

Terrain Analysis on the Arctic Coastal Plain, Northern Alaska

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1. Introduction and Literature Review

1.1 *Background information*

Peat soils in the circumpolar Arctic have long been a natural sink of organic carbon, and at present, they are believed to hold within their first three meters of depth over twice the mass of carbon present in the global atmosphere (Schuur et al., 2009). Roughly eight percent of the soil organic carbon (SOC) stored in the Arctic is estimated to be found in Alaska, with the majority concentrated in the northern third of the state (Mishra and Riley, 2012). Much of this stock is currently sequestered in permafrost, defined as ground whose temperature remains below 0°C for a period of two years or longer. SOC locked in permafrost is essentially immobile and does not interact with other reservoirs in the carbon cycle. Should recent trends in climate warming continue into the future, however, permafrost thaw will potentially mobilize a portion of the frozen SOC stock, which may become vulnerable to release to the atmosphere in the form of carbon dioxide or methane (Zona et al., 2011). Importantly, both the thermal properties of the seasonally thawed “active layer” of soil and the pathways by which microbes may metabolize SOC are heavily influenced by the soil’s saturation state. Understanding of the hydrologic processes that influence the summertime water balance in Arctic soils is therefore crucial to predicting the region’s future role in global carbon cycling.

All hydrologic processes near the Earth’s surface are affected by topography, so analysis of digital elevation models (DEMs) is a powerful tool to characterize water movement through the environment at various scales. In tundra landscapes, however, the relevant geographic features that influence water fluxes may be of very low relief, and therefore indiscernible in most available elevation datasets. One region that exemplifies this problem is the broad plain that stretches from the northern edge of the Brooks Range in northern Alaska to the coast of the Arctic Ocean, known as the Alaska North Slope (Figure 1). Here, basin-scale hydrologic processes including surface runoff and evapotranspiration are thought to be controlled by subtle changes in topography on the scale of decimeters (Liljedahl et al., 2012). To represent such features in a DEM, it is necessary to use LiDAR technology, which has only become commonplace in recent years. LiDAR, or light detecting and ranging, is analogous to sonar, but uses a laser beam mounted either on the ground or in an aircraft to generate a detailed representation of the ground surface in a relatively short time. This report analyzes a LiDAR dataset acquired over a site in the eastern portion of the North Slope in order to analyze the terrain’s impact on hydrologic processes above and within the soil at a fine scale.

1.2 *Dataset Acquisition and Original Objectives*

The Alaska North Slope is the location of Prudhoe Bay, which has historically been the largest and most productive oilfield in the United States. While production from conventional wells in the oilfield has declined in recent decades, Great Bear Petroleum, LLC, is interested in tapping the hitherto untouched source rock of the play through unconventional production methods. Because Great Bear intends to drill wells in sections of the tundra previously unexploited by the oil and gas industry, the company contracted with the Bureau of Economic Geology at UT-Austin to conduct an airborne LiDAR survey of their lease block. Among other purposes, the resultant DEM was intended for use in stream basin delineation, in order to guide road construction in such a way as to minimize alterations to surface runoff processes. The first phase of the LiDAR survey was conducted in July 2012 and generated a high-resolution point cloud of roughly 480 km² of terrain, with an estimated vertical accuracy of two centimeters and approximately twenty points per square meter at the ground surface (Paine et al., 2013) (Figure 2). Acquisition of data for the remainder of the lease block is ongoing. While coverage of the entire lease block is as yet incomplete, however, one objective of the current project is to delineate stream basins within the zone already surveyed.

1.3 *Geomorphic Study of Ice-Wedge Polygons*

Beyond the original purpose of acquiring the DEM, one interesting phenomenon that can be observed in the LiDAR data is the prevalence of unique surface features, known as ice wedge polygons, throughout the study area. Similar to the desiccation polygons that develop in clay-rich materials upon drying, ice wedge polygons, each roughly 10-30 meters across, are delineated by a network of shallow troughs that develops where the ground cracks due to thermal contraction in the Arctic winter. Polygons develop when these cracks extend vertically beyond the depth at which temperature remains below 0°C throughout the year. This condition allows melt water that drains into an open crack space during the subsequent spring and summer to freeze, producing a perennial wedge of massive ground ice (Lachenbruch, 1962). Because the tensile strength of ice is generally less than frozen soil, new cracks form each winter within the pre-existing ice wedges, which in turn grow each spring through the repeated infiltration of melt water, provided that climatic conditions remain favorable.

Ice wedge polygons are important from a hydrologic perspective because they often represent the dominant topography in an otherwise flat landscape. Individual polygons may be classified as either low-centered or high-centered according to their surface expression (Figure 3). The former are bound by continuous rims of soil 10-30 cm tall, which can impede overland flow in the marshy areas where they

develop (Morse and Burn, 2013). Thus, low-centered polygons often act as micro-catchments during the spring thaw, hosting ponded water that can only infiltrate into the ground with seasonal dropping of the water table. High-centered polygons, in contrast, have a simple mounded topography that slopes gently downwards from the polygon center to the trough, providing little obstruction to runoff. High-centered polygon trough networks are usually deeper and more continuous than the networks in low-centered polygon mires, but in both cases, the troughs may host open channel flow towards streams and thermokarst lakes (Liljedahl et al., 2012).

The elevated rims of low-centered polygons are attributed to the pressure exerted by growing ice wedges on neighboring soil, and this explanation is supported by observations of distorted soil horizons and sediment layers at the edges of polygons (Lachenbruch, 1962). Furthermore, most researchers suggest that high-centered polygons develop from initially low-centered polygons when alterations to the soil thermal regime, due to climatic, hydrologic, anthropogenic, or other environmental factors, cause wintertime cracking to cease and the upper portions of ice wedges to melt. This partial melting of the ice wedges is responsible for subsidence of troughs in transitioning polygon mires, and for slumping of previously elevated rim material into the deepened trough space, effectively changing polygon form (Jorgenson et al., 2006).

The change in form from low-centered to high-centered is accompanied by changes in hydrologic function—most notably, in the loss of depression storage capacity in the centers of low-centered polygons. The ability of low-centered polygons to hold ponded water in their centers may impact a variety of physical and biological processes. For example, the presence of a free water surface in the polygon center may increase evapotranspiration rates, and even after ponds disappear in late summer, the soil in a low-centered polygon may remain more saturated than in a high-centered polygon, thereby favoring different microbial processes. An additional goal of this research, therefore, was to examine ice-wedge polygons within the study area in detail, and to use ArcGIS and the available LiDAR data to calibrate a model of polygon erosion capable of describing changes in ponded storage capacity as a polygon transitions in geomorphic form.

2. Objectives, Study Area, and Methods

2.1 Objectives

The purpose of this study, as described above, is broken into two parts. In the first, stream basins are identified throughout the surveyed portion of the Great Bear lease block. The resulting map

may be used to minimize environmental impacts of road construction by building corridors that run along the boundaries of watersheds, rather than across them. In the second part of the study, I seek to model geomorphic change in ice wedge polygons, from low-centered to high-centered, using high-resolution LiDAR data. Specifically, I generate a 50 cm resolution gridded DEM from the original point cloud dataset that captures the two end-members in polygon geomorphology. This DEM is used to calibrate a model written in MATLAB that simulates polygon erosion using hillslope diffusion theory. As the model generates synthetic DEMs of polygons at various stages of transition, the simulated polygons are imported back into ArcGIS to evaluate changes in ponded storage capacity.

2.2 *Basin Delineation Methods*

Basin delineation was conducted in ArcGIS 10.2 using the Hydrology toolset. A one-meter resolution gridded DEM that had been created by BEG researchers from the LiDAR point cloud was uploaded into the software. This DEM was initially processed using the Fill tool to eliminate small pits in the ground surface with no obvious hydrologic outlet, which may impede the algorithms used in later stages of basin delineation. The Fill tool was especially important to use in this landscape due to the prevalence of micro-catchments associated with low-centered polygons. Subsequently, the Flow Direction and Flow Accumulation tools were used to define hydrologic flow paths across the ground surface. The Flow Direction tool assigns a number to each cell in the DEM corresponding to the direction of the steepest downwards gradient between it and one of its eight neighboring cells, and the Flow Accumulation tool quantifies the number of upstream cells potentially contributing to runoff across each cell in the raster. Thus, lines of cells with high flow accumulation values tend to represent streams. The edge of the raster was searched manually for cells of high flow accumulation, which were labeled as pour points, or basin outlets. A feature class containing the pour points was then input into the Watershed tool alongside the Flow Direction raster, in order to define the extent of each basin in raster format. The basin raster was then converted to polygons and exported outside of ArcGIS as a KMZ file to be viewed in Google Earth.

2.3 *Polygon Geomorphology*

The site chosen to calibrate the ice-wedge polygon geomorphic model is located just north of Milepost 387 on the Dalton Highway, approximately 40 km south of Deadhorse, Alaska. The site is bisected by the highway and is notable because it includes well-preserved, low-centered polygons on the east side of the corridor, which transition sharply to high-centered polygons on the western side

(Figure 4). This spatial pattern suggests that polygon degradation on the western side of the highway may have been initiated by construction of the corridor in 1974. This interpretation is compatible with observations by Reynolds et al. (2014) and Walker et al. (1987), who examined aerial photography over several decades to document changes in the tundra over several decades associated with placement of surface infrastructure in the nearby Prudhoe Bay oilfield. According to these studies, road construction can induce permafrost degradation by two mechanisms: 1) dust emitted from traffic on the highway may settle on the tundra, altering its albedo, and 2) surface runoff trapped during storms on one side of the highway may increase soil saturation and enhance the thermal conductivity of the active layer, allowing greater thaw. Assuming, then, that eroded polygons in the western half of the site resembled the low-centered polygons to the east prior to highway construction, this interpretation provides a convenient timeframe for inverse modeling of polygon evolution.

The premise behind examining this site in detail is that, if a model can receive the topographic information for a low-centered polygon as input, then replicate the observed high-centered morphology after simulating soil erosion processes, it potentially provides a reasonable characterization of ice wedge polygon geomorphic transition. The model used in this study was written in MATLAB and uses finite difference principles to apply the following equation across a raster representation of a single eroding polygon:

$$q = -D \frac{\partial z}{\partial x}$$

where q is the volume of sediment fluxed perpendicularly across a unit length along the strike of a hillslope ($L^3 L^{-1} T^{-1}$); D is the coefficient of *hillslope diffusivity* ($L^2 T^{-1}$), and $\partial z/\partial x$ is the topographic gradient (-). This equation is based on the conceptual model of hillslope diffusion, first introduced over a century ago by geomorphologist G. K. Gilbert (1909), and is based on the principle that erosion of unconsolidated material, like soil, should be proportional and opposite to the local slope of the ground surface.

In order to apply the hillslope diffusion equation to observed ice-wedge polygons, a 50-cm gridded DEM of the study area was first generated from the original LiDAR point cloud. A clipped section of the point cloud was imported into ArcGIS as a LAS file, then converted into a triangular irregular network (TIN) using the LAS to TIN tool in the 3D Analyst toolbox. A TIN is essentially a linear interpolation between pairs of neighboring points in the LiDAR dataset, resulting in a continuous surface at the ground level. The TIN was then converted into a 50 cm resolution raster using the TIN to Raster tool in the same toolbox (Figure 5).

Once the DEM was created, three pairs of ice-wedge polygons were identified, each consisting of one low-centered and one high-centered polygon of similar size and shape (shown in Figure 4). These polygons were clipped from the DEM and exported from ArcGIS as ASCII files, which were imported into MATLAB for processing in the model. The model simulated diffusive erosion of each low-centered polygon for thirty-eight years (the amount of time between highway construction and the LiDAR survey), with the polygon edges treated as fixed-elevation (Dirichlet) boundaries that were dropped gradually over the first fifteen years of the simulation, to represent the trough deepening that results from partial ice-wedge melting. The model was programmed to run iteratively on each low-centered polygon, with varying effective values of the hillslope diffusivity coefficient and varying depths of boundary subsidence, in order to identify the combination of these parameters that minimized differences between the observed high-centered polygon and the simulated high-centered polygon.

When the model was thus calibrated, synthetic DEMs of the three low-centered polygons during each year of their simulated geomorphic transition to high-centered form were imported back into ArcGIS. Each synthetic DEM was then processed using a sequence of tools streamlined in ModelBuilder, summarized as a flow chart in Figure 6. First, the Fill tool was used to fill the depression in the center of the polygon raster. The raster calculator was then used to subtract the filled polygon from the unfilled, resulting in a raster representation of the depression alone. The Set Null and Surface Volume tools were then used to calculate the surface area and volume of the depression. In this way, the surface area and volume of a transitioning polygon available to hold ponded water was estimated as a function of time during evolution from low-centered to high-centered.

3. Results and Discussion

3.1 Stream Basin Delineation

The results of the stream basin delineation throughout the LiDAR survey area are depicted atop Google Earth imagery in Figure 7. A total of seventeen basins, most of them elongated along a roughly north-south axis, were identified. The basins show good agreement with available imagery, with some centered upon visible streams. Interestingly, although the Sagavanirktok River flows through the eastern portion of the survey area, it appears that the majority of the identified basins flow slightly westward, emptying either into the Kuparuk River or directly into the Arctic Ocean. The boundary between watersheds draining into the Sagavanirktok River and those draining towards the north or the northwest appears to be a subtle ridge captured in the DEM, which may represent an ancient channel of the river

(visible in Figure 1). As described above, the basins identified in this project may be used to guide road construction through the area so as to limit impacts to surface runoff processes. By building corridors along the boundaries of watersheds rather than across them, areas of potentially high surface flow can be avoided.

3.2 *Geomorphic Model of Polygon Erosion and Pond Shrinkage*

The results of a calibrated run of the polygon geomorphic evolution model, based on polygons LC-1 and HC-1 from Figure 4, are summarized in Figure 8. The close visual match between the simulated and observed high-centered polygons suggests that the linear hillslope diffusion equation captures much of the complexity involved in the ice-wedge polygon transition process. Furthermore, optimized values for D in the three pairs of polygons modeled, ranging from $0.38 - 0.50 \text{ m}^2 \text{ yr}^{-1}$, agree well with previous studies of erosion in wet soils (e.g., Fernandes and Dietrich, 1997; Martin and Church, 1997), and best fit values for trough subsidence depth, ranging from 25-29 cm, match the observation of Jorgenson et al. (2006) that polygon troughs in northern Alaska deepen an average of 29 cm before stabilizing. Overall, although the model is based on relatively simple mathematics, it appears to provide a reasonable characterization of erosive processes during the evolution from low-centered to high-centered form. Therefore, it seems plausible that the model may provide a realistic estimate of how ponded storage capacity in eroding polygons may change with time.

The estimates of changes in both potential surface area and volume available for ponded storage in transitioning polygons are depicted in Figure 9. In this figure, the three dashed lines represent the three pairs of polygons modeled in the study, while the solid line represents the average of the three. Both surface area and volume of ponding are normalized by polygon area in Figure 9, such that area is expressed as a percent coverage and volume is expressed as an equivalent depth in centimeters. Results suggest that the volume available for ponding decreases asymptotically to zero over time, while surface area decreases more or less linearly. On average, the figure indicates that ponds at the surface of polygons can add about 1.5 cm of hydrologic storage in the low-centered end member, compared to high-centered polygons. Although this number may seem quite small, it should be interpreted in the context of the underlying soil column, which reaches a maximum summertime depth of about 50 cm before transitioning to impermeable permafrost, and much of which (beneath a surface horizon of peat) is comprised of fine-grained silt and clay with a very low specific yield. Ponded storage, therefore, may represent a significant addition to available storage within the soil column, especially during the early summer, when thaw depths may be limited to the upper several centimeters. The loss of this storage

over time may have a significant impact of the response of nearby streams to precipitation events, as well as on microbial processes of SOC metabolization that depend on the soil's saturation state. Future research, then, may seek to better constrain the impact of ponded storage on these processes, so as to develop a forecast for how they may be expected to change in transitioning polygon mires.

4. Conclusions

The results of terrain analysis on the Alaska North Slope demonstrate the extent to which subtle topographic relief may influence hydrologic processes in this very flat environment. Using data acquired through LiDAR technology, however, it is possible to create and process representations of the ground surface in order to evaluate the hydrologic characteristics of the landscape in high resolution. On the basin scale, for example, analysis of a DEM generated from LiDAR data reveals the boundaries of catchments that were previously indiscernible in available elevation datasets. Knowledge of the spatial extent of these catchments may be useful in guiding infrastructure placement throughout the study area as it is developed for commercial purposes. On a much smaller spatial scale, LiDAR-generated DEMs are also capable of representing the micro-topography associated with surface features such as ice wedge polygons. Using available tools in ArcGIS, the capacity of low-centered and transitioning polygons to store ponded water in their centers may be evaluated, and furthermore, the profiles of individual polygons may be extracted from DEMs in order to calibrate landscape evolution models. Future research may evaluate the impact that ponded hydrologic storage in polygon centers has on catchment-wide processes such as evapotranspiration and runoff, and on processes closely coupled to the hydrologic cycle such as carbon cycling in the soil column. Research into these topics may bridge the different scales at which LiDAR and GIS technologies are capable of characterizing water and carbon-related processes in the Arctic.

References

- Fernandes, N. F., and Dietrich, W. E., 1997, Hillslope evolution by diffusive processes: the timescale for equilibrium adjustments: *Water Resources Research*, v. 33, no. 6, p. 1307–1318.
- Jorgenson, M. T., Shur, Y. L., and Pullman, E. R., 2006, Abrupt increase in permafrost degradation in Arctic Alaska: *Geophysical Research Letters*, v. 33, no. 2, 4 p., doi:10.1029/2005GL024960.
- Lachenbruch, A. H., 1962, Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost: *GSA Special Papers*, v. 70, p. 1–66, doi:10.1130/SPE70-p1.
- Liljedahl, A. K., Hinzman, L. D., and Schulla, J., 2012, Ice-wedge polygon type controls low-gradient watershed-scale hydrology: Tenth International Conference on Permafrost, Salekhard, Russia, June 25–29.
- Martin, Y., and Church, M., 1997, Diffusion in landscape development models: on the nature of basic transport relations, *Earth Surface Processes and Landforms*, v. 23, no. 2, p. 273-279.
- Mishra, U., and Riley, W. J., 2012, Alaskan soil carbon stocks: spatial variability and dependence on environmental factors: *Biogeosciences*, v. 9, p. 3637–3645.
- Morse, P.D., and Burn, C.R., 2013, Field observations of syngenetic ice wedge polygons, outer Mackenzie Delta, western Arctic coast, Canada: *Journal of Geophysical Research: Earth Surface*, vol. 118, p. 1320-1332.
- Raynolds, M. K., Walker, D. A., Ambrosius, K. J., Brown, J., Everett, K. R., Kanevskiy, M., Kofinas, G. P., Romanovsky, V. E., Shur, Y., Webber, P. J., 2014, Cumulative geocological effects of 62 years of infrastructure and climate change in ice-rich permafrost landscapes, Prudhoe Bay Oilfield, Alaska: *Global Change Biology*, v. 20, no. 4, p. 1211–1224, doi: 10.1111/gcb.12500.
- Schuur, E. A. G., Bockheim, J., Canadell, J. G., Euskirchen, E., Field, C. B., Goryachkin, S. V., Hagemann, S., Kuhry, P., Lafleur, P. M., Lee, H., 2008, Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle: *Bioscience*, v. 58, p. 701–714.
- Walker, D. A., Webber, P. J., Binnian, E. F., Everett, K. R., Lederer, N. D., Nordstrand, E. A., Walker, M. D., 1987, Cumulative impacts of oil-fields on northern Alaskan landscapes: *Science*, v. 238, no. 4828, p. 757–761.
- Zona, D., Lipson, D. A., Zulueta, R. C., Oberbauer, S. F., and Oechel, W. C., 2011, Microtopographic controls on ecosystem functioning in the Arctic Coastal Plain: *Journal of Geophysical Research*, v. 116, no. G4, 12 p., doi:10.1029/2009JG001241.



Figure 1. Imagery for the state of Alaska. The Alaska North Slope is the flat region, shown in green and brown tones, located north of the Brooks Range in the northern quarter of the state. The pale blue star, which is within the eastern third of the North Slope region, indicates the location where airborne LiDAR data was captured in July 2012.

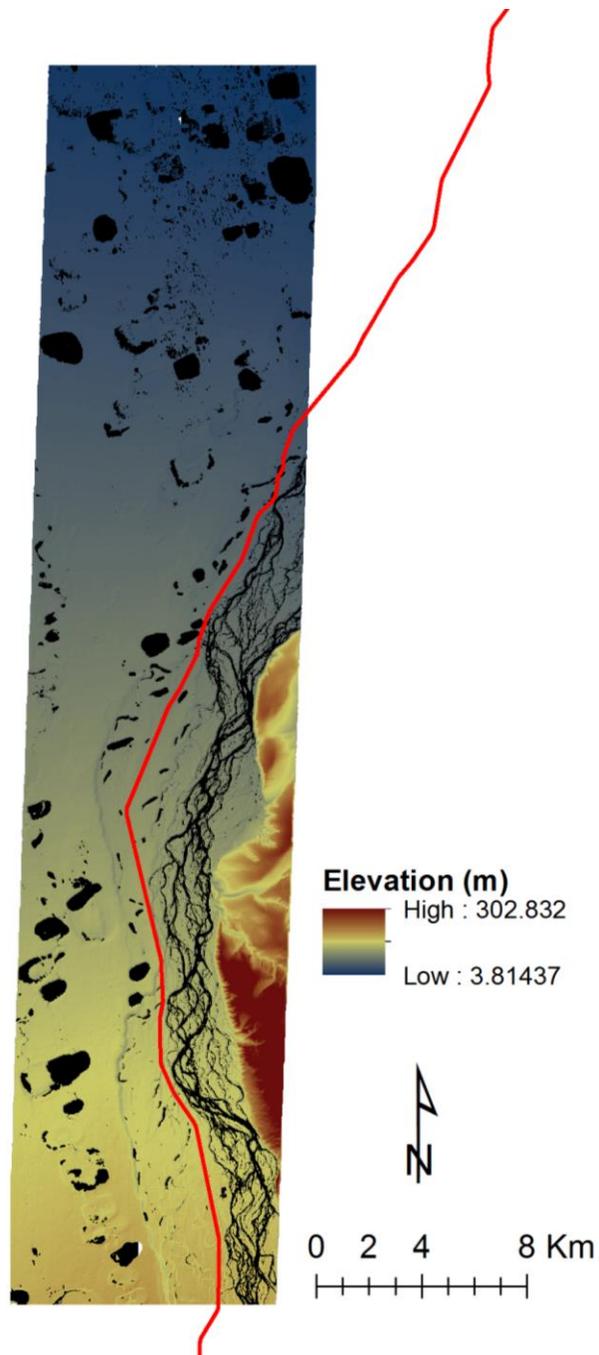


Figure 2. One meter resolution DEM of the LiDAR survey area. Surface water features, including the Sagavanirktok River, are shown in black. A hillshade effect is used to highlight subtle topographic features, such as the outline of what appears to be abandoned channels of the river near its west bank. An important transport corridor, the Dalton Highway, is shown in red.



Figure 3. Low-centered (above) and high-centered (below) polygons. Low-centered polygons are characterized by surface depressions capable of holding ponded water. High-centered polygons are thought to develop when the trough space between low-centered polygons subsides, due to partial melting of ice-wedges. This subsidence is accompanied by erosion of soil material from the low-centered polygon rims into the deepening trough space.

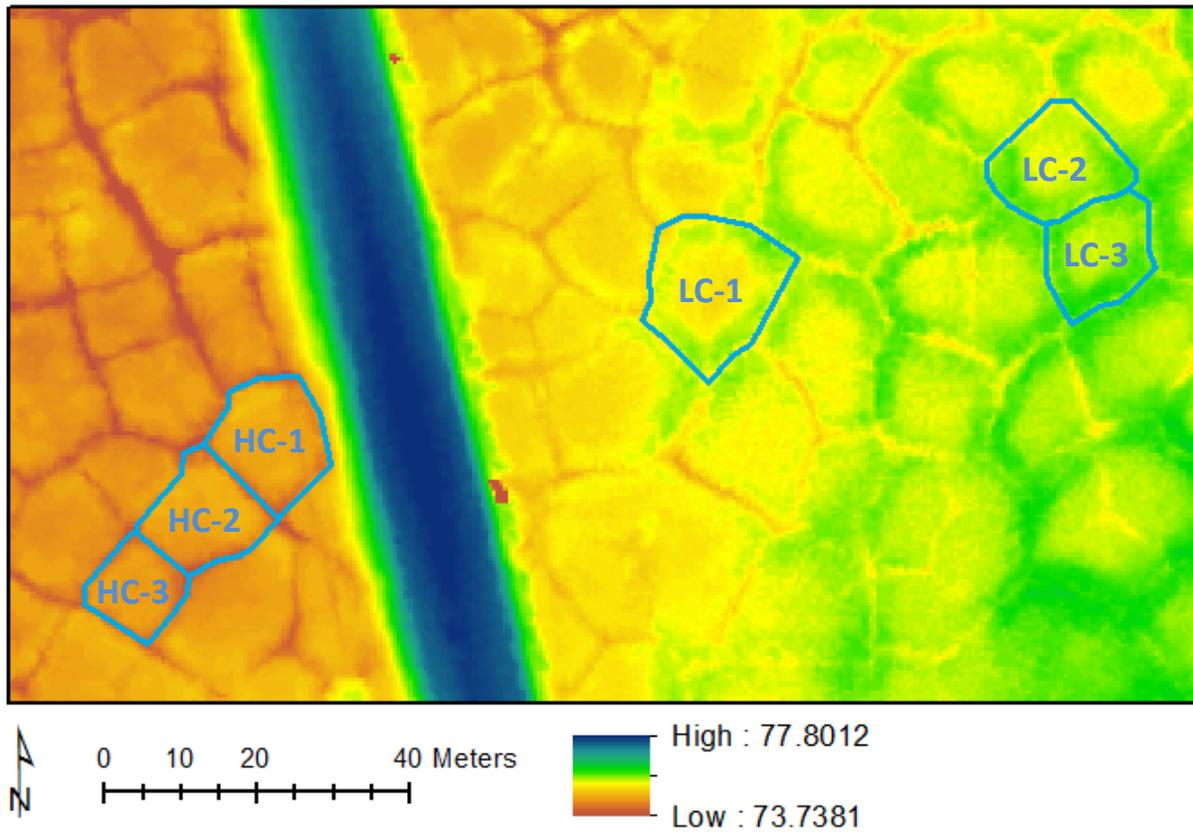


Figure 4. The study area used to calibrate the polygon geomorphic model. The Dalton Highway is visible as a blue ridge running across the center of the DEM. Low-centered polygons are visible to the east of the highway, and high-centered polygons to the west. “LC-1,” “HC-1,” etc. identify the pairs of low and high-centered polygons used to calibrate the model.

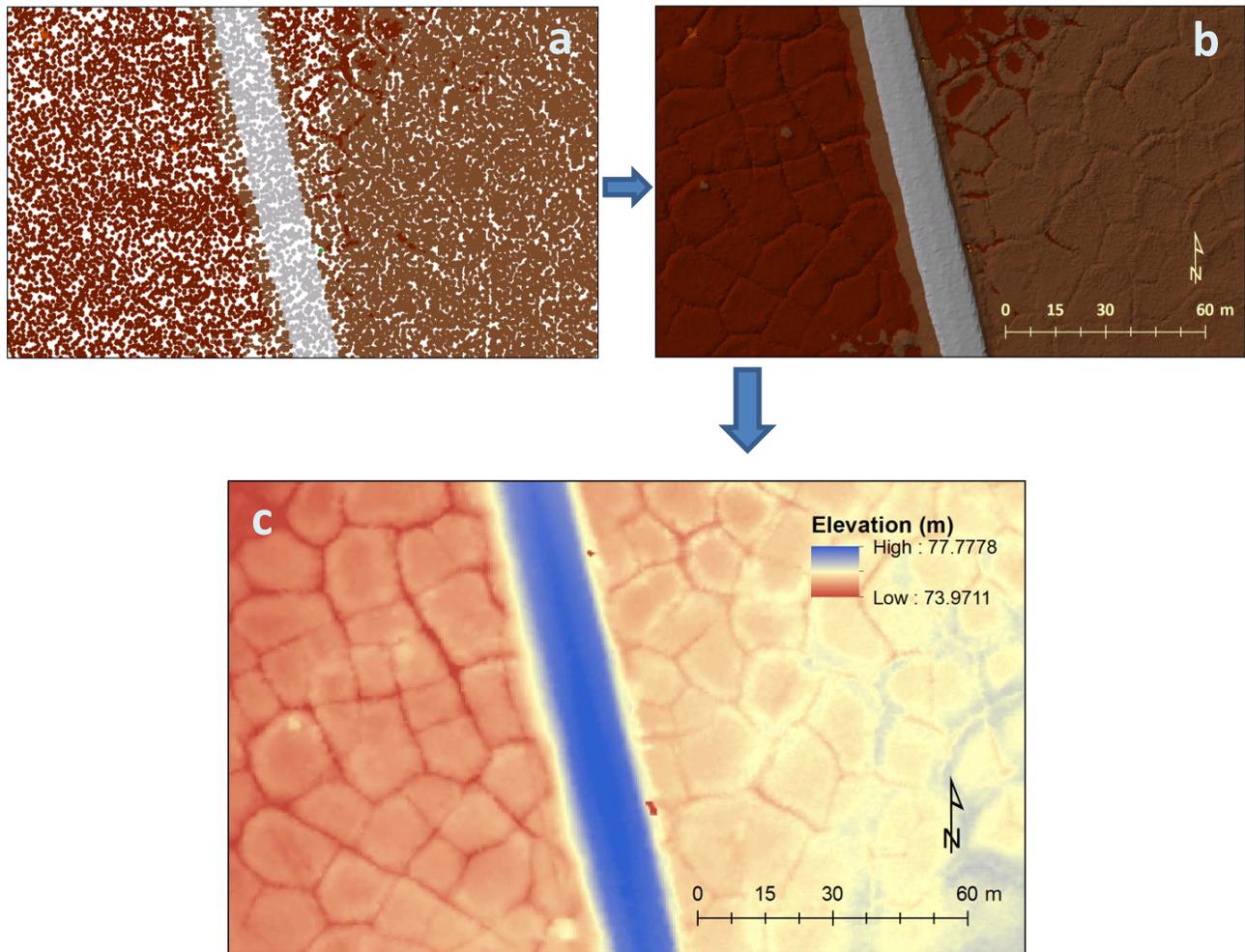


Figure 5. Creation of a 50 cm resolution DEM. Clipped point cloud data is imported into ArcGIS as a LAS file (a). The LAS file is converted into a TIN using the 3D Analyst toolbox (b). The TIN is then converted into a raster with a 50 cm cell used using the same toolbox (c).

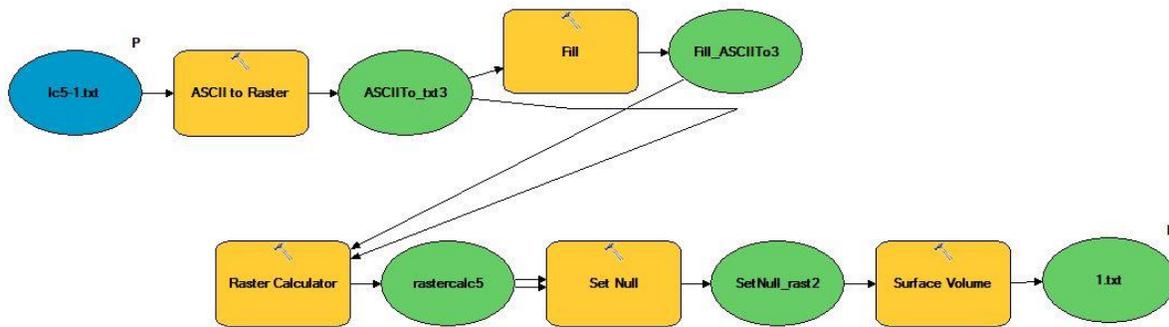


Figure 6. The workflow defined in ModelBuilder to import a synthetic DEM of a transitioning polygon from the landscape evolution model into ArcGIS, then evaluate the surface area and volume in the polygon available to hold ponded water.



Figure 7. Catchments delineated within the survey area. Catchments were exported from ArcGIS as a KMZ file to be viewed atop Google Earth imagery. Outlets for each catchment are indicated by red dots. The braided stream adjacent to the catchments is the Sagavanirktok River. The Kuparuk River, towards which some of the catchments appear to flow, is visible as a meandering channel in the western half of the image.

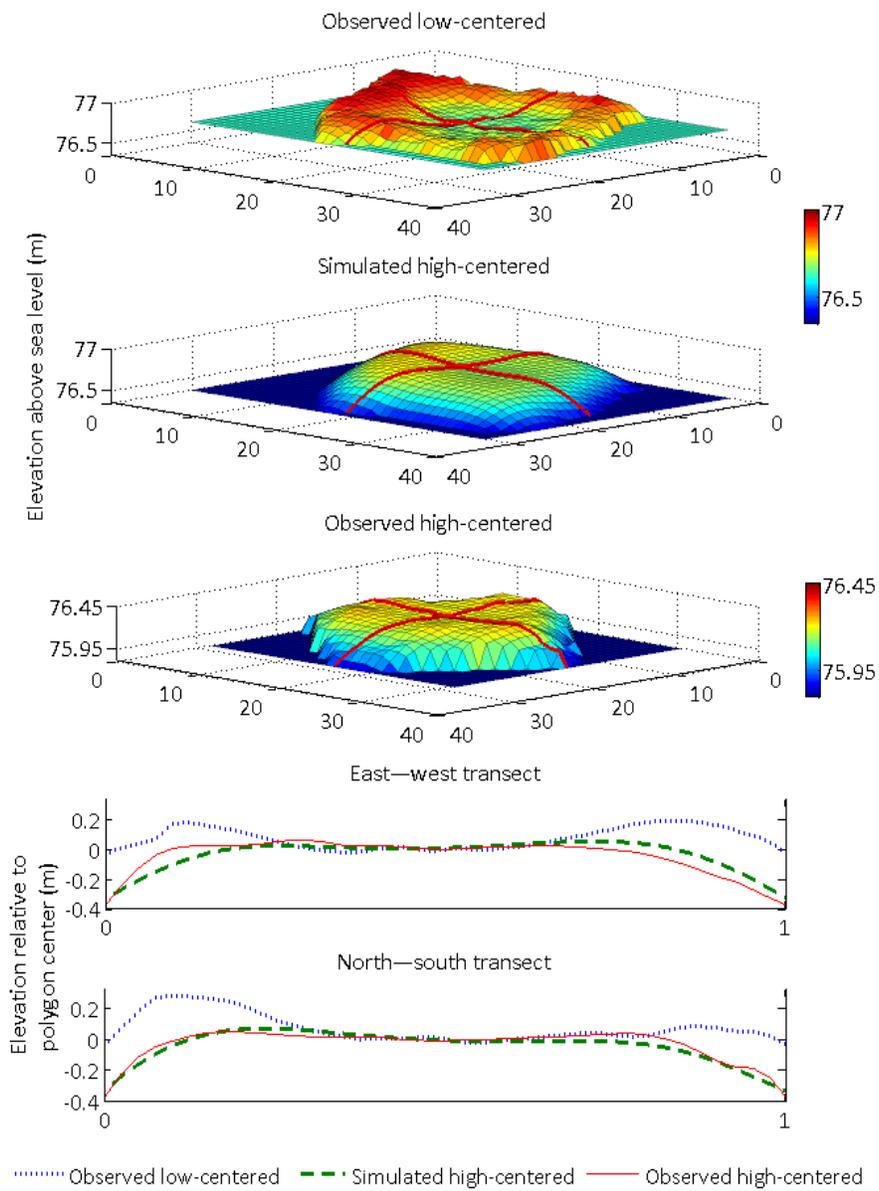


Figure 8. Calibration of the polygon geomorphic model, based on polygons LC-3 (“Observed low-centered”) and HC-3 (“Observed high-centered”) from Figure 4.

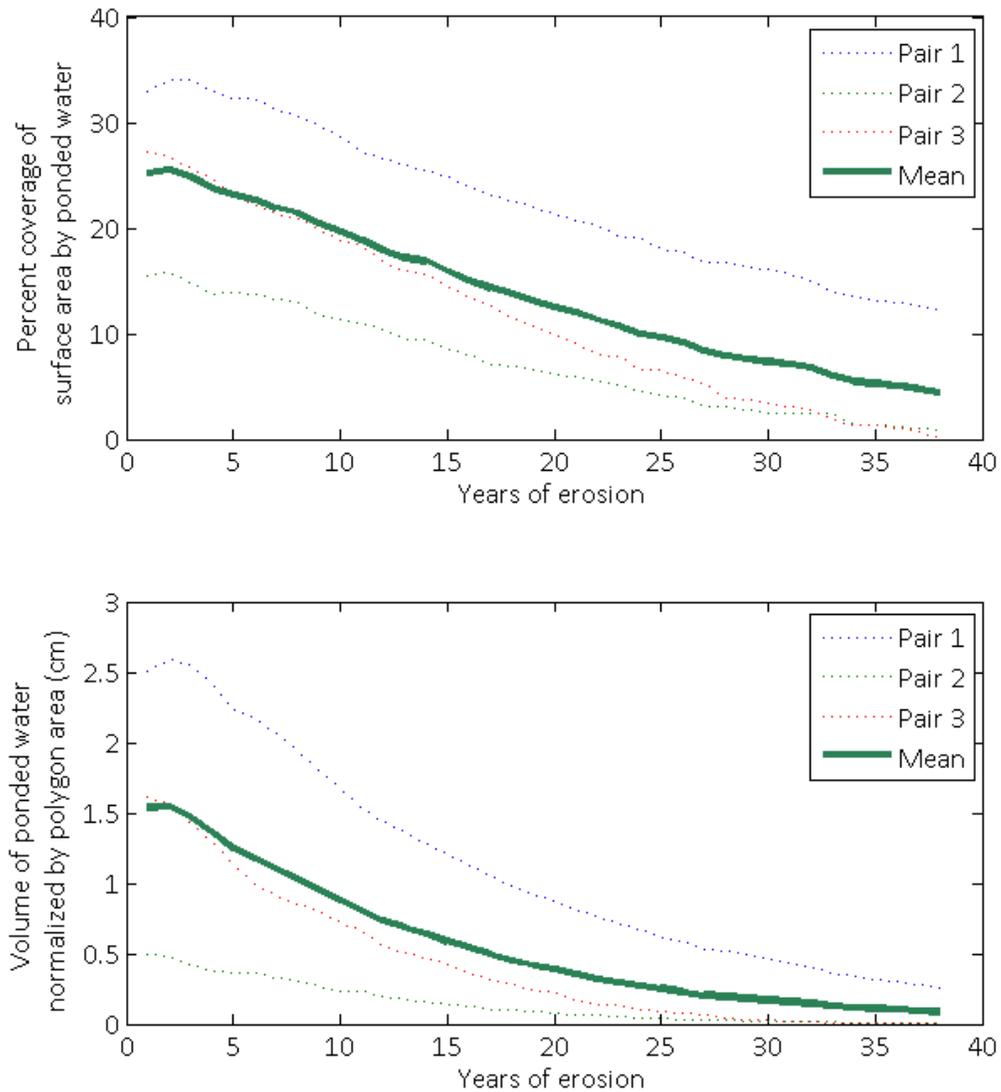


Figure 9. Modeled changes in surface area (top) and volume (bottom) available for ponded water storage in transitioning polygons. The dashed lines in the plots each represent one of the three pairs of polygons used to calibrate the geomorphic model, while the bold line represents the mean. Surface area and volume are both normalized by the area of the transitioning polygon, such that surface area is expressed as percent coverage and volume is expressed as an equivalent depth (cm).