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Evaluation of RADARSAT-2 DInSAR Seasonal Surface Displacement in Discontinuous Permafrost Terrain, Yellowknife, Northwest Territories, Canada

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Abstract. Differential Interferometric Synthetic Aperture Radar (DInSAR) is an increasingly viable method for assessing permafrost terrain stability, but the accuracy and performance within discontinuous permafrost terrain has not been well studied. We used a RADARSAT-2 DInSAR data stack for a 120-day period in the summer of 2010 to map seasonal surface displacement in the discontinuous permafrost terrain of Yellowknife, Northwest Territories. Calculated displacement was compared to surficial geology and municipal land use zones. Displacement results reveal that glaciofluvial, glaciolacustrine, humanly modified, and organic terrain are increasingly unstable, in contrast to predominantly stable bedrock. Within municipal zones, increased proportional displacement is related to higher proportions of glaciolacustrine sediments and organic terrain. Organic terrain, associated with the highest proportion of the moderate downward displacement (−3.0 cm to −6.0 cm), occupies less than 6% of the total area. Widespread glaciolacustrine sediments (30% total area) are associated with most of the downward displacement in municipal zones. Semi-quantitative field and geotechnical validations indicate that most areas of moderate seasonal downward displacement in developed areas also represent areas of long-term subsidence. This work shows that even a short InSAR data stack and a simple stack processing method can yield information that is useful for municipal knowledge and planning.

Résumé. L'interférométrie différentielle par radar à synthèse d'ouverture (DInSAR) est une méthode de plus en plus viable pour évaluer la stabilité des terrains en zone de pergélisol, mais la précision et la performance dans les zones de pergélisol discontinu ne sont pas bien étudiées. Nous avons utilisé une pile de données DInSAR de RADARSAT-2 d'une période de 120 jours au cours de l'été 2010 pour cartographier le déplacement saisonnier de la surface du sol dans la zone de pergélisol discontinu de Yellowknife, Territoires du Nord-Ouest. Le déplacement calculé a été comparé à la géologie de surface et les zones municipales d'utilisation des terres. Les résultats de déplacements révèlent qu'en ordre de stabilité, du plus stable au moins stable, on trouve les zones fluvio-glaciaires, glacio-lacustres, humainement modifiées et organiques, tandis que le substrat rocheux est essentiellement stable. Dans les zones municipales, le déplacement proportionnel accru est lié à des proportions plus élevées de sédiments glacio-lacustres et du terrain organique. Le terrain organique, associé à la plus forte proportion du déplacement modéré vers le bas (−3.0 à −6.0 cm), occupe moins de 6% de la superficie totale. Les sédiments glacio-lacustres répandus (30% de la superficie totale) sont associés à la plupart des déplacements vers le bas dans les zones municipales. Les validations semi-quantitatives de terrain et géotechniques indiquent que la plupart des zones de déplacement saisonnier modéré vers le bas dans les régions développées représentent également des zones d'affaissement à long terme. Ce travail montre que même une pile de données InSAR de courte durée et une méthode de traitement de pile simple peuvent donner des informations utiles pour la connaissance et la planification municipale.

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INTRODUCTION

Mapping of surface displacement is important for assessing ground and infrastructure stability, monitoring mitigation of problem areas, and planning future land use. Surface displacement occurs from natural and human-induced processes that cause movement of the ground. In Canada's north, surface displacement can be caused by thawing or freezing of ground ice in the near-surface active layer (seasonally frozen layer) or in the underlying permafrost (perennially frozen ground). In thaw-unstable soils, thawing of ground ice can cause downward displacement (subsidence) due to soil consolidation as ice melts and water drains from the soil. Furthermore, where drainage is poor, thawing of ice can increase pore water pressure and weaken the load-bearing capacity of the ground to the point of soil failure. Conversely, the formation of ground ice within the active layer or permafrost can cause upward displacement (heave). Surface displacement due to subsidence or heave might occur on a seasonal basis in association with active-layer thawing or freezing, respectively, but displacement that continues in the same direction over an extended period (i.e., year-over-year) may be associated with permafrost degradation (subsidence) or aggradation (heave). The magnitude of displacement associated with subsidence or heave of the ground surface is a direct function of the ground ice content, which has the potential to be higher in thaw-unstable soils than those that are thaw stable (French 2007). However, for a given thaw-unstable soil, the highest magnitude of seasonal displacement might indicate changing permafrost conditions, rather than seasonal dynamics of the active layer. The effects of these surface displacements create engineering challenges that increase the cost of constructing and maintaining infrastructure (e.g., roads and buildings), especially if there is long-term displacement continuing in the same direction. Consequently, knowledge of the relative magnitude of displacement, as well as the spatial and temporal variability, can provide engineers and municipal planners with information to reduce the risk and cost to northern infrastructure.

The Differential Interferometric Synthetic Aperture Radar (DInSAR) technique uses repeat radar observations to detect millimeter-scale displacement of the ground surface over large areas (Gabriel et al. 1989). The ground displacement information is generated by calculating phase differences on a pixel-by-pixel basis between precisely coregistered radar scenes, the image of the phase difference being called an *interferogram*. When radar echoes are well correlated, phase signals are stable and phase differences can be considered reliable measures of displacement. The correlation of radar echoes is a function of spatial and temporal factors (Zebker and Villasenor 1992). Most satellite missions today have tightly controlled orbits to optimize satellite baselines for interferometry and to minimize spatial decorrelation. Temporal factors that affect phase correlation are related to the change in surface scatterer properties between radar acquisitions. Rearrangement of surface scatterers, vegetation growth or change, changing surface dielectric properties, and wet snowfall or snow melt are all factors that can cause decorrelation of radar echoes in a permafrost environment (Short et al. 2014). Coherence is the measure used to capture the extent to which radar echoes are correlated and the quality of an interferogram (Touzi et al. 1999). High coherence (1) indicates well-correlated echoes and stable phase signals, low coherence (0), or incoherence, indicates noisy and unreliable phase signals.

Interferograms are also subject to other sources of noise and inaccuracy, for example, tropospheric water vapor (Goldstein 1995), ionospheric delay (Gray et al. 2000), or phase aliasing in which the ground displacement gradient exceeds the wrapped phase cycle of the radar wavelength within 1 pixel. Problematic scenes or areas must be excluded from DInSAR processing in order to obtain a reliable ground displacement measurement. Interferometric stacking is a popular technique that can be used to combine multiple interferograms from many data pairs to reduce noise in the results and to identify small cumulative trends (Lyons and Sandwell 2003).

The application of DInSAR to map ground displacement in permafrost terrain has produced some promising results (Rykhus and Lu 2008; Alasset et al. 2008; Liu et al. 2010; Short et al. 2011a; Strozzi et al. 2013; Short et al. 2014). Field validation of DInSAR results is difficult however, because of the large scale and remoteness of permafrost areas. To date, accuracy and value assessments of DInSAR results have focused mostly on the continuous permafrost region, where the vegetation is less developed and causes fewer complicating factors for the DInSAR. Liu et al. (2010) found that values of DInSAR derived seasonal settlement on the North Slope of Alaska were of a comparable order of magnitude to GPS surface elevation measurements and to theoretical amounts of seasonal ground settlement calculated using soil properties and ice content. Short et al. (2014) used detailed surficial geology information and thaw tube measurements of settlement to evaluate DInSAR data generated over one thaw season for Iqaluit, Baffin Island. They found that the DInSAR displacement patterns aligned well with the surficial geology units and reliably captured the relative thaw sensitivity of surficial sediments. Quantitatively, the DInSAR displacements agreed with thaw tube settlement measurements to within 1 cm in dry areas, but significantly underestimated settlement in areas subject to saturation and flooded vegetation. Electrical resistivity surveys showed that the magnitude of DInSAR surface displacement derived over a single season was likely related to both active-layer thaw consolidation and the ground-ice content of near-surface permafrost ($<$ 6 m depth; Short et al. 2014).

In contrast to continuous permafrost, the discontinuous permafrost zone is characterized by numerous patches of frozen ground, deeper active layers, and a more developed vegetation cover, including large shrubs and trees. The accuracy and performance of DInSAR within the discontinuous permafrost region south of the tree line has not been well studied. Short et al. (2011b) generated and published a map of DInSAR seasonal displacement based on RADARSAT-2 data over one thaw

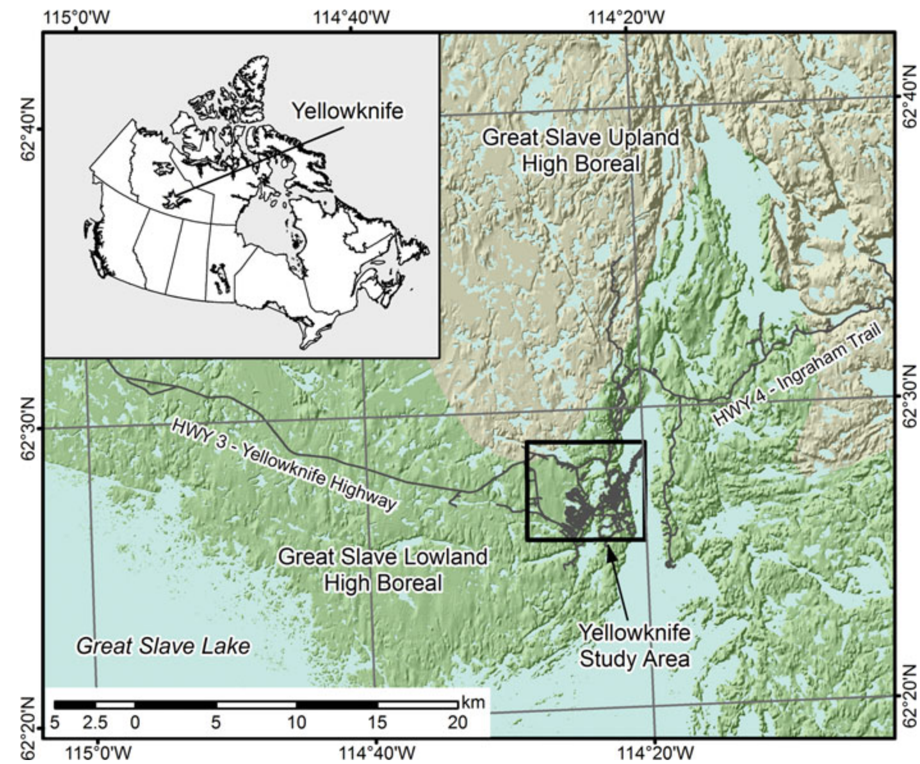

FIG. 1. Location of Yellowknife and the DInSAR study area within the Great Slave Lowland and Great Slave Upland High Boreal ecoregions, both of which lie within the extensive discontinuous permafrost region.

season for Yellowknife, Northwest Territories (NWT), but the displacements were not assessed in detail nor were the results validated.

The purpose of this study is to interpret and assess the Yellowknife DInSAR measurements of seasonal surface displacement, to evaluate the performance of DInSAR in discontinuous permafrost terrain and within a municipal setting, where undeveloped terrain is contrasted against an array of developed areas. In many northern communities, thaw-unstable soils exhibiting high seasonal surface displacement are also associated with more problematic long-term subsidence (Wolfe 1998). Thus, the distribution of higher magnitude seasonal displacement derived from DInSAR measurements might also reflect areas of long-term subsidence. Consequently, the relative magnitude of the DInSAR derived displacement is of interest.

In this study, we do not attempt to quantitatively validate the accuracy of the DInSAR measurements. Instead, utilizing the Yellowknife data generated by Short et al. (2011b), together with detailed surficial geology and semi-quantitative field observations, we test two hypotheses: (1) that the extent of seasonal surface displacement is primarily related to the distribution of fine-grained, thaw-unstable glaciolacustrine sediments; and (2) that the greatest downward seasonal surface displacement is associated with long-term (i.e., year-over-year) ground subsidence. To assess the potential contribution of DInSAR information to planning and managing infrastructure, we also compare DInSAR surface displacement results to municipal land use zones and examine the variability in terrain stability between zones.

STUDY SITE

Yellowknife is the territorial capital and largest community in the NWT. It is situated at the mouth of the Yellowknife River (62° 26′ N, 114° 24′ W), on the north shore of Great Slave Lake (Figure 1). The city resides within the Great Slave Lowland low subarctic taiga forest, an ecological region consisting of poorly drained, low-relief terrain characterized by numerous water bodies separated by fens, peatlands, mixed woodlands, white birch (*Betula papyrifera*), and black spruce (*Picea mariana*) forests and bedrock outcrops. The region is bordered to the south by the North Arm of Great Slave Lake and to the north by the Great Slave Upland of higher relief and bedrock exposures. The entire region was glaciated until about 13,000 cal BP (cal = radiocarbon dating calibrated years, BP = Before Present [1950]; Dyke et al. 2003). With the retreat of glacial ice, glacial Lake McConnell and, subsequently, Great Slave Lake inundated the area (Lemmen et al. 1994; Smith 1994). Undifferentiated glaciolacustrine and lacustrine silts and clays deposited into these former water bodies constitute the majority of the

FIG. 2. Photographs of terrain in the Yellowknife area. (A) Collapsing peatland and pond in foreground with Yellowknife Visitors Centre and downtown in background; (B) Franklin Avenue with view towards Great Slave Lake with typical city infrastructure, utilities and lawn juxtaposed by taiga forest cover of black spruce and willow; (C) urban street and mixed-density residential area on glaciolacustrine clay, note ponded areas on road indicative of subsidence.

surficial sediments across the area (Stevens et al. 2012). Sands and gravels, likely representing reworked glaciofluvial sediments, also occur within Yellowknife, underlying both the airport and downtown core areas (Aspler 1978).

Mean monthly air temperatures in Yellowknife for 1971–2000 range from 16.8 °C in July to −26.8 °C in January, and the yearly average is −4.6 °C, according to Environment Canada 2014.[1] Since the 1940s, annual mean air temperature has risen by about 0.3 °C per decade (Hoeve et al. 2004; Riseborough et al. 2012). Permafrost is extensively discontinuous (Heginbottom et al. 1995), and is typically warmer than −1°C at a depth of 10 m, with active-layer thicknesses ranging from 50 cm to 95 cm in peatlands and 130 cm or more in forested areas (Gaanderse 2011). Bedrock outcrops between low-lying pockets of glaciolacustrine silts and clays that typically preserve permafrost within undisturbed terrain.

Yellowknife was first settled in the 1930s, near Yellowknife Bay, and expanded westward between 2 gold mine properties (Giant and Con mines) as the population grew. With urban expansion, much of the original vegetation cover was replaced by buildings, roadways, tarmac, sidewalks, gravel surfaces, and urban lawns typical of more southerly settings (Figure 2). Thus, most developed areas represent disturbed terrain bearing little resemblance to the original land cover of the low subarctic taiga forest. Many areas within Yellowknife have experienced historical ground settlement due to various terrain-altering factors including vegetation removal, drainage alterations, and heat flow into the ground such as from buildings (Wolfe 1998). In Yellowknife, clean sands and gravels (and bedrock) do not typically contain excess ice, and may, therefore, be thaw stable (i.e., experience minimal settlement upon thawing). However, fine-grained silt and clay permafrost soils in the area are typically thaw unstable, and can undergo excessive settlement if allowed to thaw. Such thaw-unstable conditions have been known to pose problems for roadways, buildings, the airport, and other infrastructure in Yellowknife (Wolfe 1998). Due to considerable modification of terrain by development in the Yellowknife area, land cover per se is not considered a suitable variable for analysis in this study. Thus, we evaluate DInSAR results primarily in the context of the underlying surficial geology and the municipal zonations in the area.

DATA

RADARSAT-2 Data

DInSAR analysis was performed on a short stack of 5 repeat-pass RADARSAT-2 scenes from the summer of 2010, forming 6 interferograms (Table 1). Only scenes between May and September were used in order to isolate the summer settlement from the full annual cycle of heave and settlement. The

[1]http://climate.weather.gc.ca

TABLE 1
RADARSAT-2 data for Yellowknife using descending path, right-looking, Beam Mode Ultra-Fine 19, relative orbit 121, satellite heading −171°, acquisition time 13:53 UTC or 07:53 local, mid-incidence angle 45.58°

Data Pairs (yyyymmdd–yyyymmdd)	Time Separation (days)	Perpendicular Baseline (m)	Doppler Centroid Difference (Hz)
20100521–20100708	48	104	13.12
20100708–20100801	24	13	44.54
20100708–20100825	48	4	91.36
20100801–20100825	24	−9	46.82
20100801–20100918	48	−259	40.13
20100825–20100918	24	−250	6.69

RADARSAT-2 satellite, in operation since December 2007, carries a C-Band SAR (5.6 cm wavelength) and acquires repeat scenes at 24-day intervals. Among the acquisition modes available, Ultra-Fine Beam Mode with approximately 3 m resolution and horizontal transmit and horizontal receive (HH) polarization was used for Yellowknife.

Elevation Data

DInSAR processing uses a digital elevation model (DEM) to remove phase shifts due to topography. A high-resolution DEM was created from ALOS-PRISM stereo optical imagery acquired on July 10, 2010, with 5 m pixel spacing. Although no field validation of accuracy was performed, comparisons with another DEM derived from RADARSAT-2 data and well calibrated with ICESAT data, suggest a relative vertical accuracy of approximately 2.1 m.[2]

Surficial Geology

Surficial geology for the city of Yellowknife was derived from manual interpretation of monochromatic aerial photographs from Natural Resources Canada's National Air Photo Library at a scale of 1:13000. Historical development has obscured much of the original underlying bedrock and surficial sediment, making recent imagery less suitable for geological mapping. Therefore, aerial photographs from 1970 were selected for the surficial mapping. An area covering all of the DInSAR results within the city limits was mapped and digitized for the purposes of this study. Six surficial geology units were mapped (Table 2): glaciolacustrine and glaciofluvial sediments, bedrock, organic terrain (peatlands), humanly modified terrain, and water. The small area mapped as humanly modified terrain represents a former pond that was subsequently used as a landfill site and is now recreational land. The horizontal resolution of the final surficial geology map was ∼100 m.

[2]From personal communication with Alexandre Beaulieu (Project Officer, Canada Centre for Mapping and Earth Observation, Natural Resources Canada), December, 2013

Municipal Land Use

Municipal land use zones were obtained as Shapefiles from the Geomatics Office of the City of Yellowknife and aggregated from 26 to 9, with similar zones combined to simplify analysis and interpretation with DInSAR displacement. The composition of each zone is described in Table 3.

METHODS

DInSAR Processing

The DInSAR processing was carried out using the GAMMA InSAR processing software (Werner et al. 2000). The scene acquired on July 8 (i.e., 20100708 in Table 1) was selected as the master, based on the clarity of features and lack of ice, snow, and wind-roughened water bodies. All other scenes were coreg-

TABLE 2
Surficial geology units mapped within the study area

Surficial Unit	Description
GL	Glaciolacustrine sediments: silt and clay ≥ 5 m thick.
GF	Glaciofluvial sediments: sand and gravel to cobbles, typically forming terraces or outwash plains of variable thickness; might be reworked by wave action and might include bedrock outcrops
B	Bedrock: might be overlain by thin discontinuous cover of till or glaciolacustrine veneer or isolated glaciofluvial sediments
O	Organic terrain: fen or bog (i.e., peatland)
H	Humanly modified terrain (landfill covered by grass sports field)
W	Water

TABLE 3
Simplified municipal zones for Yellowknife

Code	Zonation	Description
AP	Airport & Environs	Airport runway, facilities, hangars and undeveloped lands
CS	Commercial Service	Retail services
GM	Growth Management	Undeveloped, landfill, trails, abandoned property, aggregate areas
IND	Industrial	Industrial, business industrial, general industrial, limited industrial
MU	Mixed Use	Commercial, industrial, residential areas including Downtown, Kam Lake light industrial/commercial, mix, N'Dilo community, Old Town mixed use, public service, site specific zone
NPR	Nature Preservation / Park & Recreation	Heritage preservation, nature preservation, park and recreation, watershed protection
R-M	Residential – Manufactured Dwelling	Preconstructed residential dwelling (i.e., mobile homes)
R-LD	Residential – Low-Density	Single detached dwellings
R-MX	Residential – Mixed-Density	Single detached and duplex dwellings; medium- and high-density residential; waterside residential

istered to this master. Following coregistration, interferograms were generated using range spectrum filtering and common band filtering in azimuth. The original SAR pixel spacing was 1.3 m in range and 2.0 m in azimuth, 3 × 2 multilooking was applied to reduce phase noise and resulted in interferograms with 5.6 × 4.0 m ground range pixels. The 5-m DEM was used to remove the topographic phase and create differential interferograms. The differential interferograms were adaptively filtered (Goldstein and Werner 1998) and unwrapped using the minimum cost flow phase unwrapping algorithm (Costantini 1998). Baseline estimates were refined using the approach of Rosen et al. (1996). This approach compares phase values simulated from the DEM at ground control points with the phase values in the initial interferograms. Long-scale trends in phase values can be identified and used to correct inaccurate baseline estimates. Interferograms are reformed using the refined baseline estimates.

The unwrapped interferograms were stacked to reduce noise in the data, such as mild atmosphere and other sources, and to improve the detection of subtle surface displacement (Lyons and Sandwell 2003). A small amount of interpolation (4-pixel radius) was used to fill small holes due to coherence loss in the unwrapped interferograms prior to stacking. A bedrock area assumed to be stable was used as the phase reference point (marked with a triangle in Figure 3). All phase unwrapping proceeded from this point, and all displacement measurements are relative to this point. The stacked summer rate of displacement was calculated for each pixel and converted from radar line-of-sight to vertical displacement as per Short et al. (2014). This stacking method calculates a linear rate of displacement for the full time period of observation using the sum of the unwrapped phase measurement in each interferogram weighted by the time period of that interferogram (Werner et al. 2012). It is a simple method, and the linear rate of displacement might not be perfectly appropriate for the permafrost environment, because displacement can often be most dramatic early in the summer season; however, it is simple to implement and it is a reasonable first estimate. Vertical displacement was used and considered generally appropriate for the mostly low-relief Yellowknife area, noting that higher relief areas are typically bedrock.

The DInSAR vertical displacement product was geocoded to a 4-m horizontal resolution raster using the coregistered DEM and was formatted as a geotiff for import to PCI Geomatica^{TM} 10 and ArcGIS for further analysis. All areas defined as water bodies in the National Topographic Map Sheet at 1:50,000 scale were clipped out and removed from the analysis, because water is typically incoherent and would produce no, or misleading, displacement results.

An estimate of the general error in the DInSAR displacements was obtained by examining the displacement statistics. The standard deviation (σ) of the stacked summer vertical displacement was determined to be 0.47 cm. In order to create a reliable map product we used 2 standard deviations and rounded up to establish our practical margin of error as ± 1 cm. Movement within ± 1 cm is therefore considered insignificant and classified as stable. This error estimate captures the general background level of noise in the data, such as residual atmosphere and other sources. As shown by Short et al. (2014), this method of error estimate is generally reliable over dry terrain; however, there can be substantial spatial variation in the error due to terrain type and surface saturation. In the Yellowknife study, large localized inaccuracies ($> 2\ \sigma$) occurred in some areas, see Figure 3. These areas frequently demonstrate a nonlinear displacement pattern. Often they are associated with forest and shrub cover and are likely the result of random phase

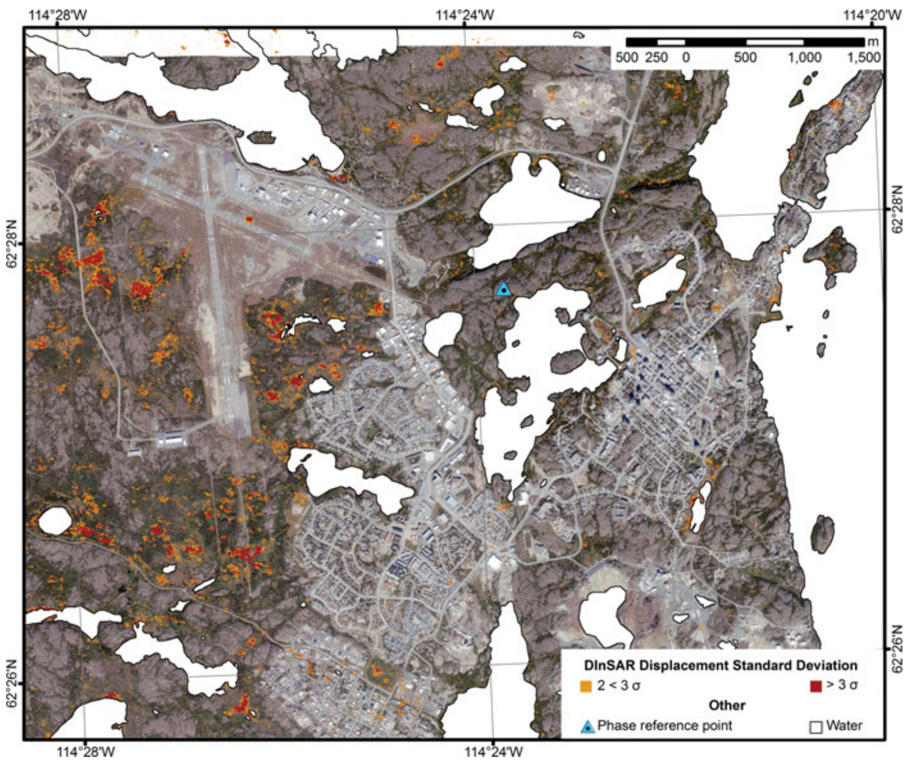

FIG. 3. DInSAR standard deviations (> 2 σ) of seasonal surface displacement overlaid on 3.2 m resolution IKONOS satellite image of Yellowknife acquired August 21, 2005. Note the IKONOS image has a slightly limited northern extent. Satellite image courtesy of GeoEYE (www.geoeye.com). © GeoEYE. Reproduced by permission of GeoEYE. Permission to reuse must be obtained from the rightsholder.

trends associated with radar reflections from randomly moving vegetation. Large errors in organic terrain might be caused by variable phase trends due to poor drainage and surface water. In non-vegetated areas the large errors might be caused by real but significantly non-linear ground displacement. These areas of high error should be interpreted with caution, particularly the vegetated areas; however, they are often small patches within larger trends and have not been removed because they might contain real information.

Spatial Analysis

DInSAR vertical surface displacement values were partitioned into 5 distinct classes using a relative scale (Table 4). Stable ground represents locations where the displacement was within the established range of error (±1.0 cm). Low and moderate downward displacement represent surface lowering on the order of −1.0 cm to −3.0 cm and −3.0 cm to −6.0 cm, respectively. Upward displacement represents surface uplift of +1.0 to +6.0 cm. Incoherent areas are those where a loss of interferometric coherence occurred due to significant temporal change in surface characteristics. A mode filter (3-by-3 window) was run 3 times on the partitioned DInSAR data to reduce noise in the results. The effect of this filter is to remove isolated pixels and smooth the output. Statistically, the filtering transfers 2% to 3% of the upward and low downward displacement pixels to the stable class. Although noticeably cleaning the dataset, this does not significantly change the spatial distribution of observed pockets of displacement.

To analyze the DInSAR displacement with the surficial geology and municipal land use zones, the vector layers of surficial geology and land use were converted to raster format with 4-m

TABLE 4
Relative seasonal surface displacement classes of DInSAR data

Class	Description
Moderate downward	−3.0 cm to −6.0 cm downward displacement
Low downward	−1.0 cm to −3.0 cm downward displacement
Stable	No change or within expected range of error (+/− 1.0 cm)
Upward	1.0 cm to 6.0 cm upward displacement
Incoherent	Loss of coherence during radar acquisition period (no displacement calculated)

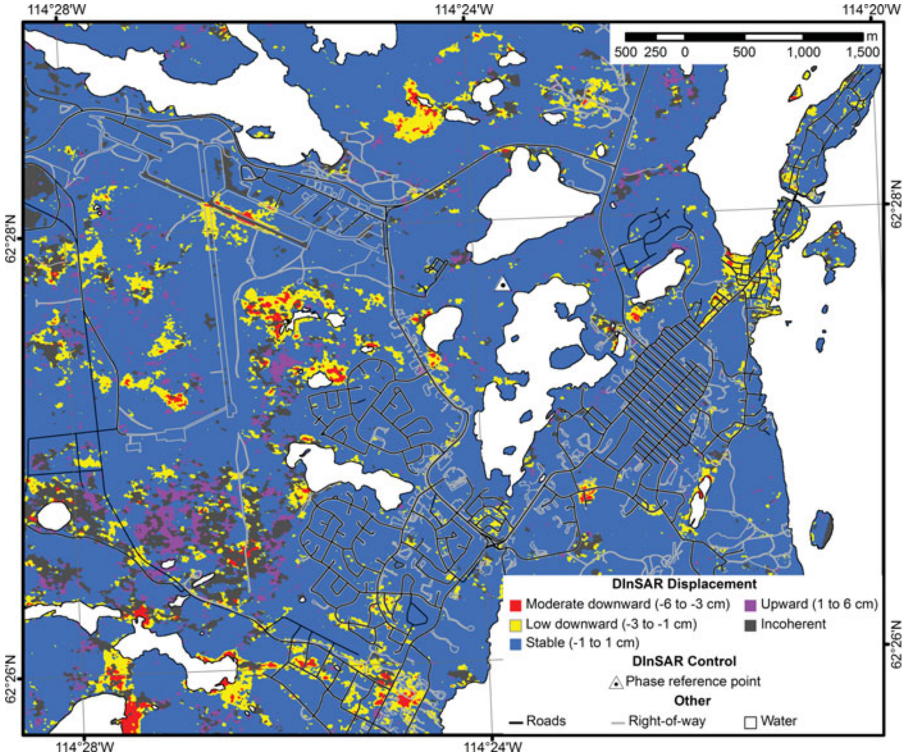

FIG. 4. DInSAR derived seasonal surface displacement for Yellowknife from May to September, 2010.

ground-resolution pixels, in agreement with the resolution of the DInSAR geotiff. The raster datasets were coregistered to the DInSAR data so that pixels were congruent. The relations of these input data layers were determined by overlay analyses, which were performed via coincidence matrices generated for DInSAR displacement values against surficial geology and municipal zoning. Statistics generated for each unique combination of classes were used to test hypothesis (1), that the extent of seasonal surface displacement is primarily related to the distribution of glaciolacustrine sediment, and to assess the potential of DInSAR data for planning and managing infrastructure.

Field Observations

To test hypothesis (2), that moderate seasonal displacement is related to long-term subsidence, field observations were made at 49 sites of DInSAR moderate downward displacement. Field observations were carried out each June between 2010 and 2013, with summary observations made June 7–24, 2013. Observations included noting indications of subsidence such as slumping of soils, surface cracking, and displacement of road surfaces and sidewalks. Where possible, field measurements were made of the amount of subsidence across roads and sidewalks, assuming that surfaces were level when first constructed, although the date of initial construction was often not known. In addition, where available, geotechnical reports, containing borehole and ground temperature information, were used to determine if moderate seasonal surface settlement correlated with reported long-term ground subsidence and to assess the causes of the observed settlement.

RESULTS AND DISCUSSION

DInSAR Displacement Map

The surface displacement derived using stacked RADARSAT-2 DInSAR for 120 days from May to September 2010 is shown in Figure 4. Of the 33 km^2 Yellowknife study area, 82% is classified as stable, 7% as low downward displacement, 1% as moderate downward displacement, 3% as upward displacement, and 7% as incoherent.

Surficial Geology and Displacement

Bedrock is the most common surface material, occupying 16 km^2 (~47%) of the Yellowknife area (Table 5). Glaciolacustrine sediments, representing clay soils that typically contain permafrost, cover about 10 km^2 (~30%) of the Yellowknife area, whereas glaciofluvial sediments cover about 6 km^2 (~17%). Organic terrain, typified by peatlands with permafrost, covers less than 2 km^2 (~6%).

Results of the DInSAR seasonal surface displacement together with the surficial geology are shown in Figure 5. DInSAR patterns of displacement align well with surficial geology. Bedrock is the most stable (~96%), with very low (~1%)

TABLE 5
Percent of DInSAR seasonal surface displacement contained within each surficial geology unit in Yellowknife

	Surficial Geology Unit				
DInSAR Displacement	B (47)	GF (17)	GL (30)	H (0.1)	O (6)
Stable	96.1	86.2	67.0	40.2	39.3
Incoherent	1.1	7.5	12.7	22.2	17.2
Low downward	1.4	4.5	14.1	37.6	30.5
Moderate downward	—	0.3	1.2	—	8.0
Upward	1.4	1.5	5.0	—	5.0
Total (%)	100	100	100	100	100

Values in parentheses indicate percent of total map area covered by that terrain type.

amounts of displacement and incoherence (Table 5). Stability of bedrock surfaces is expected, and the small areas of displacement noted likely occur within other surficial materials on bedrock but that are smaller than the limit of surficial mapping. The horizontal resolution of the surficial geology data is 100 m, whereas the resolution of the DInSAR data is 4 m; therefore, pockets of DInSAR displacement associated with areas of surficial sediments smaller than 100 m could certainly occur within the bedrock.

Organic terrain, in contrast, represented mostly by areas of peatland, is the least stable surficial unit, with 43% having some type of displacement and 17% being incoherent. Downward displacement of the organic terrain might be due to seasonal thaw within the active layer, or thawing of permafrost at depth, and possibly drying of organic terrain. Upward displacement (5%) may be caused by rising water levels, due to buoyancy of a vegetation mat or radar returns from flooded vegetation. Incoherence might be caused by open water resulting in specular reflectance and loss of the SAR signal, or structural surface change. Humanly modified terrain, a small area that was once landfill and is presently a recreational park, is another unstable surficial unit with ∼38% low downward displacement and 22% incoherence. Incoherence of this surface is likely related to the frequent disturbance of the recreational surfaces (i.e., baseball fields).

Glaciolacustrine sediments cover much of the Yellowknife area, and 20% of this terrain has some displacement representing about 2 km^2 of unstable land surface. As with other terrain, downward displacement can be related to seasonal thaw of the active layer or thawing of permafrost at depth. It could also be related to consolidation within taliks (perennially unfrozen ground). Upward displacement and incoherence on these glaciolacustrine surfaces are most likely related to anthropogenic surface modifications, including road and utility construction and regrading of gravel surfaces.

Glaciofluvial sediments are mostly stable (86%). However, about 6% shows some displacement and 7% is incoherent. Displacement occurring within this terrain might be related to glaciolacustrine deposits underlying the glaciofluvial sediments (see “Geotechnical Information” section). Lastly, some incoherence, as at the airport, appears to be related to changing surface conditions on the airstrips and to the movement of airplanes between SAR acquisitions.

Municipal Land Use Zones and Displacement

Table 6 illustrates the relation between simplified municipal zones and surficial geology, which is important for further understanding the DInSAR displacement results. The Airport & Environs zone (AP) represents the airport infrastructure and surrounding cleared and undeveloped forest lands located on a range of surficial materials, including a large proportion (∼62%) on glaciofluvial sediments. The Commercial Service zone (CS) has large and small commercial stores, paved roadways, and parking lots located primarily on glaciolacustrine sediments and bedrock, and a small amount on glaciofluvial sediments. The Growth Management zone (GM) represents mostly undeveloped land within and bordering the city, including the active landfill site, ski trails, former gold mining property, and aggregate resource areas. This zone has the highest proportion of organic terrain (10%). The Mixed Use zone (MU) represents various commercial, light industry and residential areas in several discrete parts of Yellowknife, including the downtown core. The Nature Preservation / Park & Recreation zone (NPR) represents undeveloped land, including areas deemed too unstable for infrastructure. This zone covers about one-quarter of the Yellowknife area and has the highest proportion of bedrock (62%) within it. The Residential Manufactured Dwelling zone (R-M) represents primarily mobile homes with adjustable footings on granular pads. As with most other residential zones, these are serviced by paved or unpaved roads with underground water and sewer utilities in most areas. The Residential Low-Density zone (R-LD) represents detached residential dwellings, whereas Residential Mixed-Density (R-MX) includes single detached and duplex dwellings, mixed and high-density residential, and waterside residential areas. Despite the common occurrence and stability of bedrock, construction of roadways and

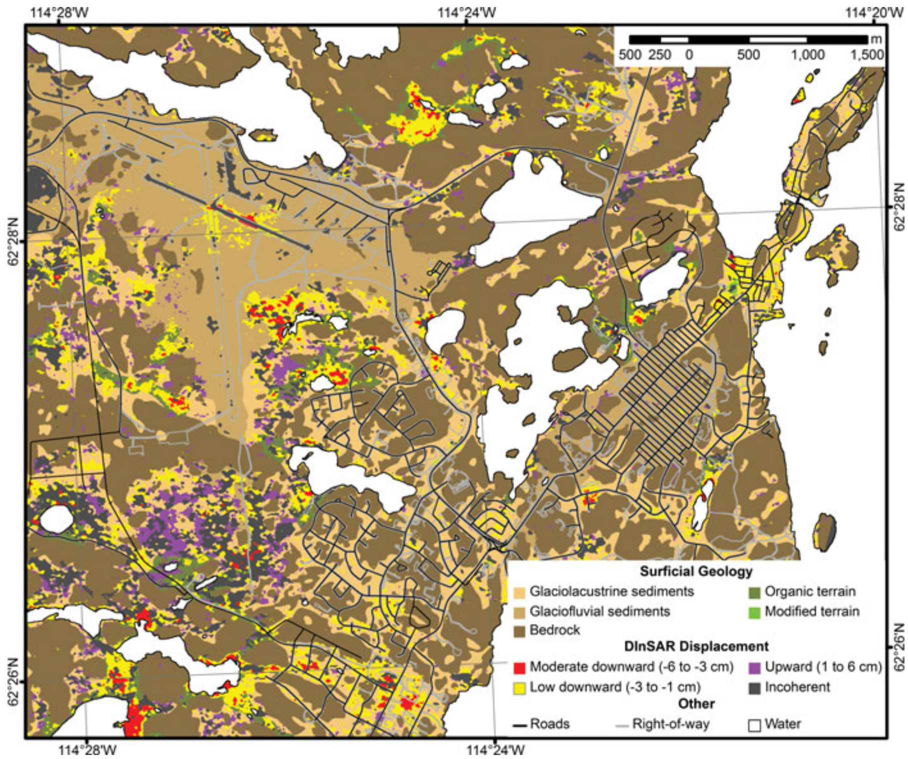

FIG. 5. Surficial geology overlain with DInSAR seasonal surface displacement. DInSAR stable areas are omitted in order to reveal the surficial geology.

utility services on rock is expensive compared to construction on unconsolidated sediments. Therefore, much of the Yellowknife infrastructure has been historically built on glaciolacustrine and glaciofluvial sediments.

Results of the DInSAR seasonal surface displacement together with the simplified municipal zones for Yellowknife are shown in Figure 6, and Table 7 indicates the percent area of DInSAR classes within each municipal zone. Results indicate that the Residential Mixed Density zone is the most stable (96%), with 2% of low downward displacement. The high stability of this zone is likely due to the fact that 57% of it occurs on bedrock, the highest proportion of any built infrastructure municipal zone. In comparison, both Residential Low Density and the Mixed Use zones are relatively stable (~90%), and each contain less than 50% area on bedrock (33% and 46%, respectively). The higher amount (8.5%) of low downward displacement within Residential Low Density is almost entirely due to occurrence on glaciolacustrine sediments, which occurs on 58% of this zone. In comparison, the low downward displacement (6%) and incoherence (3%) within the Mixed Use

TABLE 6
Percent of surficial geology unit contained within each simplified municipal zone in Yellowknife

	Simplified Municipal Zones								
Surficial Geology	R-MX (4)	R-LD (4)	MU (7)	CS (2)	R-M (4)	NPR (24)	AP (17)	IND (5)	GM (33)
Bedrock	57.0	33.4	46.3	39.5	49.0	62.0	19.0	46.3	51.9
Glaciolacustrine	27.1	58.2	23.2	55.2	48.4	24.6	14.4	52.2	33.0
Glaciofluvial	15.0	7.4	25.1	5.3	0.7	8.1	62.4	—	5.1
Organic	0.9	1.0	5.4	—	1.9	5.2	4.1	1.5	10.0
Humanly modified	—	—	—	—	—	0.2	—	—	—
Total (%)	100	100	100	100	100	100	100	100	100

Values in parentheses indicate percent of total map area covered by that municipal zone.

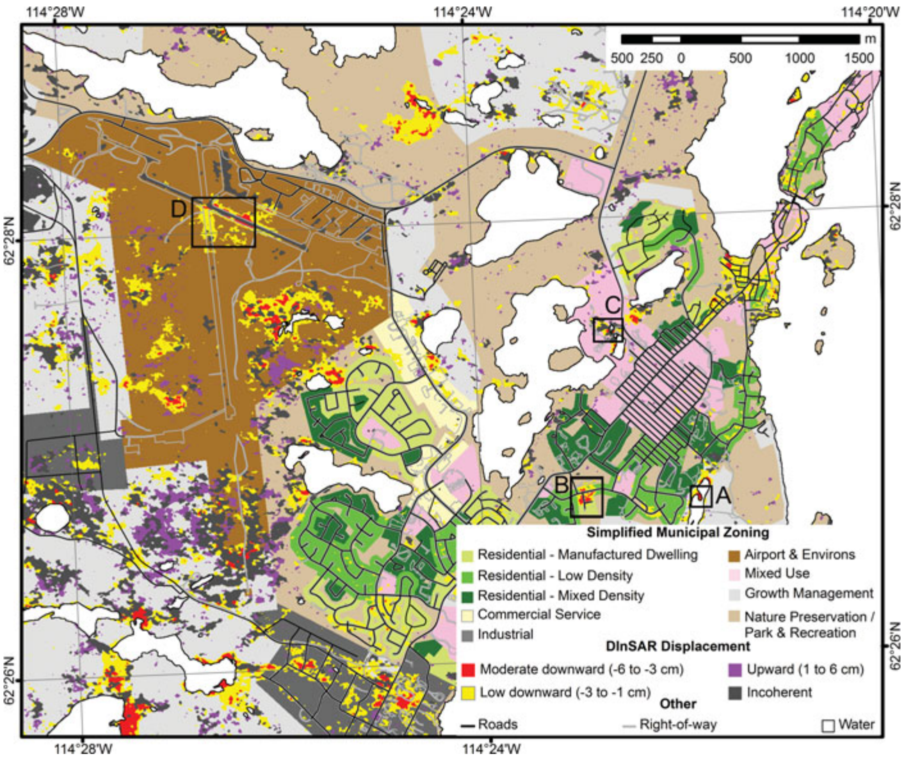

FIG. 6. Simplified municipal zones and DInSAR seasonal surface displacement for Yellowknife. Boxes labeled A, B, C, D refer to validation areas discussed in text.

zone may be mostly attributable to the occurrence of unstable organic terrain (∼5% of this zone). The Commercial Service and Residential Manufactured Dwelling zones have similar extents of stability (∼87%), total displacement (∼11%) and incoherence (∼1.5%). Displacement occurring within these zones is primarily due to occurrence of glaciolacustrine sediments (about 55% and 48%, respectively) and, in the case of the Residential Manufactured Dwelling zone, organic terrain, which occurs in ∼2% of this zone. Despite the relatively high proportion of Nature Preservation/Park & Recreation zone occurring on bedrock (∼85%), this zone is only moderately stable (85%) because of the organic terrain (5%) occurring within it. The remaining Growth Management, Industrial, and Airport & Environs zones are all less stable (77%–81% stable). In the case of the Airport & Environs zone, this is likely in part due to the occurrence of glaciofluvial sediments that are underlain by glaciolacustrine sediments (see "Geotechnical Information" section). Within the Industrial zone, displacement mainly occurs on glaciolacustrine sediments, which represent 52% of this zone, whereas within Growth Management, the combination of organic terrain and glaciolacustrine sediments, covering 10% and 33%, respectively, are the likely factors.

TABLE 7
Percent of DInSAR seasonal surface displacement contained within each simplified municipal zone in Yellowknife

	Simplified Municipal Zones								
InSAR Displacement	R-MX (4)	R-LD (4)	MU (7)	CS (2)	R-M (4)	NPR (24)	AP (17)	IND (5)	GM (33)
Stable	95.9	90.1	89.4	87.6	86.9	84.9	81.3	78.3	77.1
Incoherent	0.9	0.5	3.1	1.4	1.7	6.0	6.9	4.0	10.3
Low Down	2.4	8.5	6.2	9.7	10.3	5.7	8.1	14.2	7.5
Mod. Down	0.1	0.4	0.3	0.7	0.8	0.6	1.1	1.9	1.1
Upward	0.7	0.5	0.9	0.7	0.3	2.8	2.5	1.6	4.0
Total (%)	100	100	100	100	100	100	100	100	100

Values in parentheses indicate percent of total map area covered by that municipal zone.

TABLE 8
Area (in hectares) of low (−1.0 cm to −3.0 cm) and moderate (−3.0 cm to −6.0 cm) downward displacement within simplified municipal zones and surficial geology units.

	Simplified Municipal Zones									
	R-MX (131)	R-LD (129)	MU (225)	CS (58)	R-M (124)	NPR (817)	AP (559)	IND (184)	GM (1113)	Total (ha)
Surficial Geology	Low downward displacement (hectares)									
Bedrock	0.2	0.6	1.5	0.1	0.4	4.5	2.0	1.3	11.2	21.8
Glaciolacustrine	2.5	10.1	9.0	5.5	11.6	22.0	14.1	24.0	42.0	140.8
Glaciofluvial	0.3	0.1	1.2	–	0.2	2.2	19.9	–	1.1	25.0
Organic	0.1	0.1	2.4	–	0.5	17.5	9.3	0.8	29.4	60.1
Humanly modified	–	–	–	–	–	0.5	–	–	–	0.5
Total (ha)	3.1	10.9	14.1	5.6	12.7	46.7	45.3	26.1	83.7	248.2
	Moderate downward displacement (hectares)									
Bedrock	–	–	–	–	–	0.1	–	0.1	0.1	0.3
Glaciolacustrine	0.1	0.5	0.2	0.4	0.8	1.1	2.9	3.1	2.3	11.4
Glaciofluvial	–	–	–	–	–	–	1.8	–	0.1	1.9
Organic	–	–	0.5	–	0.1	3.6	1.3	0.3	9.9	15.7
Humanly modified	—	—	—	—	—	–	—	—	—	–
Total (ha)	0.1	0.5	0.7	0.4	0.9	4.7	6.0	3.5	12.6	29.4

Values in parentheses indicate total area (in hectares) covered by that municipal zone.
Note: single dash (–) indicates a zero value; triple dash (—) indicates the surficial unit is not present in that zone.

Testing Hypothesis (1): That Seasonal Surface Displacement Is Primarily Related to the Distribution of Fine-Grained, Thaw-Unstable Glaciolacustrine Sediments

Table 8 shows the extent (in hectares) of low (−1.0 to −3.0 cm) and moderate (−3.0 to −6.0 cm) seasonal downward displacement within each simplified municipal zone and surficial geology unit. Of the total 248 hectares of low downward displacement in the Yellowknife area, 57% (141 ha) occurs on glaciolacustrine sediments and 24% (60 ha) occurs on organic terrain. In regard to moderate downward displacement (total area of 29 hectares), about 39% (11 ha) occurs on glaciolacustrine sediments and 53% (16 ha) occurs on organic terrain. Overall, 55% (152 ha) of the total area of moderate and low downward displacement is associated with glaciolacustrine sediments, which confirms our hypothesis that the extent of seasonal surface displacement is primarily related to the distribution of glaciolacustrine sediments. As these thaw-unstable sediments are widespread (occupying 30%) in the Yellowknife area, they are not easily avoidable within the municipality and are therefore associated with most of the observed downward displacement in the Residential Low Density, Mixed Density, and Manufactured Dwelling zones, and Commercial Service and Industrial zones. However, the results further illustrate the significance of organic terrain in regard to downward displacement. Despite the fact that organic terrain occupies only about 6% of the Yellowknife area, it accounts for most (52%) of the moderate downward displacement. Given the low total area of organic terrain, it can be more readily avoided by development than glaciolacustrine sediments, and at present, much of the downward displacement within organic terrain (∼94%) occurs within undeveloped lands in the Growth Management, Nature Preservation/Parks & Recreation, and Airport & Environs zones. It is notable, however, that ∼6% of the low and moderate downward displacement within organic terrain has occurred on developed lands in the Mixed Use, Residential Manufactured Dwelling, and Industrial zones. In the case of the Mixed Use zone, most of the moderate downward displacement could be attributed to displacement on organic terrain.

Testing Hypothesis 2: That Moderate Downward Seasonal Surface Displacement Is Associated with Long-Term Ground Subsidence

This hypothesis was tested using field observations and geotechnical information taken from various reports.

Field Observations

The moderate downward displacement in Table 8 represents a total area of ∼29 hectares distributed among 519 locations in the Yellowknife area. These are primarily located on glaciolacustrine (11 ha) and organic terrain (16 ha) distributed within most municipal zones, with a small proportion (2 ha) on glaciofluvial sediment that is almost entirely within the Airport & Environs zone. Figure 7A shows the size distribution of areas within glaciolacustrine sediments and organic terrain. Most sites

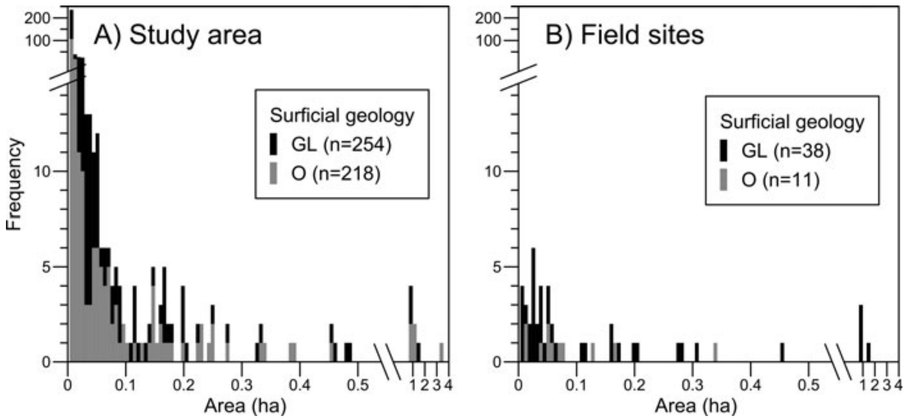

FIG. 7. Frequency distribution of moderate downward displacement areas (in hectares) on glaciolacustrine sediments and organic terrain. (A) Distribution of all sites in the Yellowknife area; (B) distribution of 49 field sites investigated.

(∼88%) are small, being less than 0.1 hectares (1000 m^2) in area, and more than half are smaller than 0.01 hectares (100 m^2).

We undertook field examinations of 49 accessible sites of moderate downward displacement. The field sites included 38 locations on glaciolacustrine sediments and 11 on organic terrain. The size-area distribution of the field sites is similar to the distribution of moderate downward displacement for organic and glaciolacustrine terrain in the Yellowknife area (Figure 7A and B). However, the higher proportion of glaciolacustrine sites to organic sites in our field examinations compared to the complete dataset reflects the fact that municipal development occurs more commonly on glaciolacustrine sediments. Table 9 summarizes the field observations and total subsidence estimates made at the 49 moderate downward displacement sites examined.

Within organic terrain, evidence of subsidence was noted at all sites (Table 9). Although it was not possible to quantify estimates of subsidence within organic terrain in the Growth Management and Nature Preservation/Park & Recreation zones, because of the absence of infrastructure, observations typically included slumping of peat into ponded areas (see example in Figure 8A), and an apparent transition of peatland to sedges, indicative of increased water saturation at these sites. These areas may be undergoing subsidence due to either degradation of permafrost at depth or seasonal thawing within near surface organic-rich materials, or both. However, for four sites on organic terrain within the Mixed Use zone, observations of rotational movement of brickwork and retaining walls, side rotation (i.e., subsidence) of road embankments, and added granular fill materials used to relevel surfaces were all indications of subsidence. Differential subsidence of about 30 cm was noted in June 2013, across a road surface that was last leveled and resurfaced in September 2010 and that was known to have also experienced subsidence prior to that period (Figure 8E).

Within the glaciolacustrine moderate downward displacement sites, evidence of subsidence was noted at most sites distributed among seven municipal zones (Table 9). Field observations included evidence of differential settlement of buildings, ground, and roads as well as granular material infilling of road embankments, road surfaces, driveways, and parking areas. Estimates of total differential subsidence were measureable at several sites and ranged from 5 cm to 50 cm and were most obvious on road surfaces. At one location, differential subsidence of 30 cm was noted where the road transitioned from shallow bedrock to thicker glaciolacustrine sediments (Figure 8B).

In general, these field observations confirm that locations of moderate downward seasonal displacement derived from DInSAR do correspond to locations of long-term ground subsidence.

Geotechnical Information

To further assess the nature of ground subsidence and the potential causes of observed surface displacement, we compared areas of moderate downward displacement to results from published geotechnical reports undertaken for infrastructure construction and remediation. Based on the availability of reports, 4 sites of moderate downward displacement were examined in detail.

The first site of moderate downward displacement was an organic terrain (i.e., peatland) located in the Growth Management zone (Figure 6 Box A) and photograph in Figure 8A. This peatland was one of several areas recorded in Table 9 that showed signs of organic slumping into ponds. In most cases, this could be evidence of subsidence and increased surface wetness, though it could also be due to heaving from ice lens formation and permafrost aggradation at depth. Geotechnical drilling undertaken in December 1970 on the eastern edge of the peatland revealed 2.30 m of frozen peat underlain by 45 cm of frozen clayey silt with ice crystals and a gravimetric moisture content of 28% to 42% on probable bedrock (Ripley, Klohn and Leonoff International Ltd. 1971). Whereas thawing of permafrost within the peatlands could result in the observed subsidence, the sea-

TABLE 9
Summary of field observations and estimated overall subsidence since initial construction for sites of moderate downward displacement.

Surficial Geology	Municipal Zone	Number of Sites	Field Observations	Estimated Overall Subsidence (cm)
Organic				
	GM	6	Vertical cracks in peat, slumping into ponds, and transition from peatland to sedge	NA
	NPR	1	Transition from peatland to sedge	NA
	MU	4	Rotation of brickwork and retaining walls; added fill; rotation of road surface and shoulders	30–35
Glaciolacustrine				
	R-LD	4	Fill added for leveling; subsidence of deck posts and horizontal wood ties	10–50; 30–50; >50
	R-MX	3	Fencing leaning; ground subsidence	NA
	MU	4	Ground subsidence around building; driveway patched; fill added	5–10; 5–10; 10–20; 10–20;
	R-M	7	Differential subsidence of road; land surface subsidence	30–50; 30–50; 15–20
	NPR	3	Road and embankment infilled	NA
	IND	11	Building subsidence	NA
	GM	6	Road infill and reconstruction	NA

Note that initial construction dates are not always known, therefore rates cannot be estimated.

sonal ground subsidence observed at this site is the one location in our study that could also be due to annual summer thaw of the active layer within the peat and frost layer in the sedge wetland.

The second site of moderate downward displacement was a glaciolacustrine sediment area within the Residential Manufactured Dwelling zone (Figure 6, Box B). As shown in Figure 8B, the area was one of several showing total differential subsidence on the order of 30 cm. Several geotechnical boreholes were drilled in the area in December 1970 (Ripley, Klohn and Leonoff International Ltd., 1971). A borehole located in the approximate area of Figure 8B revealed 1.08 m of peat, underlain by 7.75 m of frozen clayey-to-sandy medium-to-nonplastic silt with 10%–15% visible ice in the form of lenses ranging from 1 to 2 cm thick; and 3 other boreholes in the area revealed similar subsurface conditions (Ripley, Klohn and Leonoff International Ltd., 1971). Based on these, we attribute the observed ground subsidence at this site to thawing of ice-rich sediment within permafrost at depths greater than 1 m. Thus, moderate downward seasonal displacement here corresponds to long-term ground subsidence.

The third site investigated was an organic terrain peatland area in the Mixed Use zone (Figure 6 Box C). As shown in Figures 8C and 8D, the area is a paved road across a peatland, with ponds on either side. A geotechnical borehole located on the road, prior to paving in August 1996, encountered 2 m of unfrozen gravel fill underlain by 30 cm of frozen peat, 3 m of low-plastic silty-clay with up to 40%–50% visible ice, and 4.6 m of frozen nonplastic silt without visible ice (EBA Engineering Consultants Ltd. 1996). Bedrock was not encountered in this borehole to 9.9 m depth. Ground temperatures measured in November 1996 confirm permafrost within the sediments, marginally below 0 °C. As with the last site, we attribute the observed ground subsidence at this site to thawing of ice-rich sediment within permafrost at depths below 3 m. Thus, moderate downward seasonal displacement noted in the area of Figure 8E is indicative of long-term ground subsidence, likely within ice-rich silty-clay (i.e., glaciolacustrine) sediments at depth.

The final site investigated was a glaciofluvial sediment area in the Airport & Environs zone (Figure 6 Box D). It was not possible to make direct field observations at this site because it was located on the airport runway. However, moderate downward displacement, in conjunction with larger areas of low downward displacement, were noted at several localities primarily on the east–west (09–27) runway as shown in Figure 8F. An investigation and assessment of the runway conducted in 2001 encountered frozen ground in boreholes at depths between 2 m and 4 m below the surface, with permafrost temperatures of approximately −0.5°C at 5.4 m depth (Seto et al. 2004). The study further identified a settlement area on the east–west runway at that time and identified an area of near-surface clays encountered beneath the surface (Figure 8F). Whereas ground ice was generally not visible or visible in only trace amounts in most

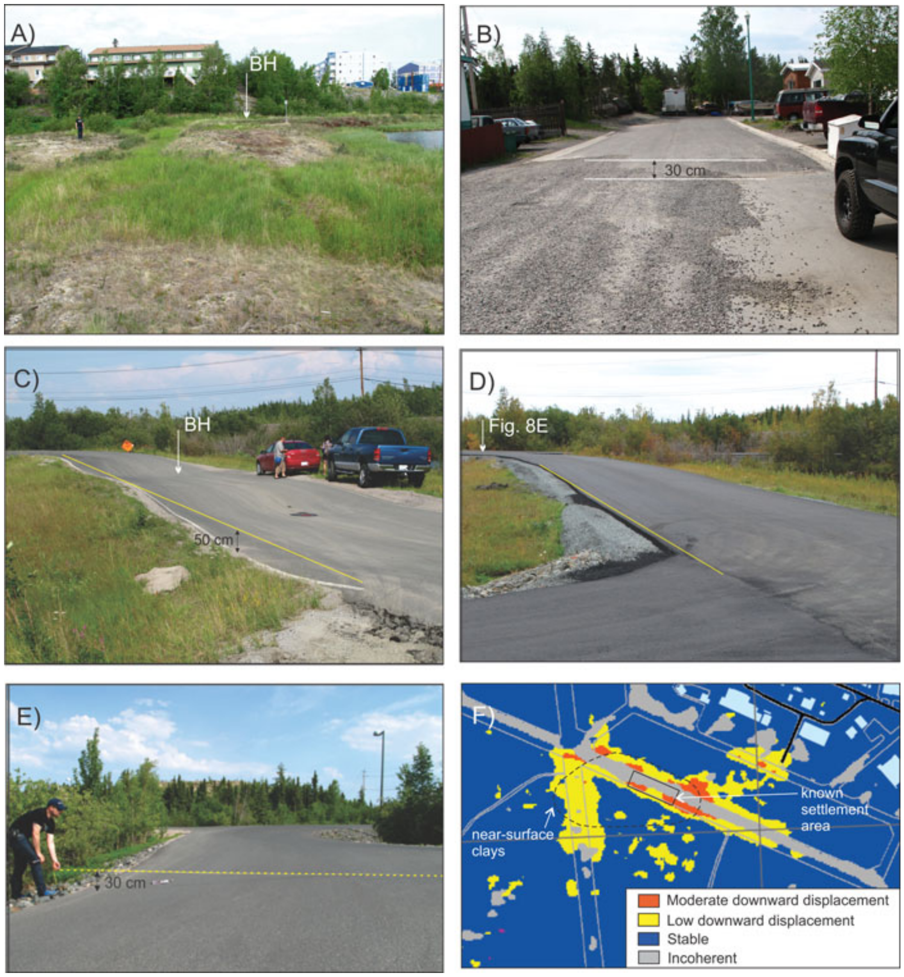

FIG. 8. Geotechnical sites with moderate downward displacement. (A) Organic terrain in Growth Management zone with arrow pointing to approximate location of borehole drilled December 1971; (B) road over glaciolacustrine sediment in Residential Manufactured Dwelling zone showing evidence of subsidence; (C) paved access road across organic terrain in Mixed Use area showing up to 50 cm of differential subsidence over 13-year period with arrow pointing to approximate location of borehole drilled December 1996 (photo taken July 14, 2010); (D) identical location as Figure 8C, showing remediated road surface and location of Figure 8E (photo taken September 6, 2010); (E) 30 cm of differential (rotational) subsidence between center and edge of road over 3-year period (photo taken June 2013); (F) seasonal surface displacement at the Yellowknife airport from May to September, 2010 with known settlement and near-surface clay areas reported by Seto et al. (2004).

boreholes, 20% excess ice was observed at a 4-m depth in a borehole within the near-surface clay area. The study attributed the observed settlement to the thawing of unstable permafrost clays and silts beneath the runway (Seto et al. 2004). Thus, we attribute the moderate downward seasonal displacement measured with DInSAR at this site as indicative of long-term ground subsidence due to thawing of near-surface clay sediments beneath the glaciofluvial sediments.

In the error analysis, a small area along the runway was the one exception to having higher-than-normal errors but being relatively unvegetated (see Figure 3). An examination of the displacement values in individual time sequential interferograms may offer an explanation. Pixels in this small area all show abrupt displacement of < -5 cm in the first month of the summer, some pixels then remain low until mid-September, but some show slight uplift in the last month. This pattern is a significant deviation from the assumption of a linear rate of displacement on which the stacking method is based. The errors for these pixels with dramatically nonlinear displacement patterns are therefore identified as higher; however, the overall displacement trends in the vicinity of the runway are likely reliable.

Based on this review it appears that, within developed municipal lands, areas identified with moderate downward seasonal displacement do correspond to sites also undergoing long-term downward displacement. In each of these cases, glaciolacustrine sediments containing excess ice were observed at depth. This leads us to conclude that the moderate downward displacement at these sites is primarily the result of thawing of permafrost and consolidation of soils at depth, hence a long-term trend, rather than the result of only seasonal thaw within the active layer.

CONCLUSIONS

A short RADARSAT-2 data stack from one summer season and simple DInSAR processing has been shown to produce useful ground displacement information for a municipal setting within the discontinuous permafrost zone. Although some areas of forest and shrub caused incoherence or higher errors, informative patterns of seasonal displacement were well identified within the Yellowknife municipal area. Comparisons with surficial geology data showed that the extent and degree of displacement was related mostly to the presence of thaw-unstable glaciolacustrine sediments and organic terrain typified by peatlands. Glaciolacustrine sediments cover about one-third of the Yellowknife area, and approximately 20% of this terrain shows some degree of displacement. Organic terrain, which occupies only $\sim$6% of the Yellowknife area, is the least stable surficial unit with $\sim$44% experiencing some type of displacement. Notably, a larger total area of organic terrain ($\sim$16 ha) is subject to moderate downward displacement than the area of glaciolacustrine sediments ($\sim$11 ha). Owing to the relatively small total area, organic terrain has been largely avoided by municipal development. It is recommended that construction on organic terrain continue to be avoided in order to reduce further potential downward displacement on developed lands. Glaciolacustrine sediments can also be problematic for construction, although they are more difficult to avoid. DInSAR information could be used to identify the areas of glaciolacustrine sediments that are most at risk in order to help plan the most resilient construction.

Field observations confirmed that areas with moderate downward seasonal displacement (-3.0 to -6.0 cm over four summer months) are likely experiencing long-term subsidence. Field observations noted subsidence on the order of 5 cm to 50 cm, evidenced as rotation in retaining walls, fences, road surfaces, and buildings. An examination of results from published geotechnical reports for sample areas of moderate downward displacement further confirmed that most moderate displacement sites are also areas of year-over-year subsidence. This may be attributed primarily to thawing at depth within permafrost, rather than seasonal thawing of the frost table or active layer.

The terrain stability within various land use zones has implications for infrastructure planning, construction, and remediation. Land use zonations are based, in part, on infrastructure tolerance and design life. The incorporation of terrain stability information guides zonation choices and ultimately reduces maintenance and remediation costs. Preliminary terrain stability information has traditionally been gained from topographical and surficial geological data, but a single seasonal DInSAR product, using as few as five acquisitions and a simple stack processing technique, covers a large area and contributes information that could be used as input to the zoning process. DInSAR products from multiple years could further be used to monitor the effects of remediation measures and evaluate the performance of construction and engineering innovations. These results show that DInSAR information can be useful for planning and decision-making purposes for municipal infrastructure in permafrost environments.

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