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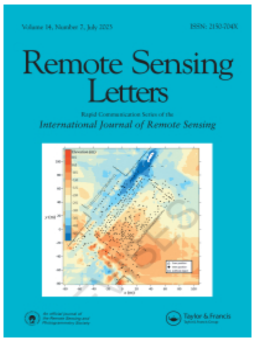
Colin J. Gleason

et. al.



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Peace-Athabasca Delta water surface elevations and slopes mapped from AirSWOT Ka-band InSAR

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ABSTRACT

In late2023 the Surface Water and Ocean Topography (SWOT) satellite mission will releaseunprecedented high-resolution measurements of water surface elevation (WSE) andwater surface slope (WSS) globally. SWOT's exciting Ka-band near-nadirwide-swath interferometric radar (InSAR) technology could transform studies of surfacewater hydrology, but remains highly experimental. We examine Airborne SWOT(AirSWOT) data acquired twice over Canada's Peace-Athabasca Delta (PAD), alarge, low-gradient, ecologically important riverine wetland complex. Whilenoisy and susceptible to "dark water" (low-return) data losses, spatiallyaveraged AirSWOT WSE observations reveal a broad-scale water-level decline of ~44cmn (σ =271 cm) between 9 July and 13 August 2017, similar to a ~56 cm decline (σ=33 cm) recorded by four in situ gauging stations.River flow directions and WSS are correctly inferred following filtering andreach-averaging of AirSWOT data, but ~10 km reaches are essential to retrieve them.July AirSWOT observations suggest steeper WSS down an alternate flow course(Embarras River–Mamawi Creek distributary) of the Athabasca River, consistentwith field surveys conducted the following year. This signifies potential forthe Athabasca River to avulse northward into Mamawi Lake, with transformativeimpacts on flooding, sedimentation, ecology, and human activities in the PAD.Although AirSWOT differs from SWOT, we conclude SWOT Ka-band InSAR observationsmay detect water level changes and avulsion potentials in other low-gradientdeltas globally.

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1. Introduction

The Surface Water and Ocean Topography (SWOT) satellite radar mission that was launched on 16 December 2022 (Tollefson 2022; https://swot.jpl.nasa.gov/) is the first near-nadir wide-swath Ka-band imaging altimeter in space (Durand et al. 2010; Peral and Esteban-Fernandez 2018). Using two radar antennae and interferometric synthetic aperture radar (InSAR) processing, SWOT measures water surface elevation (WSE) directly from free-water surfaces, unlike pioneering InSAR approaches requiring 'double-bounce' returns from flooded vegetation (e.g., Alsdorf et al. 2000; Alsdorf, Smith, and Melack 2001; Wdowinski et al. 2008). SWOT will map WSE globally in unprecedented detail, with 1 km spatial resolution over oceans. Over land, SWOT will observe WSE for lakes as small as $(250\,\text{m})^2$, and WSE and water surface slope (WSS) for rivers as narrow as 100 m wide (JPL Internal Document 2018).

Prior to SWOT, near-nadir wide-swath Ka-band measurements of WSE and WSS were demonstrated with AirSWOT, an airborne platform developed by the NASA Jet Propulsion Laboratory as a testbed and validation instrument for SWOT (Moller et al. 2011). Past AirSWOT targets include the Tanana River, Alaska (Altenau et al. 2017, 2019), the Sacramento River and Piute Ponds, California (Baney et al. 2014; Pitcher et al. 2014); the Willamette River, Oregon (Tuozzolo et al. 2019), and the Mississippi River Delta (Denbina et al. 2019; 2021; 2019b). In 2017, an extensive radar data collection (128 flight lines covering 22,775 km^2 and 23 degrees of latitude) and high-resolution colour-infrared camera water mask (Kyzivat et al. 2018, 2019) were acquired by AirSWOT in Alaska and western Canada for the NASA Arctic-Boreal Vulnerability Experiment (ABoVE) (Fayne et al. 2019, 2020; Miller et al. 2019).

Simultaneous ground-based field campaigns deployed under these previous flight campaigns established good accuracy of spatially averaged WSE and WSS observations. Relative to in situ GNSS (Global Navigation Satellite System) and/or permanent gauging station measurements, AirSWOT root-mean-square errors (RMSE) were ~ 8–15 cm for WSE (after spatial averaging of areas 1.0–0.0625 km^2, respectively) and ~ 1.0–1.5 cm km^{-1} for WSS (for river reaches ~10 km long, Altenau et al. 2017, 2019; Pitcher et al. 2019; Tuozzolo et al. 2019). In general, longer reaches improve WSS estimation accuracy (Altenau et al. 2019; Denbina et al., 2019; Langhorst et al., 2019). Scientific discoveries from AirSWOT include improved understanding of surface water gradients and subsurface permafrost (Pitcher et al. 2019), stability of WSS profiles (Altenau et al. 2019), and fundamental Ka-band backscattering physics (Fayne and Smith 2021, 2023; Fayne et al. 2023).

AirSWOT and SWOT hold promise for mapping WSE changes and channel flow directions in low-gradient wetland and delta environments, which are challenging to determine from land surface DEMs. One such system is the Peace-Athabasca Delta (PAD) in northern Alberta, Canada, a ~6000 km^2 inland river delta complex that was mapped twice in 2017 during the ABoVE AirSWOT campaigns (Figure 1). Formed by the confluence of the Peace, Athabasca, and Birch Rivers, the PAD is a RAMSAR Wetland of International Importance and dominant feature of the Wood Buffalo National Park UNESCO World Heritage Site. PAD surface hydrology consists of a complex mosaic of rivers, distributary channels, lakes, and wetlands (**Figures S1, S2**) with varying degrees of hydrological connectivity (Kay et al. 2019; Long and Pavelsky 2013; Neary et al. 2021; Pavelsky and Smith 2008, 2009; Smith and

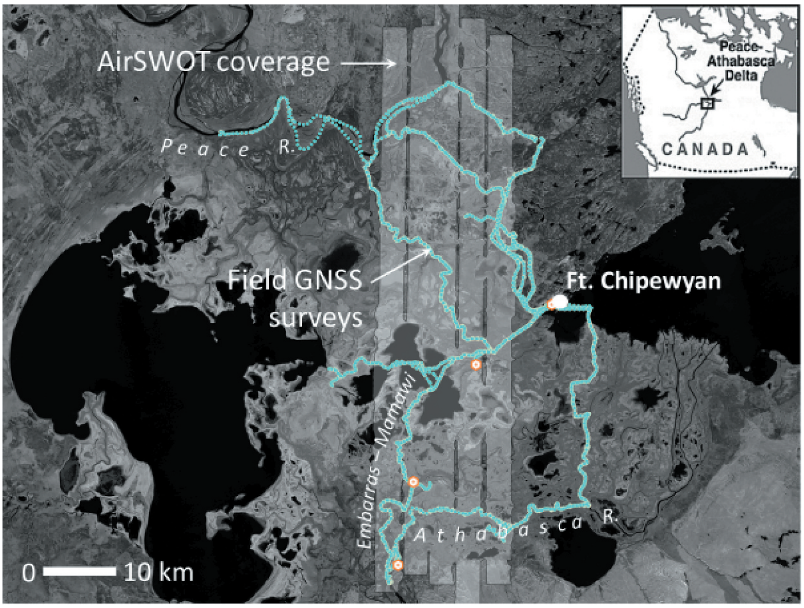

Figure 1. The Peace-Athabasca Delta (PAD), Canada. Outlined in grey is a 1500 km^2 mosaic of the central PAD imaged twice by AirSWOT on 9 July and 13 August 2017. Four Water Survey of Canada gauges recorded in situ water levels on both dates (red bullseye symbols). In 2018, in-situ longitudinal GNSS profiles of water surface elevation were collected in rivers and distributary channels by boat (cyan dots).

Pavelsky, 2009; Timoney 2013). While the overall flow directions of PAD river channels are well-known, most are low gradient (<10 cm km^{-1}) and certain channels connecting the PAD to the Peace River are susceptible to flow reversals and/or backwater effects (e.g., Quatre Fourches, Peters and Buttle 2010; Timoney 2013). A major avulsion (channel abandonment for a new flow path on a lower elevation on the floodplain) of the Athabasca River (the PAD's most direct source of water) into its enlarging Embarras River – Mamawi Creek (EM) distributary channel may be imminent, with potentially transformative long-term impacts to PAD hydrology, ecology, and human use (Wang et al. 2023). For further description see **Supplemental Material**.

Here, we use the 9 July and 13 August 2017 AirSWOT datasets to assess PAD channel WSE, WSS, flow directions, and a potential avulsion path for the Athabasca River. First, we process AirSWOT elevation data to retrieve spatially averaged WSE, WSS, and infer river flow directions. Next, we compare surface gradients of the Athabasca River and its recently opened EM distributary, using AirSWOT and in-situ field GNSS WSE surveys collected the following year. Finally, we assess the importance of river reach-averaging length for WSS estimation. We conclude with a discussion of our findings and their implications for hydrologic studies of the PAD and other low-gradient wetlands and deltas using AirSWOT and SWOT Ka-band InSAR.

2. Materials and methods

2.1. AirSWOT observations and data processing

AirSWOT flights over the PAD took place on 9 July and 13 August 2017 (Figure 1). Five 3.4 km wide, slightly overlapping parallel swaths were flown in a N – S configuration, with west and east radar look directions corresponding to N and S flight lines, respectively. The primary AirSWOT data product analysed here is the 'elevation' product, with coherence, magnitude, incidence angle, and elevation uncertainty products used for data filtering and water masking as per Fayne et al. (2020) (**see SM**). These filtering and masking steps reduced data coverage over water bodies to 15% (July) and 27% (August) of total mapped water area. The filtered data were spatially averaged to a 125 m grid to produce July, August, and composite maps of WSE and standard deviation (σ). Domain-wide July and August WSE values were determined, averaged, and differenced to estimate a seasonal summer drawdown of PAD water levels (**Figure S3**). To derive WSS throughout the study area, channel centerlines were obtained from the SWOT Rivers Database (SWORD v.12, Altenau et al. 2021) for intersection with gridded AirSWOT WSE retrievals throughout the study area. For the EM and Athabasca River data, ordinary-least-squares and loess regressions were applied to enable comparison with in situ field observations acquired the following year. For descriptions of these methods see **Supplemental Material**.

2.2. In situ observations and data processing

Four permanent Water Survey of Canada gauging stations provided daily stage observations during both AirSWOT overflights (Figure 1, Table S1). Daily stage observations for 9 July and 13 August 2017 were downloaded from https://wateroffice.ec.gc.ca/map/index_e.html?type=historical and differenced to obtain four point locations of WSE change during the two dates of AirSWOT flight acquisitions (**Table S1**).

One year after the 2017 AirSWOT campaigns, we collected high-quality longitudinal GNSS surveys of WSE throughout the PAD, using the boat-based method of Pitcher et al. (2020) from 4–26 August 2018 (Wang et al. 2023; 2023; Figure 1). While these field measurements cannot be directly compared with AirSWOT WSE or WSS due to their asynchronous timing, they offer an independent dataset of EM and Athabasca River hydraulic gradients useful for qualitative comparison. GNSS WSE measurements were logged at 1 Hz sampling frequency from a slowly moving motorboat, using a Septentrio PolaRX5 GNSS receiver and a PolaNt-x MF antenna and Precise Point Positioning (PPP) data processing. For further description see **Supplemental Material**.

3. Results

The 2017 AirSWOT flight campaigns retrieved Ka-band backscatter, water surface elevations, and water surface slopes for many of the rivers, lakes, and wetlands within a ~1500 km^2 area of the PAD (Figure 2). Spatially heterogenous areas of low radar backscatter (so-called 'dark water', Denbina et al. (2019)) caused by low wind speeds (<3 m/s, Fayne and Smith 2023) produced numerous data gaps, especially at far-range (Figure 2b). This dark water, together with viewing geometries perpendicular to some

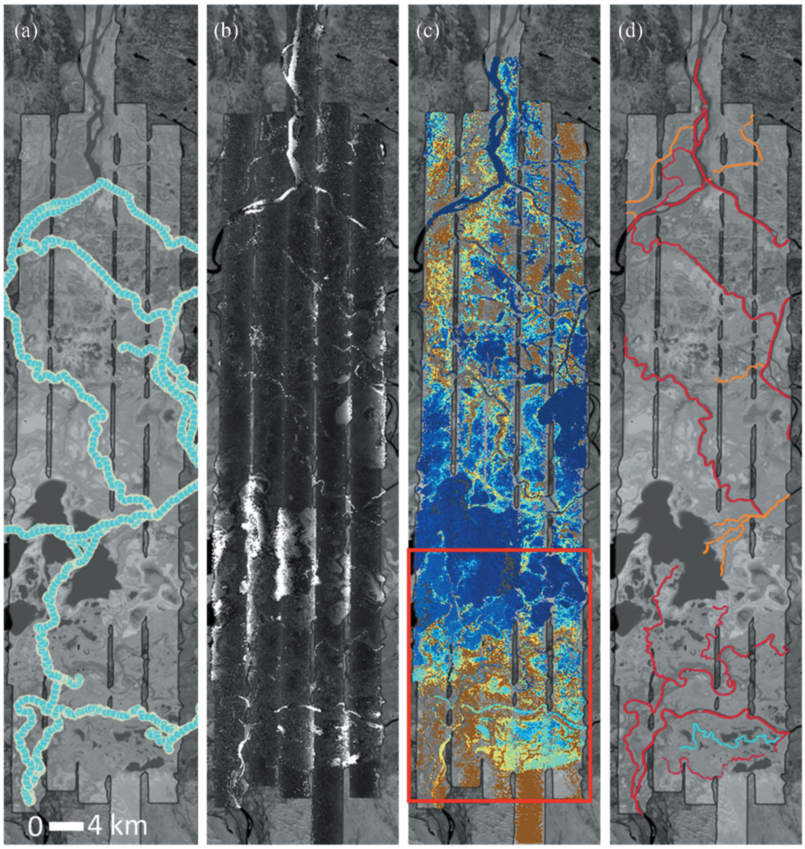

Figure 2. AirSWOT observations of the PAD: a) Close-up of Figure 1, showing 2017 AirSWOT flight coverage and 2018 in situ WSE profiles (in cyan); b) AirSWOT composite Ka-band backscatter (9 July and 13 August); c) AirSWOT surface elevations (see Figure 3 for legend); d) AirSWOT water surface slopes for rivers and major distributary channels (red= -3 cm km^{-1}, orange = 0 cm km^{-1}, blue = 3 cm km^{-1}).

river channels (Denbina et al. 2019) and data noise, created sizable WSE data losses, yielding 15% and 27% water body coverage for July and August, respectively. This WSE coverage is notably lower than a ~ 70% average for the entire 2017 ABoVE collection (Fayne et al. 2020). However, spatial averaging of available WSE observations nonetheless yields useful measurements, with derived WSEs of 180–185 m above mean sea level (WGS84 ellipsoid, or 210–215 m a.s.l. if corrected to the EGM 96 geoid) conforming with expectations. Averaged across the study domain, AirSWOT-derived water levels were ~44 cm lower in August than in July ($\sigma = 271$ cm), consistent with ~56 cm lowering ($\sigma = 33$ cm) measured by four Water Survey of Canada gauges (**Table S1**).

AirSWOT-derived WSE maps correctly identify known channel flow directions (Figures 2d, 3), as well as virtually flat channels known to be susceptible to flow reversals (e.g., in orange, Figure 2d). In general, rivers display higher WSE values upstream and lower values downstream as expected. Inferred flow directions are eastward and northward along the Athabasca River and Embarras-Mamawi distributary, consistent with a priori knowledge

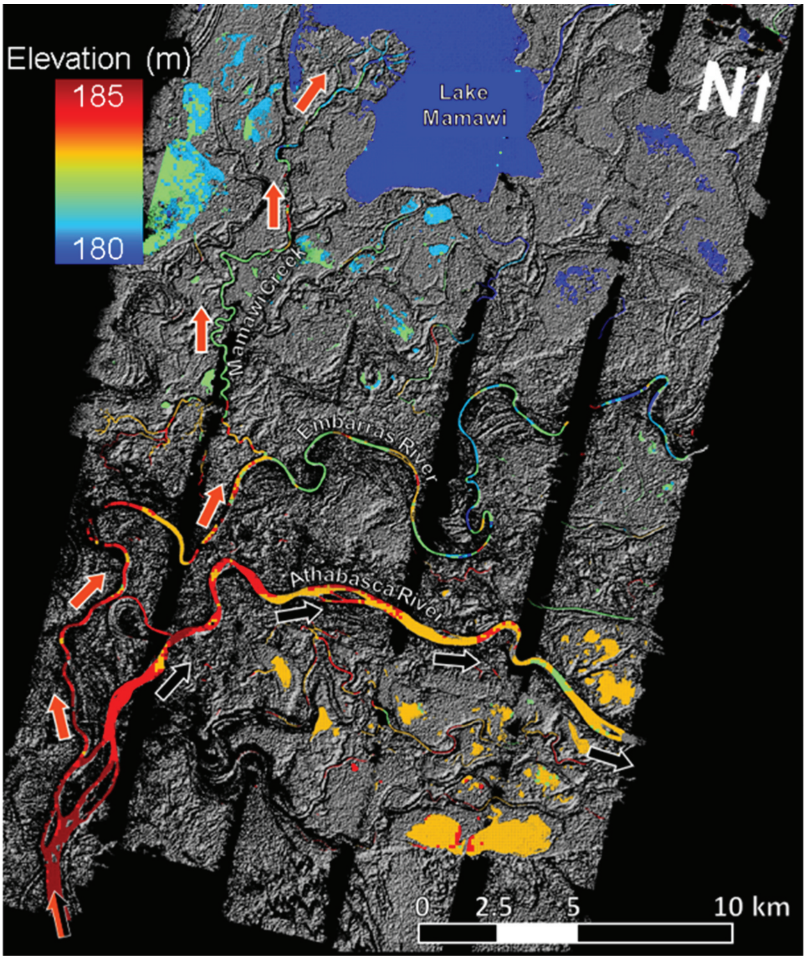

Figure 3. Composite AirSWOT water surface elevations on 9 July and 13 August 2017. Black arrows indicate the east-flowing course of the Athabasca River; red arrows indicate the north-flowing course of the Embarras-Mamawi (EM) distributary channel.

(black and red arrows, Figure 3). Lakes display little or no surface gradient with similar WSE values among proximal water bodies (Figure 3).

Comparison of longitudinal AirSWOT WSE profiles down the Athabasca River and EM distributary suggest a steeper hydraulic gradient of the EM during high-water conditions (gauging station 07DD011 stage = 9.10 m) on 9 July 2017 (Figure 4). On this day, ensemble ordinary-least-squares regressions from the AirSWOT data yield an average WSS of −10.0 cm km^{-1} (EM) and −9.1 cm km^{-1} (Athabasca) with an ensemble spread of 3.0 cm km^{-1} and 2.8 cm km^{-1} respectively. While asynchronous with AirSWOT, a similar phenomenon is evident in our longitudinal field GNSS surveys (Wang et al. 2023) collected the following summer when water levels were nearly as high (07DD011 stage = 8.84 m) averaging −8 cm km^{-1} for the EM (5 August 2018) and −4 cm km^{-1} for the Athabasca (13 August 2018). On 13 August 2017 when water levels were lower (stage = 8.18 m) AirSWOT ensemble slopes were more similar between the two channels, averaging −9.1 cm km^{-1} (EM) and −9.6 cm km^{-1} (Athabasca) with

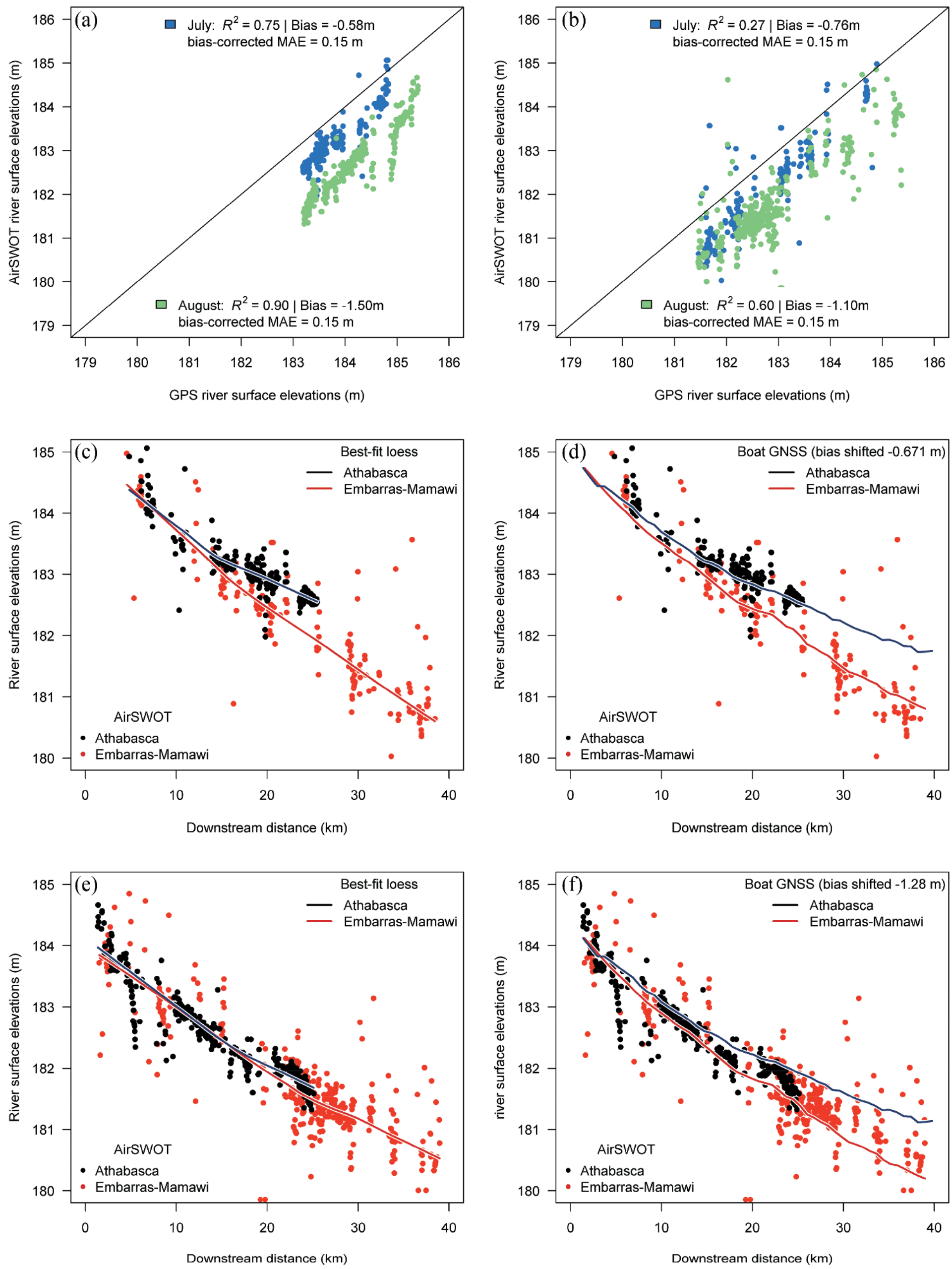

Figure 4. Comparisons between 2017 AirSWOT and 2018 field surveys. WSE profiles down the Athabasca River and Embarras-Mamawi (EM) distributary channel were sampled on 9 July and 13 August 2017 by AirSWOT (c, e); and on 5 August (EM) and 13 August (Athabasca) 2018, respectively, by boat GNSS surveys (d, f). Because the AirSWOT and GNSS data were collected in different years, the absolute elevation values are different (a, b), requiring application of a bias shift to the GNSS data to better align them with AirSWOT observations for visualization purposes (d, f). 2017 AirSWOT data are also presented with 2018 GNSS data for visual comparison (d, f).

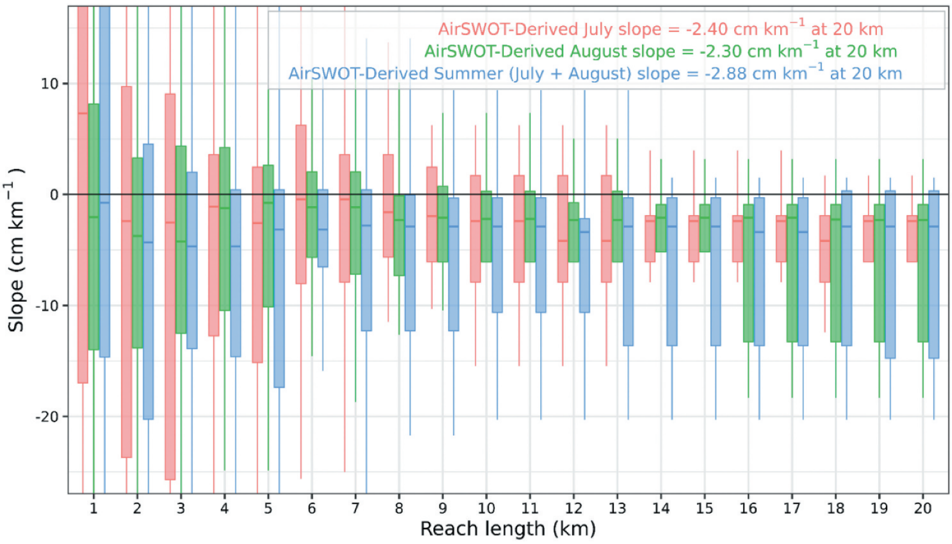

Figure 5. Influence of AirSWOT reach-averaging length on low-gradient water surface slope (WSS) estimation. The mean detected WSS throughout the PAD study area is <3 cm km^{-1} at longer reach-averaging lengths. In general, a reach-averaging length of at least ~10 km is necessary to obtain persistently negative (i.e., flowing downstream) WSS.

an ensemble spread of 3.1 cm km^{-1} (EM) and 1.0 cm km^{-1}. The July AirSWOT and in situ field measurements thus suggest hydraulic conditions favourable for avulsion of the Athabasca River into its EM distributary channel during high discharge conditions, when the EM displays a steeper slope towards a lower elevation on the floodplain.

This conclusion is tempered by the fact that channel width and reach-averaging length significantly impact estimation of WSE and WSS (Figures 4, 5), making estimations for narrow channels challenging. The Mamawi Creek portion of the EM channel is just ~ 30–50 m wide, whereas the Athabasca River is about ~ 250–375 m wide. After bias correcting the 2017 AirSWOT data to mitigate water level differences with 2018 GNSS data (Figures 4 (a,b)), this yields higher mean absolute error for the EM (47 cm in July and 36 cm in August) than the Athabasca River (15 cm in both months). Furthermore, choice of reach-averaging length exerts a profound effect on AirSWOT-derived WSS, greater even than temporal differences between July and August (Figure 5). A minimum reach-averaging length of at least ~10 km appears necessary to confidently infer flow direction (i.e., persistently negative slopes) and WSS in low-gradient PAD rivers (Figure 5).

4. Discussion and conclusion

Despite dark water and noisy elevation data, the 2017 AirSWOT flight campaigns successfully mapped water flow directions, surface elevations, and surface slopes on the PAD after standard data filtering and spatial averaging. This conclusion is supported by a priori knowledge of channel flow directions (Figures 2 and 3), in situ observations from four permanent gauges (**Table S1**), and our field GNSS surveys acquired the following year (Figure 4). The domain-averaged ~44 cm ($\sigma = 271$ cm) drawdown of PAD water levels observed between 9 July and 13 August is noisy but broadly consistent with the gauges (~56 cm, $\sigma = 33$ cm). It is also consistent with summer 2017 drawdowns observed elsewhere in the ABoVE domain by AirSWOT (Fayne et al. 2020); and from Planet smallsat imagery (Cooley et al. 2019). Our study thus affirms the PAD's general synchroneity with seasonal inundation cycles across boreal North America and, more generally, joins a small but growing AirSWOT literature affirming the utility of near-nadir wide-swath Ka-band InSAR for mapping water surface elevations and slopes (Altenau et al. 2017, 2019; Denbina et al. 2019; Fayne et al. 2020; Pitcher et al. 2019; Tuozzolo et al. 2019), including for low-relief wetland environments like the PAD.

Abundant data gaps from dark water make AirSWOT WSS retrievals highly sensitive to reach-averaging length (Figure 5). Despite this, determining flow directions through the low-gradient PAD channel network becomes straightforward if reach averaging lengths exceed ~10 km. This suggests that AirSWOT (and SWOT) could infer channel flow patterns in other, less studied low-gradient wetlands and deltas globally, especially if >10 km reach-averaging lengths are used. While the nominal reach length of the SWOT Rivers Database is 10 km, SWORD also contains many reaches <10 km so users of forthcoming SWOT observations should carefully examine WSE and WSS retrievals in shorter reach lengths to assess their data quality. That said, the dark water reported here for AirSWOT derives from a far larger range of incidence angles (2.8°–15°) than is observed by SWOT (0.5°–4.1°), thus increasing specular scattering and data loss. Ground experiments using a bridge-mounted Ka-band radar report a steep drop-off in backscatter at incidence angles ~ 5–7° (Fjørtoft et al. 2013; Moller and Esteban-Fernandez 2014); and a recent study of AirSWOT backscatter from ~ 11,000 lakes in the ABoVE domain (including the PAD) finds that wind speeds of just ~2 m/s yield bright radar returns (>10 dB) in the near-range (2.8°–5.7°) (Fayne and Smith 2023). The abundant dark water and consequently long reach-averaging lengths described here may be less problematic for SWOT, owing to its smaller incidence angles.

AirSWOT mapping of the EM distributary channel suggests it has a slightly steeper gradient than the Athabasca River during high-water conditions in July, as do in situ GNSS surveys collected the following year (Figure 4). While not the sole driver of river avulsions, hydraulic gradient advantage is a leading factor (Ethridge, Skelly, and Bristow 1999; Jones and Schumm 1999; Slingerland and Smith 1998). Therefore, our findings support Wang et al. (2023) who find potential for the Athabasca River to avulse into the EM using additional lines of evidence (increasing EM discharge, channel widening, and contrasting delta growth rate). While we cannot comment on the probability or pace of such an avulsion, its occurrence would profoundly transform the PAD's inundation patterns, ecology, and human use by diverting its largest direct source of water and sediment northward towards Mamawi Lake rather than eastward towards Lake Athabasca. The EM thus warrants focused field study to assess bank cohesion, bed sill height and grain size, and other factors that also influence whether an avulsion progresses or fails after breaching a new flow course (Slingerland and Smith 1998, 2004). Such work would provide critical physical parameters needed for sediment transport modelling to estimate a probability and timeline for an avulsion.

In addition to dark water and data noise, limitations of this study include lack of perpendicular flight paths and narrow swath overlaps, which hinder data calibration and reduce data volume. Recent Mississippi River AirSWOT campaigns (Denbina et al. 2021; 2021b) demonstrate that greater flight line overlap retains 50% or more of the swath. Future AirSWOT campaigns should 1) file flight plans having both perpendicular and parallel swaths, with at least ~ 30% overlap of the latter (Denbina et al. 2019; Fayne et al. 2020); 2) acquire data during wind speeds >3 m/s to reduce dark water (Fayne and Smith 2023); and 3) collect simultaneous GNSS elevations for calibration/validation (formal protocols for this have been developed by the SWOT mission Calibration/Validation team, JPL 2018). Implementing these recommendations in future AirSWOT flight campaigns would reduce data gaps, improve WSE and WSS retrievals, and perhaps enable shorter reach-averaging lengths.

Regardless of these limitations, AirSWOT near-nadir wide-swath Ka-band InSAR assessed channel WSE, WSS, flow directions, and avulsion potential of the low-gradient Peace-Athabasca Delta, Canada. AirSWOT (and SWOT) data enable computation of WSE and WSS in a way that is otherwise difficult to obtain without in situ GNSS. Our findings thus qualitatively support the simulations of Desrochers et al. (2023), who predict that SWOT observations should significantly improve spatio-temporal understanding of PAD hydrology. Dark water was common and a >10 km reach-averaging length essential for estimating WSS. However, Ka-band InSAR appears to offer a promising new approach for studying surface water elevations, slopes, flow directions, and avulsion potentials in low-gradient floodplains and deltas, portending exciting new research opportunities for AirSWOT and the SWOT mission.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

AirSWOT radar data (Fayne et al. 2019) are available from https://doi.org/10.3334/ORNLDAAC/1646. AirSWOT colour-infrared camera water mask (Kyzivat et al. 2018) are available from https://doi.org/10.3334/ORNLDAAC/1643. Field GNSS data (Wang et al. 2023) are available from https://doi.org/10.

5281/zenodo.7622504. Water Survey of Canada gauging station data are available from https://wateroffice.ec.gc.ca/map/index_e.html?type=historical.

Geolocation information

The approximate geographical centre of our study area is 58.67° N, 111.42° W

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