Beaver dams: How structure, flow state, and landscape setting regulate water storage and release

Amanda L. Ronnquist, Cherie J. Westbrook
Department of Geography and Planning, Centre for Hydrology, University of Saskatchewan, Saskatoon, SK S7N 5C8, Canada

HIGHLIGHTS
• Beaver dams in Canadian Rockies are highly diverse structurally and hydrologically.
• Beaver dams can be classified by their flow state.
• Dam flow state relates to dam physical structure and landscape setting.
• Dam hydrological effectiveness depends on flow state.
• Important implications for nature-based solutions to climate change.

GRAPHICAL ABSTRACT

ABSTRACT
Beaver (Castor canadensis and Castor fiber) are regarded widely as ecosystem engineers and the dams they create are well-known for their ability to drastically alter the hydrology of rivers. As a result, beaver are increasingly being included in green infrastructure practices to combat the effects of climate change and enhance ecosystem resilience. Both drought and flood mitigation capabilities have been observed in watersheds with beaver dam structures; however, how dams possess contrasting mitigation abilities is not fully understood since most studies neglect to acknowledge variation in beaver dam structures. In this study, an extensive cross-site survey of the physical and hydrologic properties of beaver dams was conducted in the Canadian Rocky Mountains in Alberta. This research aimed to improve the understanding of the hydrology of beaver dams by categorizing dams using their intrinsic properties and landscape settings to identify fundamental patterns that may be applicable across landscape types. The dam flow type classification from Woo and Waddington (1990) was evaluated in this new context and adapted to include two new flow types. The survey of intrinsic beaver dam properties revealed significant differences in dam structure across different sites. Physical differences in dam structure altered the dynamics and variance of pond storage and certain dam attributes related to the landscape setting. For instance, dam material influenced dam height and water source influenced dam length. However, a closer analysis of large rain events showed that the physical structure of dams alters seasonal dynamics of pond storage but not the response to rain events. Overall, this research shows that beaver dams can be both structurally and hydrologically very different from each other. Establishing broadly applicable classifications is vital to understanding the ecosystem resilience and mitigation services beaver dams provide.

© 2021 Published by Elsevier B.V.
1. Introduction

Climate change is altering global ecosystem services by impacting ecosystem structure, function and composition (Seidl et al., 2016). This impact is strongest in the most sensitive and vulnerable regions which includes a majority of the world’s mountainous areas (Immerzeel et al., 2020). Mountain regions provide an essential water resource for surrounding ecosystems and human needs (Viviroli et al., 2007; Wheater and Gober, 2013). The warming climate in the Canadian Rocky Mountains, for example, may result in flashier river discharges where water availability is increasingly associated with precipitation variability rather than snowmelt (Foster et al., 2016). In addition to these changes, increases in the severity and frequencies of both droughts and floods are expected (Whitfield, 2012). Predicting how basins will respond to climate disturbance is complicated. The hydrological resilience of mountain basins is dependent on the dominant hydrological processes and how they relate to climate and basin characteristics (Harder et al., 2015). To sustain the ecosystem functions of the Canadian Rockies and mountainous regions worldwide, it is imperative to conduct research that will contribute to a climate adaptation strategy that focuses on enhancing the natural resilience of ecosystems (Morrison et al., 2018). Increasing human population and a subsequent rise in land consumption has led to the emergence of green infrastructure as an approach to achieve sustainable development and maintain ecosystem services (Wang and Banzhaf, 2018). Beaver (Castor canadensis and C. fiber) are increasingly being included in green infrastructure practices to counter the effects of climate change and enhance ecosystem resilience (Dittbrenner et al., 2018; Naiman et al., 1988; Williams et al., 2015).

Beaver engineer the ecosystem around them through the construction of dams. The dam serves as a means of increasing water depth until a pond large enough to serve as a refuge is created (Gurnell, 1998). In geographically isolated wetlands, where dam-building is not as prevalent, beaver excavate pond bottom and channels perpendicular to the pond edge extensively to aid water accumulation and access to resources (Hood and Bayley, 2008; Hood and Larson, 2015). The pond keeps the burrow or lodge entrance underwater, increases accessibility to food sources, and keeps the winter cache of food unfrozen (Baker and Hill, 2003). One beaver colony (family) can oversee dozens of individual dams, which are often built in series along a section of a stream (Morgan, 1868). Dam and pond density can exceed ten ponds per km of stream under the ideal conditions (Burchsted and Daniels, 2014; Naiman et al., 1986; Woo and Waddington, 1990) and dams have been reported on as high as fourth order streams (Burchsted and Daniels, 2014; Smith and Mather, 2013; Westbrook et al., 2006).

The construction of dams alters stream and wetland ecosystems by expanding open water areas and increasing both surface and ground water storage (Johnston and Naiman, 1990; Karran et al., 2018; Westbrook et al., 2006). The increase in water retention on the landscape makes beaver ponds a vital water source during droughts (Hood and Bayley, 2008). In addition to drought protection, beaver dams have some flood mitigation capabilities (Puttock et al., 2020). Despite the potential for dam failure during large rain events to cause an increase in flood water volume (Hillman, 1998), dam failure has been low in extreme floods (Westbrook et al., 2020). Dams can also delay downstream transmission of floodwaters by slowing surface runoff and attenuating peak discharges, resulting in smaller floods (Nyssen et al., 2011; Puttock et al., 2020). The effects that beaver dams have on hydrology hold the potential to create a negative feedback loop in response to some hydrological changes resulting from the changing climate. How dams can possess such contrasting mitigation abilities is not fully understood. However, since some landscapes have the potential to support significantly more beaver dams than currently present, any drought or flood mitigation effects could be compounded and enhanced in the future if beaver populations increase (Butler and Malanson, 2005; Dittbrenner et al., 2018; Macfarlane et al., 2017).

Beaver can build dams in a wide range of landscapes and conditions. This versatility leads to a large variety of dam types. A categorization of dams based on the way water flows through each dam structure was conceptualized by Woo and Waddington (1990). Their classification consisted of four dam flow types – overflow, gapflow, underflow, and throughflow. The dam flow types differed in their ability to store water and therefore functioned differently in high and low water conditions. The overflow dam type maximized hydraulic head and commonly stored the most water. Overflow and gapflow were most successful at retaining and storing water at low flows. The underflow and throughflow dams did not store water as effectively but underflow dams were found to be the best at moderating and delaying peak flows downstream (Woo and Waddington, 1990). Since its introduction, the utility of this classification to describe beaver dam hydrology has not been assessed in other geographies.

There is a need to improve the understanding of the hydrological impacts of beaver dams across spatial scales (Brazier et al., 2020). To determine if beaver hold potential to assist in negating the increasing effects of climate change, it is imperative to obtain the ability to predict the magnitude of effects dams have on the landscape and incorporate dam structures into hydrological models. The reason studies have failed to reliably extrapolate the effect of beaver modifications to a landscape scale may be associated with the large variation in beaver dam structures. The purpose of this study is to improve the understanding of the storage and transmittance of water through beaver ponds by exploring the variation in dam structures. The aim is to identify approaches to categorize dams based on their intrinsic properties and landscape settings to identify patterns that can be applied to any beaver habitat. It is hypothesised that: 1) the extensive range of flow mitigation potential corresponds with the variety of beaver dam types present on the landscape; 2) both the stability of pond storage and how water flows through different dam types may dictate their flow mitigation potential. To test these hypotheses, the utility of the dam flow type classification developed in the flat topography of the Canadian subarctic (Woo and Waddington, 1990) was assessed in the mountainous landscape of the Canadian Rockies. The dam flow types from the classification are used to compare water storage dynamics and evaluate pond storage response to rainfall events. In addition, other approaches of dam categorization including dam morphology and landscape setting are explored to find which variables are associated with predictable patterns.

Herein, both the survey (classification) and installation (pond water storage) components of the research are presented consecutively in each section. Calculations used in the analysis conclude section two. Within sections three and four, results and discussion from the survey including flow type and dam morphology are followed by pond water storage and the response to rain events.

2. Methods

2.1. Study area

This study focuses on the Kananaskis Country region of Alberta, Canada, which straddles the easternmost mountainous region of the Canadian Rocky Mountains and adjacent foothills. Kananaskis Country is characterized by tall mountainous peaks and deep U-shaped valleys that give way to lower undulating topography to the east. Elevation ranges from over 3000 m asl from the tallest peaks to around 1000 m asl in the low valley bottoms. The region is the headwaters for several major rivers that flow north into the Bow River before progressing eastward into the Canadian Prairies as the South Saskatchewan River. Highwood Pass marks the boundary of tributaries that flow north into the Bow River. South of this pass, the rivers connect to the Bow River further east, within the foothills.

Selection of beaver-occupied sites across Kananaskis Country was performed using a combination of aerial imagery, field visits, and pre-existing datasets. An initial wetland dataset derived from aerial imagery
(Morrison et al., 2015) was refined to sites where the presence of dams constructed by beaver was confirmed after 2012 and with a known substrate (peat or mineral). The chosen sites were previously analysed for percent organic content by mass in 2012 (Morrison et al., 2015). There were six primary sites and 13 secondary sites chosen randomly from the dataset. Secondary sites were surveyed, and primary sites were both surveyed and instrumented. Four of the primary sites were derived from the initial data set and two were discovered during field visits and included due to their uniqueness. The unique sites were included to capture the breadth of variation in dam structure. The aim was to instrument across a large range of dams and sites with differing characteristics to capture the extent of natural variation. The 19 total sites occupy both mountainous and foothill regions and include both channel-spanning and spring-fed beaver dams (Fig. 1).

2.2. Data collection

162 beaver ponds were surveyed over 19 sites in the summer of 2019 to determine the occurrence of each beaver dam flow type present on the landscape for peat and mineral sites. Several other variables and measurements including dam height, dam length, dam material, level of beaver activity, and pond water source were also collected. The number of dams observed at each site ranged from 2 to 19 with an average of 8 dams.

Dams were classified based on their flow type, as adapted from the original four types created by Woo and Waddington (1990). Additional constraints were added to the original flow type definitions to maintain consistent categorization. Overflow dams had water flowing over the dam top less than 2 cm deep. The overflow area of the dam was not required to span the entire dam length. Gapflow dams had water flowing through gaps greater than 2 cm deep with no limit set on the number of gaps. For each dam, the number of gaps (\( n_g \)) was recorded and the width (\( w \)) and depth (\( d \)) of each gap was measured. The gap width was measured at the pinch point (narrowest extent) and gap depth at the maximum. Underflow dams had one or more gaps in the dam face with an obvious wood or soil connection persisting above them, creating an underflow hole. Measurements of water depth and hole width for underflows were kept consistent with those taken for gaps, also

Fig. 1. Map of the study site showing all 19 sites (10 mineral and 9 peatland) included in the beaver dam survey and the main valleys they are located in. Primary sites (circles) were used for both the survey and instrumentation whereas secondary sites (triangles) were used just for the survey. Ortho-photographs of the study area were provided by the Government of Alberta under licence agreement DMR#1707 M06.
assuming a rectangular shape for the calculation of area. An additional measurement of distance to the dam top \( d_i \) was included for both the upstream and downstream sides of underflow holes. *Throughflow* dams consisted of a porous media of sticks with water flowing through at many locations. Any dams that did not fit in the flow type categorization were independently described and temporarily placed in an ‘other’ category. These dams were later classified by the introduction of new flow types, mixed and seep dams (Section 3.1).

Dam height was defined as a difference in hydraulic head \( \Delta h \) from the upstream to the downstream side of the dam to provide a measurement referred to as the ‘hydrologically effective height’. The difference was measured manually to the nearest cm using a combination of measuring sticks. This metric was used for dam height for three primary reasons. First, it easily distills a very heterogeneous structure down to one measurement referred to as the ‘base’ of the dam to measure from. Second, most of the dam structures, especially those with large gaps, did not have water filling the dam extent. Third, the measurement is not influenced by the sediment wedge that forms on the upstream side of the dam and erosion of the stream bed that occurs on the downstream side of the dam. Using this method ensures only the height of the dam that is effectively retaining water is recorded. It is essential to understand that \( \Delta h \) is not a static parameter and can fluctuate seasonally and with precipitation events. However, since it and the other variables were measured concurrently with the identification of dam flow type; the correlation between the variables is assumed to remain accurate. If any variables were observed to change over the season, the measurements and observations that were taken concurrently remained the ones used in the analysis.

Dominant dam material was estimated through visual inspection. Most dams accumulate sediment within their structure as they age (Butler and Malanson, 1995), making it difficult to distinguish sediment dominant dams from wood dominant dams that have been completely covered in sediment. To account for the sedimentation process, the visual estimation was based on the downstream face of the dam and dams were placed in one of three categories depending on the dominant material: sediment, wood, or both sediment and wood. The dominant material was assumed to remain constant over the season.

Sites were classified as active, recently active, or old based on current beaver occupancy. Active sites had current beaver habitation. Recent sites had signs of beaver activity (e.g., cut trees and branches from the previous season, which were distinguished from recent cuts by the dulling colours in the wood) but no beaver present. Old sites had no beaver present. They characteristically had extensive pond bottom sedimentation and dams covered with regrown regenerative vegetation species such as willow and aspen.

Site instrumentation involved the installation of electronic levelloggers (Solinst, Ontario), paired with monthly manual validations to measure the depth of water in the beaver ponds. Fourteen ponds from the six primary sites had loggers instrumented from late June to late September 2019. Two additional loggers were added in stream sections lacking dams at two sites for comparative purposes. These loggers were placed instream ~25 m downstream from an instrumented pond. To protect the instrumentation and to ensure data quality, loggers were suspended by chains inside perforated pipes anchored to the pond bottom.

### 2.3 Data analysis

#### 2.3.1 Survey data

The two main parameters of dam size (dam length and \( \Delta h \)) were analysed with respect to site substrate, presence of aspen, dam materials, and pond water source. D’Agostino’s K-squared tests performed on the dam heights \( \Delta h \) \( (K^2 = 60.2, p = 8.1 \times 10^{-14}) \) and lengths \( (K^2 = 84.5, p = 4.4 \times 10^{-15}) \) revealed that neither variable is normally distributed. To account for the non-parametric nature of the variables, a combination of Kruskal-Wallis H-tests (for three or more categories) and Mann-Whitney U tests (for two categories) were performed on median values. For analyses with three categories, the Kruskal-Wallis tests were supplemented with three Mann-Whitney U tests performed between categories with a Bonferroni correction of \( \alpha = 0.017 \). All variables with non-categorical data types were compared using a correlation matrix to identify potential patterns. The Kendall’s Tau rank coefficient, \( \tau \), was chosen to find associations among variable pairs since it provides a non-parametric measure of the relationships between ordinal data types. All statistical analyses were performed in Python using functions from the scipy stats and sklearn libraries.

#### 2.3.2 Water storage dynamics

To compare water storage among ponds of different sizes, the measured pond depths were normalized using the maximum depth recorded at the ponds over the season. This maximum depth was assumed to represent the maximum capacity of the ponds; hence, the normalized pond depths correspond to a percentage of water storage of the ponds.

To quantify the variance in pond water storage over the study period, the quartile coefficient of variation \( \text{QCV} \) was calculated for each instrumented pond. The QCV was used as a metric for variation since it was found to be sensitive to the sharp fluctuations in pond water level. It is a unitless measure of relative dispersion calculated by dividing the interquartile range \( \text{IQR} \) by the median \( \langle Q_2 \rangle \). Eq. (1):

\[
\text{QCV} = \left( \frac{\text{IQR}}{\langle Q_2 \rangle} \right) \times 100
\]

A QCV of 0 represents an unchanged pond level whereas values >0 indicate variations in pond depth around the median value.

To better quantify the level of dam intactness, the area of the wetted dam face \( A_d \) (Eq. (2)) and the total area of dam gaps allowing water to flow through \( A_g \) (Eq. (3)) were calculated to determine the percentage of the dam face that has breached (PDB; Eq. (4)). These parameters were derived from the total dam length \( l \), difference in hydraulic head \( \Delta h \), and the depth \( d_i \) and width \( w_i \) measurements of all the gaps in the dam allowing water to pass. This method assumes rectangular gaps and is dependent on the fullness of the pond. The area of the wetted dam face \( A_d \) was calculated using the total dam length multiplied by the difference in hydraulic head \( \Delta h \):

\[
A_d = \Delta h d_i
\]

The total area of gaps \( A_g \) allowing water to flow through the dam face was calculated by summing the areas of each dam gap recorded from the survey:

\[
A_g = \sum_{i=1}^{n_g} d_i w_i
\]

The PDB was then calculated by dividing the total gap area \( A_g \) by the wetted dam face \( A_d \).

\[
PDB = \frac{A_g}{A_d} \times 100
\]

The PDB metric only applies to dam flow types that possess dam gaps (gapflow, underflow, and mixed). Dam flow types without measurable gaps (overflow and seep) were considered intact and given a PDB value of 0%. Due to the porous nature of throughflow dams, calculating a PDB was not applicable for this dam type.

#### 2.3.3 Precipitation event analysis

Three to four rain events from June to August were chosen to be analysed for each of the 14 instrumented ponds for a total of 57 rain events. For sites in close proximity, the analysis may have captured
the same rain event. The rain events were used to determine how the response of pond volume to rain events varies with respect to dam type. Data from the 14 ponds and 2 stream sections (without ponds) were paired with corresponding precipitation data for the region. Precipitation data were obtained from a combination of on-site meteorological stations run by the University of Saskatchewan and University of Calgary, and those run by the Alberta Agriculture and Forestry, Alberta Climate Information Service. All precipitation data were resampled to the finest common timestamp, resulting in an hourly resolution. To preserve precision, pond depth data were not resampled and remained at the original 15-min interval timestep when paired to the precipitation data.

The largest rain events, exceeding 5 mm for the whole event, were chosen to maximize the signal from the rain event and minimize the influence of other natural pond fluctuations. For each event, the minimum pond level before the rain event began, the maximum pond level, and the post-event minimum level were calculated and used to determine a total increase in pond level (amplitude) caused by the rain event. In addition, all the pond levels between the maximum and post-minimum values were designated as the receding limb of the event. A linear regression was fitted to the receding limb and a corresponding slope was calculated. Performing a log transformation on the receding limb prior to applying the regression function did not improve the overall fit and was therefore not included. Slopes were converted to represent the rate of change in pond level over time.

3. Results

Beaver dams in the 19 surveyed sites exhibited large diversity. Mean dam lengths ranged from 4 to 116 m per site and mean $\Delta h$ ranged from 0.04 to 0.83 m. The longest and shortest recorded dam lengths were 1 and 295 m, respectively. The largest recorded $\Delta h$ was 1.97 m.

3.1. Dam flow type

The survey of dams in Kananaskis Country revealed different proportions of the flow types than was found in Northern Ontario (Woo and Waddington, 1990) as well as two new types (Fig. 2). The proportions of gapflow (36%) and underflow (17%) dams were higher than the original study whereas overflow (9%) and throughflow (<1%) dams were lower. The two new flow types added to the classification scheme were seep dams and mixed dams. Seep dams were found only at sites fed by groundwater springs and were defined as dams that lacked surface water flow paths. The mixed dam type was an encompassing category created to accommodate dams that possessed more than one flow type at the same time. Seep and mixed dams represented 14% and 24% of the dams, respectively. Differences between mineral and peat substrates did not influence the distribution of flow types at the sites (Fig. 2).

Sixty-six dams (41%) from 7 sites were visited more than once during the survey period. 24% (16) of the 66 revisited dams were observed to have a different flow type. Four of these flow type changes occurred on instrumented ponds (Fig. 3). Changes in flow type were caused by changes in water level, erosion, or by beaver actively changing the dam structure (i.e., a change in PDB) (Fig. 3). Since the water levels in ponds naturally fluctuate with seasonal variations in precipitation and evaporation, it is possible that some ponds naturally fluctuate between flow types on a seasonal basis. The three most common flow type changes were gapflow $\rightarrow$ seep (3 occurrences), mixed $\rightarrow$ underflow (3 occurrences), and overflow $\rightarrow$ mixed (3 occurrences). Most revisits to the sites occurred mid-summer when water levels were at their lowest. The first two flow type changes (gapflow $\rightarrow$ seep, mixed $\rightarrow$ underflow) suggest dropping water levels from reduced inputs and may be reversible as inputs increase again. The third change type (overflow $\rightarrow$ mixed) is likely caused by erosional processes adding holes to the dam face. Other changes, such as the two occurrences of underflow $\rightarrow$ gapflow are also expected to be caused by erosion. Especially in non-vegetated dams, water can erode the soil above an underflow, transforming it into a gap. Overall, flow type changes were observed to be driven by hydrologic, geomorphic, or biotic causes (Fig. 3). Hydrologic changes do not involve any changes to the dam structure itself and therefore are reversible depending on water inputs to the ponds. Geomorphic and biotic changes do impact the dam structure and are therefore not easily influenced by seasonal trends.

When the changes in flow type were compared to the level of beaver activity at the site, older sites disused by beaver for many years were less likely to have flow type changes. Sites with active beaver or recent beaver occupancy experienced the most changes. The percentage of flow type changes for the revisited dams was higher for active sites (31%) and recently abandoned sites (30%) than old beaver sites (6%).

3.2. Dam morphology

3.2.1. Dam height

Investigation of dam size in relation to dam flow type showed that the length of dams did not differ based on flow type (Kruskal-Wallis

![Fig. 2](image-url). The frequency of dam flow types surveyed during 2019 in the Kananaskis region of Alberta. Counts are divided between sites with mineral or peat substrates ($n = 162$).
H-test: $H = 9.7$, $p = 0.045$; Bonferroni correction: $\alpha^* = 0.01$ (not shown). The hydrologically effective height ($\Delta h$) was, however, significantly different between dam flow types ($H = 19.3$, $p < 0.001$; Fig. 4). The analysis did not include throughflow dams due to their low occurrence ($n = 1$).

Fig. 5 shows the relationship between $\Delta h$ and the materials (wood, sediment, and rocks) used in dam construction. The median dam heights of three different dam material groups differed ($H = 27.3$, $p < 0.001$). Sediment dams had lower heights than wood dams or those with both materials (Mann-Whitney $U$ test: sediment vs wood: $U = 332.0$, $p = 0.002$; sediment vs mixed: $U = 1280.0$, $p < 0.001$). Dam height was similar between mixed and wood dams ($U = 671.5$, $p = 0.217$). Further, dams made primarily of sediment tended to have a smaller $\Delta h$ (Fig. 5a). Of the dams surveyed, 27% had at least one rock

---

**Fig. 3.** The four instrumented dams where changes in base flow type were observed. Dam schematics are accurate in the number and sequence of dam gaps but are not drawn to scale.

**Fig. 4.** Differences in dam height between the surveyed flow types ($n = 162$). Dam height was defined as the effective hydraulic height ($\Delta h$). See the supplementary material for illustrative explanation of the $\Delta h$ measurement.
used in construction. Dams with rocks in them had significantly greater median $\Delta h$ than those lacking rocks ($U = 1750, p < 0.001$) (Fig. 5b).

3.2.2. Dam length

Dams in peatlands were significantly longer than those in mineral sites ($U = 2533.5, p = 0.009$). In addition, sites that had aspen growing within 100 m of the ponds had significantly longer dams than those without ($U = 2196.0, p = 0.003$). To account for the high overlap between sites with aspen and peatlands, these two variables were further analysed in combination (Fig. 6b). There was an additive effect on dam length discovered between peatlands and aspen presence. No effect was found on dam length at mineral sites with aspen present.

A total of 64% of the dams included in the survey were fed entirely by systems of groundwater springs while only 14% were fed directly by major stream channels. Dam length differed significantly for varying water sources ($H = 15.9, p < 0.001$) (Fig. 6c). Spring fed ponds had

---

**Fig. 5.** Differences in $\Delta h$ for dams of different materials (a) and for those that had rocks used in their construction (b).

**Fig. 6.** Box plots of dam length by the (a) proportion of woody material visible in the dam structure, (b) site aspen presence within 100 m of the ponds and the underlying substrate, (c) pond water source, and (d) dam material with pond water source. ($n = 162$).
greater dam lengths than stream fed ponds ($U = 691, p < 0.001$). Ponds fed by both streams and springs had significantly greater dam lengths than stream fed ponds ($U = 179.0, p < 0.001$). Spring fed dams and those fed by both springs and streams had similar lengths ($U = 1436.5, p = 0.023$).

A total of 39% of the dams surveyed were made primarily of sediment, 12% were stick dominated, and 49% were a combination of both. Dam length differed in response to dam material ($H = 13.6, p = 0.001$) (Fig. 6a). Wood dominated dams were significantly shorter than sediment dominated dams ($U = 323.0, p = 0.001$) and those with both materials ($U = 350.0, p < 0.001$). Sediment dominated dams and those with both materials had similar lengths ($U = 2291.0, p = 0.176$). The relationship between dam material and dam length may be linked to the pond water source. Dams made primarily of wood tend to be more porous than those constructed from sediment. To keep a porous dam full, the water inputs must be higher than those required to keep a sediment dam full. Fig. 6d shows dams made primarily of sediment are only found at sites that are fully or partially groundwater fed.

### 3.3. Variation in pond water storage

Differences in pond storage dynamics were revealed among dam flow types when the average fullness of the ponds were compared. Fig. 7 shows the evolution of water levels over time for different dam flow types and for sections without dams (labelled stream). Gapflow dams represented the largest proportion of dams instrumented and exhibited the largest visual differences in fullness between ponds. Some gapflow ponds such as the two instrumented at the Chive site (Fig. 7) showed very little variation in pond depth and remained almost entirely full for the duration of the summer. In contrast, the Sidecut dam from the Storm site experienced variations in pond depth that closely resembled the high variation characteristic of stream sections. The average percent fullness for the different gapflow dams ranged from 97% to only 27%.

Calculation of QCV revealed that the water level of the sections without ponds exhibit about six times more variation when compared to the fluctuation of water storage in the ponds. The average QCV of the four flow types varied from 3 to 34; QCV was 119 for the corresponding stream sections lacking dams. The QCV also revealed differences between flow types. Gapflow and underflow dams experienced the largest average variation in pond depth: QCV = 34 and 31, respectively. Overflow dams experienced the least (QCV = 3) and mixed dams fell between (QCV = 13). The average variation in pond storage appeared to increase as the average percent fullness of the pond decreased ($r = -0.66$). The pond variation also appeared to increase as the PDB metric increased but this correlation was not very strong ($r = 0.47$).

PDB values calculated for relict and intact dam structures showed that the average percentage of dam face breached for relict dams...
(4.7%) was higher than intact dams (1.8%). However, the maximum and minimum values calculated did not differ. There was no maximum PDB for which a dam was guaranteed to be a relict structure. The maximum PDB for intact dams was 32.4% and the maximum observed in a relict dam was 31.5%. Minimum values revealed that both relict and intact dams could have 0% of their dam face breached.

3.4. Pond response to rainfall events

Fig. 8a shows the variation of the recession limb slope for the different flow types. Fig. 8b depicts the increase in water level in response to each event. The response of pond water storage to rainfall events did not depend on dam flow type (Fig. 8a). The recession limb slopes after rainfall events were similar among the four flow types ($H = 6.7, p = 0.081$). However, the slope of the receding limb for all the dam flow types collectively was significantly higher than for the undammed stream sections ($U = 60.0, p = 0.025$). Similarly, the total increase in pond depth observed after a rainfall event (Fig. 8b) was similar for individual flow types ($H = 4.3, p = 0.232$) and collectively lower than the undammed stream sections ($U = 38.0, p = 0.005$).

4. Discussion

4.1. Dam flow types

Beaver dams are persistent structures and can remain evident on landscapes for over a hundred years (Johnston, 2015) but this persistence does not imply dams are static and unchanging. Adaptation of the Woo and Waddington (1990) dam flow type classification revealed that dam ‘types’ in the study area are dynamic and can shift rapidly. The mechanisms responsible for transmitting water through dams are sensitive to environmental conditions. Seasonal changes in available water, erosional processes, and maintenance by beaver to the dam were found to alter the primary flow mechanism, i.e., the flow type responsible for the transmitting the most water. The ability of dams to readily change flow type within a span of weeks or months showed that flow types are dynamic states that the dams occupy for a period of time as a result of changing external conditions. We thus propose that the dynamic nature of dams may be portrayed more effectively if their classification terminology was altered from flow type to flow state.

Two new dam flow states, seep and mixed, were added to the Woo and Waddington (1990) classification based on field observations. The addition of the seep category was necessary due to differences in landscape type and water source between northern Ontario, where the flow state classification system was developed, and Kananaskis Country, where we studied. The montane environment of Kananaskis Country cultivates valley bottoms with steep slopes, resulting in fast flowing creeks. Beaver prefer gentle slopes and slower moving creeks that are easier to dam (Persico and Meyer, 2009) and the longevity of a beaver colony at a particular location is inversely related to stream gradient (Howard and Larson, 1985). To overcome these constraints, beaver constructed dams on groundwater springs adjacent to main creeks rather than damming them directly. As a result, 64% of the beaver ponds studied were fed by groundwater. These ponds obtained water from various groundwater springs and smaller, zero-order ephemeral tributaries that flow into the central valley streams. This method of building dams off-stream may temporarily increase predation risk for the beaver until the dams are successfully constructed. However, once established, spring fed dams provide long lasting habitats as they are better protected against the high flows associated with the spring freshet (Butler, 2012). Since the Woo and Waddington (1990) study did not include spring fed dams, the seep flow state was not initially described.

The new mixed category captures dams with complex flow patterns with less ambiguity and eliminates the challenge of determining a primary flow mechanism in cases where multiple flow mechanisms are simultaneously occurring. The category was not intended to incorporate dams that experience changes between multiple flow states throughout the season. Further research using the flow state classification will need to find a method to account for dams with flow states shifting over time.

Overall, the strength of the flow state method of classification is that it is hydrologically based and does not rely on beaver occupancy. Therefore, the flow state classification represents both older and younger dams. Since dam flow state is related to variation in pond storage and hydrologically effective height, the classification may prove useful for extrapolating the hydrologic effects of dams to a landscape scale. The tendency of flow state to change rapidly and its strong dependency on season complicate classification but may also help explain the contrasting

![Fig. 8](https://example.com/figure8.png)

**Fig. 8.** a) Comparison of the recession limb slopes for all individual flow types and the instrumented stream sections. b) Comparison of the increase in pond storage for all individual flow types and the instrumented stream sections. Differences between flow types were not significant but differences in dams compared to stream sections were significant.
flood and drought mitigation properties of dams. Beaver dams can be resilient to large floods (Westbrook et al., 2020) while simultaneously remaining full and providing drought mitigation during periods of low flow (Gurnell, 1998; Nyssen et al., 2011; Puttock et al., 2017). These contrasting abilities may be related to changes in dam flow state in response to the volume of water being transmitted across the structure.

4.2. Dam morphology

Dams have some attributes that are predictable by understanding their landscape setting. Dam lengths in spring fed sites were found to be longer than stream fed sites (Fig. 6c); a difference likely reflecting topographic setting. Since the final shape of a beaver dam is dependent on where the dam is built and the surrounding topography (Beedle, 1991), the initial topography of a building site may drive the final differences in dam length. Beaver build dams to establish a pond that has a sufficient depth to offer protection and serve as a refuge (Gurnell, 1998). The natural U-shape of stream channels allows a small dam anchored to each bank to quickly establish a deep pond. In contrast, when beavers begin to dam water from a groundwater spring or small ephemeral creek, no deep pre-existing channel exists. Flat topography requires longer dams and excavation from the beaver to create a deep pond. Beaver can build dams in these environments by dredging soils, shearing mat vegetation, and piling the materials to create the dam structure (Mitchell and Niering, 2016; Westbrook et al., 2017). These spring-fed beaver dams are less likely to be subjected to the high flows from spring floods that dams spanning streams must withstand (Butler, 2012). Dam less likely to be breached by floods persist longer, increasing in both height and length over multiple generations of beaver.

Beaver build dams from a variety of materials including wood, sediment, organic debris, and rocks (Woo and Waddington, 1990). The proportions of different materials used varies between dams and affects the final dam shape (Beedle, 1991). Results of this study suggest that landscape setting plays a role in the materials chosen for dam construction. The proportion of woody versus sediment dominated dams correspond to pond water source. Groundwater fed dams had higher sediment compositions whereas stream fed dams had more wood. Burchsted and Daniels (2014) reported similar observations in northeastern Connecticut, USA, describing in-channel dams with leaker structures and less mud than valley-wide beaver dams. They attributed these differences to beaver putting less effort into dam construction, but it may be better attributed to how different materials can handle and react to different flow velocities. Dams made primarily of wood with little sediment are very porous. A porous structure is well suited to high flow states (stream fed) because it can maintain a full pond while still transmitting a large volume of water, which reduces hydraulic stress on the dam (Hassani et al., 2009). In low flow conditions (groundwater fed), a porous dam would not effectively pond water since the rate of transmission through the dam could easily exceed the inputs from groundwater springs. Sediment dams are best suited to low flow conditions as they are almost impermeable, allowing the dam to maximize water ponding. In high flow conditions, sediment dams lacking reinforcing wood support would quickly erode. Since vegetation is known to decrease bank erosion in rivers (Gholami and Khaleghi, 2013), the ability of a sediment dam to resist erosion should increase once a dam becomes established with vegetation. Roots from emerging vegetation reinforce sediment dams in the same way a wood core would, protecting the structure from erosion. It is uncertain whether the behaviour of using different materials in dams is opportunistic, instinctual, or learned. An extreme example supporting opportunistic behaviour was discovered at a mine site in the central Yukon, Canada, where woody materials were scarce and beaver built their dams almost entirely of rocks (Jung and Staniforth, 2010). However, beaver also often place rocks on the crests of their dams as ballast to keep their building materials in place (Beedle, 1991; Woo and Waddington, 1990). In Kananaskis Country, dams with rocks in their structure had higher average heights ($\Delta h$).

The practice of placing rocks may be deliberately adopted to build taller and more robust dams rather than an opportunistic coincidence. Since beaver construct dams to establish ponds where they are safe from predators (Barnes and Mallik, 1996), there may be a strong evolutionary pressure to quickly make dams that persist. Woody material selected by beaver for dam construction is known to be based on size rather than species (Barnes and Mallik, 1996). Therefore, evolutionary pressure may naturally select for an instinct to use larger, woody materials in faster flows. Alternatively, beaver may learn from experience. If a dam washes out, they could learn to alter their building strategy and pass this information on to their offspring. Additional experimental research would be helpful in determining how beaver select dam material, and how material type influences dam structural integrity.

Sediment dams were observed to have a lower $\Delta h$ (Fig. 5). The lower hydraulic heads (effective dam heights) may be a result of the challenges associated with using sediment as a building material. Beaver may have to put time and energy resources into making sediment dams longer at the expense of height to impound enough water. In addition, sediment is more difficult for a beaver to carry. Beaver can carry large trees in their powerful jaws, obtaining a large amount of building material in each trip. However, sediment must be excavated and carried in the beaver's front paws, one handful at a time. The beaver may have a shorter travel distance to obtain sediment than woody material since it can be excavated from the bottom of the pond. However, ease of access to building materials may not outweigh the small volume of material each trip yields, resulting in dams with a lower hydraulic head. Significant differences in $\Delta h$ were also discovered between some dam flow states (Fig. 4). Since seep dams are characteristically spring fed dams with high sediment content, these related variables will account for some differences seen between flow states. In contrast, lower dam heights may reflect the ecological use of the dam. Hafen et al. (2020) linked dam size to ecological factors, finding that beaver dams containing a lodge or food cache (primary dams) were found to be taller than those without (secondary dams). The purpose of many secondary beaver dams is to expand accessibility to foraging areas. On flat topography a lower dam height can spread pond water over a much larger area than in channels (Westbrook et al., 2006). In these situations, increasing dam height may not be necessary to achieve the dam's purpose.

Further research combining ecological factors, landscape setting, and dam material may provide a method for predicting dam size. However, it is imperative that future research include both stream and spring fed dams. Beaver occupy a broad range of aquatic habitats (Westbrook et al., 2017) but scientific studies and beaver management plans focus strongly on in-channel, stream-fed dams. Since spring fed dams accounted for the majority of dams found in the study area (64%) and showed significant differences in flow state, dam material, and dam size, the results from studies that focus on only stream fed beaver dams should not be assumed to be applicable to spring fed dams.

4.3. Flow regulation

Dams that breach do not always drain completely (Klimenko and Epochenitsvea, 2015) and can continue to affect the surrounding hydrology by elevating the water table (Karran et al., 2018). Analysis of the percent dam breached (PDB) revealed that under certain conditions, dams with large, breached areas continued to store water and impact stream hydrology by maintaining an elevated hydraulic head. In contrast, certain intact dams were discovered to have a hydraulic height of zero (not shown). These results indicate that the physical intactness of the dam structure is not the only variable controlling the hydrologically effective height of the dam. The volume of water moving through the dam may play a role in determining the $\Delta h$. Intact dams under very low flow conditions, for example, may not be able to effectively pond water. Alternatively, breached dams in high flow conditions may be activated and contribute to water retention. Intact dams are known to trigger overbank flooding and attenuate the release of water downstream.
(Nyssen et al., 2011; Westbrook et al., 2006). However, some dams with large breaches still retain water, and therefore may also trigger overbank flooding and attenuate the release of water downstream. These results indicate that studies focusing only on intact and active beaver dams are overlooking an important piece of beaver dam hydrology.

The average QCV metric showed a large difference between the variability seen in sections without ponds when compared to the more stable levels found within ponds. It also showed some emerging differences between each flow state, indicating that not all dams decrease variability to the same extent. Water storage in beaver ponds is temporally variable but much of this variability is not random. The dam flow state, seasonal cycles, and diurnal cycles were found to influence pond water levels. Beaver ponds hold seasonally varying water volumes (Nyssen et al., 2011) with maximum impoundment often reported to occur during the fall (Scheffer, 1938) ranging from September (Clifford, 1977) to November (Nyssen et al., 2011). Contrastingly, a beaver pond studied in central Ontario, Canada, reached peak discharge in the spring months with positive changes in water storage during the spring and fall and negative changes to pond storage occurring midsummer and throughout the winter months (Devito and Dillon, 1993). Differences in seasonal maximums are likely a result of local climate, individual basin properties, and the level of active beaver maintenance on the dam. Only one instrumented pond studied in Kananaskis Country experienced maximum impoundment in the fall with all others reaching their maximum during the spring freshet (late June). In addition to seasonal trends, pond storage is influenced by diurnal cycles. Diurnal cycles are likely caused by either evaporation processes or alpine snowmelt runoff, which are both common streamflow responses observed in alpine environments (Caine, 1992; Mutzner et al., 2015). While the variation in pond depth from the daily peak to the corresponding minimum is small, only a few cm, it can equate to upwards of hundreds of cubic meters of water, depending on pond size (Beedle, 1991; Karran et al., 2018).

In future research, accounting for seasonal and diurnal variation in storage will assist in isolating the storage variability caused by dam flow state. Water storage in ponds responded not only to rainfall events, but also to other environmental factors. Ponds were observed to have both seasonal and diurnal cycles capable of producing strong responses. During the peak summer months of July and August, smaller rainstorms and peak evaporation rates amplified diurnal fluctuations, causing them to dominate over the pond’s response to the rainfall event. Two types of diurnal cycles were observed (not shown). The first was observed in a low elevation pond and had peak pond depths occurring early morning and minimums around midday. The lowest pond depths occurred during the hottest part of the day, suggesting these cycles may be a result of evaporative processes (Johnston, 2017). The second was observed in a high elevation pond; exhibited was a cycle completely out of phase with that found at the lower elevation pond. Peak pond depths occurred early afternoon and minimums occurred over night. This cycle resembles those found in glacier fed streams and may be a result of contributions from alpine snow and ice melt.

The beaver ponds instrumented in Kananaskis Country showed a collective ability to truncate peaks in pond levels and reduce receding limb slope steepness for all dam flow states. This indicates a buffering capacity may be intrinsic to all dam structures regardless of flow state (Fig. 8). No evidence was found to support that individual dam flow states alter the response of rainfall events to different extents (Fig. 8). Separating the effects of beaver dams that vary depending on the dam structure and flow state from those that are universal properties of all dams will aid in future work on predicting dam effects. Though, the new understanding of the dynamic nature of flow states questions the validity of some initial assumptions used in the analysis. Each instrumented pond was assigned a single flow state that was assumed to be applicable to the dam for the entire season. 4 out of the 14 instrumented ponds exhibited some fluidity in flow state when revisited during the field season (Fig. 3).

During large rain events, such as the ones isolated for this analysis, the large increase in flow volume passing through the dams may cause them to temporarily change flow state. Changes in the way water is transmitted across a dam in response to large rain events or changing seasonal conditions have been reported in the literature without the context of flow state. For example, the transition of a dam into an overflow flow state during large flow events has often been observed and described as overtopping or exceeding the dam crest (Butler and Malanson, 1995; Devito and Dillon, 1993; Gurnell, 1998). Since flow state is sensitive to changing conditions, the flow states assigned to each instrumented dam may only be accurate as a base states and any additional flow mechanisms activated during high flows were not accounted for in the study. Accurate flow state classification beyond the base state would require multiple inspections over varying seasonal conditions.

5. Conclusions and implications

This study entailed using a broad beaver dam survey in combination with instrumentation of individual ponds to provide a better understanding of beaver dam structure and hydrology. The flow type classification was successfully adapted to a new landscape through the introduction of two new categories, seep and mixed. Insight gained from this characterization prompted a change in terminology from flow type to flow state to better describe the dynamic nature of beaver dam hydrology. Analysis of dam size (length and $\Delta h$) revealed significant differences with respect to pond water source, flow state, and dam building materials. The new percent dam breached metric illustrated the importance of landscape setting by revealing how variables external to dam structure can control the hydrologically effective height of the dam. The instrumented beaver ponds showed a collective ability to truncate rainfall induced peaks and reduce variation in pond storage for all dam flow states when compared to sections lacking dams. Interestingly, the differing flow states affected seasonal variation in pond storage to varying extents, but no difference was found between flow states when analysing the response of pond storage to rain events.

The results of this study have illustrated that beaver dams are incredibly diverse and dynamic structures but can be characterized using their physical and hydrologic properties. Notably, both dam properties and landscape setting are important factors in determining the effect that dams have on the surrounding hydrology. As climate change increases the severity of droughts and floods on the landscape and practitioners continue to incorporate beaver in climate change mitigation and restoration practices, it is clear that a comprehensive understanding of beaver dam hydrology and the ability to predict and model the effects of dams across the landscape is increasingly important. The patterns uncovered in this study will assist in future research directed at estimating beaver dam effects on the landscape. Understanding these relationships will be vital for creating models able to predict dam effects and subsequently for determining the true mitigation potential of beaver dams.

CRediT authorship contribution statement

Amanda L. Ronquist: Conceptualization, Investigation, Formal analysis, Visualization, Writing - original draft. Cherie J. Westbrook: Conceptualization, Supervision, Funding acquisition, Resources, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
Acknowledgements

We thank S. Schut and M. Sánchez for field assistance, N. Leroux for coding support, and J.M. Waddington and K. Chutko for their comments on an earlier draft of this manuscript. Funding was provided by grants from the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery (RGPIN-2017-05873) and CREATE (463960-2015) programs, Global Water Futures (Mountain Water Futures), and Alberta Innovates. The study was carried out on Treaty 7 Territory and we pay our respect to the Blood Tribe, Piikani Nation, Siksika Nation, Tsuu TINA Nation, and Stoney Tribe.

References


Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.

Eco, 1923.