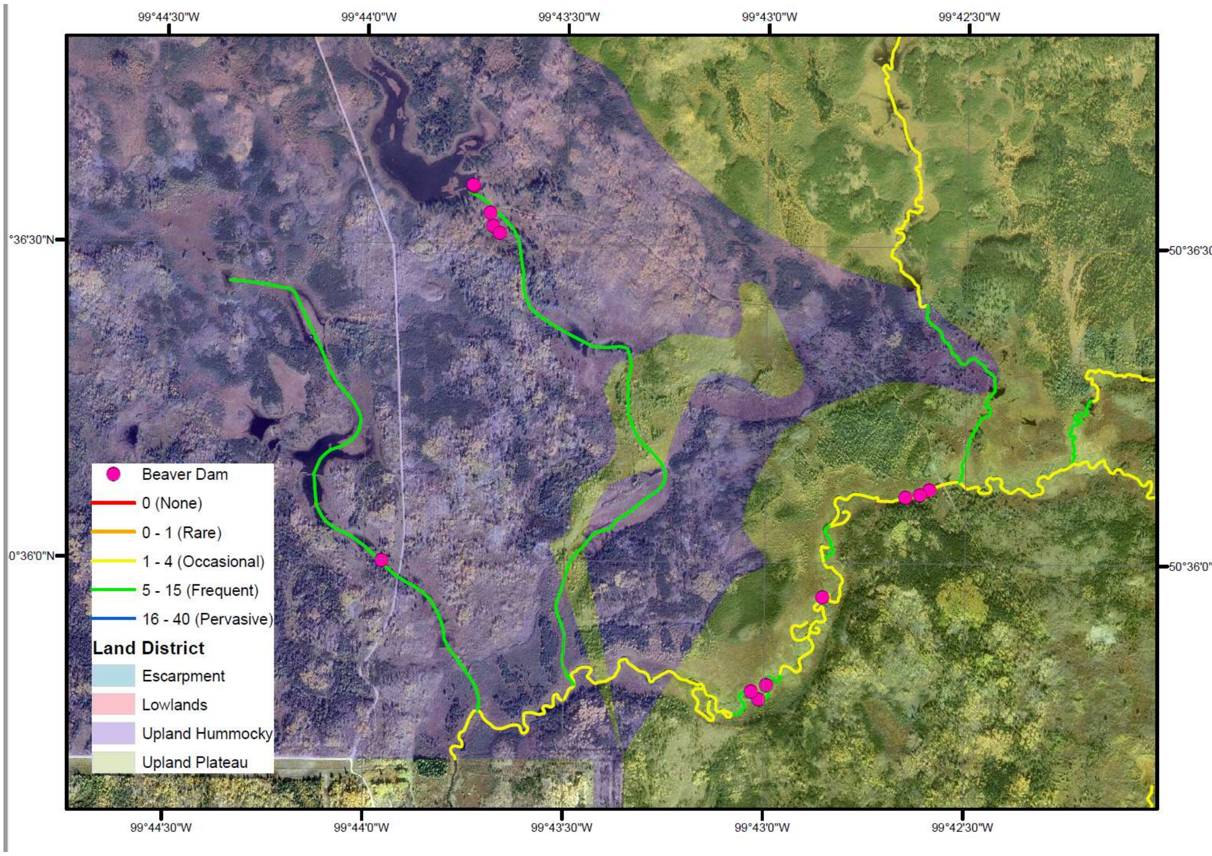

Figure 3.13 - Example of 2017 verified dam locations along the hummocky and plateau region of RMNP overlay onto high resolution imagery from 2004.

3.4 Water storage in beaver ponds

The analysis of beaver pond areas over a subset of the park - 120 km^2 (Figure 3.14) – revealed that 90% of ponds were smaller than 1.5×10^4 m^2 and that the minimum pond size of 11.3 m^2 and maximum of 2.5×10^5 m^2. BRAT modelling of the 120 km^2 indicate a potential of 5.2 million m^3 of water storage in beaver ponds, should beaver dams be at their maximum density (i.e., 100% capacity; Figure 3.15). In 2003, dam capacity in the park was at 39%, and ~2.0 million m^3 of water was stored in beaver ponds.

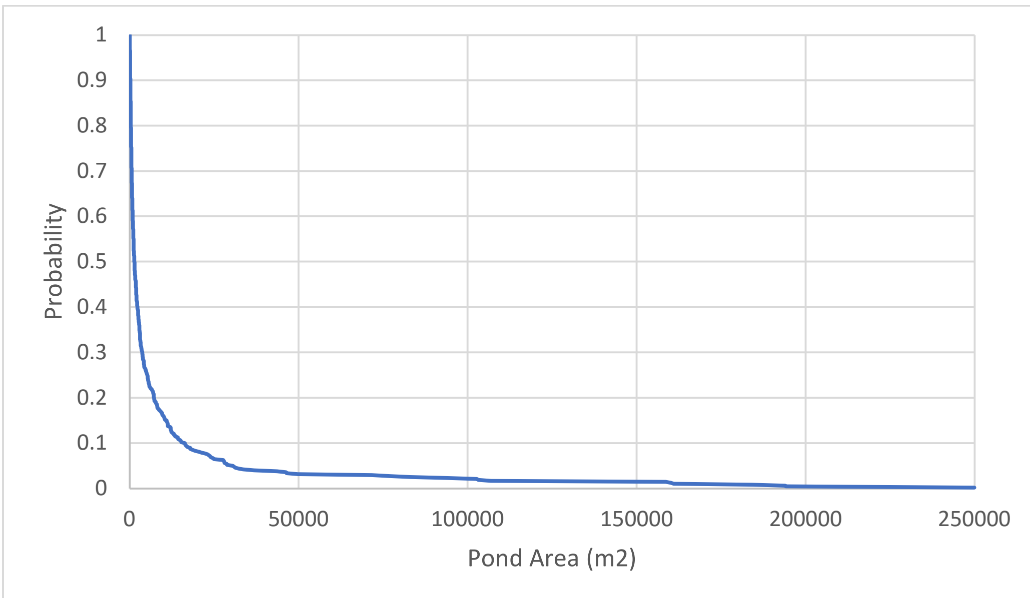

Figure 3.14 - Distribution of pond sizes within RMNP. Minimum and maximum pond size was ~11.3 m^2 and ~250,000 m^2, respectively.

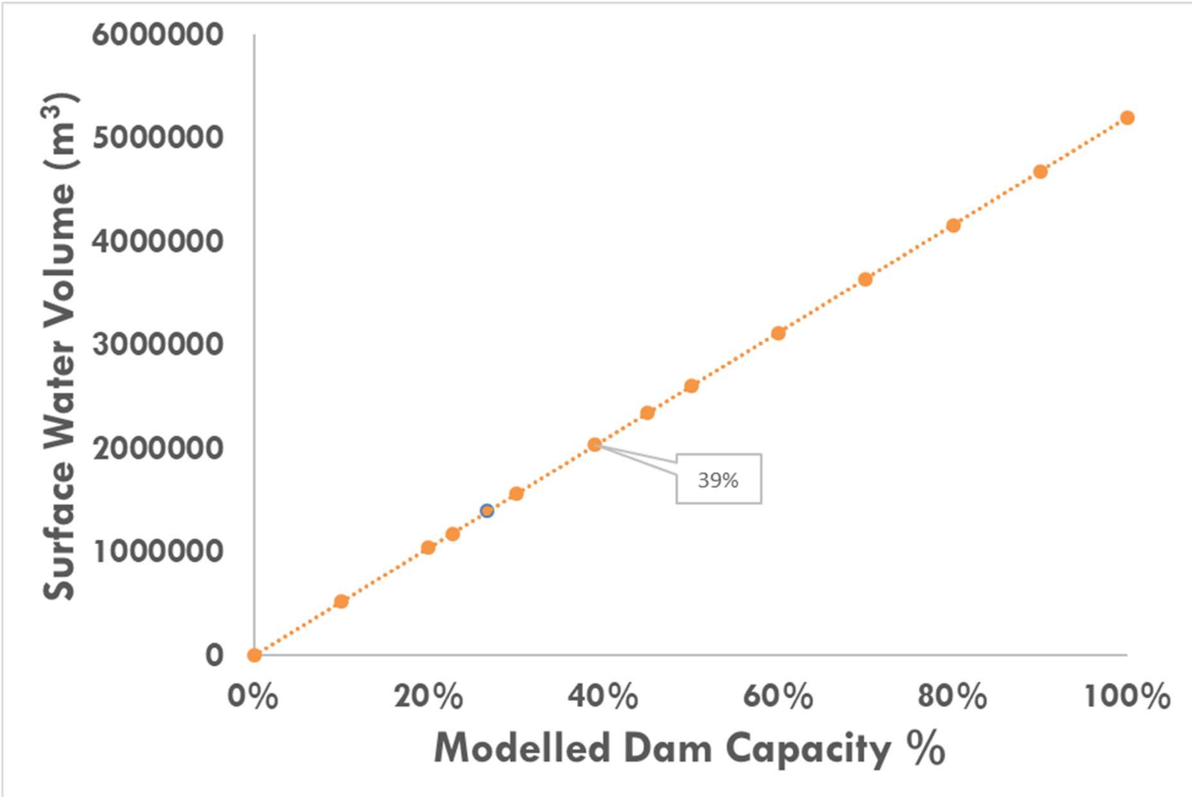

Figure 3.15 – Potential water storage in beaver ponds within RMNP (% of predicted maximum capacity).

There is a noticeable spatial variation in beaver pond storage by physiographic land district (Figure 3.16). Each block was sorted into its primary (over 50% cover) physiographic land district, along with the total volume data, and indicate that the largest volume of water is on the hummocky district (1.1 x 10^6 m^3) with the next largest amount being on the plateau (8.7 x 10^5 m^3). The least volume of water is held along the escarpment (3.4 x 10^4 m^3) and the lowlands (1.2 x 10^4 m^3) districts.

Beaver ponds though do not exclusively occur on streams (Figure 3.17). For example, the largest pond volume (4.5 x 10^5 m^3) is in block 20, which has the second smallest stream length running through it (0.55 km). Additionally, block 68 which has the longest stream length (9.75 km) but only has a total water storage of 2390 m^3. Block 108 has the smallest water storage volume (5 m^3) with total stream length of 8.09 km. Beaver dams are found located outside of streams in the hummocky land district as seen in Figure 3.18.

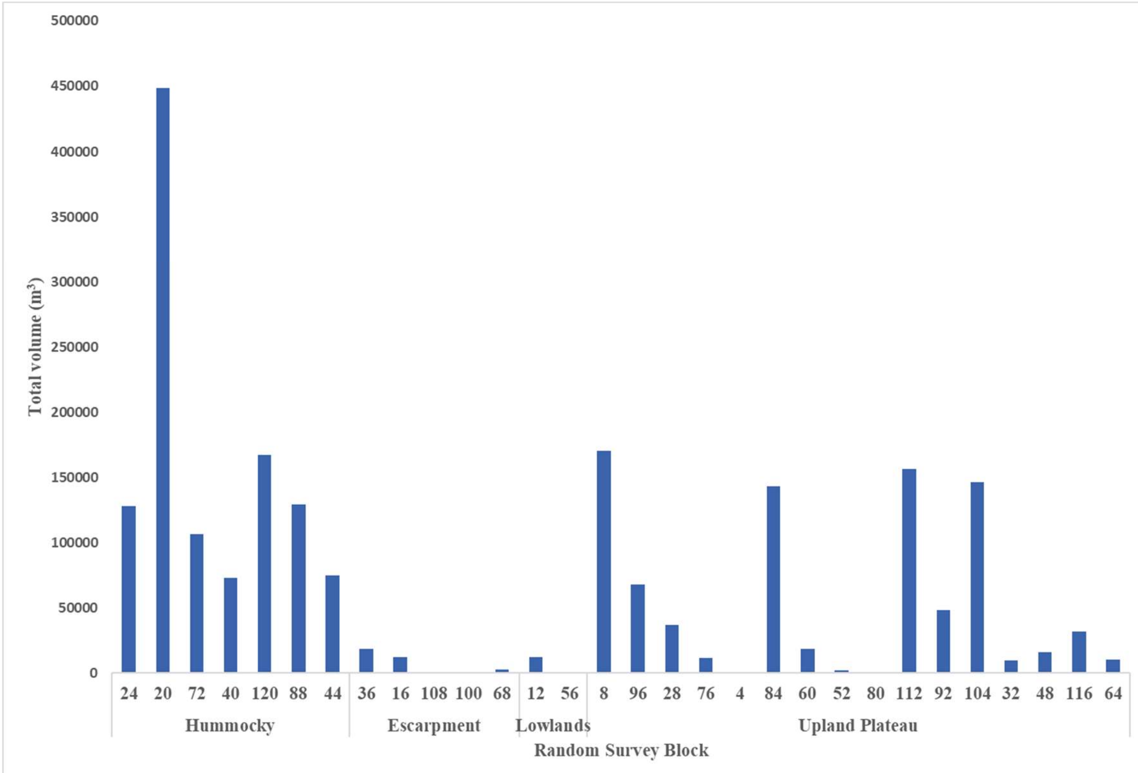

Figure 3.16 – Volume of water being held in beaver ponds in each district.

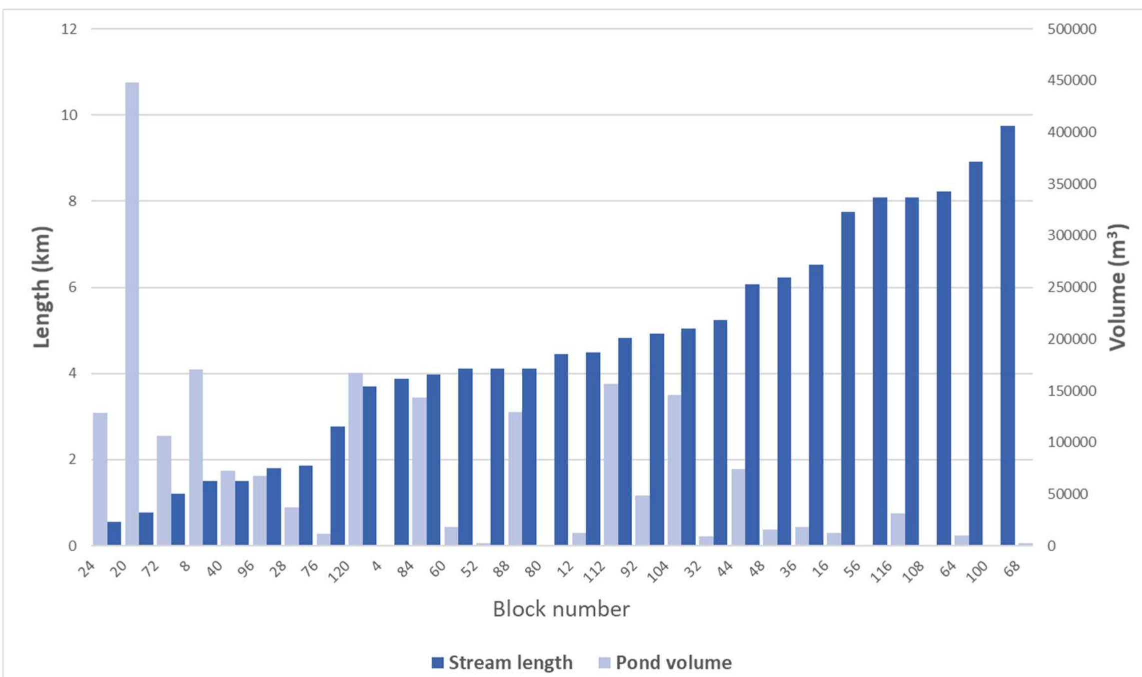

Figure 3.17 – Stream length and ponded water volume in each survey block in 2004. Survey blocks with low stream length have the highest ponded water volume owing to off-channel beaver dams. Each block is 4 km^2.

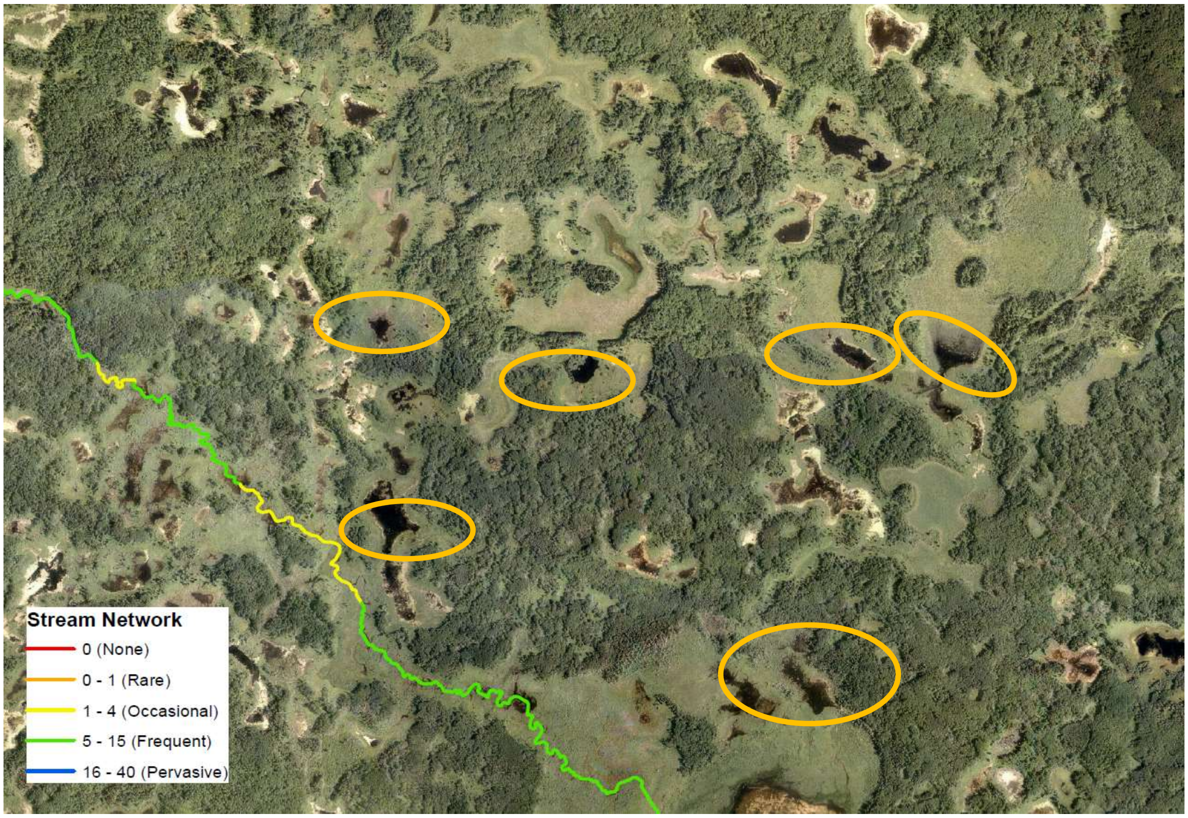

Figure 3.18 – Example of off-channel beaver dams shown in 2004 aerial imagery (62.5 cm resolution). Circled features are examples of off-stream beaver dams and associated ponds.

3.5 Climate change scenarios

The BRAT model uses stream power to determine the likelihood of a beaver dam persisting along a stream reach during low flow (Qlow) and 2-year flood (Q2) events. Increasing Q2 discharge (m^3/s) has an impact on the predicted building capability of beaver in RMNP (Table 3.8). Using the peak flow equation for a 2-year flood we simulated an increase in peak flow power by increasing Q2 by 10%, 25% and 100%. Increasing Q2 by 10% reduces total maximum beaver dam capacity by 3%. Increasing Q2 by 25% decreases the total beaver dam capacity by 6%. Doubling peak flow, however, decreases total maximum beaver dam capacity by 21%.

There is change in the spatial distribution of maximum beaver dam capacity as Q2 is increased, especially along the escarpment and eastern part of the park (Figure 3.20). The percentage of stream length in the ‘frequent’ damming category has the largest shift from ~70% to 52% with $Q2_D$, with ‘occasional’ damming increasing by ~13% (Table 3.8; Figure 3.19). The ‘rare’ damming category increases with rising size of Q2 (i.e. $Q2_{10}$ = +3.3%, $Q2_{25}$ = +4%, and $Q2_D$ = 7.6%). The ‘pervasive’ stream length remains consistent at ~3% as does the ‘none’ damming category (0.3%) for all Q2 scenarios.

Table 3.8 – Flow change scenarios

Scenarios	Pervasive (16-40 dam/km)		Frequent (5-15 dam/km)		Occasional (1-4 dam/km)		Rare (0-1 dam/km)		None (0 dam/km)		Total	Total BD		
	Length (km)	%	Length (km)	%	Length (km)	%	Length (km)	%	Length (km)	%	Length (km)	No.	Dam/km	%
Qlow and Q2	82.4	3.2	1832.9	70.4	618.1	23.7	70.6	2.7	0.3	0.01	2604	24690	9	
Qlow and $Q2_{10}$	82.2	3.2	1771.1	68	664.3	25.5	86.4	3.3	0.3	0.01	2604	24010	9	-3
Qlow and $Q2_{25}$	81.6	3.1	1693.4	65	725.3	27.8	103.7	4.1	0.3	0.01	2604	23154	8	-6
Qlow and $Q2_{D}$	80.3	3.1	1355.2	52	970.1	37.3	198.3	7.6	0.3	0.01	2604	19414	7	-21

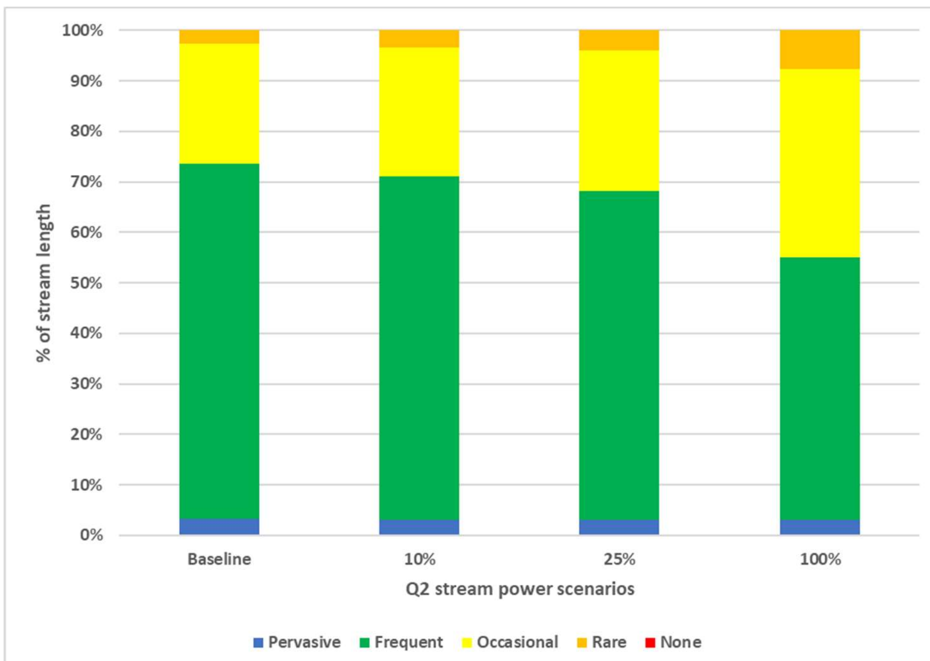

Figure 3.19 – Composition of damming categories during Q2 flow change scenarios

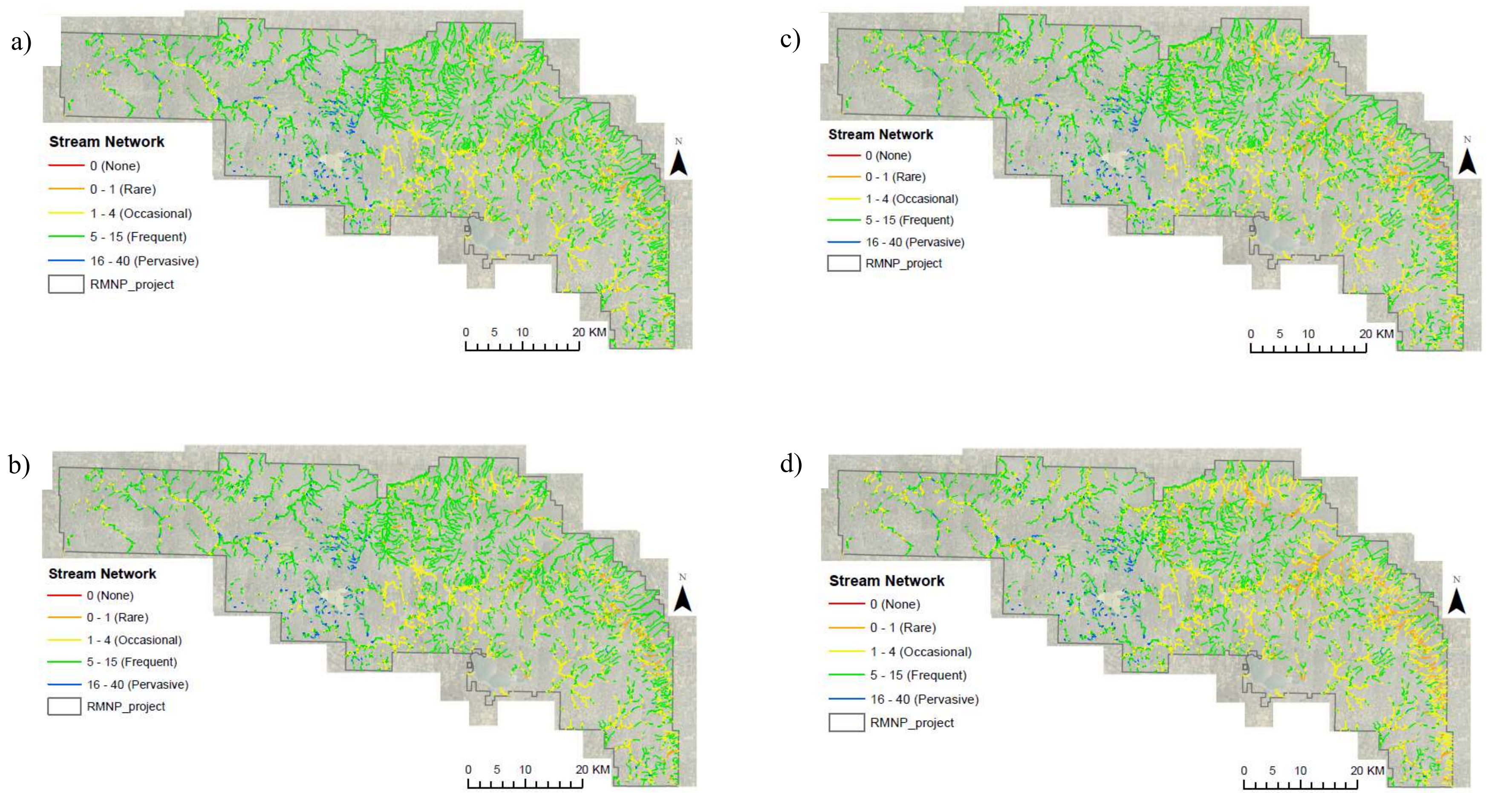

Figure 3.20 – Maximum beaver dam capacity using 2016 vegetation raster data (30m) and increasing Q2 peak flow discharge (m^3/s). (a) Qlow and Q2, (b) Qlow and $Q2_{10}$, (c) Qlow and $Q2_{25}$, and (d) Qlow and Q

4. DISCUSSION

The thesis findings show, using a modelling approach, that Riding Mountain National Park can support a large number of beaver dams. Beaver dam distribution is influenced by physiography, vegetation composition changes, and park management practices. Beaver ponds across the park have the potential to store upwards of 5.2 million m^3 of water, with the majority of water storage occurring in the hummocky land district, a common physiography across the boreal plains ecozone. The results also suggest that dam capacity will be reduced in a future climate wherein peak stream flow is increased. Overall, the BRAT model holds the potential to predict maximum beaver dam capacity in boreal landscapes, but to do so well, modifications are necessary to allow it to better capture beaver dams in hummocky landscapes lacking well defined stream channels.

4.1 Beaver dam capacity modelling

The many ecological and hydrological benefits provided by beaver dams are closely related to their frequency along a stream course (Johnston and Naiman, 1990). The BRAT simulations indicate RMNP has a large capacity to house beaver dams and subsequently, hold a large volume of surface water. The model results indicate maximum beaver dam capacity in 2016 was 24,690, which translates to 9 dams/stream km and ~5.2 million m^3 of water. To put this into context, Manitoba is known for hydro electric dams and one of the largest human-made hydro dams in Manitoba is the Limestone with a capacity of ~2.9 million m^3 (Manitoba Hydro, 2004; Noble et al., 2016) The predicted maximum dam density, while high, is not unrealistic for this region, considering beaver habitat preferences and historic (pre-fur trade) beaver occupation (Whitfield et al. 2015). Beaver prefer a diet of aspen, poplar and cottonwood trees (*Populus* spp.) and willow (*Salix* spp.); they also use these species as dam and lodge construction materials (Breck et al., 2003; Martell et al., 2006; Hood and Bayley, 2008a). RMNP, like much of the boreal forest in Canada, has an abundance of beaver-preferred vegetation. Mixed wood stands are populated by aspen and poplar trees, and common shrubs include willow and beaked hazelnut (Caners and Kenkel, 2003); mixed wood forest is extensive in RMNP, as illustrated by the vegetation cover maps.

Predicted beaver dam abundance and density are unevenly distributed throughout the park, varying by physiographic land district. The four physiographic land districts in RMNP have different topography and hydrography, and as a result, forest composition. Although all four districts have suitable beaver habitat, the BRAT model predicts a lower beaver dam density (9 dams/km) in the escarpment and plateau land districts and a higher dam density (11 dams/km) in the hummocky and lowland land districts. The differences in dam density are likely a result of varying vegetation composition and stream gradient throughout the park. Beaver require reliable sources of water, food and building materials to populate an area (Naiman et al., 1986), and so vegetation type is the primary factor driving the BRAT model (Macfarlane et al., 2017). To build dams though, beaver also require a low enough stream gradient that will allow a dam or a series of dams to be constructed and persist (Naiman et al., 1986). Dittbrenner et al.'s (2018) review of general and regional beaver habitat suitability models identified stream gradient as the most commonly shared variable. This suggests that gradient may be the most important factor in determining beaver being able to build dams that persist. Most of the park lies in the hummocky and the plateau land districts which have low topographic gradients; each maintains a dense population of beaver who build dams. The plateau makes up 58% of the park. It is characterized by gently rolling hills with an uneven distribution of glacial till, creating areas of poorly drained wetlands among the 1446 km of stream that flows through it. The plateau is dominated by boreal mixed wood forest including white spruce, trembling aspen along with balsam poplar, paper birch and black spruce. The hummocky makes up 21% of the park. It is characterized by water-filled depressions created by melting blocks of ice in the last glacial retreat and these depressions are expansive and drain slowly. The hummocky land district includes areas of open water surrounded by mixed wood forest dominated by white spruce and trembling aspen. There is also a multi-strata shrub community throughout composed of beaked hazelnut and mountain maple. The BRAT model recognizes any slope gradients over 23% as 'cannot build dam' as these reaches typically have high baseflow (Macfarlane et al., 2017) and 0 – 0.5% as 'really flat' where 'occasional' beaver dams are modelled. BRAT calculates slope using the elevation at the top and bottom of the 300 m stream reaches, differencing those values and dividing by each stream segment length (Macfarlane et al., 2017). The results indicate only 0.3 km of stream identified as 'None', meaning no dams can be built, meaning slope is not considered a limiting factor within RMNP.

While the field observations and air photo analysis revealed a large number of dams across RMNP, in general; observed beaver dam density was only ~40% of that predicted by the BRAT model. I acknowledge that the field verification only captured 7% of the park's stream length. Observed dam density in the summer of 2017 (2.5 dams/km) is more similar to that observed elsewhere. Loates and Hyenegaard (2008) observed a density of 3.1 dams/km along Camrose Creek, a 35 km stretch of stream in Alberta Canada. Camrose Creek is located within the aspen parkland ecoregion of Alberta, surrounded by farmland, urban areas, trembling aspen forest and badlands with short grasses and shrubs. Dam frequency can be as high as 2.0 – 3.9 dams/km in Voyageurs National Park located in northern Minnesota, which is similar in vegetation composition to RMNP (Naiman et al., 1988; Sinkins, 2008). Both parks have maintained large beaver populations over time owing to their expansive available habitat. Further, Woo and Waddington (1990) reported dam density between 5 – 19 dams/km in streams that run across a coastal wetland near Hudson Bay in the subarctic. The vegetation there is composed primarily of spruce and tamarack with willow, marsh marigold, and sedge. It appears that studies of flatter landscapes with an abundance of beaver-preferred vegetation tend to have higher dam densities, attributed to a lower gradient which allows for more dam cascade complexes to be built. A study in Quebec found mean stream gradient to be the most important variable in influencing dam abundance (St-Pierre et al., 2017), which may explain why the observed dam count in the hummocky land district is greater than the predicted maximum. Field verification of the hummocky district revealed areas of stream over the modelled maximum capacity, which is not surprising given the off-stream dams that occur in this type of landscape. In contrast, places with less expansive beaver-preferred plant species tend to have lower dam densities regardless of their physiography. For example, McComb et al. (1990) observed only 0.14 dams/km in an area of eastern Oregon dominated by shrub-steppe vegetation. While this vegetation cover is typical of arid mountain regions, it is less preferred beaver forage (Fryxell and Doucet, 1993). Macfarlane et al. (2017) reported a beaver dam density of 0.83 dams/km along 40,561 km of streams including 27,345 km in Utah and 13,126 km in neighbouring states of Nevada, Idaho, Wyoming, New Mexico and Arizona, all areas of focused beaver reintroductions. This study covers a large and diverse area, ranging from alpine meadows to desert canyons, across diverse stream conditions.

Maximum dam capacity was predicted by BRAT to be high in the hummocky physiographic land district at 11 dams/km. High beaver cache counts confirm that the area is desirable beaver habitat and has been so for a long time (Frey and Avery, 2004; Sinkins, 2008) despite having only 208 km of stream length flowing through it. Interestingly though, the digitized dam data indicates beaver dams are not always damming the stream channel. Rather, beavers are building dams in the riparian area. The dams observed in aerial imagery within RMNP are occurring far off stream in the wide valleys, similar to what is seen in mountain environments (Morrison et al. 2015). Hummocky landscapes are known for their disjointed drainage patterns and high density of open water bodies (Hood and Bayley, 2008a). Beaver can build dams in a wide range of environments (Gurnell, 1998), provided there is a perennial source of water available. It is likely that beaver build off-channel dams in the hummocky physiography for several reasons. One, it appears the topography allows for dams on disjointed streams to redirect the flow across broad riparian areas or morainal depressions, allowing subsequent flow to be dammed creating areas of ponded water off-stream as reported elsewhere (Westbrook *et al*., 2006). Two, this landscape allows opportunities for beaver to connect isolated pre-existing wetlands and forage for food at a great distance via extensive canals networks that they dig (Hood and Larson, 2015). Sinkins (2008) found the mean foraging distance to be 38.4 m for beaver affected shorelines in the hummocky land district and these canals open access to harder to reach habitat, giving opportunity for more dams to be built. Three, within the hummocky land district, groundwater seepage may provide a more stable water source than the disjointed streams allowing for off-stream beaver dams to be built in areas where the water table is high enough (Westbrook et al., 2017). It can be assumed that beaver utilize these activities throughout the boreal forest as it is known to consist of many drainage pathways that are not mapped as streams (Westbrook et al., 2013).

The BRAT model was constructed with the recognition that beaver dam distributions are primarily controlled by the distribution of beaver-preferred vegetation and secondarily by the local streamflow regime and stream gradient (Macfarlane et al., 2017). The BRAT results for RMNP indicate vegetation was rarely a limiting factor for beaver dam building, unsurprisingly, as the boreal forest has an abundance of beaver-preferred vegetation. As well, RMNP has ample suitable vegetation that the beaver use to build dams, even if those species not classified in BRAT as preferred vegetation. Since vegetation is not a limiting factor in the park, then we would expect that if beaver populations are present then the dam capacity would be at maximum; however, that is not the case in RMNP. The discrepancy between maximum dam capacity and the field observations appears to be caused by factors not currently accounted for in BRAT.

Novak (1987) argued that if food and water are available, beaver will continue to expand into available habitat. However, more current research shows that beaver habitation (and dam building) are more complex, owing to other pressures on beaver populations (Mumma et al., 2018). One of these critical factors is predation. Throughout much of the beaver's range, there are predators that regulate its population (Lowrey et al., 2016; Gable et al., 2018), and thus the number of dams built. In RMNP and elsewhere in the boreal forest, grey wolves are a key predator of beaver. Wolf pack ranges cover most of the park (Figure 4.1). Rounds (1980) and Menzies (1998) both reported that beaver make up ~19% of the wolf diet in RMNP, which maintains the beaver population below carrying capacity (Rounds, 1980; Menzies, 1998). An ongoing research study, however, is finding that the percentage of beaver in wolves' diet in RMNP is underestimated (Christina Prokopenko, pers. comm.), indicating wolf predation might be an even more important control on the beaver population, and potentially dam building, than previously thought. Elsewhere in the boreal forest, beavers are an important food source for wolverines (*Gulo gulo luscus*) (Scrafford and Boyce, 2018), cougars (*Puma concolor*) (Knopff et al., 2010; Lowrey et al., 2016) and bears. Additionally, predation could drive beaver to build ponds in off-channel environments (as witnessed in the hummocky district) and into less desirable habitat to minimize their movement to food sources where they are most vulnerable to predators (Gable et al., 2016). Basey and Jenkins (1995) found that beaver will trade energy maximization (energy gains through foraging) for reduced predation risk by foraging on aspen smaller in diameter but closer to the water. This might be occurring in RMNP as Sinkins (2008) reported that beaver selectively harvest small aspen suckers close to the waters edge until they no longer grow back. Even though many studies report predation impacts beaver population, it is important to note that other studies report beaver populations are density-dependent and are able to handle up to ~40% annual predation with no impact on the population density (Payne, 1989). Trottier (1980) suggested that beaver in RMNP have a natural carrying capacity within each land district once available habitat is saturated and it is possible that reaching this maximum population capacity does not equate to the modelled maximum beaver dam capacity that the BRAT predicts. In other words, beaver may simply build less dams per colony, but the area still has a high density of beaver. Using the aerial survey data, I calculated beaver cache density in each land district for all 20 years of data. Not surprisingly, the 2016 beaver cache density was highest in the hummocky district at 1.46 km^2 and lowest in the escarpment at 0.48 km^2. Unexpectedly, the beaver cache density in the plateau and lowlands were fairly similar (0.73 km^2 and 0.77 km^2, respectively) even though the 2016 modelled dam density is 11 dams/km in the lowlands and only 9 dams/km in plateau.

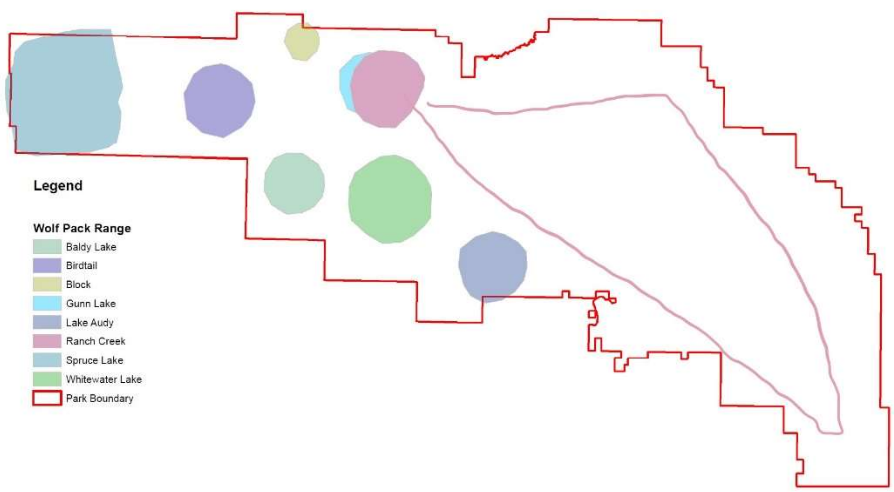

Figure 4.1 – Example of wolf packs range limits within RMNP. Pink line is example of one collared wolf movements throughout the park during the study period, dots represent main range for packs in park. (adapted from unpublished work from Christina Prokopenko and Stronen et al. 2012).

Not only are beaver facing predation risk, they also deal with ungulate competition for woody resources, which limits their ability to build dams. Ungulate overgrazing of willow communities in valleys throughout the national parks in the western US has been extensively studied (Peinetti et al., 2002; Ripple and Beschta, 2003; Baker et al., 2005). In Rocky Mountain National Park, Baker et al. (2005) found that beaver cut willow stands would recover up to 84% after two growing seasons but that stands that were also browsed heavily by elk only recovered 6% during the same time frame. Within Yellowstone National Park, the effects of this ungulate-beaver interrelationship have been prominently demonstrated. Prior to the reintroduction of the grey wolf in Yellowstone, the uncontrolled elk population and other ungulates put great enough pressure on deciduous woody species availability such that beaver were extirpated from the park for a short period (Ripple and Beschta, 2003; Beschta and Ripple, 2012). However, the beaver population started to rebound in 2002 (Beschta and Ripple, 2012) owing to reintroduction of the wolf that reduced grazing pressure enough to improve the willow community (Ripple and Beschta, 2003). In RMNP, Richards (1997) found both elk (*Cervus elaphus manitobensis*) and moose (*Alces alces*) populations had synchronous fluctuations with the beaver population. In contrast though, Hood and Bayley (2008a) found that beaver and ungulates who foraged in overlapping habitats in Elk Island National Park did not cause exclusion but rather competitive exploitation. Once preferred woody plants were foraged by ungulates, beaver adapted their foraging behaviour in favour of one of the less preferred woody plant options. Adaptive foraging behaviour is not captured by the BRAT model. Future studies should explore how adaptive foraging influences estimates of maximum dam capacity to ensure the BRAT model is widely applicable.

4.2 Change in beaver dam capacity over time

Beaver dams are not static landscape features and are constantly changing based on maintenance and abandonment cycles. The increased open water storage in ecosystems created by beaver dams (Morrison et al., 2015) may enhance the resiliency of the boreal plains ecozone to environmental change (Hood and Bayley, 2008b). The benefits of beaver dams on the landscape are numerous, including reducing channel flow velocity (Meentemeyer and Butler, 1991; Burns and McDonnell, 1998), and maintaining baseflows, including in drier years (Westbrook et al., 2006). Beaver dams and the ponds they create also function as sediment and nutrient traps, providing the huge benefit of cleaner water downstream (Devito et al., 1989). Most, if not all of these benefits occur on a temporal scale, potentially requiring many years for the full benefits to be recognized. As such, long-term beaver occupancy influences landscape features because their dams may endure much longer than the beaver lifespan (Westbrook et al., 2013).

The temporal dam capacity analysis shows that beaver dam density has slightly decreased in RMNP between 1991 and 2016, from 11 dams/km to 9 dams/km. Sinkins (2008) estimates that beaver potentially influence over 25% of the forested landscape of RMNP through their foraging and damming activity, causing extensive changes to the vegetation composition (Sinkins, 2008). Understanding how past forest change impacts beaver dam capacity over time is a crucial first step to understanding how beaver dam capacity could be impacted in the future. I analyzed the vegetation composition changes over the last 25 years and they appear to account for the spatial distribution changes in modelled beaver dam density over time. Between 1991 to 2016, ~6% of RMNP has changed to some degree. Most notable is the increase in marsh that was previously deciduous, mixed wood, and shrub land. Some of this change is most likely a result of beaver flooded areas from the formation of beaver ponds. Beaver create and maintain conditions conducive to their reoccupation of the landscape by converting forested upland to wetland by building dams (Naiman et al. 1988; Johnston and Naiman. 1990b). Johnston and Naiman (1990) found a wetland increase of 75% in Minnesota's Voyageurs National Park in the first two decades of beaver colonization and that beaver potentially impact an additional 12% - 15% of riparian vegetation through forage activities (Johnston and Naiman, 1990c). In RMNP, Sinkins (2008) study of wetland changes observed that marsh patches are able to persist long-term, even in the absence of beaver. They concluded that the beaver population, although it fluctuated between 1991 and 2004, had reached a mean where fluctuations were not extreme enough to cause the wetlands to drain from lack of dam maintenance. It appears the beaver population (using cache counts as proxy) have reached the point of recovery in RMNP and are able to regulate riparian vegetation, even if the total number of beaver colonies varies from year to year. The temporal dam capacity analysis shows a decrease of stream reaches falling within the 'pervasive' (16 – 40 dams/km) category from 8.6% in 1991 to 3.2% in 2016. There was also an increase in the 'occasional' (1 – 4 dams/km) category from 17.5% in 1991 to 23.7% in 2016. Interestingly, this decrease in dam density contrasts with the model results of Jarema et al. (2009). Their results indicate beavers are predicted to make only modest range expansion but substantial increases in density within the interior of their range. However, they failed to directly account for changes in vegetation composition that could explain why our results are showing a decrease in density.

Another factor influencing forest composition and structure over time is fire. Boreal forests are disturbance-driven ecosystems with fire being an integral part of a healthy boreal ecosystem (Johnstone et al., 2010). RMNP uses prescribed burning and selective logging as part of their park management plan, contributing to areas of rapid regrowth including a dominance of trembling aspen (Walker, 2002). While Sinkins (2008) noted that beaver disturbance in RMNP is the critical factor altering stand composition and structure because fire is strictly managed in the park, there have been a number of controlled burns. The research design used in this thesis was not conducive to explicitly address how beaver dam capacity responds to fire. That said, exploratory analysis on dam capacity in areas of the park burned over the study's time period suggests park management practices may be unintentionally creating areas conducive to beaver occupation. For streams reaches where fires occurred (Figure 3.10), beaver dam density may be increased in the first few years following a fire. But, there were some places that beaver are able to build less dams after a fire. The reason for these rather contradictory results is not completely clear, but contradictions in the response of beaver to fire disturbance are common in the literature (Thompson, 1988; Hood et al., 2007; Fairfax, 2019). Thus, an improved understanding of how beaver dam capacity is impacted through park management practices is warranted, especially given that Fairfax (2019) showed that riparian areas with beaver dams suffered ~50% less destruction by forest fires than areas without beaver dams. As climate change is predicted to increase the number of wildfires in the boreal region (Ireson et al. 2015; Tan et al. 2019), systematic study of the impact of fire on both beaver populations and the abundance of beaver dams is warranted.

4.3 Implications

Looking forward, the future climate of the boreal plains is expected to be quite different than it has been (Price et al. 2013; Ireson et al. 2015; Boulanger et al. 2016). Climate change-induced changes to the water cycle are expected, including to the precipitation regime. Already, gradual increases in precipitation over the past few decades are causing unexpected, nonlinear increases in streamflow (Dumanski et al. 2015). The modelling results under scenarios of increased streamflow indicate we should expect a reduction in beaver dam capacity and thus in beaver-mediated water storage. The modelling results indicate that a doubling of the size of the 2-yr flood will reduce beaver dam capacity in RMNP by 21%. As well, higher streamflow, particularly higher peakflows (Dumanski et al. 2015), can lead to higher rates of beaver dam failure (Butler, 1995). In the BRAT model, a stream reach will be classified as not capable of supporting beaver dams once stream power exceeds 2000 Watts/m; a threshold above which McFarlane et al. (2017) claim beaver dams commonly fail. However, other studies report that the flood discharge required to exceed the threshold for initiating major damage to beaver dams is not known (Andersen and Shafroth, 2010). In reality, the dam failure threshold probably varies widely based on the state of repair of a dam and the materials from which it was built (Woo and Waddington, 1990). Also expected in the future climate are extended periods of low flows, and for some streams, a change from perennial to intermittent flows (Bennett et al., 2012). Persico and Meyer (2013) noted that beaver were impacted by low streamflow during droughts in the early 1900s in Yellowstone National Park, causing reduced beaver activity along smaller streams. As the BRAT model sets the lower threshold for beaver dam building at a stream power of 0 watts (McFarlane et al. 2017), admittedly, the model cannot be used to predict beaver dam capacity under changing low flows. Future research should thus seek to couple BRAT with a hydrologic model that can predict the potential for stream drying.

Once built, beaver dams can persist for a long-time and as such, they require maintenance or they degrade and either blowout (Butler and Malanson, 2005) or start to seep water (Woo and Waddington, 1990). Both beaver habitat abandonment and dam removal from streams can drastically reduce surface water storage while increasing stream power (Green and Westbrook, 2009), causing flooding issues downstream. However, the presence of a series of beaver dams can assist with lowering flood risk by reducing delivery of water downstream (Burns and McDonnell, 1998). Locally, there is growing concern from farmers, particularly those with land to the north of the park, that beaver dam failures and dam abandonment will flood their fields. This concern is not unfounded, as the escarpment and plateau land districts have high beaver dam capacity, therefore failure of beaver dams can cause destructive outburst floods (Hillman, 1998). Along with the spatial variation in dam density there is also spatial variation in the amount of water stored in beaver ponds found throughout the park. Results show that the hummocky area has the largest amount of water being stored in beaver ponds (55%) followed by the plateau with 43% and the escarpment and lowlands making up the remaining 2%. That said, the extent of flooding depends on a variety of variables, including the dam height relative to the riverbank height, width of the dam and the elevation of the riparian area (Westbrook et al., 2013). Beaver dam abandonment and dam removal can drastically reduce the volume of surface water stored (Green and Westbrook, 2009).

Beaver dams and the water storage associated with them, can elevate the water table, and impact both high and low flows (Johnston and Naiman, 1987; Woo and Waddington, 1990; Gurnell, 1998; Westbrook et al., 2006). Additionally, these ponds of water can help buffer drought in drier years. Fairfax and Small (2018) determined that riparian areas with beaver are better able to maintain productivity than areas without beaver during both short and extended periods of droughts. Other processes impacted by beaver ponds include evapotranspiration, which is increased by changing the distribution of vegetation, and stream suspended sediment load which is reduced by retention behind the dam (Gurnell, 1998; Westbrook et al., 2013; Fairfax and Small, 2018). All of these factors have been shown to result in improved water quality (Rosell et al., 2005) and increased regional biodiversity (Wright et al., 2002). Westbrook et al. (2006) concluded that the main effects of beaver on hydrologic processes occurred downstream of the dam rather than being confined to the near-pond area where valleys are broad. Unfortunately, the cycle of beaver dam failures is unknown, and while water storage in beaver ponds can now be accurately estimated (Karran et al. 2017), quantification of beaver dam failure risk is not yet possible.

BRAT was created to identify areas where beaver reintroduction would be most successful in an arid riverscape. Beaver reintroduction is not currently occurring in the Canadian boreal forest – reintroductions were carried out in the 1930s and 1940s (Rounds, 1980; Sinkins, 2008). The value of the model for northern ecosystems, including the boreal forest, is its ability to recognize areas that beaver will expand into as the climate and environmental conditions change (Jarema et al. 2009). In the northern extent of the boreal forest, discontinuous permafrost is thawing (Vitt et al., 2000; Price et al., 2013). Permafrost is also thawing in tundra ecosystems (Tape et al., 2018). Permafrost loss is leading to shrubification of these ecosystems, which creates ideal conditions for beaver colonization (June et al., 2016; Tape et al. 2018). In a warmer past climate, fossil records indicate beaver habitation of the far north (Ellesmere Island) (Mitchell et al. 2016). As beaver are known ecosystem engineers, their presence in this new landscape means that they will inevitably play a large role in shaping the hydrology of the region. In RMNP, it was the hummocky land district, in which shrub cover reaches 100% in some places (Sinkins, 2008), that had the highest beaver dam density. With modification, the BRAT model possesses the potential to be a useful tool to identify where beaver are likely to dam as they continue to repopulate their former and new range.

5. CONCLUSIONS

5.1 Summary of findings

The purpose of this thesis was to improve the understanding of beaver dam capacity within the Canadian boreal plains ecozone. This was completed through meeting four study objectives.

For objective one, to determine utility of the BRAT in the boreal plains, BRAT was used to model maximum dam capacity within RMNP. The model predicted a maximum beaver dam capacity of 24,690 dams in 2016. Dam distribution was assessed, and results varied throughout the park's four physiographical land districts. The dam density is highest in the lowland and hummocky districts at 11 dams/km; dam density was 9 dams/km in the plateau and escarpment. These results were compared to observed dam density using field observations and aerial imagery to validate modelled results. The plateau, escarpment and lowlands districts are below predicted maximum beaver density. However, observed dam density in the hummocky land district was higher than the predicted maximum beaver dam density. In the hummocky physiography beaver were utilizing the disjointed drainage pattern and building off-stream dams, which were not captured by BRAT.

The second thesis objective was to determine associated water storage based on beaver dam capacity. To achieve this, a GIS analysis was carried out and used with the results from the BRAT model. Manual analysis on a subset of beaver ponds using aerial images was completed to determine surface water area and a published power regression relating pond surface area to volume was applied. Despite uncertainties in estimating pond surface area, results indicate there is a considerable volume of water being stored in beaver ponds in RMNP. The total water storage for 120 km^2 (4%) of the park is ~5.2 million m^3 of water, which is comparable to that stored in some hydroelectric dam reservoirs in Manitoba.

The third and fourth objectives were to evaluate temporal changes in beaver dam capacity, and explore factors influencing temporal changes. To do this, BRAT was run with vegetation cover from 1991, 2003, and 2016. Modelled total maximum beaver dam capacity in 1991 was 28,440, which was ~15% higher than in 2003 (24,846 dams) and 2016 (24,690 dams). To determine whether these changes in dam capacity were a result of differences in classification methods or actual vegetation composition changes, a time series change detection method 'Landtrendr' and a normalized burn ratio spectral index were used. The analysis shows that between 1991 to 2016, ~6% of RMNP vegetation composition has changed to some degree. Most notable is the increase in marsh throughout the park which is likely a result from beaver flooding to create their ponds. Looking at the analysis of temporal changes of dam density in areas burned, it would be useful to create additional vegetation raster layers throughout all of the years to provide additional opportunities for analysis and possibly draw clearer links between beaver dam capacity changes and fire in the boreal forest. Additionally, I ran climate change scenarios where I increased the size of the 2-year flood peak flow power by 10%, 25% and 100% and ran BRAT to determine any impact to beaver dam capacity. Doubling the peak flow decreased total capacity by 21%, showing that beaver dam density could be negatively impacted during times of peak flow events.

5.2 Limitations and future research directions

The BRAT model relies primarily on vegetation cover to estimate beaver dam building capacity. Thus, errors in classification of vegetation imagery or inconsistent use of the model by different researchers could introduce uncertainty. BRAT was developed to capitalize on the way in which vegetation data are classified in the United States. Canada though does not have a national database with such detailed data. As a result, it is common to use data inputs classified by others (unknown conditions, unknown error rates, etc.) in regional vegetation classifications in Canada. As already available imagery was used in the BRAT modelling, some misclassification of forest cover likely occurred. Having a standard practice of vegetation classification would be helpful in minimizing uncertainty. That said, errors in vegetation classification in this thesis likely had minimal impact on the modelled beaver dam density given the expanse of suitable beaver habitat in RMNP.

An outcome of this research is the spatial variation in dam capacity throughout the park which seems to be explained by physiography. Physiography was found to be an important control on dam capacity. Unfortunately, the ground truthing was not designed such that field observations of dam capacity were made across different physiography types, which introduces uncertainty into the estimates of how close to maximum dam capacity each physiography was. To overcome this challenge, aerial imagery were analyzed for the large study area to validate

BRAT. This is a reasonably robust method (Tape et al., 2018), and permitted comparison of modelled to observed dam density for areas of the park too remote to physically ground truth.

Investigating RMNP's potential beaver dam capacity was a novel use of the BRAT model. The BRAT was created for stream restoration projects – to identify suitable areas for beaver to be reintroduced to help with restoring incised streams in the western USA (Macfarlane et al. 2015) – as part of a shift in river restoration practice towards partnering with nature (Johnson et al. 2019). Beaver have already recovered throughout much of the boreal forest, albeit at a lesser density (Whitfield et al. 2015). As well, there is much less of a need for a tool to identify places suitable for beaver reintroduction in the boreal forest to help restore incised streams. The value of the BRAT model then for the boreal forest lies in identifying areas that beaver will build dams as their population grows, their range continues to expand northward into the Taiga as climate changes, and where forest disturbance has created opportunity for beaver to occupy reclaimed landscapes. Jarema et al. (2008) predict that beaver will densify in response to the future climate. When beaver populations are high, beavers move into marginal habitat (Hartman 1996; Busher and Lyons 1999). Understanding dam capacity in marginal habitats is useful. In the northern extent of the boreal forest, discontinuous permafrost is thawing (Vitt et al., 2000; Price et al., 2013) creating habitat for beaver. Permafrost is also thawing in tundra ecosystems (Tape et al., 2018). Permafrost loss is leading to shrubification of these ecosystems, which creates ideal conditions for beaver colonization (June et al., 2016; Tape et al. 2018). Beaver have been shown to drastically modify their environment and it can be expected that they will shape the hydrology of the thawing north. Last, an important disturbance in the boreal plains ecozone is mining for oil, especially in the oil sands area of northeastern Alberta (Eaton et al., 2013). Oil sands mining companies are required to create self-sustaining landscapes post-mining. Even though the return of beavers to this area is part of the long-term plan, there is considerable concern about the short-term risk of the return of beaver. The concern whether tree cutting and dam building activities would compromise impact reclamation plans/requirements (Eaton et al. 2013). The BRAT model could prove useful in identifying vulnerable reclamation structures, and reclamation strategies could then be employed to discourage beaver colonization (and dam building).

5.3 Recommendations

The aim of this project was to better understand beaver dam building capacity in the boreal plains ecozone. RMNP has a long history of managing beaver as the population rebounded after they were successfully reintroduced to the area in 1947. The success of beaver and their role as ecosystem engineers prompted RMNP to begin aerial surveys of cache counts throughout the park. These beaver surveys are vital and should be continued at intervals of 3-5 years. But there is the chance to optimize these surveys. Below I detail key findings from each objective, and management recommendations emerging from them.

Objective #1: Determine the utility of BRAT in the boreal plains ecozone

Key findings:

- Spatial variation of ~25,000 dams throughout park
- Predictive tool to identify areas of beaver interest or to use for monitoring

Recommendations:

- BRAT provides an estimate of maximum beaver dams each kilometre of stream can support based on input data. It would be recommended to monitor the number of dams and their condition during field visits around the park to identify what actual carrying capacity looks like when other factors missing from BRAT are at play (i.e. predation, carrying capacity).
- Expand beaver population inventory to include observations of beaver dams along 10% of the stream courses in the park. Focus these efforts primarily on the Wilson watershed in terms of perceptions by the adjacent agricultural community of high flood risk owing to (too much) water storage in beaver ponds.

Objective #2: Beaver dam abundance and associated water storage

Key findings:

- A lot of water storage potential

Recommendations:

- Inventory the condition of dams including measurements of dams to identify areas where mitigation may be necessary.

- Invest in high quality imagery to inventory beaver ponds and water that they are holding. Along with dam measurements and ponded surface water area, storage estimates can be more accurately monitored.

Objective #3 & 4: Evaluate temporal changes in dam capacity; and Explore factors influencing changes in dam capacity over time.

Key findings:

- Maximum beaver dam capacity has decreased by 13%
- Vegetation changes have occurred in the last 25 years, showing movement from deciduous dominated stands to coniferous.
- Fire (and other disturbance events) may unintentionally be creating preferred beaver habitat
- Stream flow changes from climate change may negatively impact beaver dam capacity

Recommendations:

- RMNP should regularly conduct forest inventories using consistent vegetation classification systems (5-yr intervals). These data will be useful for determining changes in beaver-preferred forage over time.
- Establish a stream flow monitoring program on perennial streams throughout the park, especially on streams in the Wilson watershed. Given that climate change is expected to change streamflow in this region, and the importance of this variable in BRAT, having an idea of actual streamflow out of the park would be very useful for future research and concerns downstream.

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APPENDIX A – Metadata for the classification of vegetation raster data

1991 Vegetation Raster (Parks Canada)	
Class Name	**Description of Class Category**
Low Canopy Deciduous	Continuous low canopy (generally < 10 m high) forest dominated by trembling aspen; minor components of balsam poplar and paper birch. Tall shrubs (beaked hazel, red-osier dogwood) are frequent. Rich and varied forb-dominated understory.
Eastern Deciduous	High-canopy deciduous forest with a herb-rich understory; pure mature trembling aspen stands on nutrient-rich sites, or mixed eastern deciduous forest (green ash, elm, Manitoba maple, mountain maple, paper birch cottonwood) at the base of the Escarpment.
Shrubland	Dense, tall shrublands usually dominated by beaked hazel; also includes dense regenerating trembling aspen stands (1980 Rolling River fire area). Mature trees occur at low density (e.g. trembling aspen, paper birch, white spruce).
Deciduous Canopy/Coniferous subcanopy	Deciduous-dominated (usually trembling aspen) forest canopy with a well-developed subcanopy and sapling layer dominated by conifers (usually white orblack spruce). Tall shrubs are sparse to relatively common. Understory is often herb-rich; feathermosses may be common.
Mixed Canopy (Deciduous/conifer)	Mixed canopy forests, typically with trembling aspen and white spruce as codominants; black spruce, paper birch, balsam poplar and jack pine are occasional
Aspen Parkland	Stands of trembling aspen alternating with shrubby grasslands, forming a complex mosaic pattern at the landscape level. Balsam poplar stands and small wetlands occur in poorly-drained areas
Regenerating Coniferous	Dense, nearly pure, regenerating coniferous forest stands. In the 1980 Rolling River fire, most of these stands are dominated by jack pine or black spruce. Regenerating stands of black or white spruce occur locally in other areas of the Park where natural disturbances (e.g. beaver activity) have occurred.
Lowshrub Grassland	Grasslands with a distinctive low shrub component; species-rich communities dominated by graminoids, forbs and low shrubs (e.g. western snowberry, shrubby cinquefoil, chokecherry, willow, hawthorn). Trembling aspen and/or white spruce may invade moister sites.
Bur Oak Forest	Open to semi-closed 'savanna' forest dominated by bur oak; minor components may include white spruce, trembling aspen and/or paper birch
Closed Canopy Coniferous	Mature, regenerating stands dominated by coniferous trees; generally pure stands of white spruce, black spruce, or balsam fir. Deciduous tree species may form a minor component. Feathermosses may dominate the understory.
Wetlands	Non-forested wetlands, typically dominated by graminoids (grasses, sedges) or cattail
Open Canopy Coniferous	Conifer-dominated stands with < 30% canopy cover; includes semi-treed bogs and fens (black spruce and/or larch), and sparsely-treed dry uplands (white spruce).
Grassland	Open, dry grasslands with few shrubs; species-rich communities dominated by graminoids and forbs
Open Water	Open water bodies (often with submergent vegetation) within and outside the Park, generally > 1m deep with low turbidity
Agriculture	Non-forested land outside the Park; used mainly for livestock grazing or crop production
Forested (outside RMNP)	Variable remnant groves of tree in agricultural areas. Outside of boundary

2003 & 2016 Vegetation Raster Data (Parks Canada)	
Class Name	**Description of Class Category**
Open Deciduous/Shrub	: Lands characterised by shallow soils and/or poor drainage which supports primarily a cover of shrubs such as willow, alder, saskatoon and/or stunted trees such as trembling aspen, balsam poplar and birch. An area could contain up to 50% scattered tree cover
Deciduous	75%-100% of the forest canopy is deciduous. Dominant species include trembling aspen (Populus tremuloides), balsam poplar (Populus balsamifera), and white birch (Betula papyrifera). May include small patches of grassland, marsh or fens less than two hectares in size.
Mixed wood Forest	Forest lands where 25% to 75% of the canopy is coniferous. May inclue patches of treed bogs, marsh or fens less than two hectares.
Marsh	Wetland vegetation of a multitude of different herbaceous species. These marshes range from intermittently inundated (temporary, seasonal, semi-permanent) to permanent depending on the current annual precipitation regime. Common vegetation species include; sedge (Carex spp.), whitetop (Scolochloa festucacea), giant reed grass (Phragmites australis), prairie cordgrass (Spartina pectinata), mannagrass (Glyceria spp.), spikerush (Eleocharis spp.), reedgrass (Calamagrotis spp.), wild barley (Hordeum jubatum), bluegrass (Poa spp.), cattail (Typha spp.), and bulrush (Scirpus spp.) depending on the depth of water. This zone can have a water tolerant shrub component (i.e. willow, Salix spp.) where the shrubs do not dominate the area, but ther is clear evidence of wetland indicators.
Treed and open bogs	Bogs are peatlands typically covered by peat mosses (Sphagnum spp.) and ericaceous shrubs (heath family; eg Labrador tea, Ledum spp.) although other mosses and lichens thrive here as well. Tamarack (Larix laricina) and black spruce (Picea mariana) are also found in boggy landscapes in the boreal forest, the transition zone and in agro-Manitoba.
Coniferous	Forest lands where 75% to 100% of the canopy is coniferous. Jack pine and spruce are combined under this class. May include patches of treed bogs, marsh or fens less than two hectares in size
Water	Consists of all open water - lakes, rivers, streams, wetland ponds and lagoons
Grassland	Lands of mixed native and/or tame prairie grasses and herbaceous vegetation. May also include scattered stands of associated shrubs such as willow, choke-cherry, saskatoon and pincherry. Areas may also be used for the cutting of hay while others are grazed. Both upland and lowland meadows fall into this class. Ther is normally less than 10% shrub or tree cover.
Wildfire Areas	Forest lands that have been recently burned (wildfires less than 5 years old) with sporadic regeneration and can include pockets of unburned trees.
Agriculture	Agricultural Cropland; All lands dedicated to the production of annual cereal, oil seed and other specialty crops. This class can be further sub-divided into three crop residue classes; 0%-33%, 34%-66%, 67%-100%.
Forage Crops	Agricultural lands used in the production of forage such as alfalfa and clover or blends of these with tame species of grass. Fall seeded crops such as winter wheat or fall rye may be included here.
Cultural	Cities, towns, villages and communities with place names. Also includes peat farms, golf courses, cemeteries, shopping centres, large recreation sites, auto wreckyards, airports, cottage areas, race tracks and rural residential.
Forest Cutovers	Forest lands where commercial timber has been completely or partially removed by logging operations. Includes areas which have been replanted (plantations less than 10 years old).
Bare Rock	Lands of exposed bedrock, gravel and/or sand, sand dunes and beaches with less than 10% vegetation. Also includes gravel quarry/pit operations, mine tailingsm, borrow pits and rock quarries.
Roads and Trails	Highways, secondary roads, trails and cut survey lines or right-of-ways such as railway lines and transmission lines.

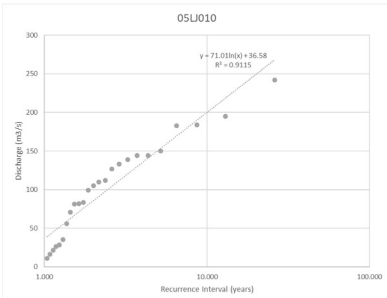
APPENDIX B – Q2 and Qlow discharge rates for hydrometric stations located around RMNP.

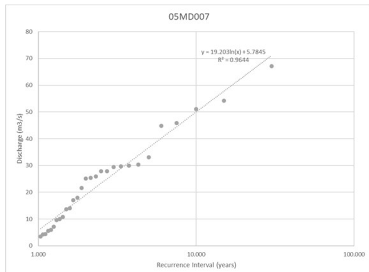
Station Number	Year From	Year To	# of years	(Q2) Peak 2yr Eq'n	Q2 Discharge (m^3/s)	Q2 Discharge (CFS)	Q2 Discharge (CFS) 10%	Q2 Discharge (CFS) 25%	(Qlow) 7-day low flow Eq'n	Qlow Discharge (m^3/s)	Qlow Discharge (CFS)	Drainage Area (km^2)
05LJ005	1975	2015	33	y = 59.918ln(x) - 8.1628	33.37	1178.43	1296.28	1473.04	y = 0.0142(x)+0.1166	0.13	4.62	348
05LJ010	1990	2016	25	y = 71.01ln(x) + 36.58	85.80	3030.04	3333.04	3787.55	y = 0.0369(x)+0.1315	0.50	17.68	2880
05LJ027	2002	2016	50	y = 8.1156ln(x) + 2.8422	8.47	299.03	328.93	373.79	y = 0.0027(x)+0.0214	0.05	1.71	70
05LJ045	1979	2015	35	y = 77.85ln(x) - 1.9551	52.01	1836.61	2020.27	2295.76	y = 0.0066(x)-0.0116	0.05	1.92	662
05LL015	1965	2016	32	y = 35.332ln(x) + 0.8563	25.35	895.11	984.63	1118.89	y = 0.0095(x)-0.0140	0.08	2.83	1070
05LL027	2002	2015	24	y = 1.6818ln(x) + 0.1109	1.28	45.08	49.59	56.36	y = 0.0002(x)-0.0004	0.002	0.06	9.2
05MD005	1948	2016	39	y = 19.307ln(x) + 11.377	24.76	874.39	961.82	1092.98	y = 0.0414(x)+0.7148	1.13	39.86	1970
05MD007	1963	2016	30	y = 19.203ln(x) + 5.7845	19.10	674.34	741.77	842.93	y = 0.3244(x)+0.3578	3.60	127.20	1320
05ME003	1953	2016	33	y = 22.711ln(x) + 6.9068	22.65	799.84	879.83	999.81	y = 0.0246(x)+0.0527	0.30	10.55	1100
05ME005	1959	2016	28	y = 4.2378ln(x) + 0.9276	3.87	136.49	150.14	170.62	y = 0.0025(x)-0.0077	0.02	0.61	70.4
05ME010	2002	2015	8	y = 13.2ln(x) + 4.6729	13.82	488.14	536.95	610.17	y = 0.0782(x)-0.0418	0.74	26.14	457
05MF008	2002	2016	38	y = 12.571ln(x) + 5.5719	14.29	504.49	554.94	630.61	y = 0.1924(x)+0.0682	1.99	70.35	749
05MF024	2004	2015	8	y = 16.974ln(x) + 6.5772	18.34	647.77	712.55	809.72	y = 0.3911(x)+0.1851	4.09	144.65	994

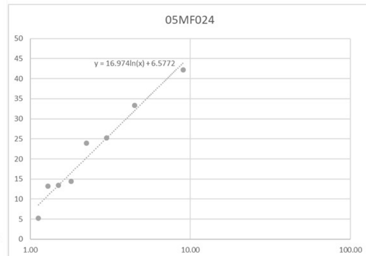
APPENDIX C - Python Script for iHyd

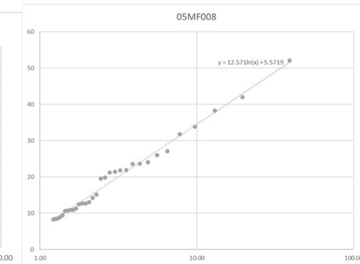
```
elif float(region) == 80:  # RMNP using Wilson hydrometric stn (CFS) - A Scenario
    Qlow = 0.198 * (DAsqm ** 0.35)
    Q2 = 189.12 * (DAsqm ** 0.35)

elif float(region) == 81:  # 05LJ045 B -25% scenario (CFS)
    Qlow = 0.148 * (DAsqm ** 0.35)
    Q2 = 189.12 * (DAsqm ** 0.35)

elif float(region) == 82:  # 05LJ045 C +25% scenario (CFS)
    Qlow = 0.25 * (DAsqm ** 0.35)
    Q2 = 189.12 * (DAsqm ** 0.35)

elif float(region) == 85:  # 05LJ045 F drying scenario (CFS)
    Qlow = 0.05 * (DAsqm ** 0.35)
    Q2 = 189.12 * (DAsqm ** 0.35)

elif float(region) == 83:  # 05LJ045 D 10% peak scenario (CFS)
    Qlow = 0.198 * (DAsqm ** 0.35)
    Q2 = 208 * (DAsqm ** 0.35)

elif float(region) == 84:  # 05LJ045 E 25% peak scenario (CFS)
    Qlow = 0.198 * (DAsqm ** 0.35)
    Q2 = 236.4 * (DAsqm ** 0.35)

elif float(region) == 86:  # 05LJ045 G Q2 Double (CFS)
    Qlow = 0.198 * (DAsqm ** 0.35)
    Q2 = 390 * (DAsqm ** 0.35)
```

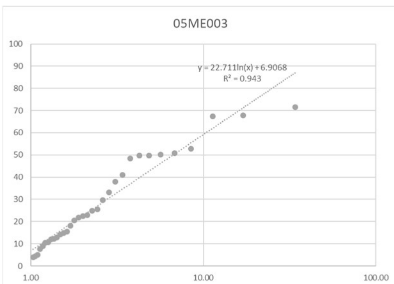
APPENDIX D – Flood frequency curves for each hydrometric station reported in Figure 2.4.

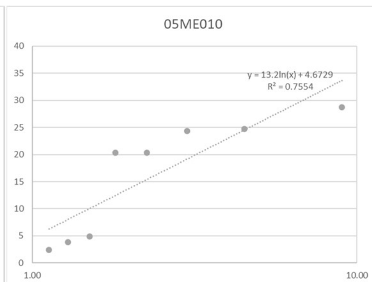


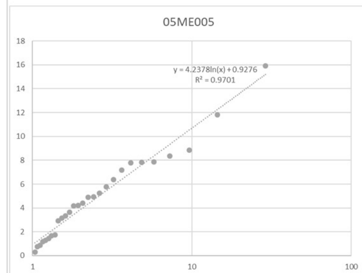


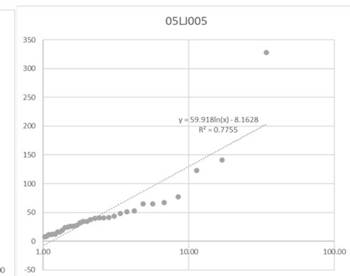


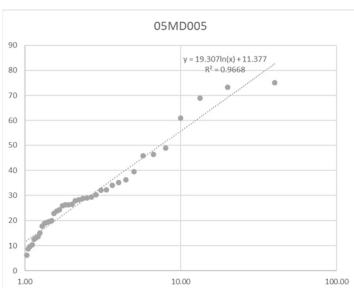


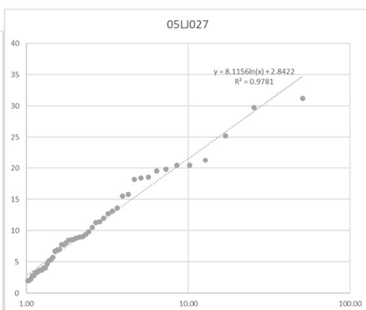


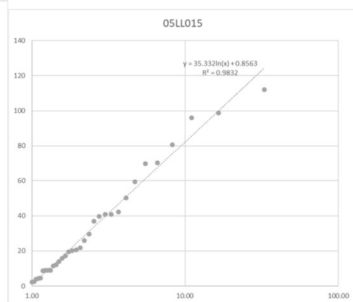


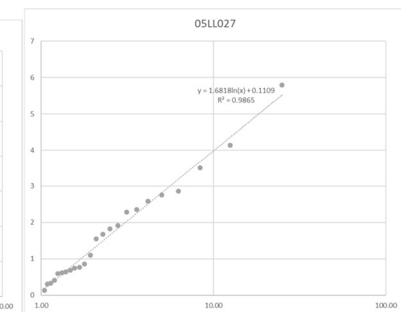












APPENDIX E – Ground truthing database excerpt

site_name	Watershed	Distance (Km)	date	Lat	Long	x	y	intact	active	classification	length	width	height	depth_upstream	depth_downstream
BT001	Birdtail	3.5	2017-08-17	50.861721	-100.838935	370584	5636059	yes	yes	Gapflow	1.6	3.32	0.65	0.35	
BT002	Birdtail	3.5	2017-08-17	50.861655	-100.839103	370572	5636052	no	no	Through Flow					
BT003	Birdtail	3.5	2017-08-17	50.86129	-100.83889	370586	5636011	yes	yes	Gapflow	1.34	3	0.5	0.53	
BT500	Birdtail	3.5	2017-08-11	50.86847501	-100.7029254	380173	5636582	no	no	Blown					
BT501	Birdtail	3.5	2017-08-11	50.86856734	-100.7033008	380007	5636471	no	no	Blown					
BT502	Birdtail	3.5	2017-08-11	50.86765375	-100.7060924	379950	5636472	no	no	Through Flow					
BT503	Birdtail	3.5	2017-08-11	50.86753749	-100.7061043	379939	5636248	no	no	Through Flow					
BT504	Birdtail	3.5	2017-08-11	50.86472511	-100.7074638	379837	5636174	yes	yes	Gapflow					
BT505	Birdtail	3.5	2017-08-11	50.86420816	-100.7079222	379833	5635847	no	no	Through Flow					
BT506	Birdtail	3.5	2017-08-11	50.861815	-100.7075406	379764	5635824	no	no	Blown					
BT507	Birdtail	3.5	2017-08-11	50.86161618	-100.7085375	379755	5635828	yes	no	Under Flow					
OC200	Ochre	1.4	2017-08-06	50.77653731	-99.97938856	430983	5625441	yes	no	Gapflow					
OC300	Ochre	1.4	2017-08-07	50.79305523	-99.97310137	431421	5627251	no	no	Through Flow					
OC301	Ochre	1.4	2017-08-07	50.77702547	-99.97921145	430984	5625456	yes	yes	Gapflow	6.7		0.6	0.35	
RR1	Rolling River	3	2017-08-01	50.84981811	-100.833318	449768	5605802	no	no	Blown					
RR2	Rolling River	3	2017-08-17	50.601811	-99.710221	449739	5605787	no	no	Through Flow					
RR200	Rolling River	3	2017-08-06	50.55692952	-99.7481212	448427	5606693	yes	yes	Overflow					
RR201	Rolling River	3	2017-08-06	50.60985264	-99.72891751	448426	5606697	yes	yes	Overflow					
RR202	Rolling River	3	2017-08-06	50.6092748	-99.72809558	448476	5606617	yes	yes	Gapflow					
RR203	Rolling River	3	2017-08-06	50.60912237	-99.72835994	448483	5606578	yes	yes	Gapflow					
RR204	Rolling River	3	2017-08-06	50.60862654	-99.72781235	448503	5606556	yes	yes	Overflow					
RR205	Rolling River	3	2017-08-06	50.59994423	-99.73288341	448154	5605598	no	no	Blown					
RR3	Rolling River	3	2017-08-17	50.601744	-99.710813	449697	5605780	no	no	Through Flow					
RR4	Rolling River	3	2017-08-17	50.599097	-99.714221	449453	5605488	yes	no	Gapflow	12.55				
RR5	Rolling River	3	2017-08-17	50.596781	-99.716531	449287	5605232	yes	yes	Gapflow	19.2	7.76	1.4	1.55	1.9
RR6	Rolling River	3	2017-08-17	50.596392	-99.716865	449263	5605189	yes	yes	Gapflow	8.3	4.38		1.7	0.75
RR7	Rolling River	3	2017-08-17	50.596606	-99.717179	449241	5605213	no	no	Through Flow					
TR600	Turtle River	0.94	2017-08-14	50.75861516	-99.67467008	452404	5623201	no	no	Blown					
WL400	Wilson	2.9	2017-08-09	50.99644848	-100.4675642	396968	5650509	yes	yes	Gapflow	10.1			0.6	0.05
WL401	Wilson	2.9	2017-08-09	50.99095431	-100.4686128	396914	5649848	yes	yes	Gapflow	6.7			0.9	0.05
WL402	Wilson	2.9	2017-08-09	50.99092992	-100.468866	396940	5649829	yes	yes	Gapflow	11.5			1.5	1