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ORIGINAL PAPER

Simplified Volume-Area-Depth Method for Estimating Water Storage of Prairie Potholes

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Abstract The Prairie Pothole Region (PPR) of North American contains millions of wetlands that provide important hydrological and ecological functions. Modeling these processes relies on relationships that relate wetland water depth to volume. Methods suitable for investigating water storage in regularly shaped wetlands have already been developed when two coefficients are known. We tested the robustness of the full and simplified volume (V) area (A) depth (h) methods to accurately estimate volume for the range of wetland shapes occurring across the PPR. The full *V-A-h* method was found to accurately estimate volume (errors ≤5%) across wetlands of various shapes, and is therefore suitable for calculating water storage in the variety of wetland shapes found in the PPR. Analysis of the simplified *V-A-h* method showed that <10% volume error can be achieved with concurrent measures of surface area and depth in the spring when water levels are ~70% of $h_{\max}$, and also in late summer prior to water levels dropping below 10 cm. Applying the simplified *V-A-h* method according to the guidelines presented herein will allow for accurate, time effective water storage estimates for multiple wetlands, thereby allowing hydrological and ecological functions to be modeled.

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Introduction

The Prairie Pothole Region (PPR) of North America is a vast area (~780,000 km^2) that contains between 5 and 60 wetlands per km^2 (National Wetlands Working Group 1988). These wetlands, termed potholes, support more than half of North American waterfowl (Ogaard et al 1981; Johnson et al. 2005), act as a sink for agricultural derived nutrients (van der Valk 1989; Whigham and Jordan 2003), and store surface water that can attenuate flood flows (Hubbard and Linder 1986; Gleason and Tangen 2008). Prairie pothole wetlands are shallow topographic depressions created by the last glaciation. They are characterized by mineralized soils, emergent vegetation, and standing or slow moving water caused by an absence of permanent inlets or outlets (Brinson 1993; Warner and Rubec 1997). Since potholes generally lack permanent surface hydrologic connections to other water bodies and lose water primarily through evapotranspiration (Brinson 1993), they have dramatic fluctuations in water levels that exert a strong control on hydrological and ecological functions. For example, wetland water levels exhibit long term wet-dry cycles due to climatic variability (van der Valk 2005). This greatly affects the composition of wetland vegetation due to tolerance of waterlogging (Kantrud et al. 1989; van der Valk 2005) or salinity (Stewart and Kantrud 1972). Waterfowl presence is also closely linked to varying water levels through the need for nesting cover (Murkin et al. 2000). Since many wetland functions have water-level dependent requirements (Leibowitz 2003), modeling these processes rely on accurately characterizing the depth-volume relationship (Woo and Rowsell 1993; Poiani et al. 1996; Waiser 2006; Voldseth et al. 2007).

Depth-volume relationships usually take the form of regression equations that are derived from detailed topographic surveys of the study wetlands. While this approach is useful for the individual wetland, the equations are time consuming to produce and lack transferability to other locations. Hayashi and van der Kamp (2000) investigated the area (*A*) depth (*h*), and volume (*V*) depth (*h*) relationships of wetlands in three PPR sites to develop two simple equations that can estimate wetland volume and area based on the depression profile (*p* coefficient) and size of the wetland (*s* coefficient). This method provides accurate volume and area estimations when detailed survey data are available, and has since been used to model depth-volume relationships for individual or small groups of wetlands in select areas of the PPR (Hayashi et al. 2003; Carroll et al. 2005; Hill et al. 2006; Waiser 2006). The *V-A-h* method has proven to estimate volume well for small, natural wetlands in smooth depressions; however there are many wetlands in the PPR that differ greatly in surface area and depression morphology. Thus, there is a need to ensure that the *V-A-h* equations can estimate volume well for the range of morphologies observed in the PPR.

When a detailed topographic survey is not available, the *V-A-h* coefficients can be derived through a simplified, less data intensive method (Hayashi and van der Kamp 2000). The method requires concurrent measures of surface area and depth at only two points in time. Since less topographic information is required, area and depth measurements for tens of wetlands could be easily collected. Although the simplified *V-A-h* method holds much potential for estimating storage at the scale of multiple wetlands, Hayashi and van der Kamp did not include procedures or guidelines for the method or a detailed test of the method. Thus, the lack of information on the simplified *V-A-h* method may have limited its use by other researchers. The objectives of this paper are thus to: 1) determine how variable wetland surface shape influence estimates of water storage volumes through the Hayashi-van der Kamp *V-A-h* method, and 2) develop guidelines for applying the simplified Hayashi-van der Kamp *V-A-h* method to wetlands throughout the PPR.

Methods

Study Sites

Data from two sites were used in this study. The main site is the Smith Creek Research Basin (SCRB) which is located in east-central Saskatchewan (101° 47′ W and 51° 00′ N), approximately 400 km south-east of Saskatoon (Fig. 1). This site is part of a larger study aimed at developing a hydrological model to better predict runoff in prairie watersheds. SCRB is ~445 km^2 and is relatively flat (slopes are 1–5%). Agriculture is the dominant land-use in the basin, occupying ~48% of the watershed. In recent years, agricultural drainage has de-watered many of the wetlands; analysis of air photos showed wetlands accounted for ~17% of the land-cover in the basin in 1958 and only ~8% in 2007. Most of the wetlands can be classified as depressional because they have no apparent natural outlet and lose water primarily to evapotranspiration (Brinson 1993). The climate in nearby Yorkton (70 km west of SCRB) is characterized by average July and January temperatures of 18°C and −19°C, respectively. Between 1971 and 2000, the annual average precipitation was ~450 mm with 75% falling as rain. Evapotranspiration in the prairie region is 3–5 mm day^{-1} (Rosenberry and Winter 1997), which is approximately double the rate of summer precipitation. Streamflow is generated primarily by spring snowmelt, with peak streamflow occurring in late April and subsiding to substantially lower or intermittent flows throughout the summer.

The second study site is St. Denis National Wildlife Area (SDNWA), which is located 40 km east of Saskatoon (106° 6′ W and 52° 2′ N) (Fig. 1). This site was included because it represents a different type of prairie topography with fewer impacts from agriculture, has many wetlands with an extensive long term water level record, and was one of the sites used by Hayashi and van der Kamp (2000). SDNWA has a rolling knob and kettle moraine (slopes are 10–15%) topography (Miller et al. 1985). SDNWA is 4 km^2 and includes ~100 wetlands that are part of a 24 km^2 watershed. The watershed is internally drained except in extremely wet years (van der Kamp and Hayashi 2009). The region is typical of the prairie landscape with glacial deposits consisting mostly of clay with low permeability (Hayashi et al. 1998). The land use of SDNWA was dominated by cultivation until the mid-1980's when approximately one-third of it was converted to natural grassland (van der Kamp et al. 1999). The average temperature range at nearby Saskatoon is the same as Yorkton; however annual average precipitation is 350 mm with 76% occurring as rain.

Study Design

We selected 14 wetlands within SCRB and 13 wetlands in SDNWA for a detailed topographic survey (Electronic Appendix 1). In SCRB, an electronic total station was used to collect coordinates with ~1 m spacing in the wetland and upland. An attempt was made to collect enough points in the upland so the point at which water spills from the wetland was included. However, for some wetlands this was not possible because vegetation restricted the total station line of sight. On average, 150 elevation points were

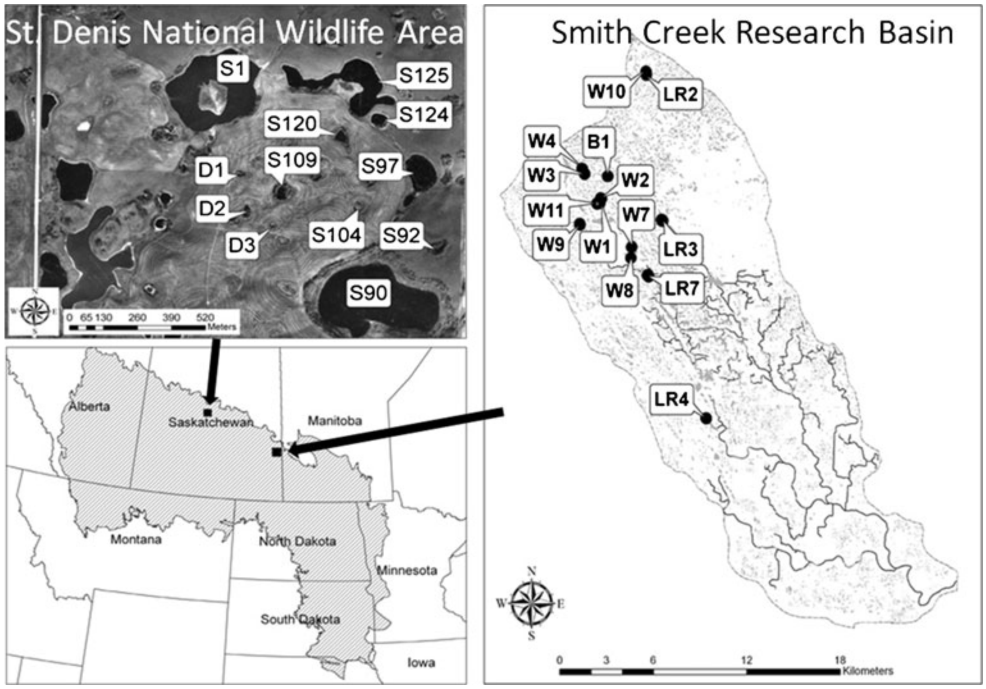

Fig. 1 Location of the Smith Creek Research Basin (SCRB) and the St. Denis National Wildlife Area (SDNWA) within the Prairie Pothole Region (PPR). Shown are the wetland ID's. Refer to Electronic Appendix 1 for the characteristics of each wetland. SCRB (*right*) illustrates the watershed boundary, stream network as of 2007, and distribution of wetlands within the basin as of 2000. SDNWA (*top left*) is depicted by an aerial photo (1997)

gathered for each wetland. In SDNWA, eight of the 13 wetlands were surveyed with a total station (Hayashi and van der Kamp 2000), while topographic data for the others (S1, S90, S97, S124, and S125) were collected with a hand-held GPS and a sounding rod to measure water depth. Survey data were used to generate a three-dimensional, 1-m resolution digital elevation model (DEM) for each wetland in Surfer, version 8 (Golden Software, Golden, CO, USA). Data were interpolated using ordinary kriging (Cressie 1990) with a linear variogram and no drift to create a 1-m resolution DEM (Zimmerman et al. 1999; Hayashi and van der Kamp 2000).

The pond perimeter of each study wetland was digitized from air photos in order to characterize the surface area shape. Multiple air photos were consulted (years: 2000 for SCRB; 1968, 1970, 1980, 1985, 1997 for SDNWA) so the perimeter would be digitized from the year that best represented the pond shape when the topographic survey data were collected. In addition to the surveyed wetlands, 100 wetlands in SCRB were randomly selected for digitizing so the range of pothole surface area shape in the watershed was fully represented. A power regression line was fitted to these data to obtain a frequency curve that characterized the shape distribution of wetland shapes in SCRB. Inconsistent perimeter measurements were avoided by using a constant 2 m step length between nodes. This prevented the scaling effect of fractal objects, as described by Mandelbrot (1967), where perimeter measurements increase when a smaller step length is used. Perimeter and area were calculated by using the geometry function in ArcGIS, version 9.2 (ESRI, Redlands, CA, USA). Measurements for each wetland were used to calculate the shape index, SI (McGarigal and Marks 1995):

$$SI = \frac{P}{2\sqrt{\pi A}} \tag{1}$$

where SI is defined as the ratio of the wetland perimeter (P) to the circumference of a circle with the same area (A) as the wetland of interest (Forman and Godron 1986). Wetlands that are similar in shape to a circle have an index value close to one and are considered regularly shaped. While wetlands that are more irregular will have a higher SI value. Unlike previous indices that describe the inverse, non-linear ratio of perimeter to area (Millar 1971; Brooks and Hayashi 2002), the square root of area is used for the SI to make it dimensionless and ensures that values are comparable for small and large wetlands.

Calculation of Wetland Area and Volume

Hayashi and van der Kamp (2000) presented two simple equations for estimating wetland pond area and volume:

$$A = s\left(\frac{h}{h_o}\right)^{2/p} \tag{2}$$

$$V = \frac{s}{(1+2/p)} \times \frac{h^{1+(2/p)}}{{h_o}^{2/p}} \tag{3}$$

where s represents the size of the wetland, p represents the depression profile, h is the depth of water (m) above the lowest point of the wetland ($h_{\min}$), and h_{o} is the unit depth

(h_o=1 m). The s coefficient is further defined as the actual area of the wetland when water depth is equal to the unit depth (h=h_0). For example, if the unit of depth is meters then the s coefficient represents the area (m^2) of the pond when h=1 m. The p coefficient is further defined as a power coefficient that represents the wetland as a symmetrical, concave depression. A small p value (e.g., p=2) "corresponds to a paraboloid basin that has smooth slopes extending from the center to the edge, and a large value corresponds to a basin that has a flat bottom" (Hayashi and van der Kamp 2000).

The *A-h* relationship for each wetland needed to be characterized in order to determine the s and p coefficients for the full Hayashi-van der Kamp *V-A-h* method. This was accomplished by calculating the water surface area of each wetland from the topographic survey derived DEM at 0.05 m depth increments, starting at 0.1 m above the lowest point in the wetland (h_{min}), to the depth where the depression capacity is exceeded (h_{max}) (Fig. 2). For each wetland the surface area was plotted against water depth on a log-log graph. A power regression line was fitted to these data to obtain the s and p coefficients required for the full *V-A-h* method. Since a power regression line can be generalized as y = ax^b, the s coefficient is equal to "a" and the p coefficient is equal to 2 divided by "b". The s and p coefficients for each wetland were used in Eqs. 2 and 3 to estimate area and volume at 0.05 m depth increments from h=0.1 m to h_{max}.

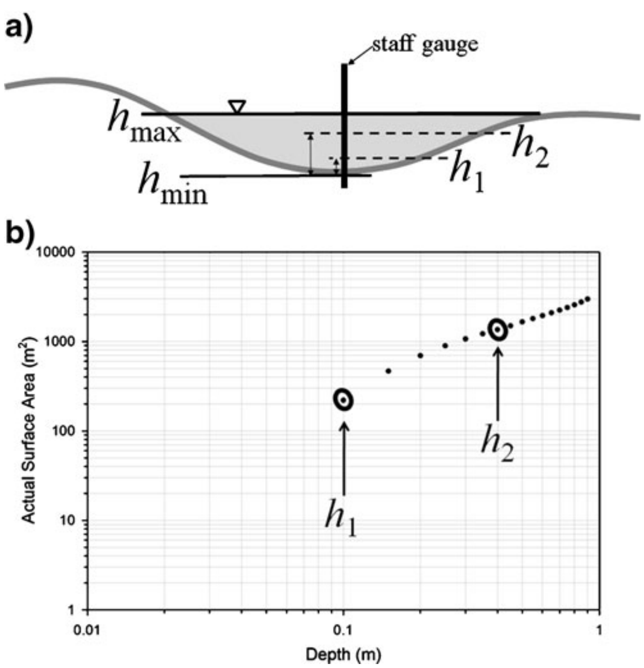

Fig. 2 **a** Profile of a hypothetical wetland illustrating: h_{min}, the lowest point in the wetland; h_{max}, the maximum depth of water before the depression capacity is exceeded; h_1 and h_2, arbitrary depths at which area are measured for the simplified *V-A-h* method. Exact values of h_1 and h_2 are user defined, provided that $h_1 < h_2$. **b** Characterizing the *A-h* relationship through a log-log graph where h_1 and h_2 correspond to particular area measurements

The actual volume and surface area at 0.05 m depth increments were calculated for each wetland DEM using the grid volume function in Surfer. Actual volumes and areas were compared to estimated ones using the root-mean-squared (RMS) error (Hayashi and van der Kamp 2000):

$$RMS_{err} = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(DEM - EST)^2} \tag{4}$$

where m is the number of data points. DEM represents either the actual volume or area calculated from the topographic survey derived DEM, while EST represents either the volume or area estimated by the *V-A-h* method. The magnitude of error, in percent, was calculated by dividing V_{err} and A_{err} by the actual volume and area at a certain evaluation depth (referred to as V_{eval} and A_{eval}). Hayashi and van der Kamp (2000) recognized that the magnitude of error increases as the evaluation depth is set closer to h_{min}. As a result, V_{eval} and A_{eval} should not be set to h_{max} or a depth near h_{min} (Fig. 2) because the magnitude of error would not adequately represent the accuracy of the volume or area estimation. We decided to use the depth interval closest to 80% of h_{max} for V_{eval} and A_{eval} (Electronic Appendix 1) because this depth is usually reached each spring when the maximum volume would be estimated. These values were consistent with the V_{eval} and A_{eval} depths of between ~80% and 100% of h_{max} that Hayashi and van der Kamp (2000) used.

Hayashi and van der Kamp (2000) suggested a simplified *V-A-h* method that could be used to derive the s and p coefficients when detailed survey data are not available. The simplified *V-A-h* method only requires concurrent measurements of surface area and depth at two points in time. We modified Eq. 2 so that the p and s coefficients could be directly calculated using:

$$p = \left(\frac{\log(h_1/h_2)}{\log(A_1/A_2)}\right) \tag{5}$$

$$s = A_1\left(\frac{h_1}{h_o}\right)^{-2/p} \tag{6}$$

where A_1 and A_2 are the surface area measurements at the depths h_1 and h_2 (Fig. 2). Since Hayashi and van der Kamp did not specify when area and depth should be measured, we examined two scenarios for collecting the measurements required for the simplified *V-A-h* method. The first scenario mimicked a hydrologically dry year when a limited range of area and depth measurements would be available. Scenario

1 is referred to as the 'simplified *V-A-h* method for drought conditions'. The second scenario involved a wider range of area and depth which spans the average wetland storage capacity. Scenario 2 is referred to as the 'simplified *V-A-h* method for average or wet conditions'. When applying either of the simplified methods we used area and depth measurements from the topographic survey derived DEM. This allowed for a range of scenarios to be tested without having to collect additional measurements.

The 1968–2007 water level records for SDNWA were analyzed to identify the depths for which surface area should be measured for both simplified *V-A-h* scenarios. The average maximum water depth for wetlands in Hayashi and van der Kamp's (2000) study (S92, S109, S120, S125s, S104; Electronic Appendix 1) is ~0.58 m, which is approximately 50% of h_{max} for these wetlands. Furthermore, there were many years where the average water depth was below 0.2 m, i.e., ~25% of h_{max}. For example, wetlands S109 and S120 illustrate these water level fluctuations because they did not exceed a 0.2 m maximum depth more than ~25% of the time (Fig. 3). From this analysis, and from water levels published for other PPR wetlands (Winter and Rosenberry 1998; Fang and Pomeroy 2008), it is apparent that many periods of drought have impacted wetland water levels across the prairies. Thus, there are many years when low water levels are a barrier to collecting surface area and depth measurements. Therefore, for scenario 1 the *s* and *p* coefficients were derived from area and depth measurements that would reflect drought-like conditions. When applying the simplified *V-A-h* method for drought conditions, we used surface area measurements at h=0.1 and 25% of h_{max}. For some shallow wetlands 25% of h_{max} was not greater than 0.1 m, therefore a depth of 0.15 m was used. For each wetland, the area and depth measurements were inserted into Eqs. 5 and 6 to generate the *s* and *p* coefficients. Although *s* and *p* values were derived from drought-like conditions, these values were used to estimate area (Eq. 2) and volume (Eq. 3) at 0.05 m depth increments from h=0.1 m to the maximum depth of each wetland (h_{max}). Equation 4 was used to calculate the goodness of fit between the actual and estimated area and volume.

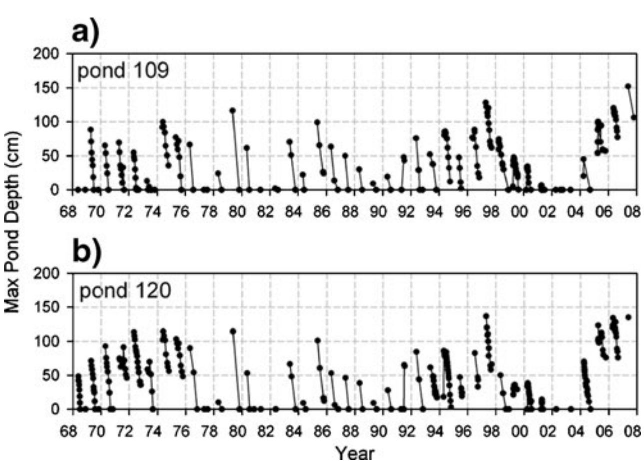

Fig. 3 Water depths from 1968 to 2007 for **a**) pond S109 and **b**) pond S120 in St. Denis National Wildlife Area. Data collected by Environment Canada

When applying the simplified *V-A-h* method for average or wet conditions, we used area and depth measurements that spanned the wetland storage capacity to calculate *s* and *p*. Given the seasonal fluctuation of wetland water levels (Fig. 3) due to snowmelt and evapotranspiration, measurements that span the storage capacity of a wetland would include a depth measurement near h_{max} in spring and a minimum measurement once water levels have declined. For semi-permanent wetlands, the minimum water depth is likely to occur in late summer or fall, prior to the wetland freezing. With temporary or seasonal wetlands, the minimum water depth is likely to occur in mid-summer before the pond completely dries out. The surface area measurements we used for the simplified *V-A-h* method for average or wet conditions were those when h=0.1 m and h=~50% of h_{max}. The maximum value was chosen because the water level analysis identified an average depth of ~0.58 m, which represents approximately 50% of h_{max} over the 39 year record at SDNWA. These values of area and depth were used to derive the unique *s* and *p* coefficients for each wetland and were used to estimate area (Eq. 2) and volume (Eq. 3) at 0.05 m depth increments from h=0.1 m to h_{max}. Equation 4 was used to test the goodness of fit.

Since both simplified *V-A-h* scenarios rely on surface area and depth measurements to derive the *s* and *p* coefficients, we assessed the sensitivity of volume error to the potential variability when measuring area and depth. When analyzing the area measurements we simulated error in delineating the wetted pond perimeter of a wetland to assess the effect on volume estimation. We selected pond S120 from SDNWA for this analysis because the ponds' wetted perimeter is difficult to define from air photos (Fig. 4) and thus, would be subject to error depending on the method used. Pond S120 represents a typical PPR wetland with a h_{max} of 1.1 m and an A_{max} of 3,150 m^2. Area at two depths, which are commonly reached each year (A_1 at h=0.1 m, A_2 at h=0.45 m), were used for the simplified *V-A-h* method. The actual wetted perimeter at these depths were selected from the topographic survey derived DEM and exported to ArcGIS where area was calculated using the geometry function. The buffer tool was used in ArcGIS to create a new perimeter at 0.5 m increments from −3.0 m to +5.0 m from the actual perimeter (Fig. 4). Three types of perimeter analysis were conducted: 1) the perimeters for A_1 and A_2 were varied the same distance, ranging from −3 m to +5 m, 2) the actual perimeter for A_1 was held constant

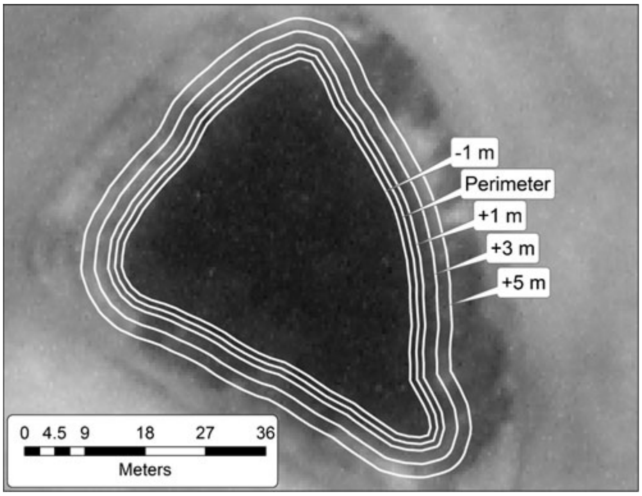

Fig. 4 Air photo (1980) of pond S120 illustrating the effect of wetted perimeter delineation error on area calculation (limited perimeters shown). Analysis varied the perimeters for h=0.1 m and h=0.45 m from -3 m to +5 m of the actual perimeter by 0.5 m increments

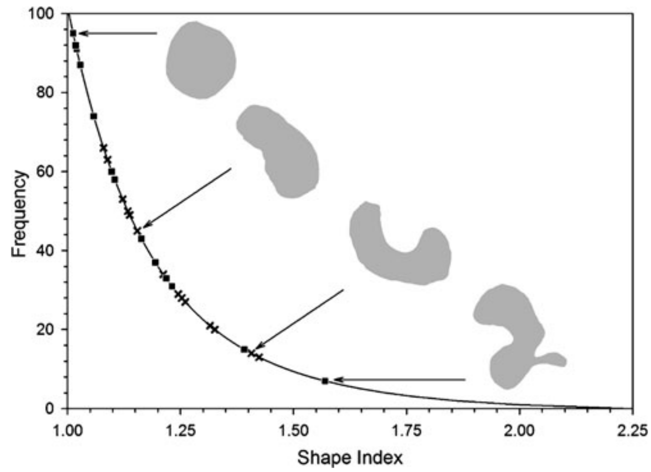

Fig. 5 Frequency distribution of 100 wetland surface shapes in the Smith Creek Research Basin as illustrated by a power regression line. Shown are the wetlands studied in Smith Creek watershed (×) and St. Denis NWA (■). Shaded illustrations are surface shapes for wetlands (*left to right*) D2, W10, W3, S125. See Eq. 1 for computation of the shape index

while A_2 was varied from −3 m to +5 m, and 3) the perimeter for A_1 was varied from −3 m to +5 m while the actual perimeter at A_2 was held constant. The s and p coefficients were derived for each perimeter analysis using Eqs. 5 and 6. These coefficients were used to estimate volume at 0.05 m depth increments from h=0.1 m to h_{max} using Eq. 3. The root-mean-square error was calculated (Eq. 4) to test the goodness of fit.

When analyzing the depth measurements we varied the depth that A_2 is measured to assess the effect on volume estimation for the simplified *V-A-h* method. A_2 was investigated because this area could potentially be measured at any depth from h_1 up to h_{max} (Fig. 2). Therefore, three wetlands (D2, W7, and W2; Electronic Appendix 1) with varying morphologies had A_2 varied from h=0.15 m to h_{max} by 0.05 m depth increments. Each combination of A_1 and A_2 were used to calculate the s and p coefficients (Eqs. 5 and 6). These coefficients were used to calculate volume (Eq. 3) at 0.05 m depth increments from h=0.1 m to h_{max}. Equation 4 was used to test the goodness of fit.

Results

The 100 randomly selected wetlands in Smith Creek ranged in surface area shape from 1.0 to 2.2 (Fig. 5, power regression line), with 95% of these wetlands having an SI < 1.6. The 14 wetlands in SCRB and the 13 in SDNWA selected for detailed study covered most of this range. The full *V-A-h* method estimated volume and area very well for all wetland shapes (Electronic Appendix 1); RMS errors were ≤5% for volume and area (Fig. 6). There was no relationship between volume percent error and SI (r^2= 0.005, P=0.725) and a weak relationship between area percent error and SI (r^2=0.198, P=0.021).

We examined the simplified *V-A-h* method to test its robustness for two scenarios: 1) a hydrologically dry year, and 2) an average or wet year. For scenario 1, 13 of the 27 wetlands had volume errors >10% (Fig. 7a), which is the error Hayashi and van der Kamp (2000) advocate as acceptable. In some instances (i.e., B1, W2, and W7), volume errors were >40% and upward to ~290%. Nineteen of the 27 wetlands had an area error of ≥10% (Fig. 7a). Wetlands B1, W2, and W7 had area errors >70% and upward to ~550%. Scenario 2 produced volume errors that

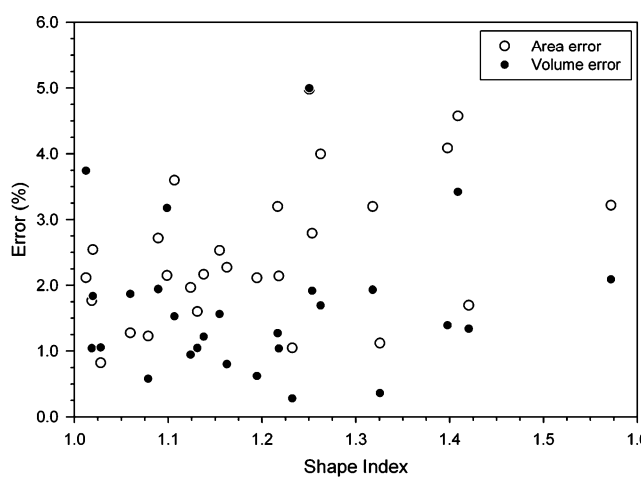

Fig. 6 Errors in volume and area for 27 wetlands using the full Hayashi-van der Kamp *V-A-h* method. Regression analysis of volume error against shape index: r^2=0.005, P=0.725; and area error against shape index: r^2=0.198, P=0.021

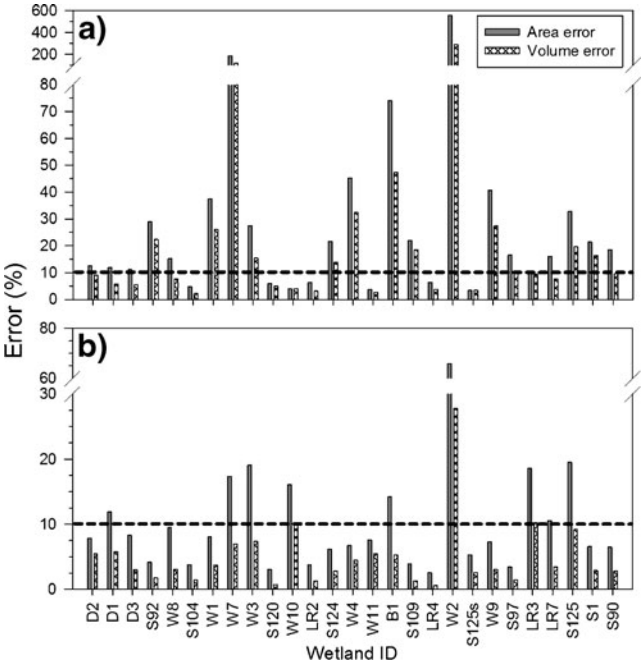

Fig. 7 Error from using **a**) scenario 1: the simplified *V-A-h* method for drought conditions, and **b**) scenario 2: the simplified *V-A-h* method for average or wet conditions. Wetlands are organized from left to right according to increasing $A_{\max}$. *Dash line* represents the 10% error limit. Upper limit for error (%) axis is different for scenario 1 (**a**) and scenario 2 (**b**)

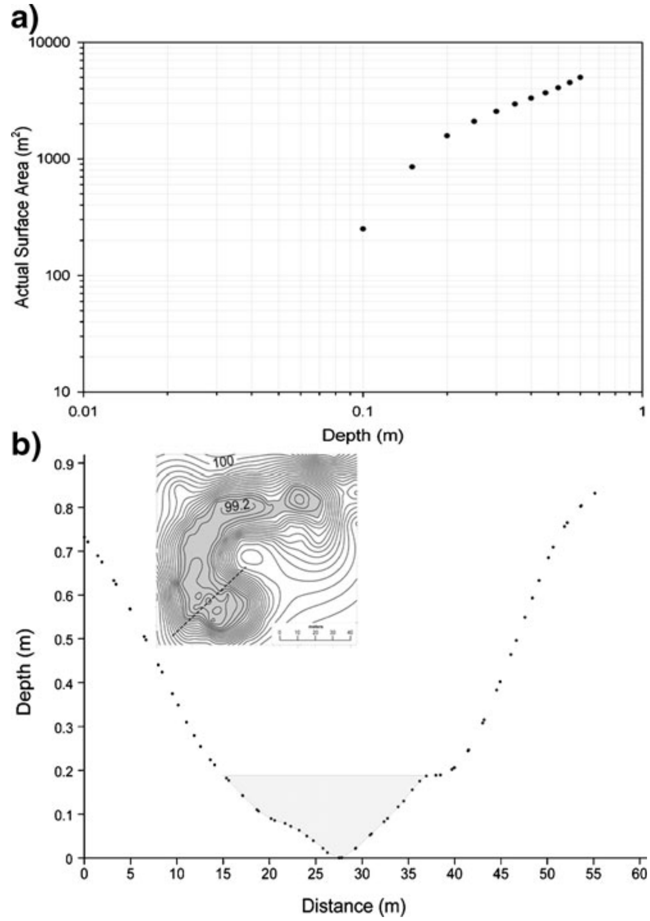

Fig. 8 **a** *A-h* relationship determined from the topographic survey derived DEM for wetland W2 in the Smith Creek Research Basin. Full *V-A-h* method provides an s=8,876 and p=1.82 in this example (Electronic Appendix 1). **b** Cross-section through the deepest point of wetland W2 to illustrate the basin morphology. Inset: plan view of wetland W2 with 5 cm elevation contours and water level at the time of surveying shown in *gray shading*

were <10.5% for all wetland but W2, and area errors of <10% for nine of the 27 wetlands (Fig. 7b).

To illustrate how different s and p coefficients can be derived from scenarios 1 and 2, we present the *A-h* relationship for wetland W2 (Fig. 8a). From h=0.1 to 0.2 m, the rate of surface area increase is relatively rapid because of the depression morphology (Fig. 8b). However, when the wetland is filled above the 0.2 m depth, the rate of surface area increase slows. Thus, this wetland would have very different s and p coefficients depending of the *A-h* combination used.

Our sensitivity analysis of wetted perimeter delineation showed a linear increase in volume error with distance from the actual wetted perimeter (Fig. 9). Volume error increased most rapidly when the wetted perimeter for A_1 (at h=0.1 m) was held constant and A_2 (at h=0.45 m) was varied. In this situation, errors exceeded 10% when the wetted perimeter was located > +1.5 m or < −2.0 m away from the actual perimeter.

Our depth analysis showed that volume errors were highest when A_2 was measured at a shallow depth (i.e., smaller percent of $h_{\max}$), while the minimum volume error occurred when A_2 was between ~60–80% of $h_{\max}$ (Fig. 10). The range in volume error was smallest for the wetland with the most regular morphology (D2, range of 5%), while the most irregular wetland had the largest range (W2, 280%) in volume error (Fig. 10).

Discussion

The full *V-A-h* method performed well when detailed survey data comprised of many area and depth measurements were used. Volume estimates were not affected by pothole shape and area errors were within an acceptable range. Hayashi and van der Kamp (2000) found that survey-derived coefficients allowed for accurate estimations because depression characteristics were considered. The good performance of the full *V-A-h* method in our study and in other studies (e.g., Brooks and Hayashi 2002; Carroll et al. 2005; Hill et al. 2006; Waiser 2006) confirms that the *V-A-h* coefficients can approximate volume by considering wetlands to have a circular surface area shape and parabolic depression. This is

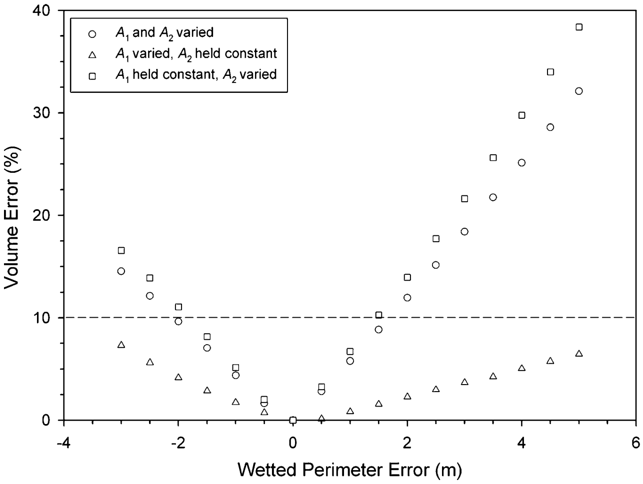

Fig. 9 Volume error for pond S120 when the wetted perimeter is delineated incorrectly. Surface area and depth measurements corresponding to A_1 at h=0.1 m and A_2 at h=0.45 m were used for the analysis. Perimeters were varied from −3.0 m to +5.0 m of the actual perimeter

true even when wetland morphology deviates from this approximation. For example, wetland S125 is the most irregularly shaped wetland in this study (see Fig. 5 for shaded illustration) and is composed of two primary depressions (S125n and S125s) that connect when the water level exceeds ~1.3 m. Despite the irregular surface shape, the full *V-A-h* method still estimated volume within ~2% of actual. Our results verify that the *V-A-h* equations are robust and can be applied to the range of wetland surface shapes present in the PPR.

Our analysis of the simplified *V-A-h* method revealed that volume estimations were not consistently accurate when s and p were derived from drought conditions. Volume errors for several wetlands (B1, W1, W2, W4, W7, W9, and S92) were quite large (i.e., V_{err} >20%). This is because the s and p coefficients are sensitive to the wetlands' basin morphology. This is illustrated by wetland W2 which shows an inconsistent rate of surface area increase relative to water depth across its storage capacity. Thus, the coefficients derived during drought conditions may not estimate volume of the entire depression well because an *A-h* range near h_{min} does not provide enough data to accurately derive a p coefficient that characterizes the shape of the entire depression. Our analysis of volume error sensitivity to depth measurements also illustrates that volume errors are highest when A_1 and A_2 are measured in drought-like conditions. Hayashi and van der Kamp (2000) developed their *V-A-h* equations for wetlands in smoothly shaped depressions. If the wetland is shallow and smoothly sloped (e.g., D2, Fig. 10) then the coefficients derived during a drought period may represent the possible *A-h* range and estimate volume well. However, many prairie potholes differ significantly in their basin morphology, ranging from cone shaped to flat, pan-like depressions. If the wetland basin is discontinuous (i.e., has different rates of surface area increase with depth) or is irregular (e.g., W2; Fig. 10) then the s and p coefficients derived during drought conditions should be limited to estimating volume for a range of area and depth that represents the conditions in which s and p were derived.

It is clear from the above discussion that the timing of area and depth measurements for deriving s and p is important for estimating volume and area correctly. We found that deriving s and p from the simplified *V-A-h* method for average or wet conditions provided reasonably good estimates of volume and area. This is because the coefficients were derived from an *A-h* range that spanned the storage capacity of the wetland. Basin coefficients (p) derived from this method were a better approximation of the actual depression shape and thus provided a better estimation of storage. When using the average or wet conditions for a discontinuous wetland depression (W2) we found that volume errors were much lower than for drought-like conditions. Although the volume error was >10% for scenario 2, our analysis illustrated that lowering the depth for which A_2 is measured (Fig. 10) would produce errors within the acceptable limit. Therefore, when applying the simplified *V-A-h* method the depth at which A_2 is measured should be less than h_{max}, ideally between 60–80% of h_{max}. When collecting two concurrent sets of area and depth measurements it would be ideal to have a sufficient difference in depth between them so the range in storage capacity is captured. Practical guidelines for most wetlands (seasonal and semi-permanent) would involve a measurement of area and depth in spring when water levels are near 70% of h_{max}, and a measurement of area and depth in late-summer before water levels are lower than 0.1 m. For deeper wetlands, it is necessary to capture the water level fluctuations over multiple years when the water levels exhibit a declining or increasing trend.

In addition to considering when area and depth should be measured, accurate measurements of the pond wetted perimeter and water depth are also essential for estimating volume correctly with the simplified *V-A-h* method. Our analysis revealed that area measurements corresponding to the deepest water level are the most important perimeter to delineate correctly when using the simplified *V-A-h* method for average or wet conditions. Inaccurate measurements of A_2 caused the s coefficient, which represents the wetland surface area when h=1 m, to have a maximum of 95% variation as compared to 40% variation when A_2 was accurate. As a result, the estimated size of the wetland did not represent the actual wetland well and the volume estimation errors were greater. From Fig. 4 it is clear how the wetted perimeter could be delineated differently.

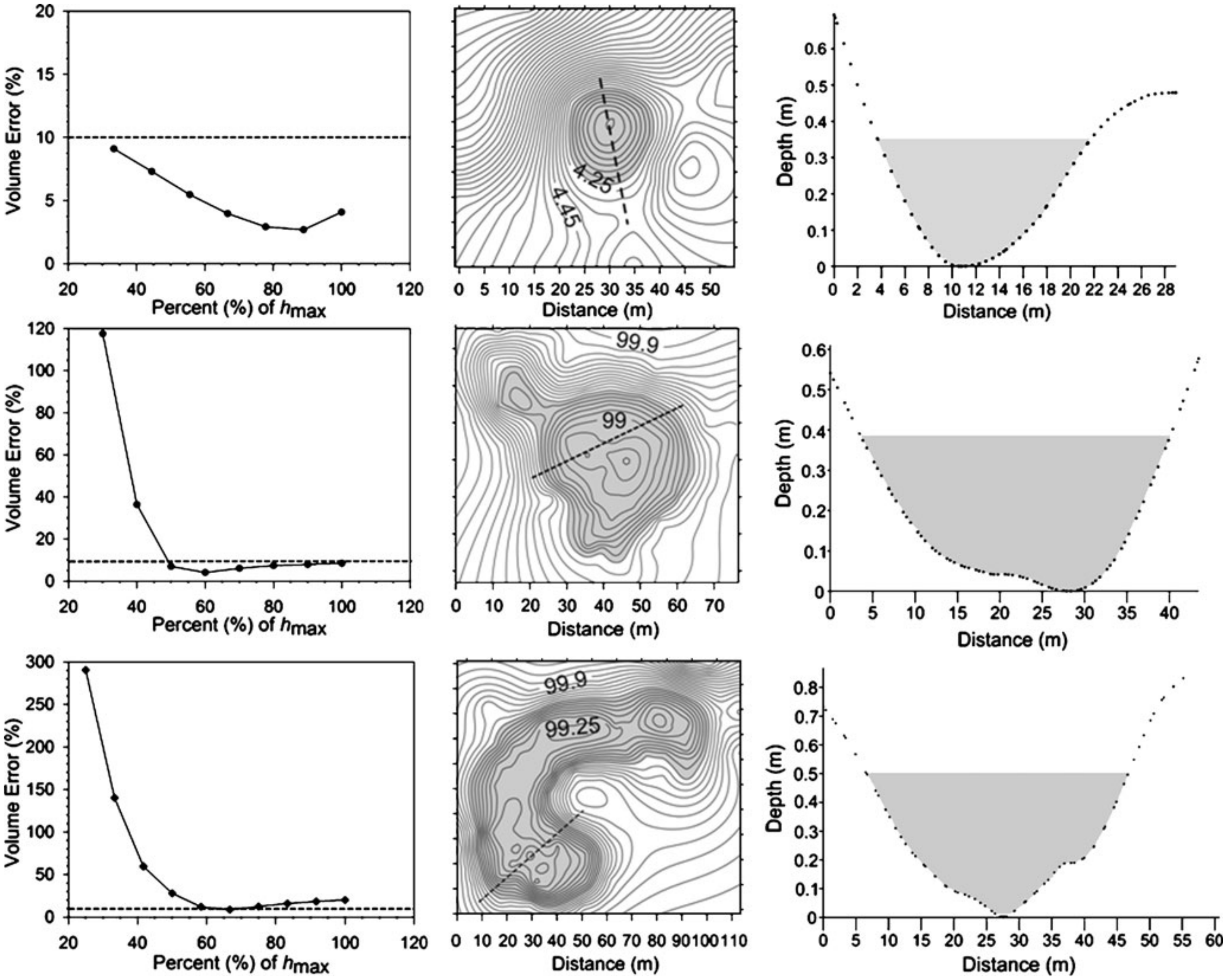

Fig. 10 Results from analyzing the sensitivity of volume error to depth measurements. Graphs shown (*left to right*) are: the relationship between volume error and the depth at which A_2 is measured for the simplified *V-A-h* method; plan view of the wetland with 5 cm contours, illustrating the water level at ~80 of h_{max} shown in *gray* and the location of the cross section shown by the *dashed line*; and a cross section through the wetland illustrating the basin morphology. Wetlands used for this analysis were: a) D2, regularly shaped morphology; b) W7, semi-irregular morphology; and c) W2, irregular morphology

Therefore, data sources that allow the wetted perimeter to be resolved with greater detail are preferable (e.g., measuring wheel, GPS, low altitude air photos). Furthermore, since wetland ponds are fractal objects it is important to use a constant scale of measurement (i.e., step length) when collecting perimeter measurements. For example, using a constant distance of two meters between high-resolution GPS coordinates will ensure that perimeter measurements for different wetlands can be compared. Volume errors can be reduced if accurate methods are used such that the perimeter of the pond is delineated within ±1.5 m of actual. For larger ponds the sensitivity to perimeter delineation error will be less. Accurate measurements of water depth are also important when using the simplified *V-A-h* method. Conly et al. (2004) reported that point measurements of water depth can be accurate to within 0.02 m. However, this accuracy can be compromised by soft wetland substrate, inconsistent measurement techniques, and by not measuring depth at the same location (Conly et al. 2004).

An easy to implement, accurate method such as the one presented here should be useful to other researchers interested in modeling water dependent hydrological and ecological wetland functions. Since this method fits separate *V-A-h* relationships to individual wetlands, this approach is most appropriate for parameterizing water storage in small numbers of wetlands. To overcome this limitation, we will describe an automated method for parameterizing the coefficients from remote sensing products in a future paper so that the simplified *V-A-h* method can be used to predict wetland storage at larger spatial scales (i.e., entire watersheds).

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