POINT BY POINT RESPONSE TO REVIEWERS

Reviewer comments are in blue, our proposed changes are in grey, and the actual changes we made to the document are in red.

Response to reviewer #1:

Thank you for the opportunity to review the draft manuscript "Rapid surface water volume estimations in beaver ponds" by Daniel J. Karran, Cherie J. Westbrook, Joseph M. Wheaton, Carol A. Johnston, and Angela Bedard-Haughn. I found this article to be a very interesting description of a method for determination of storage in beaver ponds using a minimum of input information. The authors make a compelling argument for this method with examples. I found this draft to be very clean and well written.

Please consider the following comments.1. eqn 8: Just to be clear about where equation 8 came from, add: "For ease of visual interpretation, equations 6 and 7 can be combined as:" 2. eqn 9: Is this correct? If eqn 8 is substituted into eqn 9, you get RD = RDˆp/2 3. p 5, ln 5 – I don't understand the statement "thereby eliminating issues of scale and aiding in the analysis of error."

Equation 9 is used to fit a power function to the actual points on the bathymetric curve, which makes Equation 8 redundant, and its inclusion confusing. Thus, we will remove Equation 8 from the revised manuscript. We will also more plainly state that the intentions of Equations 6-9 are to scale the bathymetric curves to one another to facilitate comparison among them.

Equation 8 was removed and the following sentence proceeds what used to be Eq. (9) but is now Eq. (7) in the revised document:

"Power functions described by Eq. (1) can then be fit to a bathymetric curve with the following equation:"

We clarified what we intended to convey with regards to scale and error with the following paragraph after Eq. (7)"

"where the p coefficient here is equal to the p coefficient in Eq. (1). This allows for a visual aid in the analysis of error by superimposing estimated curves produced via either Eq.(1) or Eq. (4) to the pond's actual bathymetric curve. It also eliminates issues of scale between different ponds so that bathymetric curves can be visually compared to one another."

eqn. 10 – define Vland. Also, add more description to the paragraph starting at page 5, line 6. It is hard to understand BI just by reading the text (e.g. what is the "reference solid" that you refer to). I had to refer to Strahler, 1952 to understand this paragraph.

Vland will be defined in the revised manuscript (Eqn 10). We will also improve our description of BI, probably using a simple example, in the revised manuscript to improve understandability.

We added a perceptual diagram (Figure 1) showing the relationship between all the morphometric variables.

table 1 – what is the column "n" in the table? I assume number of ponds at the site.

Yes, "n" does indeed represent pond numbers. We will add this to the table caption.

We added that "n" represents the number of ponds in the tables captions where it was used.

Response to reviewer #2:

This study explores the capabilities of different geometric methods to estimate surface water storage in beaver ponds; to do so, the authors use topographic datasets from multiple beaver ponds that range in hydrogeologic setting. The paper is generally well written (but see technical corrections) and presents results in informative, polished figures. The paper's main contribution is its quantitative comparison of different methods, which require different input datasets (from simply dam length to coupled measures of water depth and inundated area), to predict beaver surface water storage (see Section 4.4). Considering the number of beaver ponds and their contribution to watershed storage and release, such assessed tools are useful for watershed assessments, planning, and modeling over large spatial scales. However, I find the paper too long and with unnecessary text for a focused evaluation of methodologies for storage volume estimation. With that said, there are also opportunities (often alluded to in the text) to expand the work, where the focus is broader: beaver pond morphologies, their drivers, and their implications. As such, I see two options to reframe the paper that should be considered:

Technical Note: Streamline the paper's text and focus to compare methods for predicting volumes. This will also require clarifying some of the methods and their linkages (see specific comments below). Text to consider removing/shortening includes: Page 1, Line 25 through Page 2, Line 23. Rather, the introduction could succinctly state: beaver ponds are ubiquitous and important to watershed water storage, highlighting the need for methods to quickly estimate storage use; methods have been developed for other wetland features, and here we apply these for beaver ponds. Section 2.5. No need to describe the sites in detail (e.g., vegetation); instead, simply present needed information (hydrogeologic setting, DEM datasets) in the table. Text distributed throughout results (e.g., Page 8, Lines 26-31) that describes the variation in beaver pond morphology. This text should be retained for Option 2 (below), but removed for a technical note solely focusing on a methodology. Similarly, Sections 4.2 and 4.3 could be removed for a technical note; instead, the discussion should simply revisit the methods to discuss tradeoffs between accuracy and data needs among the methods evaluated (i.e., section 4.4).

Research Article: For this option, the manuscript could be expanded, where it focuses on the variation, drivers, and implications of a suite of morphological metrics (in addition to storage volume) for beaver ponds. At times, the manuscript points to some of these topics (e.g., the importance of SI for groundwater exchange, beaver ponds store less water than potholes b/c of ontogeny of ponds, time variation of pond mor-phometry, etc), but these points seem somewhat tangential for the current manuscript focus. However, the paper could make a meaningful comparison across ponds and regions by deemphasizing the volume storage methodology and including: 1) a full comparison of the different metrics (SI, storage, dam lengths, maximum depth, etc) across systems, 2) analyses of their drivers (e.g., predictive relationships with stream order, watershed slope, etc), and 3) focused intro and discussion text regarding implications (cumulative storage, perimeter to area ratios for water exchange and habitat, sediment storage, etc). Again, there is some mention of such topics (e.g., Section 4.5), but a quantitative evaluation of the drivers and importance of beaver morphology means a full treatise on this subject, where the volume storage estimation is one method applied. For this option, authors could consider either just including the 40 ponds used here (in which case, the actual bathymetric curves could be used), or they could use the 40 ponds to verify the Simple V-A-h method, and then use a larger set of ponds with available required datasets to derive volume, SI, and other metrics. In short, I contend that the manuscript is lacking clear and organized scope. The two options suggested above will help frame the work in a clear way, be it as a technical note or an evaluation of beaver pond morphologies; I believe either option will provide a valuable contribution. Given this suggested shift in scope, specific comments depend on option chosen. As such, I have limited the number of comments below, and include only those that should be addressed regardless of option, or that I point to an Option specific revision.

Our goal was to discover tools useful for estimating surface water storage in beaver ponds at large and small spatial scales – ones that are easy to apply in relatively data-sparse environments, and ones that hold potential for incorporation into hydrological models in future research initiatives. While we agree with reviewer 2 that a full treatise on beaver pond morphology is needed, enhancement of water storage on the landscape owing to biota – in our case beaver damming activities - is the focus of our paper. Indeed, a treatise on beaver pond morphology may not yet be possible. For our research, we contacted all the leading beaver impact researchers across the world and learned pond morphometry is rarely documented as part of their research initiates. Thus, the 40 ponds we studied represent nearly the whole of the global population of beaver ponds with detailed morphometric measurements.

That said, we agree with reviewer 2's suggestion to streamline the paper's text and focus. But, we do not think the streamlining will reduce the text and content enough to align the manuscript with requirements for a technical note. Reduction of the manuscript to a technical note would require solely evaluating the Simplified V-A-h method. Such focus would be of more limited interest and use to readers of HESS as it would eliminate our evaluation and discussion of tools useful for estimating surface water volumes at larger spatial scales. The discussion of tools for estimating surface water storage volumes at larger scales originates through our characterization of pond morphometry.

To shorten the paper, we will, as reviewer 2 suggests, reduce the length of the Introduction. We will re-focus the Introduction to succinctly make the following points: beaver ponds are ubiquitous and important to watershed water storage, highlight the need for methods to quickly estimate storage use; identify methods that have been developed for other types of wetlands, and state how we here apply these to beaver ponds. We also foresee shortening section 2.5 by removing non-critical site detail, such as the description of site vegetation. We plan to retain section 4.2 as it is critical to discussion of our results. Section 4.3 will be removed in its entirety.

We refocused and shortened the introduction by removing the information about using beaver for river restoration and the expansion of beaver habitat due to climate change. We also altered our objectives in accordance with changes to the methods as follows:

"We studied beaver ponds across much of their habitat range and: i) evaluated the utility of the Simplified V-A-h method in estimating surface water storage; ii) evaluated correlations between surface water storage and beaver pond morphometry; and, iii) described beaver pond morphometry in relation to surface water storage capacity."

We removed all the non-critical site detail from section 2.4 and removed section 4.3 entirely.

Page 1, Line 14: Be specific when discussing surface water storage as a function of stage vs. storage capacity.

We will make the suggested changes

We define what we mean by surface water storage in the first sentence of the introduction as follows:

"The volume of water stored at the surface of wetlands, ponds and lakes (as a function of stage) is of great concern to those responsible for assessing risks and balancing water supplies to societal demands."

Page 2, Line 6: Why are beaver populations expected to increase with climate change?

We will detail that climate change is expected to produce a modest expansion of the northern range limit of beaver by 2055 (Jarema et al., 2009).

We removed this sentence from the manuscript to shorten the introduction

Page 2, Lines 12 – 23: Too much focus here on restoration, even for Option 2, and especially for a technical note. Instead, informing restoration is just one importance of good volume estimation.

We agree that informing restoration is just one importance of good volume estimation and will change the text to say so instead of going into detail on the application of the method to restoration.

We removed this section of the introduction to address the reviewer's comment and shorten.

Page 2, Line 31: Define basin morphometry.

We will follow the example of Brooks and Hayashi (2002) and define basin morphometry parenthetically as "(surface, volume, depth)."

We added this exactly as proposed

Page 3, Line 2: Qualify "with little additional effort".

We will qualify this statement to make it less subjective

We removed “with little additional effort” and changed the sentence to read:

“Requiring only two measurements of depth and surface area, it has been shown to provide reliable estimates of surface water storage in the pothole wetlands of the North American prairies for which it was designed (Minke et al., 2010).”

Methods: For option 1, a conceptual 2-panel figure (cross section and plan view) would really help to define terms used in the equations.

We will include a figure like this in the revised paper to help define terms used in the equations.

We added this figure to the manuscript. It is now Figure 1

The methods are hard to follow; some reorganization and explicit text to link methods would help; how this is done will depend on the manuscript’s new scope. For Option 1, this would mean revising Section 2.2 to explicitly distinguish the variables that were used for simple predictions of volume (dam length, SI) versus the relationships that were used to evaluate model predictions (i.e., Dact). It could also be clearer what Dact and Dest refer to; the “actual V-h relationship or point on the bathymetric curve” makes that confusing without more clarification. It might help to switch 2.2 and 2.3. For Option 2, methods would reflect the various different metrics used to describe pond bathymetry and how these were compared across sites.

The methods will be modified in accordance to the suggestions provided for Option 1 and addition of a figure, as suggested in the last comment.

We divided the methods into two subsections- “2.2.1 Metrics for surface water volume estimations”, and “2.2.2 Morphometric analysis.” We streamlined the text in each of these sections to be more concise about what we are trying to achieve with each morphometric variable. Further, we added a perceptual diagram (Figure 1), providing a visual aid for understanding the relationship between variables.

Page 5, Eqns 8 and 9: Where is the exponent in Eqn 8 that then appears as p/2?

As identified by Reviewer #1, there is an error in equation 8, which will be removed from the revised paper and replaced by equation 9.

We removed Equation 8 from the paper and revised that section as noted above.

Section 2.4: Again this information could be streamlined and probably just included in a table.

We will make the suggested changes

We removed all the non-critical site detail. Section 2.4 is now a short paragraph and a table.

Section 4.3: Points raised here are not addressed by the results. For Option 1, remove text altogether, other than just pointing to the importance of a simple method to estimate storage considering this time variability. For Option 2, consider retaining text, but only if some results can point to this time variability.

We will remove section 4.3 entirely as suggested by the reviewer.

We removed this section entirely

Page 12, Lines 29-31: Good point and method application.

Thank you.

Section 4.5. Example of inferences that could be expanded in Option 2 but minimized in Option 1.

Section 4.5 will be fleshed out with examples based on the changes we indicated above.

All the inferences in this section are in accordance with our discussion as revised.

Page 1 Line 27: Complete sentences should be follow semicolons. This needs to be addressed throughout in a number of places (e.g., Page 2, Line 27)

Noted errors were corrected throughout

Page 2, Line 8: “by virtue of the fact that it..” Awkward.

This was removed from the manuscript

Page 9, Line 4: Need a comma after Aerr.

These three grammatical changes will be made.

Noted error was corrected

Page 2, Line 32: : : :basin morphometry are not considered.

We will change ‘is’ following ‘basin morphometry’ to ‘are’ to make grammatical sense.

We changed exactly as proposed

PLEASE FIND THE MARKED UP MANUSCRIPT BELOW

Rapid surface water volume estimations in beaver ponds

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Abstract. Beaver ponds are surface water features that are transient through space and time. Such qualities complicate the inclusion of beaver ponds in local and regional water balances, and in hydrological models, as reliable estimates of surface water storage are difficult to acquire without time and labour intensive topographic surveys. A simpler approach to overcome this challenge is needed, given the abundance of the beaver ponds in North America, Eurasia and southern South America. We investigated whether simple morphometric characteristics derived from readily available aerial imagery or quickly measured field attributes of beaver ponds can be used to approximate surface water storage among the range of environmental settings in which beaver ponds are found. Studied were a total of 40 beaver ponds from four different sites in North and South America. The Simplified V-A-h approach, originally developed for prairie potholes, was tested. With only two measurements of pond depth and corresponding surface area, this method estimated surface water storage in beaver ponds within 5% on average. Beaver pond morphometry was characterized by a median basin coefficient of 0.91, and dam length and pond surface area were strongly correlated with beaver pond storage capacity, regardless of geographic setting. These attributes provide a means for coarsely estimating surface water storage capacity in beaver ponds. Overall, this research demonstrates that reliable estimates of surface water storage in beaver ponds only requires simple measurements derived from aerial imagery and/or brief visits to the field. Future research efforts should be directed at incorporating these simple methods into both broader beaver-related tools and catchment scale hydrological models.

1 Introduction

The volume of water stored at the surface of wetlands, ponds and lakes (as a function of stage) is of great concern to those responsible for assessing risks and balancing water supplies to societal demands. Arriving at reliable estimates of such storage is difficult without some knowledge of the feature's morphometry, i.e. information that is often time consuming and impractical to acquire, especially when the features are numerous and transient through space and time (Milly et al., 2008). This is particularly true for beaver ponds owing to their cyclic creation and abandonment.

Beaver dams and their associated ponds are ubiquitous in streams and wetlands in the northern hemisphere and southern South America (Whitfield et al. 2015). Beaver dam densities have been reported to exceed 40 dams per kilometer (Macfarlane et al., 2015), making them one of the most frequent obstructions to flowing water (Naiman et al., 1986; Pollock et al., 2003). Beaver dams increase open water area within watersheds (Hood and Bayley, 2008) and ponds bring numerous ecosystem benefits (Johnston, 2011). But, beaver ponds can also be viewed as burdensome or even dangerous from an anthropomorphic perspective (Butler and Malanson, 2005; Green and Westbrook, 2009). Such concerns, whether positive or negative, generally centre around the pond's capacity to store water and sediment, highlighting the need for quick and accurate surface water storage estimation methods.

Numerous hydrological investigations have sought to estimate surface water storage in other types of wetlands (Trigg et al., 2014; Xu and Singh, 2004). For hydrological modellers, an ideal approach is one that overcomes the need for often time-intensive topographic surveys and that is more practical for use in models at varying scales and locations. Previous studies have set about this by defining statistical relationships between surface area and volume for wetlands of specific physiographic regions (Gleason et al., 2007; Hubbard, 1982; Lane and D'Amico, 2010; Wiens, 2001). Such approaches have been found useful for modelling entire watersheds (Gleason et al., 2007), but limited for estimating storage in individual wetlands because depth and basin morphometry (i.e surface area, volume, depth) are not considered (Huang et al., 2011; Lane and D'Amico, 2010; Wiens, 2001). Brooks and Hayashi (2002) presented an equation that includes depth and basin morphometry, but in order to use it, basin morphometry must be predefined and no such information yet exists for beaver ponds.

Another approach, the Simplified Volume-Area-Depth (V-A-h) method (Hayashi and van der Kamp, 2000), accounts for depth and calculates basin morphometry for each individual wetland. Requiring only two measurements of depth and surface area, it has been shown to provide reliable estimates of surface water storage in the pothole wetlands of the North American prairies for which it was designed (Minke et al., 2010). Prairie

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Deleted: With little additional effort potholes are depressional wetlands that have fairly regular shapes, i.e. concave profiles with smooth slopes. Beaver ponds, by contrast, typically encompass a bathymetry that is far more complex because their size and shape is controlled by the dimensions of the dam and the land surface that becomes flooded upon dam establishment (Johnston and Naiman, 1987). Whether statistical or analytical approaches can reliably estimate water storage in beaver ponds has yet to be determined. Our goal was thus to explore tools useful for estimating surface water storage in beaver ponds. We studied beaver ponds across much of their habitat range and: i) evaluated the utility of the Simplified V-A-h method in estimating surface water storage; ii) evaluated correlations between surface water storage and beaver pond morphometry; and, iii) described beaver pond morphometry in relation to surface water storage capacity.

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2 Methods

2.1 The Simplified V-A-h method

The Simplified V-A-h method is based on a simple power equation (Hayashi and van der Kamp, 2000), where the area of a pond (A), at a given height above the pond bottom (h), is described as:

$$A = s\left(\frac{h}{h_0}\right)^{2/p}, \quad (1)$$

where h_0 is the unit height of the water surface (e.g. 1 m for SI units), s is a scaling coefficient that represents the area of a circle (m^2) with a radius that corresponds to h_0, and p is a dimensionless morphometry coefficient that represents the shape of the bathymetric curve (i.e. the area-depth relationship of the pond). The volume of the pond is then determined by integrating all the area profiles below h to give:

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$$V(h) = \int_0^h s\left(\frac{h^*}{h_0}\right)^{2/p} dh^* = \left(\frac{s}{1+2/p}\right)\left(\frac{h^{1+2/p}}{h_0^{2/p}}\right). \quad (2)$$

Using Eq. (1) and Eq. (2) requires parameterizing the s and p coefficients. The Simplified V-A-h method arrives at these values by rearranging Eq. (1) to give (Minke et al., 2010):

$$s = A_1\left(\frac{h_1}{h_2}\right)^{-2/p}, \quad (3)$$

And

$$p = 2\left(\frac{Log\left(h_1/_{h_2}\right)}{Log\left(A_1/_{A_2}\right)}\right), \tag{4}$$

where A_1 and A_2 are surface areas of the pond at corresponding depths of h_1 and h_2, respectively, and $h_1<h_2$. With only two measurements of area and depth in time, Eq. (3) and Eq. (4) can be used to calculate s and p coefficients that are then reinserted into Eq. (1) and Eq. (2) to define the entire area-depth and volume-depth relationship of the pond.

2.2 Beaver pond morphometry

2.2.1 Metrics for surface water volume estimations

A beaver pond's capacity to store surface water is defined simply by its bathymetry, and can be directly calculated if an accurate topographic survey is available. The problem here relates to how well we can approximate that volume given some simple measures of the dam and pond dimensions. To discover if metrics exist, a series of morphometric variables were generated in addition to the p coefficient described in Eq. (1). They include: the maximum dam height (h_{max}) defined as the difference in elevation (m) between the dam crest and the lowest point in the pond; the maximum surface area (m^2) of the pond (A_{max}) at h_{max}; and, the length (m) of the dam (D_{len}) measured along its crest. Regression analysis was then used to determine if any of the variables are correlated to the maximum volume of the pond (V_{max}).

2.2.2 Morphometric analysis

Understanding the underlying mechanics of the Simplified V-A-h method and how morphometry relates to a pond's capacity to store water requires a deeper analysis of the bathymetric curve. The bathymetric curve is equivalent to the hypsometric curve defined by Strahler (1952) as the ground surface area of a landmass with respect to elevation. In order to compare curves for ponds of different size and relief, it is necessary to express the variables as relative depth (R_D) and relative area (R_A) as:

$$R_D = \frac{h}{h_{max}}, \tag{5}$$

and

$$R_A = \frac{a}{A_{max}}, \tag{6}$$

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Deleted: where P is the perimeter of the pond (m) and A_{max} is the surface area (m^2) at h_{max}. Ponds with an $S_I = 1$ have shapes that are perfectly circular, whereas ponds with $S_I > 1$ are increasingly complex. Pond shape is an important metric as much of the interaction between surface water and groundwater happens at the shoreline (Shaw and Prepas, 1990). Previous studies have used the perimeter-to-area ratio to describe the shape of forest wetlands (Brooks and Hayashi, 2002) and the boundary conditions of beaver ponds (Johnston and Naiman, 1987). We chose S_I for its ease in interpretation and because it enables a relative comparison between the shapes of beaver ponds and other types of wetlands, such as those reported by Minke et al. (2010).

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where, h is the stage (m) elevation of the pond and a is the corresponding surface area (m^2) at any given h. For ease of visual interpretation, we express the bathymetric curve as R_D vs. 1-R_A (Fig. 1). Power functions described by Eq. (1) can then be fit to a bathymetric curve with the following equation:

$$R_D = (1 - R_A)^{p/2} \,, \tag{7}$$

where the p coefficient here is equal to the p coefficient in Eq. (1). This allows for a visual aid in the analysis of error by superimposing estimated curves produced via either Eq.(1) or Eq. (4) to the pond's actual bathymetric curve. It also eliminates issues of scale between different ponds so that bathymetric curves can be visually compared to one another.

From the relative bathymetric curve, it is possible to compute the Bathymetric Integral (B_I), a modified form of the hypsometric integral defined as the measure of landmass volume with respect the entire reference solid created by the maximum dimensions of the pond (Fig.1; Strahler, 1952):

$$B_I = \frac{V_{land}}{h_{max}A_{max}} = \int_0^1 R_A \, dR_D \,. \tag{8}$$

Equation 10 produces values between 0 and 1, with 1 representing a reference solid entirely composed of landmass. Using the B_I, we introduce a new metric that represents the pond's bathymetric capacity to store water (B_{WC}). Since the total volume of the reference solid is comprised of either land or water, the B_{WC}, relative to the reference solid, is expressed as:

$$B_{WC} = 1 - B_I = \frac{V_{max}}{h_{max}A_{max}} \,. \tag{9}$$

The B_I and B_{WC} are quantitative measurements of the pond's morphometry and capacity to store water, respectively. The value in using these metrics is that they facilitate the comparison of surface water storage capacity among beaver ponds and other wetland types.

Finally, we described the shape of the beaver pond surface using a dimensionless Shape Index (S_I), which is essentially the ratio of the pond perimeter to the circumference of a circle with the same area (Hutchinson, 1957):

$$S_I = \frac{P}{2\sqrt{\pi A_{max}}} \,, \tag{10}$$

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where P is the perimeter of the pond (m). Ponds with S_I = 1 have shapes that are perfectly circular, whereas ponds with S_I > 1 are increasingly complex. Pond shape is an important metric as much of the interaction between surface water and groundwater happens at the shoreline (Shaw and Prepas, 1990). We chose S_I as it is easy to interpret and enables a relative comparison between the shapes of beaver ponds and other types of wetlands (Minke et al., 2010).

2.3 V-A-h models for surface water storage estimation in beaver ponds

Three versions of the power function model described by Eq. (1) were tested in this study. They are referred to as the *Full, Simplified,* and *Optimized* models. The *Simplified* model is the actual test of the Simplified V-A-h method and the other two models were included to aid in the analysis of this approach.

The *Full* model is a power function fitted to the complete dataset of each pond's bathymetry (i.e. empirical fit). We arrive at values for s and p by fitting a simple power function, $y = ax^b$, to the pond's bathymetric curve, and assume $a = s$ and $b = 2/p$ in accordance with Eq. (1). Non-linear least squares regression was used to determine the best-fit; the ability of this model to make accurate area and volume estimates depends on its 'goodness of fit' to the dataset. Analysis of the *Full* model was included to: i) identify the p coefficient that best describes each beaver pond's morphometry; and, ii) assess the overall suitability of power functions to describe beaver pond bathymetry.

The *Simplified* model is a power function using s and p coefficients created from the same two relative measurements of depth (i.e. h_1 and h_2 as a percentage of h_{max}) in each pond. Minke et al. (2010) evaluated the Simplified V-A-h method by applying it to two scenarios: a dry one where h_1 and h_2 are taken at 0.1 m and 25% of h_{max}, and a wet one where h_1 and h_2 are taken at 50% and 75% of h_{max}. They found that estimation errors were lowest using the wet scenario; therefore, we chose this scenario to simulate the application of the Simplified V-A-h method as it may be practically used in the field.

The *Optimized* model differs from the *Simplified* model through parameterizing coefficients via the optimum combination of h_1 and h_2 for each pond. This required calculating s and p coefficients at every possible combination of h_1 and h_2 along the bathymetric curve (Note: h_1 and h_2 are expressed as a percentage of h_{max} from 1–100; therefore, the total number of combinations where $h_1 < h_2$ is 5000 for each pond). Each set of s and p coefficients was then reinserted into Eq. (1) and Eq. (2) to estimate area and volume, respectively, and the set that produced the least combined area and volume error was selected as the optimum. The *Optimum* model was included in this study to discover how best to use the Simplified V-A-h method with regards to differences in pond morphometry.

Error for all three models was evaluated using root mean square error (E_{RMS}), defined as:

$$E_{\mathrm{RMS}} = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(D_{\mathrm{ACT}} - D_{\mathrm{EST}})^2}\,, \qquad (11)$$

where m is the number of data points, D_{ACT} is the point on the actual bathymetric curve calculated from the pond itself, and D_{EST} is the point on the estimated bathymetric curve derived from the s and p coefficients at a given combination of h_1 and h_2. Finally, to allow for coherent comparisons of error among the different beaver ponds, the magnitude of error, referred to as A_{ERR} (%) for area and V_{ERR} (%) for volume, was calculated by dividing the E_{RMS} by the actual area and volume of the pond at 80% of h_{max}. This particular depth was chosen to avoid inconsistencies in error magnitudes that arise when the evaluation depth is set too close to the minimum and maximum (Minke et al., 2010).

2.4 Test sites

Forty beaver ponds were selected for this study and simulated in digital elevation models (DEMs). Our sample design captured the range of structures built by beaver along streams with mineral and organic substrates in both mountainous and lowland terrain. Beaver ponds were thus analyzed from multiple locations where bathymetric data existed, which included: Kananaskis Provincial Park, Alberta, Canada; Escondido, Tierra del Fuego, Argentina; the Logan River watershed, Utah, USA; and, Voyageurs National Park, Minnesota, USA. Details of the location, terrain, number of ponds, survey methods, and survey resolution for each site are provided in (Table 1).

2.5 DEM creation and manipulation for variable calculations

Sites selected for this study were former beaver ponds that had drained sufficiently to either reveal pond bottom bathymetry or allow it to be surveyed. Beaver ponds extracted from LiDAR, when available, were fully drained with visible relic dams, whereas some ponds surveyed by total station and rtkGPS often were still full with water up to their crest elevations, but not enough to impede point collection by wading. DEMs that relied on total station and rtkGPS surveys were created with Surfer® v10 (Golden Software, Colorado) using ordinary

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Deleted: The beaver ponds in Kananaskis are in the Sibbald research wetland; a rich, flow-through fen formed in an unconstrained basin of the southern Canadian Rocky Mountains (Westbrook and Bedard-Haughn, 2016). The site is dominated by shrubs (e.g. *Salix* spp. and *Betula* spp.), sedges (*Carex* spp.), brown mosses (e.g. *Drepanocladus* spp. and *Scorpidium* spp.), and clusters of stunted black spruce (*Picea mariana*), all of which form the peat that reaches depths of up to 6.5 m. Air photo analysis confirms that beaver returned to the basin in the 1950s after their likely extirpation from the region as a result of the fur trade (Morrison et al., 2015). Half of the 10 beaver ponds were surveyed with a Leica total station in 2009 and the other half were surveyed with a Leica GS15 real time kinetic GPS (rtkGPS) in summer 2015. ... [4]

kriging. The beaver ponds were then isolated from the unneeded areas of the DEM by extracting all of the points in the raster below and upstream of the dam crest (i.e. h_{max}). This was done in ArcGIS v10.2 (ESRI, 2015) as was the calculation of the morphometric variables. The V-h relationship and bathymetric curve of each pond was calculated at 5 cm increments using a script written in Python™ that utilizes the 'volume' feature of ArcGIS Toolbox. The V-h relationship and bathymetric curve of each pond were the primary inputs for the three models, which were built and run in R Studio (RStudio Team, 2015). Finally, the bathymetric curve for each pond was established using linear interpolation to create 100 points, i.e. 1–100% of h_{max}.

3 Results

3.1 Beaver pond morphometry

Pond morphometric characteristics are provided in Table 2 and examples of the DEMs from each location are provided in Fig. 2. The 40 ponds well represented the various types of beaver ponds that are created in riverine and wetland habitats (Baker and Hill, 2003), with max dam heights (h_{max}) ranging from 0.25–2 m and dam lengths (D_{len}) spanning 3–308 m, with medians of 0.83 m and 40 m, respectively. Pond volumes (V_{max}) ranged between 1–9,001 m^3 and showed strong power correlations to D_{len}, h_{max} and A_{max} (Fig. 3). Among the ponds, there was considerable variability in shape as S_I values ranged from 1.5–5.3 (mean = 2.6). No strong correlations (i.e. -0.10 > R^2 < 0.10) were found between S_I and the other morphometric variables used in this study (i.e. p, B_I, B_{WC}, D_{len}, h_{max}).

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The p coefficients for the beaver ponds followed a log normal distribution, and ranged from 0.45–2.58 (median of 0.91) (Fig. 4). Of the 40 beaver ponds analyzed, 70% (28) had p coefficients that were <1, indicating that beaver ponds tend to have convex bathymetries. The majority of beaver ponds tended to be more convex than they are concave, given the shape of the bathymetric curves (Fig. 5) and the range of B_I (0.45–0.85; median of 0.69). In all but one case, V_{land} was greater than 50% of the total volume of space, indicating that most beaver ponds are shallow, which limits the volume of surface water they can store. This phenomenon is well described by the strong exponential relationship between the p coefficient (R^2 = 0.96) and B_I and B_{WC} (Fig. 6). Soil substrate type (Table 1; organic vs. mineral) did not affect the value of the p coefficient, as evidenced by a t-test (P = 0.97).

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3.2 Surface water storage estimations

The *Full* model had the least A_{ERR}, and the *Optimized* model had the least V_{ERR} (Fig. 7; Table 3). The highest A_{ERR} and V_{ERR} was associated with *Simplified* model estimates, which also produced the greatest variability of error among the different ponds. With regards to study locations, *Full* V_{ERR} ranked as Escondido<Voyageurs<Logan<Kananaskis, whereas *Full* A_{ERR} ranked Logan<Escondido<Kananaskis<Voyageurs. Overall, the beaver ponds in Kananaskis proved most difficult to model (i.e. highest V_{ERR} and A_{ERR} overall); however, mean error for the *Full* model remained below 5% for both area and volume estimates.

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Compared to the *Full* model (Fig. 7), the *Simplified* model had higher V_{ERR} in 65% of cases (26 ponds) and higher A_{ERR} in 98% of cases (39 ponds), whereas the *Optimized* model had lower V_{ERR} in 100% of cases but slightly (<1%) higher A_{ERR} in 100% of cases. The optimum p coefficients for volume tended to be slightly different than the optimum p coefficients for area, which are the coefficients derived from the empirical fit of the *Full* model. The *Optimum* model proved useful for revealing the two points on the bathymetric curve that can be used to obtain the optimum p coefficient for volume estimates. Pond 7 had the largest A_{ERR} and V_{ERR} (Fig. 7), and so was selected for more detailed study (Fig. 8). The optimum points were found at the approximate location of where the empirical fit intersects with the bathymetric curve. Thus, using the optimum points in Eq. (4) computes a p coefficient that is closest to the same coefficient generated by the curve fitted by non-linear least squares regression. The points used by the *Simplified* model for Pond 7 fall on segments of the bathymetric curve that are farther away in distance from the empirical fit; hence, the p coefficient generated by these points creates a curve that is farther away from the bathymetric curve, which ultimately leads to a less accurate estimate of volume.

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In a number of ponds, the empirical fit nearly overlapped the entire bathymetric curve, and in such cases, there were a large number of combinations of h_1 and h_2 that produced reasonable estimates of volume. For example, Pond 10 had the lowest *Full* A_{ERR} and V_{ERR} of all the beaver ponds. In this case, there were 1899 combinations of h_1 and h_2 that produced estimates with total error below 5%, and the distance between the points ranged from 1% to 84% of h_{max}. Overall, the error was not sensitive to distance between h_1 and h_2 as long as the points were on or near the *Full* fitted curve. That said, the average minimum and maximum for h_1 (for all of the optimum combinations for each pond) was 18–74%, respectively, and for h_2, it was 42–98%, respectively.

4 Discussion

The Simplified V-A-h method estimated surface water storage in the beaver ponds with high accuracy. Also, strong statistical relationships were found between surface water storage capacity in beaver ponds and the dimensions of the dam and pond. The beaver ponds studied have a convex shape that permits less water storage than do other open water wetland types. Surface water storage estimates can be made in beaver ponds without the need for topographic surveys if pond morphology is used instead.

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4.1 V-A-h model performance in beaver ponds

The low *Full* A_{ERR} and V_{ERR} overall indicates that beaver pond morphometry is adequately described by power functions. This is because the bathymetric curve proved resilient to fluctuations in 'elevation' inherent to the impounded land surface. Also, the dams, intricate canals and holes that beaver create in the areas they inhabit (Hood and Larson, 2015) do not warp the shape of the bathymetric curve enough that a power function becomes inappropriate to sufficiently describe it. However, it appears that volume estimations are more resilient to aberrations in the bathymetric curve than are area estimates. The power functions in the *Full* model are fitted to pond bathymetry. When the power curve moves up and down, A_{ERR} will increase, but sometimes the V_{ERR} can decrease because volume is the integration of everything above the bathymetric curve. When the curve moves slightly up or down from the empirical fit, irregularities on the bathymetric curve are captured, which improves volume estimations at the sacrifice of area estimations. This explains why the *Optimum p* coefficients for volume are different than they are for area. It also explains why, in many cases, the *Simplified* model had V_{ERR} that was less than 10%, while A_{ERR} was greater than 25%. Without a complete set of pond bathymetry, it is unlikely that users of the Simplified V-A-h method would be able to discern the optimum points for h_1 and h_2; however, as long the chosen values for h_1 and h_2 are selected within the range identified here (i.e. 18–74% of $h_{\max}$ for h_1 and 42–98% of $h_{\max}$ for h_2), fairly accurate estimates of surface water storage should be expected. Overall, the *Simplified* model performed reasonably, exceeding 10% V_{ERR} in only three cases. Given that the Simplified V-A-h method appears to work well across the broad range of beaver pond bathymetry reported here, and across a wide range of prairie potholes (e.g. Minke et al., 2010), it should be a robust enough approach to be used other open water wetlands.

4.2 Beaver pond morphometry and surface water storage capacity

Our results show that *p* coefficients in beaver ponds are lower overall than those reported in prairie wetlands (Hayashi and van der Kamp, 2000) and those reported in forest pools in New England (Brooks and Hayashi, 2002). Because of the strong exponential relationship between *p* coefficients and B_{WC}, we can conclude that beaver ponds typically store less water. For example, the prairie potholes studied by Hayashi and van der Kamp (2000) had a median *p* coefficient of 3.22. Using Fig. 6, this *p* coefficient is equivalent to a B_{WC} of 0.61, which is almost double the median beaver pond B_{WC} equivalent of 0.32. The most likely explanation for this is the ontogeny of beaver ponds compared to other open water wetland types. Beaver ponds occur via inundation of an existing channel and adjacent riparian area surface, whereas prairie potholes are bowl shaped geomorphic depressions created by the deposition of glacial till (Richardson et al., 1994). These different origins are reflected in the shape of the bathymetric curves, and they also explain the strong statistical relationships between surface water storage capacity and the dimensions of the dam and pond. The stream channel in Fig. 3, for example, is represented on the far right side of the bathymetric curve. Beaver ponds built on deeper and narrower stream channels tend to have lower *p* coefficients than ponds built on wider, less constrained channels. This happens because there is a rapid expansion of surface area inundated as the dam exceeds the height and width of the stream channel; a phenomenon that is well described by the 'power' relationships between D_{len}, h_{max}, A_{max} and V_{max}. Pond 12 is a good example of this; the *p* coefficient was highest (2.58) and a distant outlier compared to the other ponds. The uniqueness of this site is that the beaver built a small dam (0.3 m) with excavated peat and impounded groundwater seepage rather than damming channel flows. Despite the fact that the dam is relatively small, it has a large B_{WC} (0.55) relative to the other ponds because the dam is entirely dedicated to impounding a mostly flat land surface. In contrast, Pond 6, which was also built in a peatland, has a much lower B_{WC} (0.26) because most of the dam height (2 m) is dedicated to impounding water in an incised stream channel. An advantage of using the B_{WC} metric over pond volumes is that it allows for a comparison of surface water storage capability in a way that is independent of pond size and shape.

4.3 Tools for surface water storage estimation in beaver ponds

There are a variety of ways our results can be used to estimate surface water storage in beaver ponds under different data availability scenarios. In situations where only aerial or remotely sensed imagery is available (i.e. world-wide), dam length and pond area can be approximated and used in the generalized power regression relationships presented in Fig. 3. This is a quick and easy way to incorporate beaver pond surface water storage capacity into land-use planning decisions and watershed-scale hydrological models. However, this approach is

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not suitable for detailed study in individual beaver ponds as it does not account for pond morphometry (Huang et al., 2011; Wiens, 2001). Including dam height should improve estimates. Measuring dam height in the field is quick and straight forward, but it can also be reasonably approximated with remotely sensed imagery alone using spectral-depth correlation methods (e.g. Passalacqua et al., 2015). If dam heights are available, we recommend using our median *p* coefficient (0.91) for beaver ponds in the equation presented by Brooks and Hayashi (2002):

$$V_{\max} = \frac{A_{\max} \times h_{\max}}{1 + {}^{2}/_{p}}. \quad (12)$$

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This equation is a modified form of Eq. (2) used to estimate surface water storage capacity. It is easily incorporated into spatially distributed hydrological models. Fang et al. (2010) had success in using this approach, albeit for prairie potholes, in their Cold Regions Hydrological Model.

With a moderate amount of data, the Simplified V-A-h method offers an alternative that produces surface water storage estimates with minimal error. The advantage of this method over the others is that it is robust, it is customized to each pond's basin morphometry, and it calculates a coefficient of scale (i.e. *s* coefficient) for use in estimating surface water storage across the range of pond stages, unlike the generalized power regression models and Eq. (12), which are limited to estimates of $V_{\max}$. Combined with a few field visits and something as simple as automated water level observations, the Simplified V-A-h method can be a powerful tool. But, it also has practical application in relatively data rich environments. For example, many LiDAR datasets are collected when beaver ponds are not fully drained. If the beaver pond is not entirely full, the measurements for A_2 and h_2 can be measured within the vertical distance between the crest of the dam and the surface of the water, thus allowing an appropriate *p* coefficient to be derived. Furthermore, the Simplified V-A-h method is increasingly practical with the advent of new technologies. For example, Structure from Motion software facilitates the creation of high resolution DEMs from ordinary photographs (Javernick et al., 2014). Theoretically, with both of these tools, one field visit to collect a few pictures and depths measurements should be all that is needed to make reliable estimates of wetland surface water storage.

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4.4 Implications of study results

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The results of our study provide some simple tools that enable surface water storage in beaver ponds to be estimated without the need for topographic surveys. This allows environmental managers to better assess the risks and benefits associated with beaver ponds that appear on landscapes, and allows the easy inclusion of the surface water storage component of beaver ponds into hydrological models at various scales. This study also demonstrates that beaver pond morphometry is different than other types of wetlands, which requires consideration. For example, based on this analysis we might expect beaver ponds to reach their capacity faster during rainfall events, while impounding larger surface areas than depressional wetlands. Although we show that some beaver ponds store less surface water than other wetland types, their relevance to local and regional water balances should not be underestimated. Beaver population recovery, post fur trade, has led to the creation of between 9,494–42,236 km^2 of new beaver ponds globally (Whitfield et al. 2014). Using Whitfield et al.'s (2014) estimates and our median p coefficient (0.91) and median dam height (0.83 m) in Eq. (12), we crudely estimate that between 2.5 and 11 km^3 of water are stored in beaver ponds.

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5 Conclusions

The primary goal of this study was to test the utility of readily applicable tools for estimating surface water storage in beaver ponds. We examined whether the Simplified V-A-h method was appropriate for this purpose and described beaver pond morphology to explore its relationship to surface water storage capacity. A number of valuable insights were revealed. The Simplified V-A-h method proved to be a simple and effective tool as it was able to estimate beaver pond surface water storage with an average volume error of 5%. The median basin coefficient for beaver ponds was 0.91, suggesting that they tend to have a convex basin morphometry, and that they typically store less water than other wetlands studied in the same way. Pond capacity was strongly correlated to the dimensions of the dam and surface area of the pond, further cementing the idea that beaver ponds exhibit characteristic traits in pond morphometry that make reliable estimates of surface water storage possible without the need for topographic surveys. Future research efforts should be directed at applying these simple methods more remotely, and incorporating them into both broader beaver-related planning tools and catchment-scale hydrological models.

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TABLES

Table 1 Site locations, characteristics and details of topographic pond surveys. "n" is the number of ponds studied at each site

Comment [DK1]: Corrected as per reviewer comments

Site	Latitude and Longitude (°,’)	n	Soil Substrate Type	Terrain	Survey method	DEM resolution (m)
Kananaskis Provincial Park, AB, Canada	51° 3.553’ N, 114° 52.009’ W	10	Organic	Mountainous	rtkGPS	1
Escondido, Tierra del Fuego, Argentina	54° 36.908’ S, 67° 44.540’ W	3	Organic	Mountainous	rtkGPS	1
Logan River Watershed, UT, USA	41° 50.327’ N, 111° 33.668’ W	14	Mineral	Mountainous	Total Station	0.1
	41° 49.568’ N, 111° 34.516’ W	2	Mineral	Mountainous	Total Station	0.1
	41° 48.868’ N, 111°35.553’ W	5	Mineral	Mountainous	Total Station	0.1
Voyageurs National Park, MN, USA	48˚ 32.773’ N 93˚ 4.328’ W	1	Organic	Lowland	LIDAR	1
	48˚ 27.975’ N 92˚ 53.864’ W	3	Mineral	Lowland	LIDAR	1
	48˚ 30.405’ N 92˚ 40.331’ W	1	Mineral	Lowland	LIDAR	1
	48˚ 31.262’ N 92˚ 52.794’ W	1	Mineral	Lowland	LIDAR	1

Table 2 Pond morphometric characteristics, including the shape index (S_I), bathymetric integral (B_I), bathymetric water capacity (B_{WC}), length of the dam (D_{len}), and maximum depth (h_{max}), area (A_{max}), and volume (V_{max}) of the ponds.

Location	Pond #	S_I	B_I	B_{WC}	p	s (m^2)	D_{len} (m)	h_{max} (m)	A_{max} (m^2)	V_{max} (m^3)
Kananaskis	1	2.05	0.75	0.25	0.69	889	164	1.50	2974	1135
	2	2.37	0.77	0.23	0.61	356	152	1.75	2006	867
	3	2.57	0.69	0.31	0.97	959	127	0.85	686	186
	4	1.79	0.77	0.23	0.61	123	27	1.50	446	163
	5	3.71	0.77	0.23	0.62	705	226	1.95	5496	2503
	6	3.47	0.74	0.26	0.67	1845	199	2.00	16357	9001
	7	1.76	0.76	0.24	0.56	1334	308	1.85	12912	5734
	8	2.55	0.75	0.25	0.63	701	159	1.80	3787	1757
	9	1.71	0.68	0.32	0.92	290	39	1.25	448	184
	10	1.51	0.66	0.34	1.05	247	30	1.10	297	113
Escondido	11	2.32	0.59	0.41	1.16	5352	162	0.55	1528	325
	12	1.72	0.45	0.55	2.58	2181	59	0.30	748	130
	13	1.99	0.54	0.46	1.61	3223	124	0.55	1342	344
Logan	14	2.19	0.66	0.34	1.06	438	7	0.30	54	6
	15	2.03	0.72	0.29	0.83	464	3	0.25	15	1
	16	1.89	0.56	0.44	1.51	87	4	0.60	41	11
	17	2.63	0.75	0.25	0.67	112	17	0.75	52	10
	18	2.14	0.70	0.30	0.91	91	19	0.80	63	15
	19	2.17	0.67	0.33	0.97	138	10	0.65	53	11
	20	1.95	0.67	0.33	0.94	352	16	0.45	50	8
	21	2.47	0.64	0.36	1.11	179	11	0.50	45	8
	22	2.70	0.67	0.33	0.98	96	7	0.45	17	2
	23	1.90	0.64	0.36	1.20	56	10	0.55	23	5
	24	1.97	0.69	0.31	0.80	430	27	0.60	82	15
	25	2.37	0.59	0.41	1.36	154	6	0.30	22	3
	26	2.83	0.75	0.25	0.68	124	21	0.90	90	19
	27	2.79	0.73	0.27	0.75	114	5	0.60	36	6
	28	1.73	0.67	0.33	0.96	278	13	1.00	265	87
	29	4.32	0.81	0.19	0.45	975	87	1.00	980	189
	30	3.43	0.71	0.29	0.79	620	21	0.85	374	94
	31	5.31	0.69	0.31	0.90	551	43	0.85	432	115
	32	2.61	0.69	0.31	0.83	1647	46	0.50	210	32
	33	2.59	0.66	0.34	0.99	409	51	1.65	1123	621
	34	2.40	0.58	0.42	1.41	470	12	0.45	130	26
Voyageurs	35	4.65	0.71	0.29	0.83	3683	144	1.10	4725	1517
	36	3.82	0.70	0.31	0.94	4539	161	1.10	5928	1999
	37	3.54	0.72	0.28	0.78	36105	57	0.40	2297	264
	38	2.52	0.66	0.34	0.88	11836	58	1.10	12985	4740
	39	2.72	0.61	0.39	1.11	18033	97	0.90	12482	4350
	40	2.78	0.63	0.37	1.18	4867	41	0.55	1504	316

Table 3 V-A-h model performance comparisons based on the mean (± standard deviation) volume (V_{ERR}) and area (A_{ERR}) error magnitude. "n" is the number of ponds studied at each site.

Comment [DK2]: Added as per reviewer comments

Site	n	*Full*		*Simplified*		*Optimized*	
		V_{ERR}(%)	A_{ERR} (%)	V_{ERR}(%)	A_{ERR} (%)	V_{ERR}(%)	A_{ERR} (%)
Kananaskis	10	4.3 ± 3.1	3.8 ± 2.1	7.2 ± 6.0	14.6 ± 12.3	2.3 ± 1.6	4.2 ± 2.5
Escondido	3	3.1 ± 1.4	3.8 ± 0.7	4.3 ± 2.5	6.7 ± 3.8	1.6 ± 0.7	4.0 ± 0.9
Logan	21	4.0 ± 2.6	3.6 ± 1.7	4.6 ± 3.5	9.9 ± 8.5	2.0 ± 1.2	3.9 ± 1.9
Voyageurs	6	3.8 ± 1.8	4.1 ± 1.6	3.8 ± 1.8	4.1 ± 1.6	1.9 ± 0.9	4.4 ± 1.7
All Ponds	**40**	**4.0 ± 2.5**	**3.8 ± 1.7**	**5.2 ± 4.1**	**11.0 ± 9.4**	**2.1 ± 1.2**	**4.0 ± 1.9**

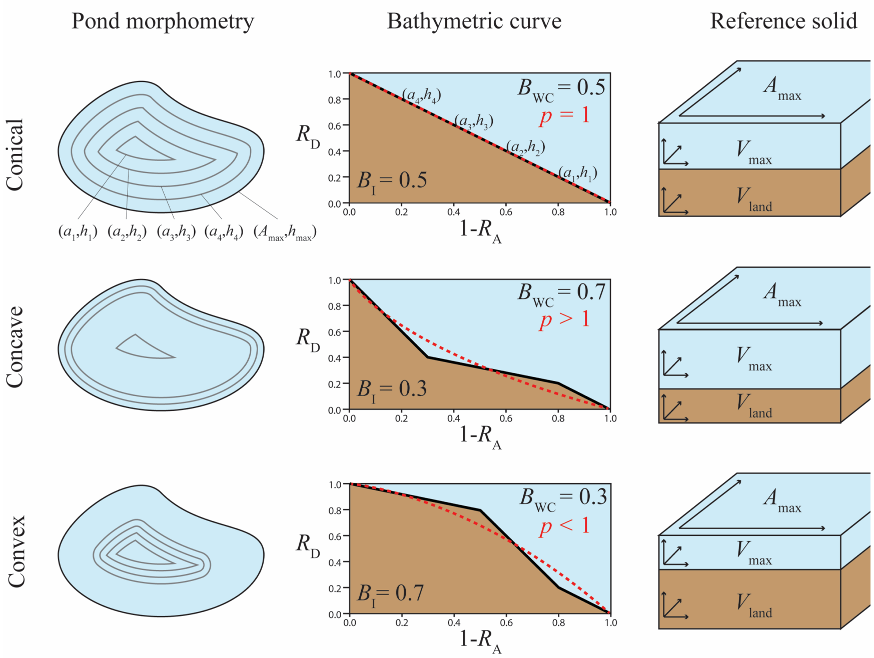

Fig. 1. Perceptual diagram of the relationship between morphometric variables. The area (*a*) at a given stage of the pond (*h*) is a point on the bathymetric curve (thick black line), where R_A is the relative area and R_D is the relative depth. The bathymetric integral (B_I) is the integration of everything below the bathymetric curve and the pond's capacity to store water (B_{WC}) is the integration of everything above the bathymetric curve. The *p* coefficient represents the shape of the bathymetric curve in the power function equation (red-dashed line; Eq. (7)). The reference solid is the box created by multiplying the maximum height of the dam (h_{max}) by the maximum surface area created by the pond (A_{max}), and is entirely comprised of land (V_{land}) and/or water (V_{max}) proportional to B_I and B_{WC}.

Comment [DK3]: New figure for visual aid of morphometric variables in methods

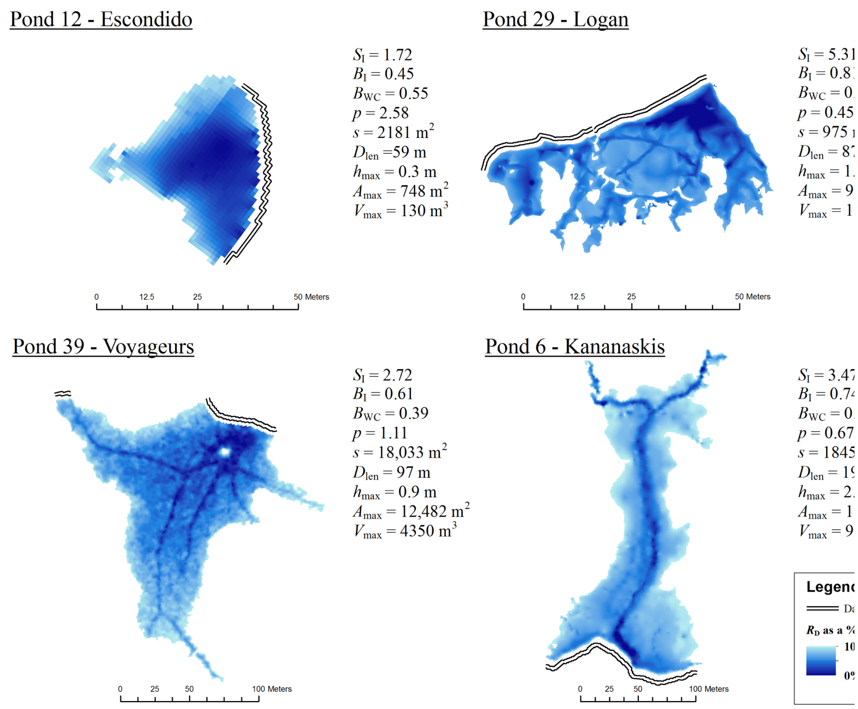

Fig. 2. Four examples of detrended beaver pond DEMs used for this study, one from each study area. (S_I = shape index, B_I = Bathymetric integral, B_{WC} = Bathymetric water capacity, p = Basin coefficient, s = Scaling coefficient, D_{len} = Dam length, h_{max} = Maximum height of the dam, A_{max} = Maximum surface area of the pond, and V_{max} = Maximum volume of the pond)

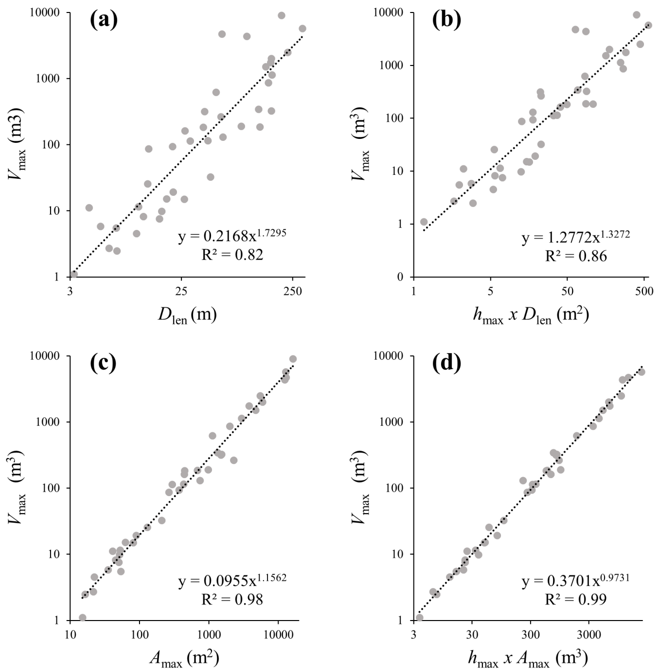

Fig. 3. Power regression relationships between the maximum volume of the beaver ponds (V_{max}) and: (a) the length of the beaver dams (D_{len}); (b) the product of the maximum depth of the ponds (h_{max}) and the length of the beaver dams; (c) the

maximum surface area (A_{max}) of the ponds; and, (d) the product of the maximum surface area and maximum depth of the pond.

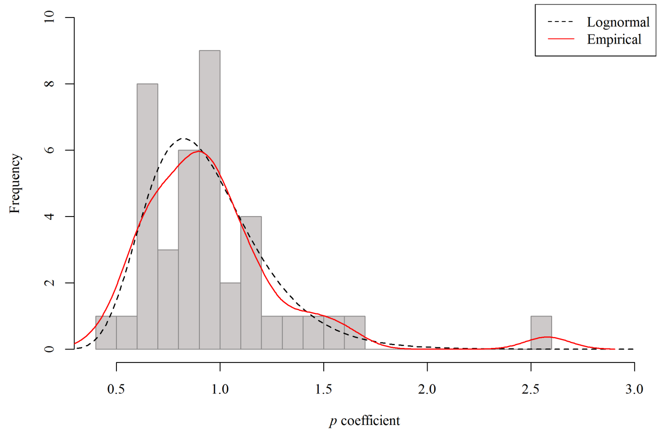

Fig. 4. Distribution of *p* coefficients for all beaver ponds sampled (n=40).

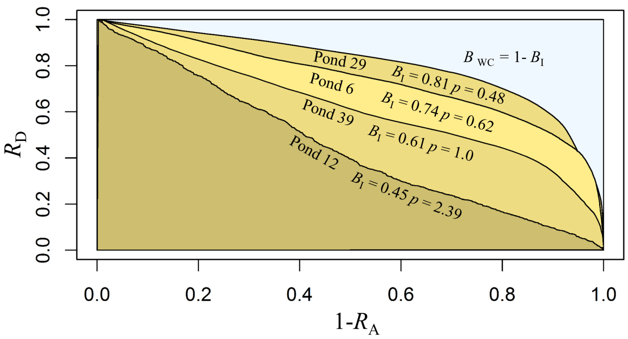

Fig. 5. Bathymetric curves for ponds shown in Figure 1.

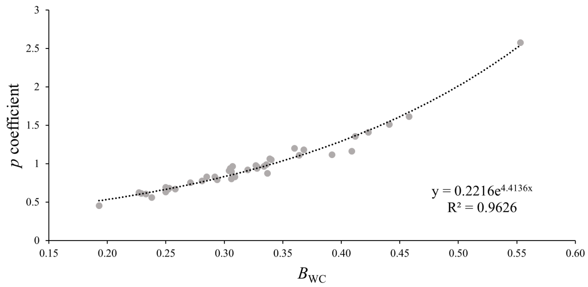

Fig. 6. Relationship between the p coefficient and B_{WC}.

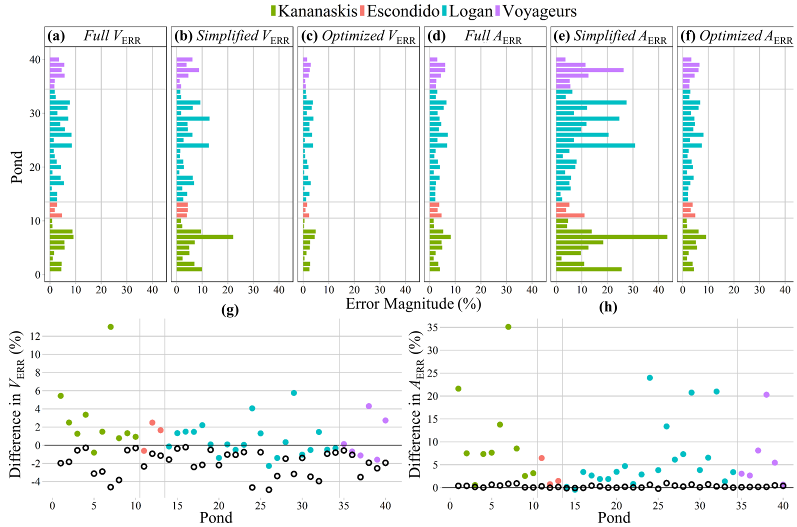

Fig. 7. Volume (V_{ERR}) and area error (A_{ERR}) from each beaver pond using the three different approaches (a-f). Plots on the bottom show the difference in volume (g) and area (h) error of the *Simplified* (solid circles) and *Optimized* (open circles) models relative to the *Full* model (the *Full* model is represented by the solid black line at zero on the y-axis). Bars and solid circles are colour coded by location as per the legend at the top of the figure.

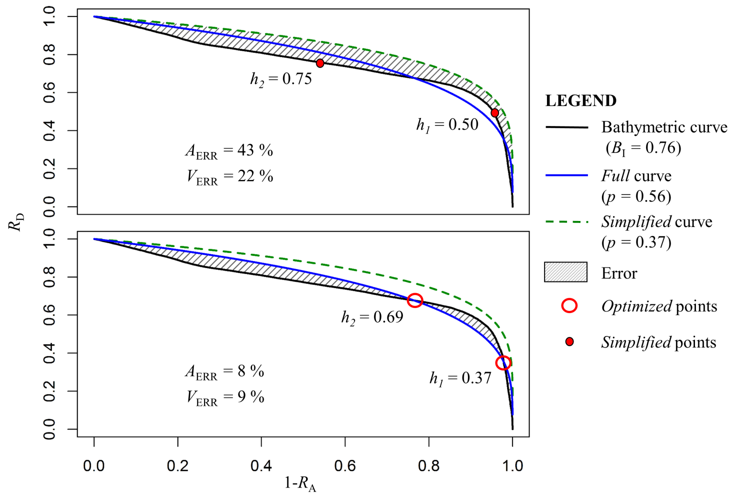

Fig. 8. Comparison of the hypsometric curve for Pond 7 with the *Full* and *Simplified* curve. The top shows the error associated with the *Simplified* curve that was calculated using Simplified h_1 and h_2 and the bottom shows the error associated with the *Full* curve and the optimum location for h_1 and h_2.

5

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A common goal of river restoration is to re-establish the natural flow regime and geomorphic function of the system (Poff et al., 1997; Wohl et al., 2015). Within this context, some beneficial aspects of beaver ponds include an expansion of the riparian zone (Marshall et al., 2013; Pollock et al., 2007), increased aggradation and lateral stability of eroded streams (Burchsted and Daniels, 2014; Pollock et al., 2014), and an alteration of the timing and peak delivery of water and sediments (Woo and Waddington 1990; Levine and Meyer 2014). Assessment of these benefits would be better contextualized if coupled with the surface water volumes stored in beaver ponds. This would also facilitate a proper risk assessment of using beaver as a river restoration tool, since it is not uncommon for the presence of beaver to be

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(S_I), which is essentially the ratio of the pond perimeter to the circumference of a circle with the same area. It is defined as (Hutchinson, 1957):

Key characteristics of any beaver pond are the dimensions of its dam and the corresponding shape of the pond area inundated. The maximum dam height (h_{max}) was defined as the difference in elevation (m) between the dam crest elevation and the lowest point in the pond. The length (m) of the dam (D_{len}) is measured along its crest. The shape of the beaver pond surface was described using a dimensionless Shape Index (S_I), which is essentially the ratio of the pond perimeter to the circumference of a circle with the same area. It is defined as (Hutchinson, 1957):

$$S_I = \frac{P}{2\sqrt{\pi A_{max}}}, \quad (5)$$

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:

$$R_D = (1 - R_A)\,. \quad (8)$$

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The beaver ponds in Kananaskis are in the Sibbald research wetland; a rich, flow-through fen formed in an unconstrained basin of the southern Canadian Rocky Mountains (Westbrook and Bedard-Haughn, 2016). The site is dominated by shrubs (e.g. *Salix* spp. and *Betula* spp.), sedges (*Carex* spp.), brown mosses (e.g. *Drepanocladus* spp. and *Scorpidium* spp.), and clusters of stunted black spruce (*Picea mariana*), all of which form the peat that reaches depths of up to 6.5 m. Air photo analysis confirms that beaver returned to the basin in the 1950s after their likely extirpation from the region as a result of the fur trade (Morrison et al., 2015). Half of the 10 beaver ponds were surveyed with a Leica total station in 2009 and the other half were surveyed with a Leica GS15 real time kinetic GPS (rtkGPS) in summer 2015.

Escondido is a southern beech (*Nothofagus pumilio*) dominated forest situated between the well-studied Escondido raised bog and Lago Fagnano on *Isla Grande*, Tierra del Fuego, Argentina. The site is a functioning peatland, dominated by *Sphagnum magellinicum*, in a 150-300 m wide valley that lacks a defined stream channel and instead supports diffuse surface flowpaths (Westbrook et al. submitted). Beaver are an invasive species in South America, and were purposely introduced to the region in 1946 (Lizarralde et al., 2004). Beaver have since excavated and built low dams composed of peat to form many ponds throughout the length of the valley, hydrologically connecting the Escondido bog to Lake Fagnano. Bathymetry was acquired in three abandoned and drained ponds in the valley during a field visit in February 2013. Surveys of each pond were conducted using a Leica GS15 rtkGPS.

The beaver ponds in the Logan River Watershed are from three different tributaries to the Logan River, namely Spawn Creek, Temple Fork, and Right Hand Fork (Lokteff et al., 2011, 2013; Lokteff, 2014). These sites all occupy partly-confined valley settings with valley fills and a stepped floodplain morphology reflecting centuries of beaver damming. Valley fills are comprised largely of beaver pond deposits and beaver meadows. A few of the ponds are isolated, but most are part of larger dam complexes consisting of between three and six beaver dams each. Vegetation in the riparian zones and meadows are typically dominated by various assemblages of shrubs (e.g. *Salix* spp.) and herbaceous species (e.g. *Carex* spp. and *Poa* spp.) (Hough-Snee et al., 2013). The beaver ponds were primarily surveyed with a Leica TS15 total station in 2010. Bathymetry was entirely acquired by a Leica TS15 total station and in some localities a Leica 1200 rtkGPS (Lokteff et al., 2011).

Voyageurs National Park lies 35 km east of International Falls, Minnesota, on the U.S.-Canada border. Its Precambrian bedrock is part of the Laurentian Shield, with many outcrops of biotite schist and granite. The soils of beaver ponds are derived from loamy glacial till and clayey glacio-lacustrine sediments that overlie the bedrock, as well as from post-glacial peat deposits (Johnston, 2001). The primary upland vegetation is aspen–birch/boreal conifer forest (*Populus tremuloides, Betula papyrifera, Abies balsamea*). Grasses and sedges (*Calamagrostis canadensis, Carex* spp.) grow in the meadows that form in drained beaver ponds. Beavers occupied this landscape as of the earliest aerial photos (1927), and the beaver population density peaked at 1.4 colonies/km^2 in the 1980s (Johnston and Windels, 2015). Pond DEMs were obtained from light detection and ranging (LiDAR) data flown in May 2011 (MDNR, 2011).

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4.3 Why surface water storage in beaver ponds varies through time

There are a wide variety of reasons that water storage in beaver ponds vary through time. Some are the result of hydrologic and geomorphic processes, whereas others are the direct result of the ecosystem engineering activity of beaver and/or lack thereof. Among the most common factors include: 1) partial dam breaches by floods (Woo and Waddington, 1990); 2) aggradation of sediments from upstream sources (Butler and Malanson, 1995); 3) inactive/passive lowering of water surface by dam degradation (Woo and Waddington, 1990); 4) active manipulation of dam height and extent by beaver; and, 5) the excavation of extensive channel networks by beaver (Hood and Larson, 2015). Channel excavation, for example, increases the cumulative area at lower depths of the bathymetric curve, and so increases both the *p* coefficient and B_{WC}. This equates to an increase in surface water storage and we would expect mature ponds (Woo and Waddington, 1990), where beaver have been active for many years, to have higher p coefficients overall than ponds that were recently built in the same environment. However, the extent by which excavation impacts surface water storage may be partially offset by sediment aggradation, which averages 0.26–2.54 cm/yr in riverine environments (Butler and Malanson 1995). Ponds can thus accumulate large volumes of sediment relative to their surface area (Naiman et al., 1986), which would, over time, increase B_I and decrease the amount of surface water storage in the pond. Studies that explore the influence of beaver pond age on surface water storage are needed.

An interesting consideration is the significance of this variation through time. For any single beaver dam, the results could be dramatically different, but if the population of beaver ponds sampled reflects ponds at various stages of development (Woo & Waddington 1990), the temporal variation is presumably captured in the spatial variation by sampling over a larger area. For individual beaver ponds, it would be worth testing whether or not the simple methods presented herein still work reasonably well if dam lengths and dam heights are measured or specified to reflect actual stage instead of just the crest stage. It may be that the variation in water surface storage could be reasonably estimated by considering different crest elevations. Such an analysis may allow exploration of the role of active beaver maintenance on water storage and we would postulate that active maintenance increases such storage. We have observed, in many systems, that a very high quantity of beaver dams are actually ‘maintained’ by very few beaver that move around quite regularly. Such mobile beaver should spend less time maintaining water surface elevations than those that stay locally and just maintain one complex and lodge. The water storage benefit of beaver ponds in areas that are very under-seeded with beaver and below population capacity (even if at dam capacity), is that the benefit is minimized where beaver populations are not close to carrying capacity.