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Remote sensing of volumetric storage changes in lakes

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ABSTRACT: Three-dimensional remote sensing promises a giant leap forward for surface-water hydrology in much the same way that radar altimetry transformed physical oceanography. However, the complex geometries of small terrestrial water bodies introduce difficulties, particularly with respect to trade-offs between changing water depth and inundation area. We use *in situ* measurements of water-surface stage ($\Delta H/\mathrm{d}t$) and remotely-sensed area (A) to compute time varying storage changes (ΔS) in nine lakes of the Peace-Athabasca Delta, Canada. Despite their identical geomorphic setting, regression slopes between ΔH and A vary significantly between lakes, primarily from a predictable 'area-effect' but also small bathymetric variations between basins. On average, lateral contraction/expansion (versus stage adjustment) contributes as little as 7% (versus 93%) to as much as 76% (versus 24%) of overall storage change ΔS. We conclude that both surface-area and $\Delta H/\mathrm{d}t$, rather than just either alone, must be measured to confidently estimate ΔS from space. Copyright © 2009 John Wiley & Sons, Ltd.

KEYWORDS: remote sensing; volumetric storage; lakes; storage change; SWOT

Introduction

Satellite remote sensing of surface water fluxes and storages in rivers, lakes, reservoirs and wetlands is an immature but rapidly growing field. Except for a handful of early Landsat studies (reviewed by Smith, 1997), nearly all research began in the 1990s and has experienced sustained momentum only in recent years (see new reviews by Alsdorf *et al*., 2007a; Smith and Pavelsky, 2008). One common approach is to measure spatial variations in inundation area to estimate changing stage or discharge (e.g. Smith *et al*., 1995; Smith *et al*., 1996; Hamilton *et al*., 1996; Pietroniro *et al*., 1999; Al-Khudhairy *et al*., 2002; Xu *et al*., 2004; Zhang *et al*., 2004; Brakenridge *et al*., 2005; Brakenridge *et al*., 2007; Temimi *et al*., 2005; Ashmore and Sauks, 2006; Smith and Pavelsky, 2008). Another is to obtain point measurements of water surface elevation using radar altimetry (e.g. Koblinsky *et al*., 1993; Birkett *et al*., 2002; Coe and Birkett, 2004; Kouraev *et al*., 2004; Calmant and Seyler, 2006; Leon *et al*. 2006). Still other approaches include combining satellite observations with topographic data (Brakenridge *et al*., 1998; Bjerklie *et al*., 2005; Matgen *et al*., 2007; Schumann *et al*., 2008a, 2008b), hydraulic models (Horritt and Bates, 2002; Bates *et al*., 2006; Andreadis *et al*., 2007; Roux *et al*., 2008; Durand *et al*., 2008), or informed estimates of channel properties (Lefavour and Alsdorf, 2005).

Perhaps the most exciting advance is the direct mapping of both water surface height and area changes with radar, allowing direct, three-dimensional observation of storage changes (Alsdorf, 2003; Alsdorf *et al*., 2000; Alsdorf *et al*., 2001; Alsdorf *et al*., 2007b; Frappart *et al*., 2005; Frappart *et al*., 2006; Frappart *et al*., 2008). While it may seem obvious that both height and area should be measured, the remote-sensing community has traditionally been divided on which is most important because, except for repeat-pass interferometry, currently existing technologies can retrieve only one or the other. However, a new satellite mission with a fully three-dimensional imaging capability has now been proposed (the SWOT, Surface Water Ocean Topography wide-swath altimeter, see Alsdorf *et al*., 2007a and http://bprc.osu.edu/water). Because SWOT would map water surface elevation changes continuously over space and time, it represents a giant leap forward for terrestrial hydrology in much the way that radar altimetry has transformed our understanding of physical oceanography. Before radar altimeters began providing three-dimensional surface height fields of the world's oceans, oceanographers used point-based tide gauges. SWOT portends an analogous revolution for today's terrestrial hydrologists, currently using a scattering of river gauges and lake level stations.

For the purpose of monitoring water storage variations in lakes, reservoirs or wetlands, the key measurements retrieved by SWOT would be repeat estimates of water surface area (A) and stage change ($\Delta H/\mathrm{d}t$) (Alsdorf *et al*., 2007a). These two variables would then be multiplied to estimate storage changes for the water body ($\Delta S/\mathrm{d}t$, in m^3). While seemingly straightforward, the real-world relationship between the two observables A and $\Delta H/\mathrm{d}t$ remains largely unexplored. Here, we present a first empirical study of this relationship,

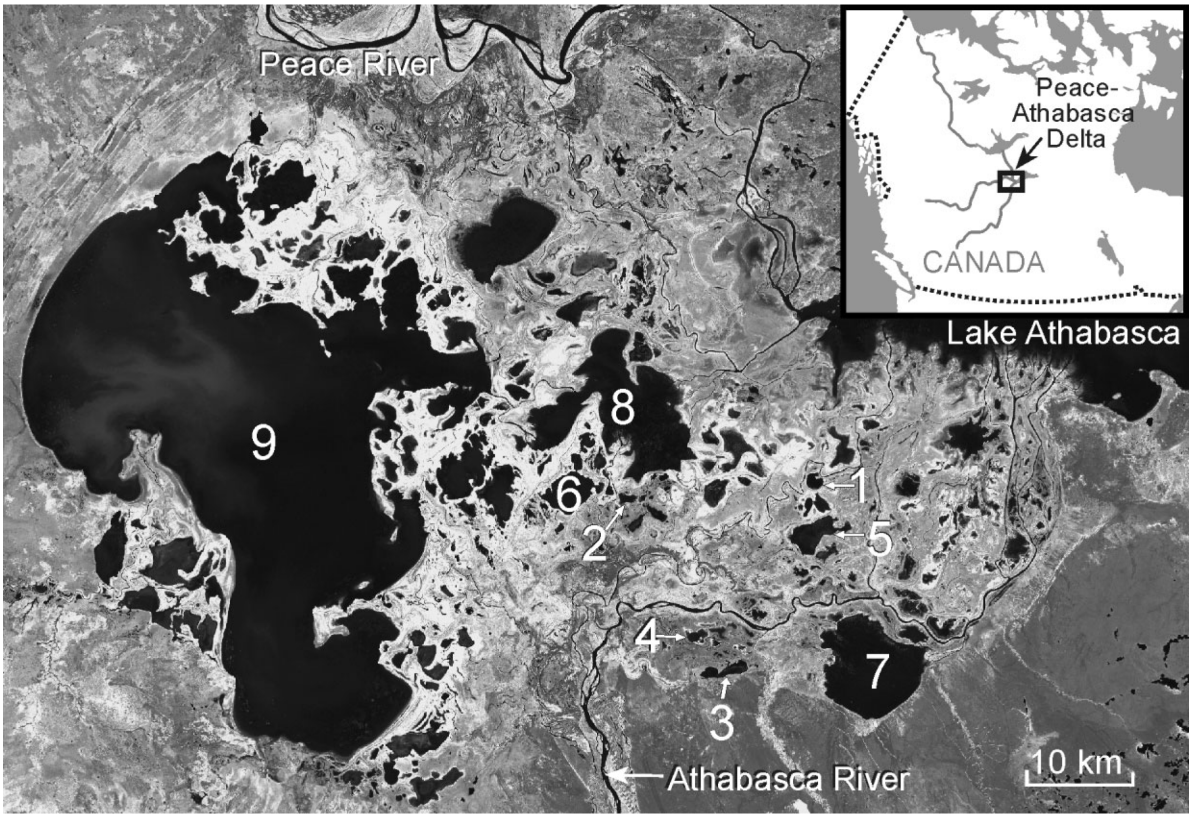

Figure 1. *In situ* measurements of stage ($\Delta H/\mathrm{d}t$, in centimeters), and remotely-sensed estimates of water surface area (A, in m^2) were collected for these nine study lakes in the Peace-Athabasca Delta (PAD), Canada.

using remotely-sensed and *in situ* measurements to essentially simulate SWOT retrievals for nine low-relief lakes in the boreal Peace-Athabasca Delta (PAD), Canada. Owing to their varying degrees of hydrologic linkage with the nearby Athabasca River (Pavelsky and Smith, 2008), these lakes are sensitive to nearby river discharge variations and thus experience changing water storages throughout the year.

Study Site and Methods

The PAD is formed by the convergence of the Peace and Athabasca Rivers near their confluence with Lake Athabasca in northeastern Alberta, Canada (Figure 1). Lying partially within Canada's Wood Buffalo National Park and covering over 5000 km^2, it ranks among the world's most ecologically significant wetlands and is a UNESCO World Heritage Site and Ramsar Convention Wetland. The PAD is characterized by low relief (<10 m) and high complexity, consisting of hundreds of shallow lakes, wetlands, and distributary channels with varying degrees of hydrologic connectivity. Low-frequency, high-magnitude ice-jam floods in the Peace and Athabasca Rivers are crucial for replenishing 'perched' lakes and wetlands in the PAD. In absence of water recharge, lakes and wetlands gradually infill with *Salix*-dominated vegetation to the detriment of PAD ecosystems (Prowse and Conly, 1998; Toyra and Pietroniro, 2005; Timoney, 2006). For further description of PAD inundation hydrology see previous work by Peters *et al.* (2006) and Pavelsky and Smith (2008).

Time series of lake stage ($\Delta H/\mathrm{d}t$) were collected for nine PAD floodplain lakes during summer 2006 (Lakes 1–9, Figure 1) and six lakes during summer 2007 (Lakes 1–5 and 9). Lakes were selected to capture the full range of lake sizes within the PAD (1·5 km^2 to 1313·2 km^2, Table I). For each site, stage variations were logged every 15 minutes using a submerged Solinst Levelogger® pressure transducer, later corrected for atmospheric pressure variations using Solinst Barologgers®. Precision of the final corrected stage fluctuations is ±1 cm. For all but two locations, stage changes were converted to absolute water surface elevation values using differential global positioning system (GPS) surveys with accuracy of ±1 to 5 cm (referenced to the Canadian Gravimetric Geoid Model 2000, http://www.geod.nrcan.gc.ca/publications/papers/abs26_e.php), enabling absolute referencing of $\Delta H/dt$ data across study years. For Lakes 1 and 5, however, stage data for 2006 and 2007 could not be merged because no benchmarking GPS survey was conducted in 2006. Therefore, for these two sites each year is presented as a separate time series. Bathymetric transects along the long axes of Lakes 3 and 4 were obtained with ~5 cm precision and 50 m posting using a stadia rod.

For all sites, temporal variations in lake inundation area A were obtained using a daily time series of 250 m MODIS near-infrared satellite images (band 2, 841–876 nm, http://redhook.gsfc.nasa.gov/~imswww/pub/imswelcome/). Inundated area for each lake was determined by binary classification using a dynamic threshold (T) defined as:

$$T = W + (L - W)d$$

where W is the average reflectance value of 12 known and consistent water pixels, L is the average reflectance value of 12 known and consistent land pixels, and d is a constant between 0 and 1·0 (0·6 used here) (Pavelsky and Smith, 2008). Cloud presence was detected using a simple threshold (2·5T), and in each image any lake with cloud-covered area greater than 0·0 was removed from consideration. Final time series of lake area contain 29–100 observations for the nine study lakes (Table I).

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Table I. Summary of results

Lake	n	Mean area (km^2)	Regression slope (%/cm)	r^2	$\Delta A/\Delta H$ (km^2/cm)	H_c	A_c
Lake 1 – 2006	57	1·5 ± 0·5	1·39	0·37	0·21	0·52	0·48
Lake 1 – 2007	38	2·8 ± 1·3	1·42	0·71	0·13	0·50	0·50
Lake 2	84	3·4 ± 2·0	0·80	0·55	0·15	0·28	0·72
Lake 3	100	6·7 ± 2·1	0·97	0·48	0·13	0·71	0·29
Lake 4	100	7·1 ± 4·0	0·56	0·67	0·15	0·24	0·76
Lake 5 – 2006	54	15·0 ± 3·3	1·18	0·17	0·83	0·67	0·33
Lake 5 – 2007	29	31·6 ± 15·2	0·87	0·83	0·30	0·65	0·35
Lake 6	52	17·5 ± 1·7	0·80	0·53	1·38	0·73	0·23
Lake 7	51	80·6 ± 3·8	0·15	0·40	1·06	0·91	0·09
Lake 8	49	110·1 ± 7·3	0·44	0·59	4·25	0·86	0·14
Lake 9	46	1313 ± 60·2	0·09	0·32	3·20	0·93	0·07

Note: Number of samples (n), mean lake inundation area and variability (±1σ), regression slopes and r^2 values from Figure 3, and lake-averaged inundation change per centimeter of stage (km^2/cm). The values of H_c and A_c capture the relative importance of each lake's expansion/contraction versus stage adjustments, respectively, in determining total storage change (ΔS). Lakes 1 and 5 could not be benchmarked across years and are separated accordingly.

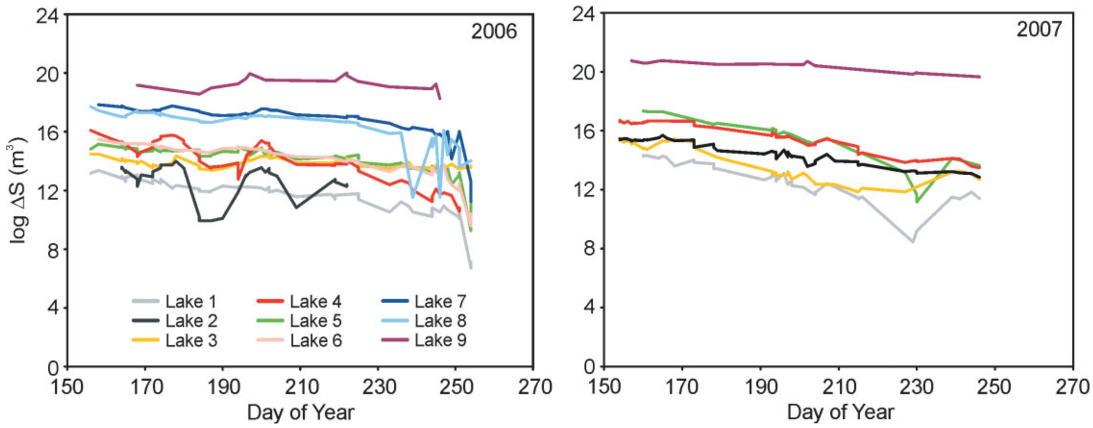

Figure 2. Time-series of volumetric water storage change, ΔS, the product of water-surface area, A, and stage change ($\Delta H/dt$) in our study sites. Lakes 1–9 were monitored in 2006, Lakes 1–5 and 9 were monitored in 2007. Log ΔS is shown owing to the great range in lake size. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Results

The product of our *in situ* measurements of stage changes ($\Delta H/dt$) with corresponding same-day, MODIS-derived inundation areas (A) yields time-series of changing water storage, ΔS (Figure 2). Values are plotted in log-normal space owing to the large range of lake sizes in this study. Storage changes range from 813 to 1 033 532 500 m^3, with largest values found in largest lakes. Note that ΔS represents the storage change (relative to its long-term observed minimum ΔS_{min}), not the total volume of storage within the lake basin.

In both 2006 and 2007, all of the measured lakes display a trend of decreasing water storage throughout the summer (Figure 2). This result is in general agreement with our field observations of maximum PAD inundation immediately after the spring freshet, followed by gradual stage drawdown throughout the summer. Furthermore, oscillating storages in two of the sites (Lakes 2 and 4) reflect their known hydrologic connectivity to the Athabasca River via distributary channels (Wolfe *et al.*, 2007, Pavelsky and Smith, 2008). As such, the remotely-sensed lake storage changes appear to be sensitive indicators of nearby river discharge variations.

A positive relationship is found between remotely-sensed inundation areas (A) and $\Delta H/dt$ data for all lakes in all years (Figure 3). However, the relationship is not uniform despite the similar geomorphic setting for all study sites. A simple linear regression model between the two variables yields regression slopes ranging from as low as +0·09 %/cm to +1·39 %/cm, with a mean value of +0·79 %/cm (Table I). Coefficients of determination (r^2) range from 0·32 to 0·83, with a mean value of 0·53. Inspection of Figure 3 suggests that with the exception of Lake 2, a linear model is a reasonable descriptor of area–stage relationships in these lakes.

In general, small lakes are characterized by steep area–stage relationships whereas large lakes are not (Lakes 1, 3, 5, versus 7, 8, 9; Figure 3 and Table I). This overall pattern emerges most clearly in a log-normal plot of mean lake area versus each lake's corresponding regression slope (Figure 4). Similarly, lake-averaged values of the relative apportionment between stage (H_c) versus areal expansion/contraction (A_c) contributions to overall ΔS are greatest for large lakes and lowest for small lakes (Table I). Put another way, in large lakes more of the overall volumetric storage change consists of a stage adjustment; in small lakes more of it consists of a surface-area adjustment.

Two bathymetric survey cross-sections of Lakes 3 and 4 revealed maximum depths of just 95 cm and 80 cm, respectively (Figure 5). Lake 3 has a relatively simple, slightly asymmetric convex bathymetry, whereas Lake 4 is more complex with three saddles instead of one. Taken together with their respective wetted-perimeter width/depth indicate Lake 3 may be characterized as having the 'steeper' bathymetry of the two (width/depth = 7677 for Lake 3; width/depth = 8982 for Lake 4).

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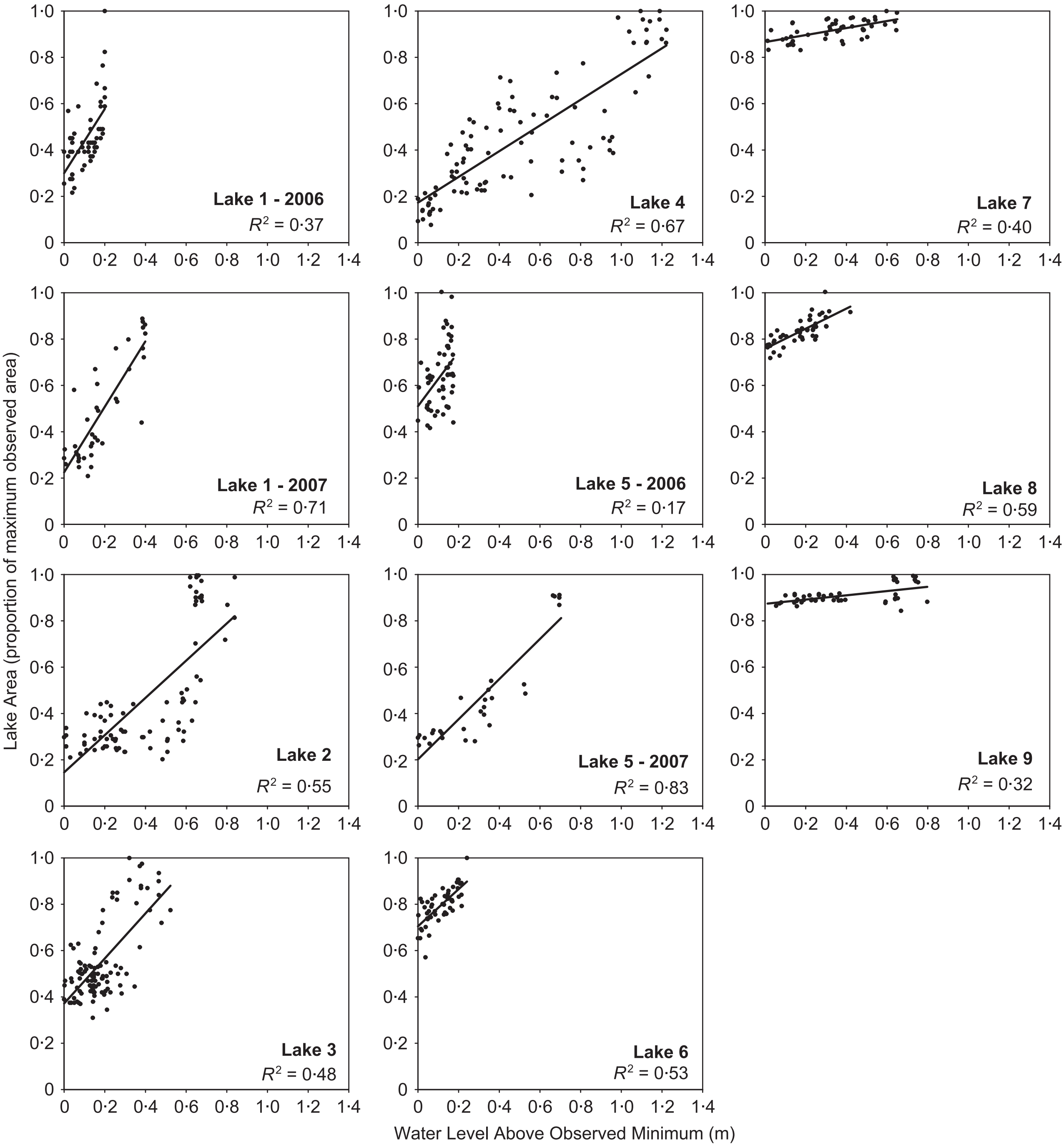

Figure 3. Area–stage relationships for all study lakes, constructed from *in situ* measurements of stage change ($\Delta H/\mathrm{d}t$) and same-day MODIS measurements of lake surface area (A). Each point represents one stage measurement and one satellite image. Regression slopes are generally linear except in Lake 2, and are generally steepest (more area-sensitive) in smaller lakes. Despite similar geomorphic settings, significant variations are found in area–stage relationships between lakes.

Discussion and Conclusion

A global capacity to measure storage changes in water bodies and discharge changes in rivers, from space, would transform hydrologic science. But the field remains immature. A key issue is the transferability of retrieval algorithms between sites, or in the case of rivers, to different locations downstream. The early results shown here suggest that even similar-appearing lakes can display individual behavior with respect to their three-dimensional inundation geometries. This is reminiscent of the situation with rivers, where remotely sensed at-a-station hydraulic geometries are highly variable at short length scales, but approach a constant value at length scales exceeding 2–3 × valley width (Smith and Pavelsky, 2008). Unlike rivers, however, the hydraulic geometries of lakes and wetlands do not lend themselves to spatial averaging over a long axis. The key, therefore, is three-dimensional imaging, which obviates the need to compute area–stage relationships as we have done here. Three-dimensional imaging also sidesteps the havoc introduced by lakes separating, merging, or shifting as topographic sills are overtopped, a notorious difficulty that requires advanced informatics to solve (e.g. Sheng *et al.*, 2008).

The observed positive correlations between all remotely-sensed inundation areas and *in situ* water levels affirm the notion that fluctuations in stage, with few exceptions, trigger changes in inundation area that are observable from space. Furthermore, assumption of a linear response between the two

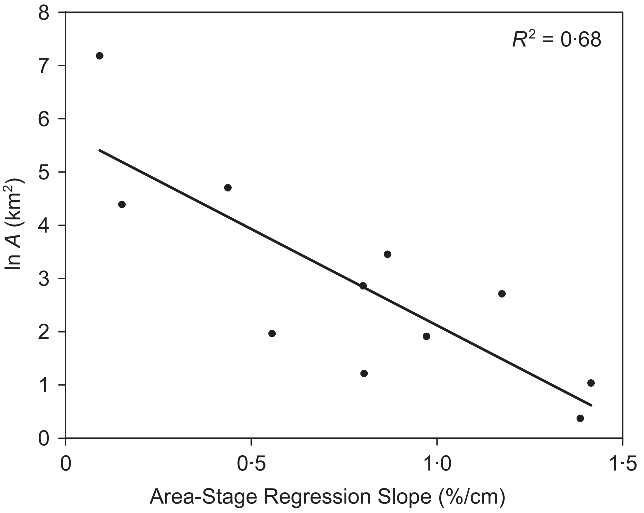

Figure 4. 'Area effect' of overall lake size on the area–stage relationships (regression slopes) shown in Figure 3. Large lakes have lower regression slopes, meaning they are less 'area-sensitive' than small lakes. This overall trend follows a ~1/*x* relationship and is attributed to scaling geometry.

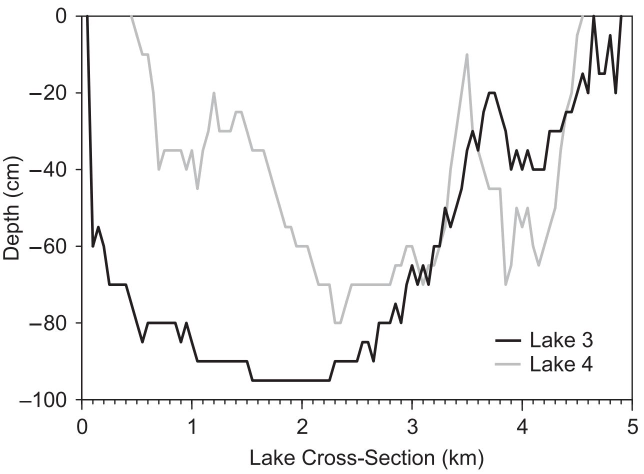

Figure 5. Bathymetric field transects were collected for two of the study lakes. Lake 3 has a steeper shoreline bathymetry (width/depth = 7677) yet more area-sensitive (higher) area–stage regression slope (0·97, Table I). Lake 4 has a gentler bathymetry (width/depth = 8982) yet less area-sensitive (lower) regression slope (0·56).

variables appears warranted, at least for eight of the nine lakes examined here (Lake 2 being the sole exception, Figure 3). However, a unit increase or decrease in stage does not translate to equivalent storage changes at all lakes. Area–stage regression slopes vary significantly between them, and even in the same lake for different years (Figure 3, Table I). One immediate explanation for these differences is geomorphic control, i.e. lake depressions with gently sloping shorelines are expected to display more sensitive area–stage relationships (steeper regression slopes) than steep ones. But this expectation was not validated by our two bathymetric surveys: Lake 3 has a slightly smaller width/depth ratio but steeper regression slop (0·97 %/cm), whereas Lake 4 has larger width/depth ratio but gentler regression slope (0·56 %/cm, Table I).

However, for this particular collection of wide, shallow lake basins in the PAD, bathymetric subtleties are secondary to contrasts in overall lake size. In general, large lakes tend to have 'flatter' area–stage regression slopes (Figure 3) meaning that ΔS is driven more by changes in stage than changes in inundation area (i.e. H_c is greatest in the largest Lakes 7, 8, 9; whereas A_c is greatest in the smallest Lakes, 1, 2, 4, Table I). It is possible that large lakes, with their higher wind fetch and deeper littoral cells, experience deeper nearshore erosion and therefore steeper shorelines, but a more likely explanation for this observed 'area effect' lies in geometry, not geomorphology: For any polygon, as perimeter increases its perimeter/area ratio declines non-linearly (depending on shape), roughly what is seen here (Figure 4). Since lateral expansion/contraction processes occur mainly around a lake's perimeter, its regression slope (Figure 3), and area-change apportionment A_c (Table I) generally diminish with increasing lake size. As such, a first-order 'area-correction' (e.g. weighting the contribution of ΔH by p/A where p = lake perimeter and A its surface area) should be applied in studies using remotely-sensed inundation or height variations alone to infer ΔS. The overall effect of this correction would be to weight surface area changes more strongly in small lakes and height changes more strongly in large lakes for the purpose of estimating storage change. Note that this 'area-effect' correction becomes unnecessary when both A and $\Delta H/dt$ are measured directly, such as done here *in situ* or as would be obtained by SWOT in the future. However, it does influence satellite design considerations with respect to determinations of acceptable measurement error: For large lakes, precision in the water-surface height retrieval is most important; whereas for smaller lakes precision in the water-surface area retrieval becomes increasingly crucial.

It is clear from Figure 4 that even after correcting for lake area (i.e. 'subtracting' the regression line in Figure 4), residual contrasts still remain between area–stage relationships among different lakes. Clearly, the trade-off between lateral expansion/contraction (A_c) or vertical stage adjustment (H_c) to accommodate changing water storage varies significantly from one water body to the next depending on lake bathymetry, hydrologic connections to distributary channels, and other site-specific factors. Therefore, remote-sensing estimates of ΔS based on 'height-only' or 'area-only' methods each miss part of the picture; both variables must be recovered for best success.

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