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Remote sensing of hydrologic recharge in the Peace-Athabasca Delta, Canada

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[1] Northern wetlands like Canada's Peace-Athabasca Delta (PAD) have global environmental significance, yet fundamental processes of hydrologic recharge critical to their functionality remain poorly understood. We use in situ water level and MODIS satellite data to examine how main-stem river level fluctuations drive inundation across the delta. Temporal covariance between the two datasets allows inference of hydrologic connectivity processes, not just inundation extent. A strong contrast is found between hydrologic connectivity properties in a high-water (2007) vs. low-water year (2006). Results suggest that existing theoretical models of floodplain recharge fail to capture observed patterns of inundation in the PAD. Instead, we find a dichotomy between the distributary channel network, which responds to summer high-water events, and floodplain lakes and wetlands, which do not. The latter occurs even where hydrologic connections do exist between the two. Results have strong management implications for the impact of proposed up-river water diversion on PAD hydrology. **Citation:** Pavelsky, T. M., and L. C. Smith (2008), Remote sensing of hydrologic recharge in the Peace-Athabasca Delta, Canada, *Geophys. Res. Lett.*, *35*, L08403, doi:10.1029/2008GL033268.

1. Introduction

[2] High-latitude wetland environments are of global environmental significance due to their high levels of biological productivity [*Leconte et al.*, 2001; *Cao et al.*, 1996], large-scale storage of soil carbon [*Sheng et al.*, 2004; *Frey and Smith*, 2005], and critical habitat for migratory birds and other species [*Prowse and Conly*, 2002]. The functionality of these wetland systems, including fens, bogs, river floodplains, and deltas, is dependent upon regular hydrologic recharge through precipitation, groundwater flow, and surface water processes, i.e., river flooding [*Mitsch and Gosselink*, 2007]. However, precise understanding of the mechanisms behind such recharge remains limited. In particular, the response of floodplain inundation to changes in water level on the axial river channel is poorly understood due to complex flow patterns, limited *in situ* observations, and the discovery of non-uniform water level change across the floodplain [*Alsdorf and Lettenmaier*, 2003; *Alsdorf et al.*, 2007a].

[3] Early models of floodplain recharge and drainage envisioned a horizontal water surface in which variations in floodplain water level exactly track changes in river water level, i.e., in a planar fashion [e.g., *Richey et al.*, 1989; *Bedient and Huber*, 1992]. More recently, a diffusion model has been proposed to explain how floodplain water levels respond to main-stem water level as a function of distance from the river channel [*Alsdorf et al.*, 2005]. However, the limitations of both models are revealed with satellite interferometric synthetic aperture radar (InSAR)-derived images of water surface elevation change, indicating that topography, vegetation, water storage, and channel geomorphology introduce bewilderingly complex spatial and temporal heterogeneities in floodplain response to river main-stem fluctuations [*Alsdorf et al.*, 2007b]. Because of the complexity of such environments, remote sensing is a powerful tool in studying their inundation hydrology, especially for large, remote wetland systems. However, the InSAR methodology utilized by *Alsdorf et al.* [2007b] is limited by long repeat time and the requirement of inundated, woody vegetation to preserve interferometric phase coherence through "double-bounce" of the radar signal. Moderate-resolution optical sensors therefore offer an attractive alternative in many areas due to their high temporal resolution and utility in wetlands lacking flooded forest. However, unlike InSAR they are limited to tracking variations in inundation extent rather than water surface elevation changes.

[4] In low-relief floodplain environments, small increases in water level result in large changes in inundated area. As a result, a high temporal correlation between the inundation area of a lake or wetland and nearby river water level fluctuations can be presumed indicative of a hydrologic connectivity between the river main-stem and its surrounding floodplain. Methods for extracting floodplain inundation extent from optical and microwave imagery are well established and relatively simple to apply, particularly in areas lacking dense flooded vegetation [e.g., *Smith*, 1997; *Brakenridge et al.*, 1998; *Sheng et al.*, 2001; *Overton*, 2005]. In this study, we combine ground-based water level monitoring with satellite-derived observations of inundated area to examine how variations in river main-stem water level of differing magnitudes and time scales impact the inundation and inferred hydrologic connectivity with surrounding lakes and wetlands.

2. Study Area

[5] Among the world's most globally significant boreal wetlands is Canada's Peace-Athabasca Delta (PAD), a 5200 km^2 freshwater delta at the confluence of the Peace and Athabasca Rivers with Lake Athabasca (58.7N, 111.5W; Figure 1). Owing to its high biological diversity, the PAD has been declared a Ramsar Convention Wetland, a UNESCO world heritage site, and is mostly contained

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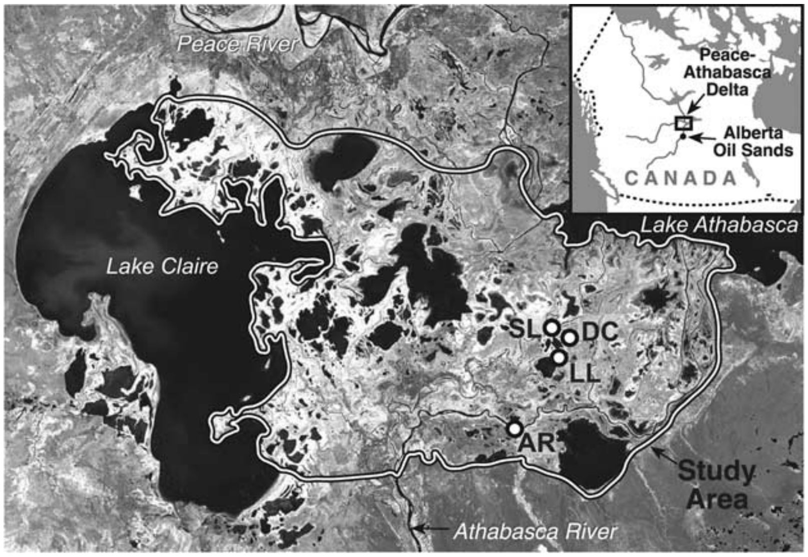

Figure 1. Landsat Band 4 (near-infrared) image of Peace-Athabasca Delta acquired August 1999. Dark areas are inundated. White outline shows study area, and locations of water level sensors are shown as dots. Inset map shows location of delta within Canada.

within Wood Buffalo National Park, Canada's largest park. Aside from some exposed bedrock features in the northern sector, the PAD consists of hundreds of interconnected wetlands, shallow lakes (<2 m depth), and active and relict distributary channels. Delta ecosystems depend largely upon regular hydrologic recharge, without which many of the graminoid-dominated wetlands and shallow lakes revert to *Salix*-dominated environments that are both less biologically productive and less conducive to use by migratory birds [*Prowse and Conly*, 2002; *Toyra and Pietroniro*, 2005; *Timoney*, 2006]. The Athabasca River, which enters the delta from the south, is the major source of water and sediment to the PAD under most flow conditions. More rarely, the Peace River also recharges the delta during extreme floods, normally from ice-jams [*Beltaos et al.*, 2006; *Leconte et al.*, 2001; *Peters et al.*, 2006]. The last such flood occurred in 1996–1997, ending a 22 year period with no major input of Peace River water into the PAD. The critical importance of these rare Peace River ice-jam floods to the replenishment of perched lakes and wetlands in the PAD has attracted much scrutiny since the 1970s [e.g., *Peace-Athabasca Delta Project Group*, 1973; *Prowse and Lalonde*, 1996; *Wolfe et al.*, 2005; *Peters et al.*, 2006]. In comparison, the role of Athabasca River water recharge to the PAD, especially during the open-water season, has received far less attention.

[6] This recharge is now of keen environmental interest in light of recent proposed increases in water diversion from the Athabasca River to enable increased crude oil production from the Alberta Oil Sands, located some 150 km upstream of the PAD (Figure 1). Oil production is projected to increase by $\sim$200% over 2006 levels by 2015, requiring water diversion from the Athabasca to rise from 17 m^3/s currently to 51 m^3/s in the next few years [*Griffiths et al.*, 2006]. By comparison, mean annual flow in the Athabasca River near the oil sands development is 629 m^3/s over the period 1958–2006. Moreover, these diversions will occur in the context of overall declines in Athabasca River discharge of approximately 20% since 1958 associated with climate warming [*Schindler and Donahue*, 2006]. If hydrologic connectivity and inundated area in the PAD are closely coupled to water level on the Athabasca River during the open water season, the proposed withdrawals could have important consequences for PAD ecosystems downstream.

3. Methods

[7] Field campaigns were carried out in 2006 and 2007 to obtain time-series of river and lake water level at four locations in the PAD throughout the entire open water season (June–September). Water levels were logged every fifteen minutes using submerged Solinst Levelogger® pressure transducers and were later corrected for atmospheric pressure variations using Solinst Barologgers®. Precision of the corrected water levels is ±1 cm. Water level measurements were converted to water surface elevation values using differential GPS-based surveys with accuracy ranging from ±1 to 5 cm. All elevation values presented were leveled to the Canadian Gravimetric Geoid Model 2000 (http://www.geod.nrcan.gc.ca/publications/papers/abs26_e.php). Water surface elevations were collected in the Athabasca River (AR), one of its distributary channels (DC), a large (19 km^2) floodplain lake adjacent to DC (LL), and a smaller (2.8 km^2) floodplain lake also adjacent to DC (SL) (Figure 1). 2006 LL and SL Lake water surface elevations were not manually surveyed, so their absolute magnitudes are arbitrary and only relative changes within each time series are considered.

[8] Temporal variations in PAD inundation area were obtained using cloud-free 250m MODIS near-infrared imagery (band 2, 841–876 nm) yielding a total of 108 temporal measurements (57 in 2006 and 51 in 2007). The method used to estimate inundation area is similar to those of *Sheng et al.* [2001] and *Overton* [2005]. A dynamic threshold (T) is used to differentiate water pixels from

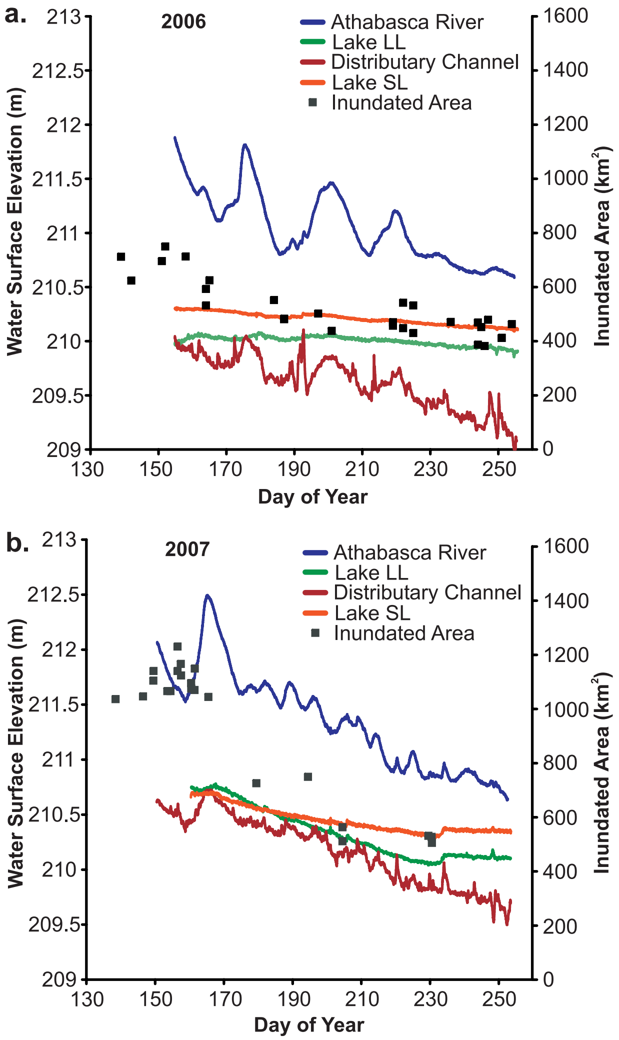

Figure 2. Time series of water surface elevation at four locations within the Peace Athabasca Delta for (a) 2006 and (b) 2007. LL and SL lake water surface elevations in 2006 were not manually surveyed, so their absolute magnitudes in Figure 2a are arbitrary and only relative changes within each time series are considered.

nonwater pixels for each scene, with the threshold (T) computed as:

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

where W is the average value of 12 known and consistent water pixels, L is the average value of 12 known and consistent land pixels, and d is a parameter between 0 and 1. We compared total MODIS-derived inundated area extracted using values of d between 0.30 and 0.80 with inundated area extracted from four 100m ALOS ScanSAR images acquired in July and August 2007. On average, ALOS-derived inundated areas matched values computed from MODIS to within 6% for d = 0.60, the closest observed match.

[9] To assess hydrologic connectivity between the Athabasca River system and different sectors of the PAD, a 5 km × 5 km (20 pixel × 20 pixel) grid was superimposed on each cloud-free MODIS image of the delta (Figure 3). For each grid cell, the total inundated area contained within the cell was calculated from each corresponding MODIS scene. Pearson's product-moment correlation coefficients were then calculated between the inundation time-series for each grid cell and our field time-series of water levels in the Athabasca River and Lake LL.

4. Results

[10] Time series of water level at AR, DC, LL, and SL are shown in Figure 2 for summers (a) 2006 and (b) 2007. Main-stem water levels at the AR site show considerable variability, with several high water events superimposed on an overall pattern of declining water level during both years. A similar pattern is evident at the DC site, though the signature of individual events is somewhat muted. The two floodplain lakes, each within 2 km of the DC site, were both personally observed to be hydrologically connected to the river system during the summer 2007 field season via ~6 m wide channels (2006 connectivity is unknown). In summer 2006, lake levels declined markedly slower than the linear trend in Athabasca River level (Table 1). In contrast, summer 2007 lake water levels declined at a rate similar to (LL) or somewhat less than (SL) the linear trend in Athabasca River water level. Moreover, during neither year did lake water level mirror high-frequency variability in river water level despite immediate proximity to the river system and known hydrologic connectivity during 2007. These observed differences in hydrologic response between the two years are likely related to overall higher water levels in 2007. Same-day water levels at the AR site were, on average, +0.48 m higher in 2007 than 2006. At the DC site, the same-day difference was +0.52 m.

[11] Patterns in MODIS-derived inundated area also differ substantially between the two study seasons (Figure 2). Late May inundated area was approximately 500 km^2 higher in 2007 than 2006 due to elevated winter snowpack in the Athabasca Basin in 2007 (160–162% of normal 2007, 19–56% in 2006) and extensive ice-jam flooding on the Athabasca in May 2007 (http://www3.gov.ab.ca/env/water/ws/WaterSupply/index.html; R. Grandjambe, personal communication, 2007). Inundation declines in 2007 matched overall decreases in water level at our four field sites but did not mirror short-duration high water level events on the Athabasca River (Figure 2). This result is consistent with the lack of hydrologic response to such events observed in LL and SL. Smaller declines in inundated area during 2006 mirrored minimal changes in water level in these two lakes.

Table 1. Linear Trends in Water Level at Four Points Within the PAD Shown in Figure 1 for June–September 2006 and 2007

	Linear Trend in Water Level, m/day	
	2006	2007
Athabasca River	−0.009	−0.014
Distributary Channel	−0.007	−0.010
LL Lake	−0.001	−0.008
SL Lake	−0.002	−0.004

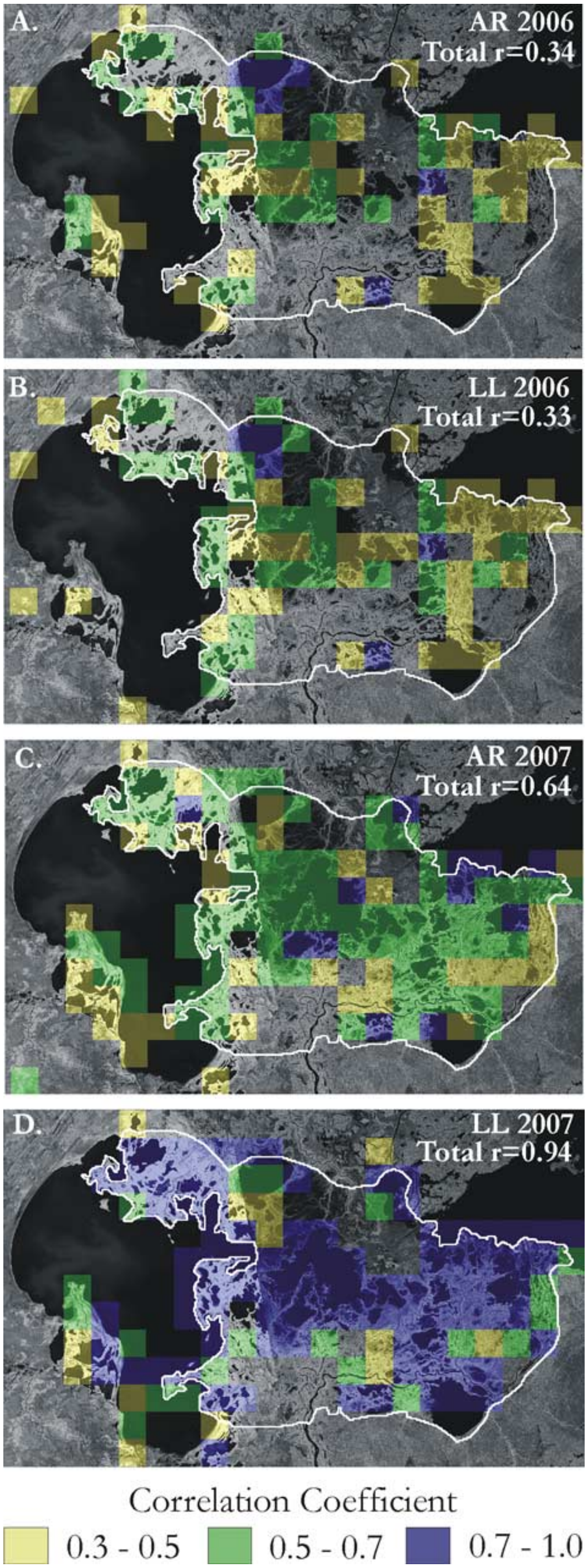

Figure 3. Maps showing correlation between time series of MODIS-derived inundated area and (b and d) Athabasca River (a and c) and LL Lake water levels during summers 2006 and 2007. Highest correlation is in areas shown in blue and green.

[12] Correlation of MODIS-derived inundated area with AR and LL water levels on a 5 km × 5 km grid (20 × 20 pixels) reveals close agreement between the two variables in many areas as well as substantial differences between 2006 and 2007 (Figure 3). A high degree of correlation between Athabasca River water levels and inundated area in 2007 (Figure 3c) suggests hydrologic recharge of much of the PAD, whereas lower correlations in 2006 (Figure 3a) reflect less inundated area overall and a lower degree of hydrologic connectivity in areas that were inundated. 2006 correlations between LL water level and inundated area (Figure 3b) are not markedly different than for AR water levels. We attribute this similarity to the relatively small changes in water level observed in LL during 2006, as inundated area variations associated with such decreases may not be detectable using 250 m MODIS imagery. Moreover, the small inundated area and limited connectivity associated with low 2006 water levels results in low correlations across the PAD and suggests limited responsiveness to summertime high water fluctuations. Overall correlation is much greater during summer 2007, with LL correlation substantially exceeding AR (r = 0.94 for LL, r = 0.64 for AR over entire study area). Pervasively high correlations between inundated area and LL water level suggest that even during high-water conditions when hydrologic connectivity throughout the PAD is greatest, responsiveness to summertime fluctuations during the open water season remains low.

5. Discussion and Conclusions

[13] A comparison of water levels and inundation patterns in the PAD for 2006 and 2007 reveals a system in which interannual variations in water level are associated with profound differences in floodplain hydrology. 2007 water levels were, on average, approximately 0.5 m higher than in 2006, associated with a near-doubling of maximum inundated area and a marked increase in hydrologic connectivity across the delta. The observed variations in floodplain response to Athabasca River water level fluctuations also shed new light on the theoretical models proposed by *Richey et al.* [1989] and *Alsdorf et al.* [2005, 2007b]. Clearly, water levels in PAD floodplain lakes do not mirror Athabasca River water levels, suggesting that Richey's simple planar model is inadequate. The linear diffusion model suggested by *Alsdorf et al.* [2005] also fails to match observations in the PAD. Instead, we find that hydrologically connected lakes (LL and SL) have markedly different hydrographs compared to a floodplain distributary (DC) less than 2 km distant. On the other hand, the strong similarity in water levels between AR and DC and between LL and SL, as well as the strong regional correlations apparent in Figure 3, suggests that the PAD is not dominated by the complex heterogeneity observed in the Amazon River by *Alsdorf et al.* [2007b].

[14] We suggest that floodplain hydrologic response in the central and southern PAD is neither planar, nor diffusive, nor hopelessly complex but instead is best described as a dichotomy between the distributary channel network and the surrounding lakes and wetlands. Within the network, water levels respond in concert with Athabasca River water level across all time scales. In lakes and wetlands, hydro-

logic response is limited to the spring flood, with summertime high-stage events having little impact even in hydrologically connected lakes and wetlands. This finding supports the work of *Peters et al.* [2006] and emphasizes the importance of spring ice jam-induced flooding on the Athabasca (not just the Peace River) to the hydrologic recharge of PAD lakes and wetlands.

[15] The reasons for this dichotomy remain unclear. One possible mechanism, an inverse relationship between water body size and water level change, does not appear to explain the observed differences in hydrologic response within the PAD. For example, LL is 19 km^2 in maximum extent while SL is only 2.8 km^2, yet SL exhibits no greater response to changes in Athabasca River water levels than does LL. The channels connecting each lake to DC are similar in size, suggesting that degree of connectivity to the open water system is also an insufficient explanation. Other possible mechanisms include differences in bathymetry between lakes and channels and the role of vegetation in slowing water movement in shallow lakes and wetlands. Further study is required to test these ideas.

[16] Regardless of mechanism, from an environmental management perspective it is likely that an upstream withdrawal of 51 m^3/s for use in the Alberta Oil Sands would have only a modest impact on the hydrologic recharge of the PAD. A simple regression between monthly mean water levels on the Athabasca River within the PAD and Athabasca River discharge near the oil sands development suggests that such withdrawals would generate a $\sim$6 cm decline in PAD water levels, substantially smaller than the $\sim$50 cm difference observed between water levels in summers 2006 and 2007. However, larger diversion from the Athabasca could significantly impact the hydrology of the PAD. For example, an upstream withdrawal of 420 m^3/s would lower downstream PAD water levels by $\sim$50 cm, a decrease comparable magnitude to the large differences observed here between 2006 and 2007.

[17] Our results also suggest that the timing of withdrawals is of paramount importance in minimizing diversion impacts on downstream PAD hydrology and ecology. The principal determinants of PAD recharge extent are the magnitude of the spring freshet and the impact of any ice jam floods, while short-duration, high-water events during summer have only small impact on delta inundation. Our finding of low impact of summertime high-water events on PAD inundation suggests that if upstream Athabasca River diversions could be timed to "decant" only these summertime events, downstream impacts on PAD inundation hydrology would be minimized.

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