Ice-Wedge Polygon Type Controls Low-Gradient Watershed-Scale Hydrology

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Abstract

Ice-wedge polygons and related microtopographic variations are ubiquitous in landscapes underlain by permafrost. High- and low-centered polygons are typical, but surprisingly their role on hydrologic fluxes and stocks is not well quantified. We performed hydrologic modeling analyses using the physically-based model WaSiM-ETH which was forced by data from the Biocomplexity Experiment, Barrow, Alaska (1999 to 2009), to assess the effect of ice-wedge polygon type on watershed-scale hydrology. Low-centered polygons, through elevated rims, reduced runoff while increasing evapotranspiration and surface water storage. The high-centered polygon landscape produced more than twice the runoff than the low-centered polygons, while storage and runoff drastically decreased. It is evident that microtopography plays an important role on the watershed-scale hydrologic fluxes and stocks of low-gradient arctic wetlands. Permafrost degradation could transform low- into high-centered polygons, which could potentially dominate the direct effects of climate change on arctic wetland hydrology.

Keywords: ice-wedge polygons; watershed; hydrology; water balance.

Introduction

Wetlands are common across the pan-arctic landscape (Tarnocai and Zoltai 1988) and their unique geomorphological and hydrologic features are important components of the tundra ecosystem (Walker et al. 2004) and the global climate system (Chapin et al. 2005). Landforms associated with arctic wetlands, such as vegetated drained thaw lakes and patterned ground may play an important role in basin hydrology (Kane et al. 2003). It has been proposed that not accounting for the role of tundra micro-scale heterogeneity could lead to large uncertainty in regional estimates of carbon and energy exchange (Sellers et al. 1997, Ostendorf et al. 2001).

Changes to the surface topography of arctic wetlands can be abrupt and easily initiated. Despite the cold and continuous permafrost in Northern Alaska, Jorgenson et al. (2006) documented a widespread degradation of ice wedges occurring over a decadal time scale of moderate climate warming (2 –5°C). Further, Fortier et al. (2007) demonstrated that in just four summers, infiltration of snowmelt runoff into ice-wedge cracks can result in a continuous system of gullies through thermo-erosion. Thus, in a relatively short time period, a low-centered polygon landscape can turn into a high-centered polygon landscape due to melting of ice wedges.

Projected effects on the tundra ecosystem may not have properly accounted for the dynamic control of geomorphology under a changed climate (Ellis and Rocherfort 2004). Considering that a) a substantial portion of the pan-arctic landscape is represented by polygon mires (250,000 km^2) (Minke et al. 2007) with b) dynamic low- and high-centered polygons, and c) that the air temperature and precipitation is projected to increase (Walsh 2008), more research is needed to examine the effect of patterned ground on hydrology. This paper assesses the watershed-scale hydrologic impact as a low-centered polygon landscape is transformed into high-centered polygon tundra. We evaluate the change in the basin water balance through simple modeling experiments forced by data collected at a vegetated drained thaw lake basin in Barrow, northern Alaska. The model experiments represent a first approximation in assessing the effects of ice-wedge polygon type on watershed hydrology as we did not include the effects of frozen ground on hydraulic conductivity and subsurface storage capacity.

Background

In the field of geocryology, the term polygon refers to closed, multisided, roughly equidimensional patterned ground features, bounded by more or less straight sides (van Everdingen 1998). The two major types of ice-wedge polygons are low-centered and high-centered polygons. Both of these features strongly influence the hydrologic, pedological, and biological variations in low-land tundra (Brown et al. 1980) including meter-scale variations in near-surface soil moisture (Engstrom et al. 2005), plant distribution (Webber 1978), snow accumulation (Webber et al. 1980), active layer depth (Minke et al. 2009), soil biological activity (Mueller et al. 1999), and the export of natural chlorine and bromine to the stratosphere (Teh et al. 2009). Even though the tundra wetlands may at first appear as a featureless plain, its typical polygonal landforms result in a highly variable and dynamic environment.

The mosaic in surface hydrology results in extensive spatial variations in soil respiration (Sommerkorn 2008) and net ecosystem carbon fluxes (Olivas et al. 2011). Basins of low-centered polygons are either temporary or continuously flooded during the summer (Liljedahl 2011). High-centered polygons are well drained with the troughs often serving as effective pathways for the movement of water and nutrients, especially during snowmelt (Woo and Guan 2006). Rims of the low-centered polygons and centers of the high-centered polygons are both exposed to summer and winter climate extremes (Brown et al. 1980). A topographic reversal of a low-centered polygon into the formation of troughs and, thus, eventually a well-drained high-centered polygon can therefore have major implications for ecosystem structure and functioning.

Field studies have shown complex micro- and watershed-scale lateral hydrologic connectivity of arctic wetlands. Widespread flooding (Rovansek et al. 1996) allows effective surface flow connectivity during freshets (Woo and Guan 2006). In summer, the shallower thaw in combination with a higher ground surface of low-centered polygon rims form ridges of frozen ground (Minke et al. 2007), which can serve as hydrologic barriers (Donner 2007). Accordingly, the threshold water level that allows for a subsurface lateral connection varies in time due to the seasonal development of the active layer. Adding to the complexity is the advective heat transfer, where lateral flow can produce pathways within these barriers (Donner 2007). Such thermal erosion is an effective positive feedback mechanism that results in further lowering of the threshold water levels. Thus hydrologic fluxes and stocks are intrinsically and dynamically linked to the unique tundra microtopographic units. Still the role of low- and high-centered polygonal ground on watershed-scale water balance is poorly constrained and rarely, if ever, represented in hydrologic models.

Site Description

The site, here referred to as the Biocomplexity Experiment (71°16′51″N, 156°35′47″W, elevation 4.5 m), is located a few kilometers from the Beaufort Sea near Barrow on the Arctic Coastal Plain in northern Alaska. Mean annual air temperature at the Barrow Airport is -12.0°C (1977–2009) where summer (June through August) averages 3.3°C. About 55% of the annual precipitation (173 mm, 1977–2009) falls during June through September (99 mm) and represents adjusted precipitation following the WMO method described by Yang et al. (1998).

The Biocomplexity Experiment site is largely represented by a vegetated drained thaw lake basin (DTLB). DTLBs occupy approximately 26% of the western Arctic Coastal Plain (Hinkel et al. 2005) and 50% of the Barrow Peninsula north of ~71° latitude (Hinkel et al. 2003). The site has poorly drained wet tundra meadow with Typic Aquiturbels soils (Bockheim et al. 1999) underlain by 600 m of ice-rich permafrost (Brown and Johnson 1965). Low-centered polygons are common within the lake bed, while high-centered polygons dominate the upland tundra. Interannual variation of the mean active layer depth at nearby locations varied from 29 to 35 cm (1995–2009) (Shiklomanov et al. 2010).

Mosses represent most of the live above ground biomass at the site (Zona et al. 2009). Vascular plant composition is represented by sedges (*Carex aquatilis*) and grasses (*Eriophorum* and *Dupontia*) with an average LAI in mid-August 2006 of 0.43, 0.13, and 0.02, respectively (Zona et al. 2011). Senescence in the region begins in August (Myers and Pitelka 1979).

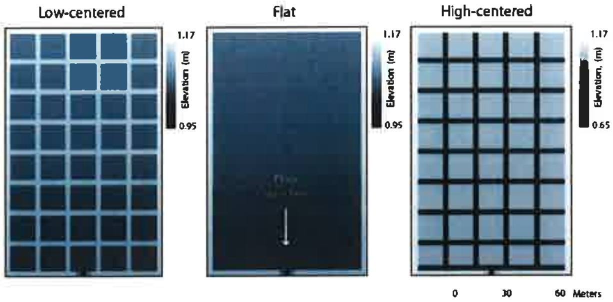

Figure 1. The schematic digital elevation models used in the modeling analysis representing low-centered polygons with 8-cm-high rims, a flat surface, and high-centered polygons with 30-cm-deep troughs. The surface has a general slope of 0.03% as determined by airborne Lidar surveys of a vegetated drained lake basin near Barrow, Alaska.

Methods

Schematic DEMs

The effect of polygon rims on the water balance was quantified using three artificially produced DEMs (Fig. 1). The artificial DEM represent a simplistic DTLB by having the same slope (0.03%) as the DTLB at the Biocomplexity Experiment, Barrow, Alaska (Liljedahl 2011). Airborne Lidar and field surveys of the Barrow DTLB show low-centered polygon rims up to about 10 cm height. Accordingly, low-centered polygon rims were represented by a network of elevated pixels (+8 cm) within the schematic DTLB. A second schematic DEM represents the DTLB as a featureless surface, while the third presents a DTLB having high-centered polygons and a connected network of 30 cm deep troughs.

Hydrologic model

We chose the physically-based hydrologic model Water Balance Simulation Model (WaSiM-ETH) (Schulla 1997, Schulla and Jasper 2007). WaSiM-ETH is a well-established tool for modeling the spatial and temporal variability of hydrologic processes in complex basins ranging from less than 1 km^2 to more than 500,000 km^2. Its application has ranged from water management in arid and semi-arid regions (Bharati et al. 2008), flood forecasting (Jasper et al. 2002), water balance analyses of wetlands within lowland floodplains (Krause et al. 2007) and, in the Arctic (Liljedahl 2011), to the distribution of water and phosphorus yield-producing areas (Lindenschmidt et al. 2004), and many other hydrologic studies.

The WaSiM-ETH includes the Richards equation to represent the fluxes within the unsaturated soil zone. It is a 1-D finite difference scheme with multiple user-defined discrete soil layers. Here the infiltration into the soils was presented as if the soils were thawed. The lower boundary condition to the unsaturated zone is the groundwater layer (i.e., saturated zone), which is constant for a specific time step but variable in time. The extraction of water from the different soil layers is done separately for soil evaporation and for transpiration before calculating the soil water fluxes. The first step is the extraction through transpiration (Penman-Monteith), which includes stress induced by soil moisture. The second step is the extraction of soil evaporation from bare soil (or moss), which is also linked to soil moisture status. The modeling of the groundwater and lateral flow is 2-D where the flux is estimated from the continuity and Darcy equations through an implicit finite difference approach (Gauss-Seidel-Algorithm with automatic estimation of successive over-relaxation factors).

Lateral flow is represented through channel routing (Manning-Strickler), base flow, interflow, and a surface routing module designed for small-scale applications. Infiltration excess and direct runoff from snow melt is used as input for the surface routing model. The surface runoff flows from cell to cell until a river cell is reached. In diverging areas, up to three flow paths are possible, while only one flow direction is allowed in converging areas (the steepest slope). The flow velocity depends on slope, roughness, and water film depth (Manning-Strickler) where the slope depends upon the elevation model plus the water storage. The dynamic generation of ponds occurs when elevation and local storage lead to a zero or inverted gradient. The time step of surface routing is dynamically decreased but, if necessary, it can also be parameterized.

Two different approaches were applied to represent surface flow. We utilized the surface routing module in the low-centered polygon and flat ground scenarios, while the troughs were parameterized as a channel network in the high-centered polygon landscape.

WaSiM-ETH was forced with 11 summers of hourly meteorological data collected near Barrow, Alaska, by the Center for Climate Change at San Diego State University, Circumpolar Active Layer Monitoring program, NOAA, ARM, and the National Weather Service. The model simulations were started just prior to each year's snow ablation and stopped during the onset of winter. The latter was defined as being the first day of ten consecutive days experiencing mean daily air temperatures below 0°C. In this particular application we did not represent the seasonal changes in the active layer nor the presence of permafrost. Instead, the model sensitivity analysis is solely based upon the change DEM and surface routing parameterization. Model parameters were given the same values as those presented by Liljedahl (2011).

Results

The polygon rims affect several components of the water balance. The multi-week-long ponding (hydroperiod) of the DTLB was only replicated when low-centered polygons were represented (Fig. 2). When no elevated rims were present, the hydroperiod was limited to 5.2 (flat) and 0 days (high-centered) compared to 36 days in the low-centered polygon scenario. The mean inundated depth at low-centered polygons was 40 mm compared to 11 mm at the flat wetland scenario. Water levels were higher throughout the summer in the low-centered polygon DTLB, where the absence of rims resulted in larger soil water storage deficits prior to freeze-up. In five of the 11 years, the ground surface was inundated prior to freeze-up in the low-centered polygon scenario, while the fall water table was always below the ground surface in late summer on the flat and high-centered polygon ground. The change in soil water storage, ΔS, was negligible on a decadal time scale, but year-to-year variations were found in all three scenarios.

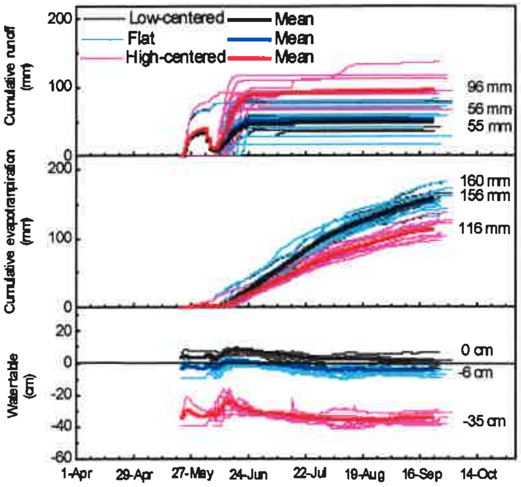

Figure 2. Simulated water table and cumulative runoff and evapotranspiration from the three schematic DEMs. Thin lines represent individual years, while thick lines are the long-term average. The mean runoff was about twice as high from the high-centered polygons compared to the low-centered polygons and the flat wetland. Evapotranspiration and soil water storage were reduced at the high-centered polygon. The typically observed multi-week-long ponding was only produced by the low-centered DEM.

Despite the larger soil water storage deficit, total runoff was higher in the high-centered polygon (96 mm) than the flat (53 mm) and low-centered polygon (49 mm) scenarios. The runoff ratio (runoff/SWE) was nearly doubled from the high-centered polygons (0.83) compared to the low-centered and flat basins (0.44 and 0.47, respectively).

Total evapotranspiration was reduced when troughs were present and also less variable among years. The flat and the low-centered polygon scenario had nearly identical evapotranspiration losses (156 and 160 mm, respectively), while the high-centered polygon area lost on average 116 mm. Total transpiration was the same amongst the scenarios (mean 55 mm). Accordingly, the role of transpiration on total evapotranspiration was increased during the high-centered polygon scenario (47% of total evapotranspiration) compared to the low-centered (34%).

Discussion

Micro-scale variations in surface topography, induced by ice-wedge polygons, control the water balance in these extremely low-gradient arctic watersheds. A transition from low- to high-centered polygon landscape resulted in a dramatic alteration in the partitioning of the water balance. Overall, losses from the low-centered polygon scenario were dominated by evapotranspiration but total runoff was similar to evapotranspiration at the high-centered polygon landscape. We show that structural changes in the arctic soils at the order of centimeters can have dramatic effects on the watershed-scale hydrology.

Soil and surface water storage

The near-surface was typically saturated when rims were present. The autumn water table fluctuated above and below the ground surface amongst the years in the low-centered polygon scenario, while the fall water table of high-centered polygons always remains at depths where one would normally expect the permafrost table (see Shiklomanov et al. 2010). In that sense, the water table of high-centered polygons was less variable by supporting a consistently deep water table.

The 11 years of simulations suggest that it is typical for these systems, whether they are dominated by low- or high-centered polygons, to experience interannual variations in the soil water storage, ΔS. Annual water balance calculations based on assumptions of no change in ΔS would, according to the simulations, result in errors of up to 90 mm, which is half of the long-term mean annual precipitation in the Barrow area. Our simulations suggest that such methods should only be applied to datasets representing approximately a decade.

Lateral flow

The type of polygon feature affects the total discharge as well as the timing of the runoff. About half of the SWE did not contribute to streamflow from the low-centered polygon (56%) and flat wetland (53%). The limited difference was due to the larger soil water storage deficit (fall water table depth) at the flat scenario, which was of similar magnitude as the surface storage capacity of the low-centered polygons. The high-centered polygon scenario resulted in 27% of the SWE recharging the soils. In comparison, field studies performed by Kane et al. (2008) showed that on average 22% (1999–2007) of the SWE did not contribute to runoff in the Putuligayuk River watershed (471 km^2), Arctic Coastal Plain, Alaska. In addition, the simulated runoff exits the basin earlier from the high-centered polygon scenario due to an effective network of channels and steeper micro-topographical gradients when compared to the other scenarios. Runoff is therefore drastically reduced and evaporation increased due not only to the presence of larger-scale features such as lakes and wetlands (Bowling and Lettenmaier 2010), but also to micro-scale features such as the presence of rims and the absence of a connected network of troughs and short, relatively steep slopes typical of high-centered polygons.

The high-centered polygon scenario represented an extreme scenario of the basin-scale lateral surface connectivity through the unified drainage network. Field observations have shown that the ground subsidence may not necessarily form a continuous network but rather disconnected channels and therefore small water bodies (Jorgenson et al. 2006).

Vertical fluxes

Total evapotranspiration from the high-centered polygon scenario was similar to the total amount of runoff. This is due partly to a larger runoff compared to flat and low-centered scenarios and to reduced evaporation. Open water/moss evaporation was lower from the high-centered polygons as the surface was water-limited due to the deeper water tables (~30 cm). The simulated water table in the flat scenario rarely dropped below 10 cm depth, which was within the parameterized zone of water accessible for evaporation (*Sphagnum* moss has shown to effectively transport water from a 10–15 cm deep water table through capillary flow (Price et al. 2009)). Hence, the position of the water table resulted in similar total evapotranspiration amongst the flat and low-centered polygon scenario, while reduced at the high-centered polygons.

Future directions

The modeling analysis presented a first-order approach in simulating the role of low- and high-centered polygons on arctic wetland hydrology. Neither the freeze-thaw dynamics within the active layer nor the permafrost was represented, both of which have shown to be important in tundra wetland hydrology. Consequently, the modeling did not include the differential distribution of lateral and vertical hydrologic barriers caused by the presence of ice-rich frozen ground. In addition, the trough network was continuous. Therefore, both the lateral hydrologic connectivity and the (liquid) soil water storage were likely overestimated, which suggests an overall underestimation in surface water storage. A representation of frozen ground would likely result in an increased hydrologic sensitivity to polygon type, although any disconnected channels (troughs) could partly offset the differences between ice-wedge polygon type on watershed-scale fluxes and stocks.

Conclusions

The model experiments presented a first-order approach in evaluating the role of microtopography on watershed-scale hydrology. A shift from low-centered to high-centered polygon dominated landscape results in drastic changes to watershed-scale water storage, runoff, and evapo-transpiration. Low-centered polygons promote extensive ponding, while high-centered polygons enhance runoff. Evapotranspiration is suppressed at high-centered polygon landscapes as the near-surface soil moisture is reduced. Therefore, not accounting for the role of microtopographical variability on hydrology can have dramatic consequences when estimating regional scale water and energy exchange. It is necessary to account for the microtopography and the dynamic role of geomorphology in regulating tundra microclimate in order to reduce the uncertainty in present and future pan-arctic hydrologic fluxes and stocks.

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