Investigating environmental, climatic, and geomorphic controls on short-term lake area variability in Alaska

by

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THESIS ABSTRACT

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Master of Science in Geography

Title: Investigating environmental, climatic, and geomorphic controls on short-term lake area variability in Alaska

Arctic and sub-Arctic lakes are dynamic components of high-latitude landscapes, yet short-term surface water variability remains poorly studied relative to long-term trends. This study presents a fine-resolution analysis of short-term lake area variability across the entire state of Alaska using the Alaska Lake and Pond Occurrence Dataset (ALPOD), a high-resolution (10 m) map of surface water occurrence derived from Sentinel-2 imagery spanning 2016-2021. Using this dataset, we calculated variable water and permanent water (over the six-year period) in 25 x 25 km grid cells. We then used a variety of climatic and geomorphological datasets to assess local to regional-scale drivers of surface water variability. Our findings reveal that short-term surface water variability is not uniformly distributed; it is highest in unglaciated, lowland landscapes without continuous permafrost, especially in Yedoma-rich regions prone to thermokarst development. This variability is further amplified in warm areas and in regions with high evapotranspiration and fluvial connectivity. These results highlight the critical influence of permafrost degradation, landscape history, and climatic forcing on lake behavior. By analyzing lake dynamics across >800,000 lakes and integrating these results with high-resolution environmental data, this research offers a scalable framework for understanding fine-scale Arctic water dynamics and their implications for ecosystem change and carbon-climate feedbacks.

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1 | Introduction

The Arctic is warming two-to-four times faster than any other region on Earth (Rantanen et al., 2022). This phenomenon, known as Arctic amplification, is driving widespread ecological, hydrological, and geomorphological transformations across Arctic-Boreal environments, altering fundamental processes such as permafrost stability, surface energy balance, and freshwater dynamics (Stuefer et al., 2017; Levenson et al., 2025; Webb et al., 2022). In Alaska, these transformations are particularly pronounced, with regional warming reaching two to three times the global average (Ballinger and Overland, 2022).

Central to these complex environmental changes are shifts in lake dynamics. Lakes dominate the landscape of high latitude regions (Webb et al., 2022; Milner et al., 1997), especially in Arctic lowlands, where they can comprise over 40% of the surface area (Grosse et al., 2013). These systems are critical to the function of Arctic-Boreal ecosystems; they regulate surface and subsurface hydrology, modulate greenhouse gas fluxes, sustain freshwater availability, and support subsistence livelihoods for Native communities (Holgerson & Raymond, 2016; Mullet et al., 2023; Milner et al., 1997; Bring et al., 2016). The sensitive behavior of Arctic lakes are indicators of ongoing climate change but also play an important role in feedback mechanisms through processes like permafrost thaw and methane release (Walter Anthony et al., 2018; Holgerson & Raymond et al., 2016; Jones et al., 2011). As such, understanding lake variability at a range of spatial and temporal scales has been a major focus of Arctic hydrology research for more than two decades.

Long-term observational studies using satellite imagery have documented significant reductions in lake surface area over the past several decades (Smith et al., 2005; Carroll et al., 2011), reporting widespread surface water loss due to enhanced drainage through permafrost degradation, talik formation, and subsidence-driven geomorphic change (Smith et al., 2005; Roach et al., 2011; Lantz & Turner, 2015). In both Alaska and northwestern Canada, thermokarst processes have been shown to destabilize lake basins and reduce surface water extent, especially in lowland terrains where high ground ice content and shallow active layers amplify hydrologic change (Jones et al., 2011, Lantz & Turner, 2015). However, these trends are not spatially uniform. While some regions exhibit widespread lake loss, others show surface water expansion or relative stability, reflecting complex feedbacks among climate, permafrost condition, and landscape setting. For example, recent literature reveals divergent trends across Alaska's permafrost zones, with lake shrinkage dominating discontinuous regions, while lakes in continuous permafrost have remained more stable or even expanded (Webb et al., 2023). In addition to these long-term shifts, more recent studies have documented the importance of short-term and seasonal variability, particularly among smaller, thermokarst-prone lakes. These studies have revealed notable sub-annual dynamics in Alaskan lakes, thus emphasizing the need to examine lake behavior across shorter temporal scales (Cooley et al., 2019; Mullen et al., 2023).

Despite these advances, the existing literature generally emphasizes long-term decadal changes in lake area, with considerably less focus on short-term (seasonal and interannual) surface water variability. Yet, emerging evidence suggests that fluctuations under shorter time periods are crucial for understanding carbon cycling, nutrient mobilization, and habitat variability, particularly in shallow or partially-drained systems (Koch et al., 2013; Cooley et al., 2019; Jones et al., 2011). These seasonal changes are often most pronounced in smaller lakes and ponds, which dominate the Arctic landscape but are often missed in coarse-resolution products (Mullen et al., 2023; Levenson et al., 2025). While acknowledgement of the importance of short-term variability is growing, the existing body of research on seasonal lake area variability predominantly focuses on comparatively small study regions. This is largely due to data limitations, as observing short-term variability in small water bodies requires the use of high-resolution satellite imagery and thus entails analysis of large data volumes (Cooley et al., 2019; Mullen et al., 2023). Few studies have systematically assessed these dynamics at a fine spatial resolution at very large spatial scales, leaving a critical gap in understanding how short-term lake variability is structured across diverse permafrost and ecological zones.

This study provides a novel quantification of fine-scale, short-term (2016-2021) surface water variability across the entire state of Alaska and the relationship between local surface water variability and various environmental and climatic variables. We first present a detailed analysis of short-term surface water variability derived from the Alaska Lake and Pond Occurrence Dataset (ALPOD), which captures surface water dynamics at 10 m resolution for lakes greater than 0.001 km^2 using six years of Sentinel-2 imagery (Levenson et al., 2025). We then combine these results with a variety of ancillary environmental datasets to investigate how lake variability is influenced by permafrost conditions, land cover, topography, and climate. The synthesis of high-resolution remote sensing with multi-dimensional environmental data allows for a novel examination of lake responses to environmental drivers, building on recent studies that highlight the complexity of lake change in the context of Arctic amplification (Webb et al., 2022; Lantz & Turner, 2015; Mullen et al., 2023).

This study is structured around three central objectives that aim to advance our understanding of short-term Arctic lake variability in the context of environmental change:

1. How does short-term surface water variability vary across the entire state of Alaska?
2. How does land cover type influence surface water variability across Alaska's diverse landscape?

3. Does permafrost influence short-term surface water variability and/or stability?

2 | Study Area

This study analyzes surface water dynamics across the state of Alaska, spanning latitudes from 54ºN to 71ºN and encompassing more than 1.7 million km^2. Alaska provides a natural laboratory for understanding drivers of lake variability due to its wide range of landscapes and climatic conditions. Ranging from glaciated alpine regions to unglaciated lowland Yedoma basins, this environmental diversity makes Alaska a globally significant region for studying lake responses to climate and environmental change.

Alaska has a large range of climates, with mean summer temperatures varying by more than 10ºC from the cooler North Slope to the warmer interior and southwestern boreal lowlands (Muñoz Sabater et al., 2021). This gradient, coupled with variations in precipitation and evapotranspiration, produces a range of hydrologic and thermokarst conditions across the landscape. Unlike many Arctic regions, Alaska includes both ice-rich, carbon dense Yedoma terrains, and non-Yedoma soils with contrasting geomorphic stability and drainage behavior (Jones et al., 2011; Walter Anthony et al., 2018). The state also supports a rich diversity of lake and wetland ecosystems. These include shallow tundra ponds along the Barrow region of the North Slope (Hinkel, K., et al., 2003), thermokarst lands in the Lower Kuskokwim River basin (Olefeldt et al., 2021), riverine floodplain lakes in the Outley Yukon River watershed, and large glacially carved basins in the Kenai Peninsula and Kvichak-Port Heiden region.

Across these diverse settings, lake fraction varies widely, from extremely lake-dense landscapes such as the Yukon-Kuskokwim Delta to sparsely inundated basins where surface water is scarcer. This spatial heterogeneity is illustrated in Figure 1, which shows the distribution and density of lakes statewide. Alaska's ecological and environmental diversity, combined with its broad range in permafrost, soil, and topographic conditions, thus represents an excellent case study for understanding how lake variability responds to interacting climatic and geomorphic forces at local to regional scales (Levenson et al., 2025).

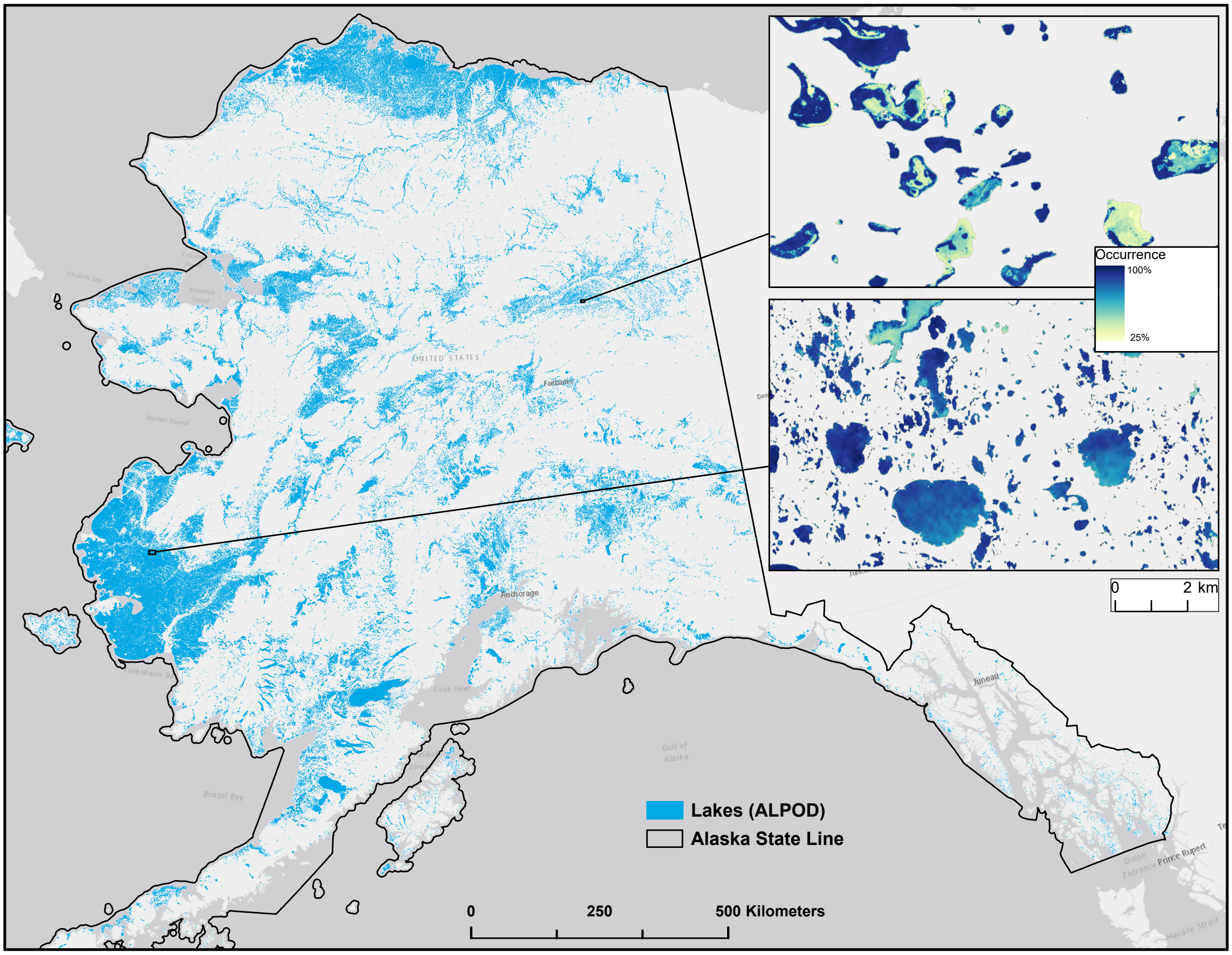

Figure 1. Study region and lake distribution across Alaska using the Alaska Lake and Pond Occurrence Dataset (ALPOD). Light blue shading represents surface water features derived from ALPOD between 2016 and 2021. Insets (a) and (b) illustrate fine-scale lake dynamics and variability in two representative regions: (top inset)) a lake-rich coastal plain near the Yukon-Kuskokwim Delta and (bottom inset) a vast wetland region in central Alaska, also known as the Yukon Flats. Color scale in inset (top) and (bottom) represent lake water occurrence, with darker shades indicating persistent water.

3 | Methods

3.1 | *Quantifying short-term lake variability using the Alaska Lake and Pond Occurrence Dataset (ALPOD)*

The Alaska Lake and Pond Occurrence Dataset (ALPOD), developed by Levenson et al., (2025), provides a high-resolution (10 m) depiction of lake and pond distribution throughout Alaska between 2016 and 2021. ALPOD was explicitly designed to overcome the limitations of static or snapshot-based surface water datasets, which often do not represent the high-frequency variability observed in Arctic-Boreal Lake systems. By incorporating all available Sentinel-2 imagery from the ice-free season, ALPOD captures dynamic lake behavior across both seasonal and interannual timescales.

Central to ALPOD is an occurrence raster, where each pixel records the proportion of cloud-free observations during which it was classified as open water. This temporal aggregation provides a robust signal of surface water presence, minimizing the confounding effects of individual cloud-obscured scenes (Levenson et al., 2025). To delineate lakes, vector-based masks were derived from this raster using multiple water occurrence thresholds (25%, 50%, and 75%). For this study, lakes exceeding 0.001 km^2 in area and meeting the 25% occurrence threshold were used to define the surface water domain, consistent with prior hydrological analyses in high-latitude systems (Levenson et al., 2025).

The construction of ALPOD employed a hybrid classification approach. First, a deep-learning U-Net model was applied to high-quality, cloud-free Sentinel-2 mosaics to generate a maximum possible lake extent mask. This model, trained on PlanetScope Imagery, excels at distinguishing lakes from rivers, shadows, and other spectrally similar features (Mullen et al., 2023). The resulting mask was manually reviewed and edited in QGIS to correct errors and was then used to constrain all subsequent water classification.

Within the lake extents identified by the U-Net and buffered by 60m, adaptative NDWI histogram thresholding was then conducted in Google Earth Engine (GEE) for every valid, cloud-free Sentinel-2 scene from June to September 2016-2021. NDWI values were calculated for each pixel, and adaptive bimodal thresholds were used to classify open water presence based on local land-water spectral contrasts. Pixels with water fractions of at least 75% were assigned a value of 1 for that date. These binary classifications were averaged across the study period to produce the final lake occurrence product.

Post-processing steps included watershed segmentation to eliminate spurious isolated water pixels and ensure spatial contiguity of lake features. Final outputs were exported as raster and vector products at three occurrence thresholds. To ensure data reliability, a rigorous uncertainty assessment was conducted by comparing ALPOD against high-resolution basemap imagery in 100 randomly sampled 25 km^2 tiles. Following removal of lakes smaller than 0.001 km^2, the F1 score for ALPOD was calculated to be 0.999, indicated exceptional classification performance (Levenson et al., 2025).

In this study, we used ALPOD to generate four surface water metrics that characterize spatial and temporal variability across the Alaskan landscape. First, short-term surface water variability was quantified using the interquartile range (IQR) of total surface water area (calculated on a pixel basis) for a standardized 25 x 25 km^2 analysis grid covering the entire state of Alaska (n=3,173 grid cells). The IQR, derived from the annual ALPOD occurrence rasters for 2016 to 2021, captures the difference between the 75^{th} and 25^{th} percentile lake area values over the study period. This approach reduces the influence of extreme outliers while effectively summarizing short-term variability.

In addition to the IQR, we calculated three summary hydrologic metrics: (1) total lake area per grid cell, (2) the area classified as a variably inundated, defined as water pixels that occurred in 25-75% of annual observations, and (3) the percentage of total water area that was classified as variable. We normalized (1) and (2) by the total terrestrial area of each grid cell to obtain fractional water coverage values. As Levenson et al (2025) present a detailed analysis of drivers of total lake area in ALPOD, this study primarily focuses on two specific metrics of short-term variability: namely (1) the variable water fraction (%), which quantifies the area of variable water (defined as lake pixels with 25-75% occurrence) relative to the total area of the grid cell, providing an absolute hydrologic footprint; and (2) the variable water as a percentage of total water, which captures the proportion of variable water relative to the total lake area within a grid cell, serving as a metric of relative hydrologic instability.

To characterize the influence of lake size on surface water variability, we also calculated the median lake area per grid cell. This metric was derived from the ALPOD vector product by computing the area of each individual lake polygon and extracting the median value per 25km^2 grid. Median lake size provides a representative measure of lake size distribution within each grid and was used to explore the stabilizing influence of larger lakes.

3.2 | *Other Input Datasets*

We evaluated the drivers of surface water variability in Alaska using surface water metrics derived from ALPOD in combination with a suite of environmental datasets representing key climatic and landscape characteristics. These variables were selected to reflect both physical and ecological controls on Arctic Lake behavior, and include land cover, permafrost characteristics, elevation, geologic substrate, actual evapotranspiration (AET), and river presence. Each dataset was standardized, clipped to the study area, and summarized per 25 km^2 grid cell, and reprojected to EPSG: 3338, ensuring consistency for statistical and machine learning analysis. Table 1 summarizes the variables, spatial and temporal resolution and source references. Figure 2 shows visualizations of several key variables, highlighting their landscape distribution and environmental heterogeneity across the Alaskan domain.

The Boreal-Arctic Wetland and Lake Dataset (BAWLD) is the primary land cover dataset for this research. BAWLD spans the circumpolar region with approximately 23,469 grid cells of 0.5º x 0.5º resolution at latitudes above 50ºN (Olefeldt et al., 2021). Although BAWLD is commonly used for studying methane emissions, its detailed land cover classifications are valuable for analyzing surface water variability. For this research, we specifically use BAWLD's "WETSCAPE" attribute, which identifies regions with unique combinations of wetland and lake types. We take the WETSCAPE attribute and extract the predominant attribute per grid cell across our study region. As a result, we gain a better understanding of which land cover type reveals higher surface water variability.

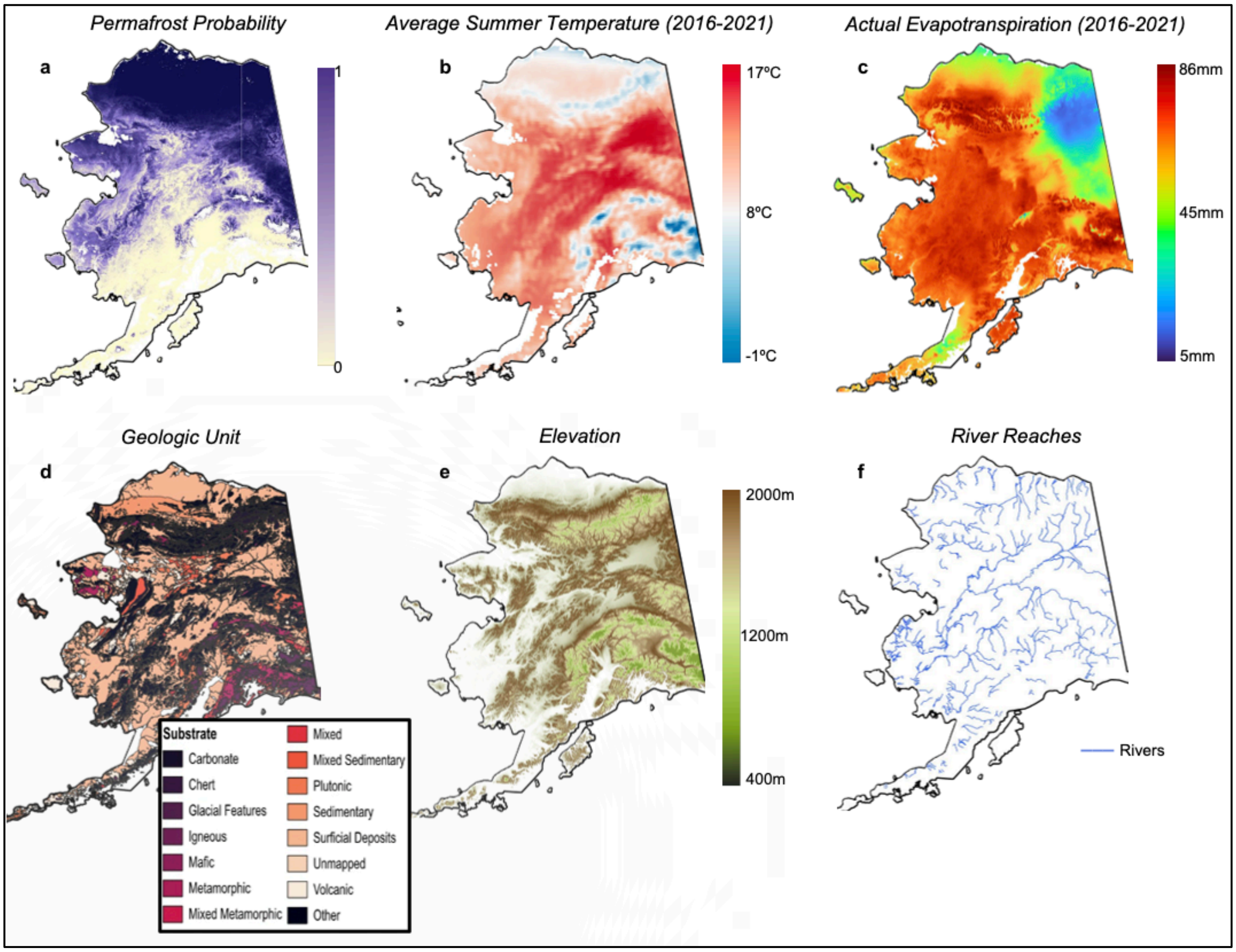

Figure 2. Environmental drivers used in the analysis of surface water variability across Alaska. (a) Permafrost probability, (b) river network, (c) average summer temperature (June-August 2016-2021), (d) dominant geologic substrate, (e) actual evapotranspiration (AET) during June-August from 2016-2021, and (f) mean elevation. These covariates were summarized at the 25 km² grid scale and used to model regional controls on lake variability.

For permafrost data, we use the pan-Arctic permafrost map produced under the GlobPermafrost project, which provides high-resolution information on permafrost extent and mean annual ground temperature (MAGT) across the Northern Hemisphere with a 1km spatial resolution (Figure 2a; Obu et al., 2023). This dataset is valuable for understanding spatial variability in permafrost conditions at high resolution and how permafrost may influence surface water bodies across Arctic landscapes. We take the permafrost probability and average the mean over the 25km^2 grids across our study region. This dataset also includes permafrost zones (continuous, discontinuous, sporadic, and isolated), and we extract the dominant zone per grid cell across the study region.

For climate data, we use ERA5-Land, a high-resolution reanalysis dataset that provides consistent, daily statistics of land surface variables since 1950. Produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) through the Copernicus Climate Change Service, ERA5-Land integrates model data with global observations using physical laws to create a complete and reliable record of past climate conditions (Muñoz Sabater et al., 2021). From this dataset, we average the daily air temperature values over June, July, and August for 2016-2021 for each grid cell of our study region (Fig. 2b).

We also incorporate actual evapotranspiration (AET) from the TerraClimate dataset (Fig. 2c, Abatzoglou et al., 2018). We average June-August AET values between 2016 and 2021 for each grid cell. AET serves as a proxy for atmospheric demand and moisture availability, which are two key constraints on lake persistence.

We assessed the influence of geologic substrate on surface water variability using both statewide geologic datasets. For landscape-scale visualization (Fig. 2d), we used the U.S. Geological Survey's 1:250,000-scale geologic map of Alaska, which includes detailed information on rock types, unit ages, and geomorphic features (Wilson et al., 2015). This dataset was used to qualitatively illustrate substrate variation across Alaska. For statistical modeling, we derived a dominant surficial deposit classification per 25 km² grid cell using the DepositNAM attribute from the ALPOD dataset (Jorgenson et al., 2008; Levenson et al., 2025). This attribute integrates underlying geologic unit data and identifies primary surface deposits such as eolian silt, coastal sediments, and glaciomarine materials. We computed the modal DepositNAM value per grid cell to capture prevailing depositional environments and linked this categorical variable to surface water metrics to evaluate how sediment type influences hydrologic variability. Though this classification is derived from the broader USGS geologic map, it is embedded within the ALPOD product and allows for grid-scale quantification of surface processes relevant to lake stability.

We analyze elevation's influence using MERIT DEM, a high-accuracy digital elevation model that reduces common errors in elevation data, such as absolute bias, stripe noise, speckle noise, and tree height biases, by combining and processing data from several satellite-based DEMS (Fig. 2e Yamazaki et al. 2017). With a 3-arcsecond resolution (~90 meters at the equator), it provides detailed terrain elevations, referenced to the EGM96 geoid. We integrate MERIT DEM into this research to better understand how topography influences lake occurrence across different landscapes. Specifically, here we assess the role of elevation using the average elevation per grid cell across our study region.

Finally, to assess river connectivity, we incorporate data from the Surface Water and Ocean Topography (SWOT) River Database (Fig. 2f, SWORD), which provides a global synthesis of river reach centerlines and hydrologic attributes (Altenau et al., 2021). River networks were used to generate a binary indicator reflecting the presence or absence of fluvial features in each grid cell. This variable serves as a proxy for lateral hydrologic connectivity and fluvial influence. Because riverine environments often promote dynamic surface water behavior through floodplain interaction and groundwater exchange, this dataset supports the investigation of how river presence modulates lake variability across different geomorphic and climatic settings (Figure 2b).

Table 1. Summary and Explanation of Datasets Used in the Analysis of Environmental Drivers of Lake Variability

Variable	Description	Spatial Resolution	Temporal Resolution	Data Source(s)
Land cover (WETSCAPE)	Modal WETSCAPE class per 25 km² grid cell; derived from wetland/lake types	0.5° (~50 km)	Static	Olefeldt et al. (2021)
Permafrost extent (zone)	Mode per-grid permafrost zone classification (continuous to isolated)	1 km	Static	Obu et al. (2019)
Permafrost probability	Mean permafrost probability averaged per 25 km² grid cell	1 km	Static	Obu et al. (2019)
Summer air temperature	Mean June–August temperature (2016–2021) per 25 km²	9 km	Summer 2016–2021	Copernicus C3S (2024)
Elevation	Mean elevation per 25 km² from MERIT DEM	~90 m	Static	Yamazaki et al. (2017)
Geologic unit	Dominant geologic unit per 25 km² grid	1:250,000 scale	Static	Jorgenson et al. (2008)
River presence	Binary indicator for whether river intersects the grid	Variable (~90 m)	Static	Altenau et al. (2021)
Evapotranspiration (AET)	Mean June–August AET (2016–2021) averaged per grid	~4 km	Monthly (summer avg.)	TerraClimate (Abatzoglou et al., 2018)
Median lake size	Median lake area (km^2) of all lakes within each grid	Derived from ALPOD	Summer 2016-2021	Levenson et al. (2025)

Table 1. Each dataset was selected for its relevance to hydrologic, climatic, or geomorphic controls on surface water dynamics. Variables span land cover, permafrost conditions, temperature, topography, geologic substrate, and fluvial connectivity. Datasets vary in spatial and temporal resolution but were standardized to a 25km^2 grid for spatial analysis. Sources include global and regional data products for high-latitude applications.

3.3 | *Preprocessing*

To ensure analytical consistency across geospatial datasets, all input layers were projected into EPSG:3338 (Alaska Albers Equal Area), which preserves area and is appropriate for large-scale landscape analyses in Alaska. The spatial extent of each dataset was clipped to match the defined study area.

Raster-based datasets, including ERA5-Land climate reanalysis, permafrost probability, and elevation, were resampled as needed to align with the 10-meter ALPOD grid resolution or aggregated to 25 km^2 analytical units using zonal statistics. Where applicable, interpolation was applied to fill small temporal or spatial gaps in the data. For instance, linear interpolation was used to fill missing values in the ERA5- Land time series, maintaining temporal coherence.

Continuous variables, such as mean elevation, mean annual air temperature (June-August), actual evapotranspiration (AET), and permafrost probability, were selected based on previous literature addressing the influence of these variables on Arctic Lake dynamics and were summarized for each 25 km^2 grid cell using zonal means. Elevation values were extracted from the MERIT DEM and averaged to characterize the broader topographic context of each grid. Mean annual air temperature during summer months and AET were derived from ERA5-Land daily data and TerraClimate, respectively, which were temporally averaged across the June-August ice-free period for each year from 2016 to 2021, then spatially aggregated to grid scale. Permafrost probability values were extracted from the GlobPermafrost dataset and averaged per grid to capture spatial gradients in ground ice presence and thaw susceptibility.

Categorical variables, including BAWLD land cover classifications and permafrost zones, were summarized using modal statistics, identifying the dominant category within each grid. these variables were chosen to reflect prevailing ecological and permafrost conditions that shape surface water stability. The resulting standardized variables enabled comparative statistical analysis across Alaska’s diverse geography and climatic regimes, facilitating a robust evaluation of environmental controls on short-term lake variability.

3.4 | *Analytical Framework*

To investigate the relationship between surface water variability and its environmental drivers, we used a statistical framework that integrated descriptive statistics, exploratory analyses, and inferential modeling. This approach allowed us to disentangle the relative and combined influences of climatic, topographic, permafrost, and land cover variables on both absolute and relative measures of lake variability.

First, descriptive statistics were calculated for all hydrologic and environmental variables across the study area. These included measures of central tendency and dispersion (mean, median, standard deviation, interquartile range) for short-term surface water variability, variable water fraction, and variable water as a percentage of total water. Summary statistics were also generated for mean summer temperature, elevation, actual evapotranspiration (AET), and permafrost probability, and categorical variables including permafrost zone, BAWLD land cover type, and geologic substrate. These descriptive analyses helped identify based spatial patterns, outliers, and the distributional characteristics of each variable.

To investigate interactive effects between climate and landscape variables, we used linear regression models to test interaction terms. Based on prior literature (Rantanen et al., 2022; Burke et al., 2020; Olefeldt et al., 2016), we examined the interaction between mean summer temperature and permafrost probability. We also explored an elevation and AET interaction to assess topographic modulation of evapotranspiration effects. All continuous predictors were standardized to enable coefficient comparison and reduce collinearity. In addition to these regression-based approaches, we used Pearson's correlation tests for continuous variables and ANOVA tests for categorical variables to assess linear relationships between surface water metrics and environmental variables, providing a supplementary measure of effect size and direction.

To further quantify the relative importance of predictor variables and capture potential non-linear relationships, we implemented a histogram-based gradient boosting regression tree (HGBRT) using the HistGradientBoostingRegressor from the scikit-learn library. We chose this method because HGBRT models can handle the multicollinearity among predictors and are highly effective for discovering complex, non-linear interactions without overfitting. Additionally, boosting ensemble methods typically outperform single tree models by minimizing both bias and variance (Elith et al., 2008). Permutation importance scores were calculated for each variable to determine their contribution to model performance.

Following this initial analysis, we computed grouped permutation importance to evaluate the relative contributions of broader variable categories–specifically, climate variables (e.g., temperature and evapotranspiration) and landscape characteristics (e.g., geology, permafrost extent, elevation, and median lake size). To do this, we aggregated the permutation importance values of individual predictors within each group, recalculating model error after jointly permuting all variables in that group. This machine learning approach complemented our statistical models by offering a flexible, non-parametric means of assessing variable influence across the full landscape.

All statistical analyses were performed in Python using the statsmodels, scikit-learn, pandas, and seaborn libraries. Spatial visualizations and zonal summaries were generated using geopandas and rasterstats. This multi-scale, integrative framework allowed for a comprehensive examination of how environmental variables structure surface water variability across Alaska's changing landscape.

4 | Results

4.1 | *Variable surface water distribution across Alaska*

From 2016 to 2021, lakes and ponds collectively covered 79,241 km^2 of the state of Alaska, or 4.6% of Alaska's terrestrial landscape. Of this surface water, 82.6% was classified as persistent (present in more than 75% of observations over 2016-2021) and 17.4% (13,819 km^2) was classified as variably inundated (present between 25-75% of observations), leading to a total statewide variable water fraction of 0.81%. The statewide numbers, however, mask wide regional variability in short-term surface water dynamics (Fig. 3).

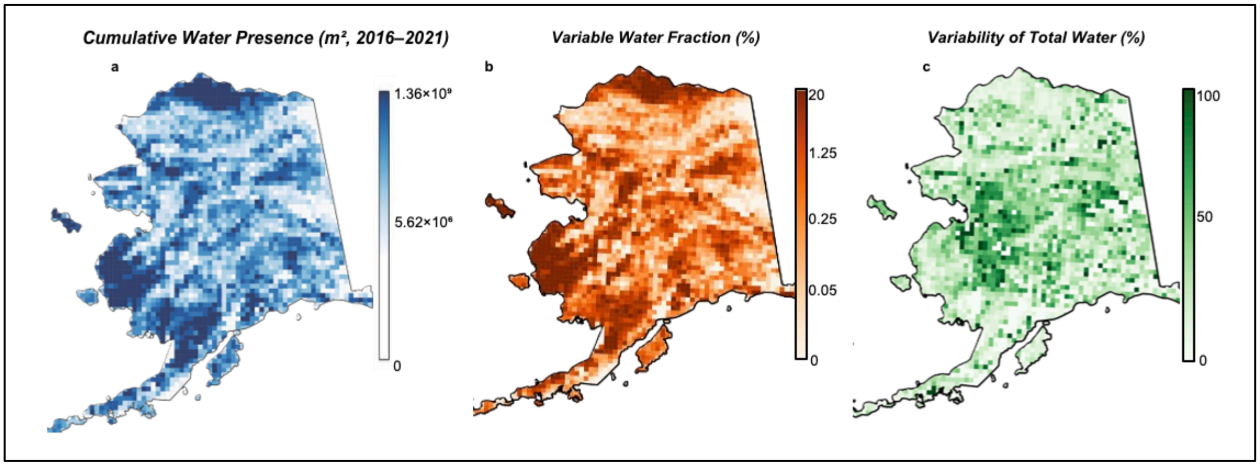

Figure 3. Spatial distribution of short-term surface water metrics across Alaska derived from the ALPOD dataset (2016-2021). (a) Cumulative water presence across Alaska, (b) variable water fraction, defined as the percentage of land area (i.e. not-ocean) classified as variably inundated (25-75% water occurrence), and (c) variable fraction of total water, representing the proportion of variable water relative to total water area per grid cell. These metrics reveal distinct hydrologic patterns across permafrost zones, highlighting regions of elevated water coverage and interannual variability.

Most of Alaska's surface water is concentrated in a few large lake-rich basins, notably Kvichak-Port Heiden (19,355 km^2), the Lower Kuskokwim River (9,996 km^2), the North Slope (9,545 km^2), and the Outlet Yukon River (7,108 km^2). These low-lying watershed basins account for most of Alaska's lake and pond coverage (Fig. 4). In contrast, higher elevation watersheds and mountainous regions, such as those in the Alaska Range, have much less extensive surface water coverage and contribute minimally to the statewide surface water footprint.

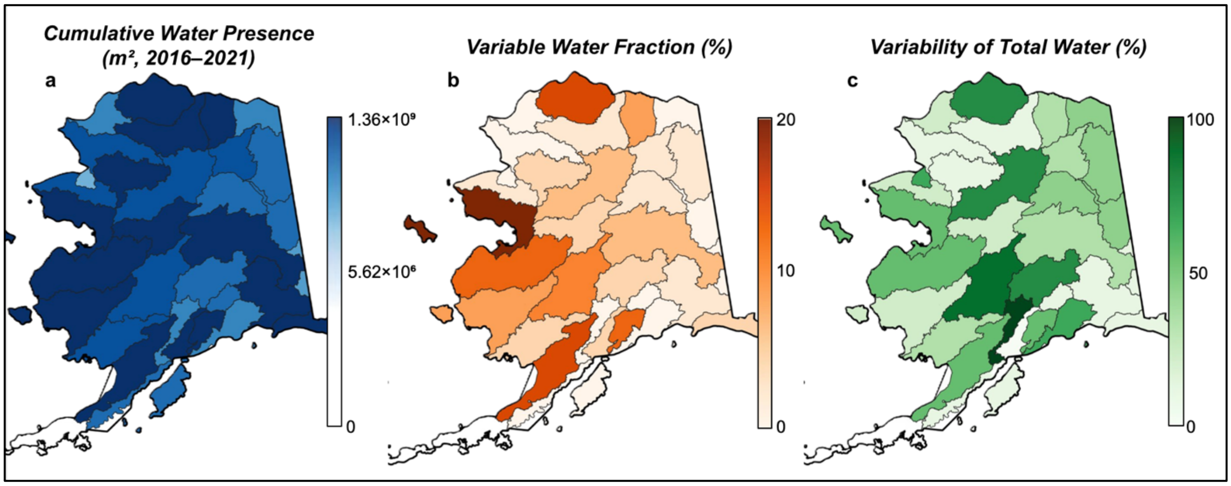

Figure 4. Watershed-scale patterns of surface water dynamics across Alaska. (a) Cumulative water presence across Alaska, (b) variable water fraction expressed as a percentage of watershed land area, and (c) variable fraction of total water, representing the proportion of variable water relative to all surface water within each watershed. These metrics reveal regional differences in both absolute and relative hydrologic variability.

Absolute water variability is similarly concentrated in a handful of key basins. The Outlet Yukon River (2,126 km^2 of variable water; 2.10% variable water fraction), Lower Kuskokwim

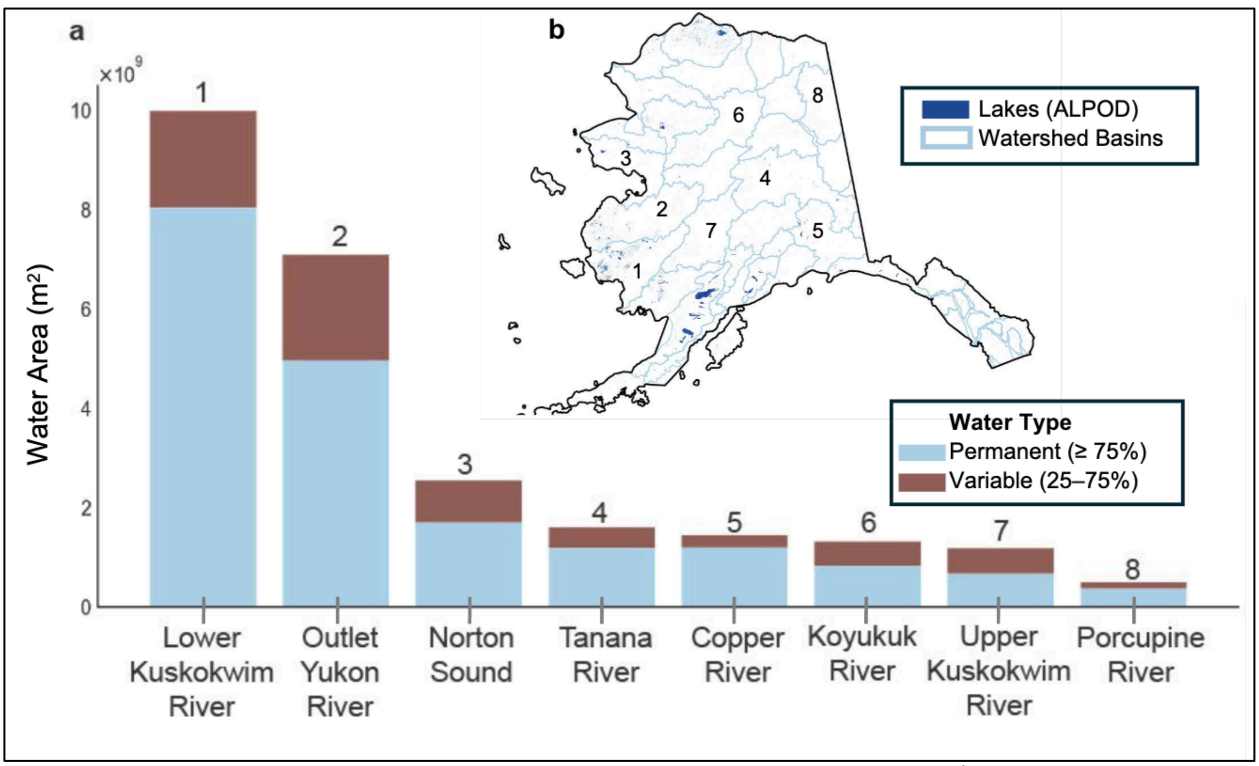

Figure 5. Cumulative permanent (≥75%) and variable (25-75%) surface water area (m^2) across the eight largest Alaskan watersheds from 2016 to 2021. Water area was derived from ALPOD using a 25% occurrence threshold. Note that a) reflects the total area of variable water per watershed and not its proportion relative to total water area; therefore, watersheds with large total lake coverage may appear disproportionately dominant.

River (1,950 km^2 of variable water; 1.94% variable water fraction), North Slope (1,652 km^2 of variable water; 2.40% variable water fraction), and Kvichak-Port Heiden (1,177 km^2 of variable water; 1.92% variable water fraction) collectively account for over 75% of Alaska's total variable surface water. This uneven distribution indicates that most short-term surface water change occurs within a small subset of regions (Fig. 5).

Statewide, only a small fraction of watersheds–roughly 16%–exhibited moderate to high variability as a percent of total water, defined here as variable water accounting for more than 30% of the total surface water area, and the vast majority of watersheds had relatively stable surface water conditions (Fig. 5). Watersheds such as Melozitna River–Yukon River (48.7%), Outlet Yukon River (46.6%), and Upper Kuskokwim River (45.2%) show the highest relative variability, meaning they have substantial short-term lake area fluctuations relative to their total lake area. In contrast, the North Slope (20.8%), Kvichak–Port Heiden (18.3%), and Gulf of Alaska (17.2%) rank among the most stable, despite their large total lake extent. Together, these results reveal that both lake-rich and lake-poor watersheds can experience hydrologic variability, but in different ways.

In addition to regional variation, landscape types defined by land cover with permafrost-wetland associations reveal key patterns in hydrologic instability. Analysis across the Boreal-Arctic Wetland and Lake Dataset (BAWLD) land cover classes identified Yedoma wetland tundra (WETSCAPE 15) as having the highest absolute variability, with a 4.42% variable water fraction. Lake-rich wetlands (WETSCAPE 8) and upland boreal zones (WETSCAPE 14) also exhibited substantial variability, each exceeding 3.54%. When normalized by total surface water, Yedoma wetland tundra again emerged as the most unstable, with 44.6% of its surface water classified as variable. Other highly variable systems included permafrost peatlands (WETSCAPE 1) and riverine landscapes (WETSCAPE 3), both with relative variability above 36%.

4.2 | *Environmental Drivers of Surface Water Variability*

To evaluate how landscape and climatic characteristics modulate short-term surface water variability across Alaska, we stratified surface water metrics by key environmental variables. For each driver, we examined two complementary hydrologic metrics: (1) variable water fraction and (2) variable water as a percentage of total water. Below we discuss the effect of elevation, permafrost zone, lake size, fluvial connectivity, actual evapotranspiration, and temperatures on these hydrologic metrics (Fig. 6).

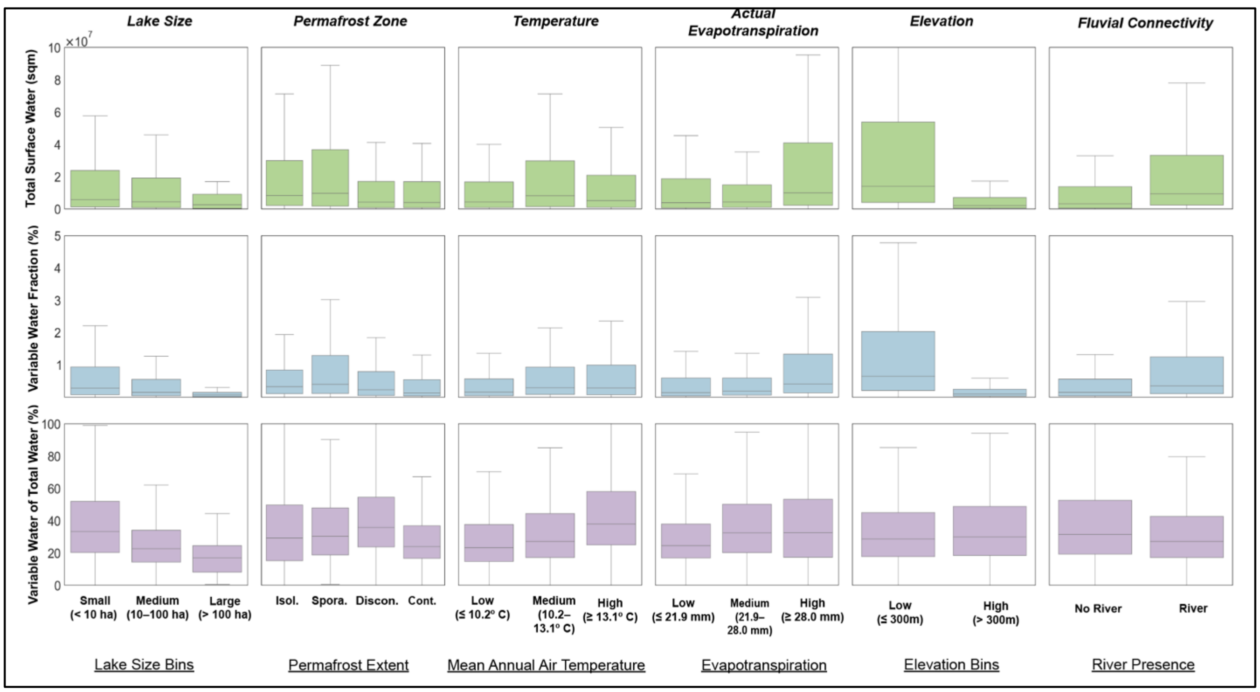

Figure 6. Boxplots showing spatial variation in short-term surface water dynamics across environmental drivers. Rows represent hydrologic metrics (top: total water, middle: variable water fraction, bottom: variable water as a % of total water); columns represent environmental variables. These visualizations highlight both absolute and relative variability patterns and their dependence on terrain, climate, and hydrologic context.

4.2.1 | Influence of Median Lake Size on Hydrologic Variability

Median lake size at the grid level emerged as a strong determinant of both absolute and relative surface water variability across Alaska. Grid cells with smaller median lake sizes (<0.54

ha) exhibited the greatest variable water fraction, averaging 0.90%, compared to 1.11% for medium-size basins (0.54–1.09 ha) and just 0.60% for large-lake dominated cells (>1.09 ha). These differences were statistically significant (ANOVA $F = 15.6$, $p < 0.0001$) confirming that basins composed of smaller lakes exhibit more dynamic surface water coverage.

This pattern was even more pronounced when considering variability relative to total water area. Grid cells with small median lakes had a mean relative variability of 44.6%, compared to 29.9% in medium-sized basins and 23.8% in large-lake regions. These patterns reflect a fundamental hydrologic sensitivity in small-lake systems: their shallow depth, high perimeter-to-area ratio, and limited buffering capacity make them often faster to respond to hydrologic and/or environmental perturbations.

4.2.2 | Permafrost

Surface water variability also appears to be modulated by permafrost extent, with areas with less permafrost exhibiting the greater hydrologic instability across both absolute and relative metrics. Isolated, sporadic, and discontinuous permafrost regions all demonstrated higher variable water fractions—0.90%, 0.87%, and 0.85%, respectively—compared to the continuous permafrost zone, which had a lower mean variability of 0.7%**.** While these differences are statistically significant (ANOVA $F = 4.8$, $p < 0.0001$) the range is relatively narrow in terms of absolute water fluctuation.

However, clear differences emerge when variability is analyzed relative to total lake area. Discontinuous permafrost zones exhibited the highest relative variability at 40**%,** followed by sporadic **(**33.6%**)** and isolated **(**32.4%**)** zones. In contrast, lakes in continuous permafrost Averaged just 27.7% relative variability (ANOVA $F = 27$, $p < 0.0001$). This reinforces the interpretation that thaw-affected permafrost zones, especially those undergoing degradation, host not only more variable lake systems but also more hydrologically unstable ones.

Collectively, these results reveal an important distinction between where variability occurs. While variable water fraction varies less between continuous and transitional (i.e. not continuous) permafrost zones, the much sharper rise in variable water as a percentage of total water in discontinuous and sporadic permafrost suggests that lakes in these regions are not only more spatially dynamic but also proportionally more unstable. In other words, transitional permafrost does not necessarily produce more variable water in absolute terms, but the water that is present is more hydrologically volatile, reflecting a potential heightened sensitivity to thaw processes and seasonal moisture fluxes. This divergence between absolute and relative metrics suggests a causal relationship between surface water instability and thaw-induced landscape change; however, the signal likely reflects the combined influence of multiple climatic and geomorphic factors, including temperature, actual evapotranspiration, and river connectivity, rather than permafrost transitions alone.

4.2.3 | Mean Annual Air Summer Temperatures

Temperature also appears to be correlated with surface water variability across Alaska. Grid cells in the highest temperature class showed the greatest variable water fraction, averaging 0.92%, compared to 0.74% in moderate-temperature zones and 0.60% in colder regions (ANOVA $F = 7.1$, $p = 0.007$). When evaluated in terms of variability relative to total water, these differences were even more pronounced: warm zones averaged 36.6% relative variability, versus 25% in moderate zones and 24% in cold regions ($F = 1.0 \times 10^{-33}$).

These patterns suggest that warmer environments are associated with both greater surface water fluctuation and proportional hydrologic instability. While the increase in absolute variable water fraction across temperature classes is modest, the steep rise in relative variability indicates that lakes in warmer regions are not only expanding and contracting more frequently but are doing so within less stable hydrologic systems. This relationship shows the role of climate as a driver of lake dynamics, amplifying seasonal water variability particularly in regions where thaw, snowmelt timing, and evaporative demand interact to shape short-term lake behavior.

4.2.4 | Actual Evapotranspiration (AET)

Actual evapotranspiration (AET), as a proxy for atmospheric moisture demand, emerged as a modest but statistically significant driver of surface water variability in Alaska. Grid cells with high AET values had the greatest variable water fraction, averaging about 1%, followed by medium-AET zones (0.81%) and low-AET regions (0.71%) (ANOVA $F = 7.9$, $p < 0.01$). When variability was expressed relative to total water, grid cells in high-AET zones exhibited a mean relative variability of 29.3%, compared to 36.4% in medium-AET zones and 27.3% in low-AET areas ($F = 5.9 \times 10^{-10}$), indicating a perhaps non-linear sensitivity to atmospheric water demand.

These results suggest that AET influences surface water dynamics through varying mechanisms. In some regions, higher AET may intensify drying and reduce the persistence of marginal lakes, particularly in shallow basins with limited inflow. In others, higher AET may coincide with high solar exposure and permafrost degradation, thus promoting water redistribution through thermokarst processes. The pronounced variability in medium-AET zones may reflect changing landscapes where both wetting and drying processes are occurring simultaneously.

4.2.5 | Elevation and Terrain

Short-term surface water variability shows clear stratification by elevation, with distinct trends across both absolute and relative metrics. Low-elevation regions (0–300 m), which holds

87% of total water, exhibited significantly greater absolute variability, with a mean variable water fraction of 1.13%, compared to just 0.24% in higher elevation areas (>300 m), which account for the remaining 13.6% of the landscape. This difference is statistically significant ($p < 0.0001$) and reflects the abundance of lowland lakes in flat, thermokarst-prone terrain.

However, due to the higher density of total surface water in lowland regions, the variable water as a percentage of total was only moderately different between elevations. Higher elevation areas exhibited slightly higher relative variability, with a mean of 31.7%, compared to 26.5% in lowlands ($p < 0.0001$). This suggests that although there is less total water at higher elevations, the lakes that do exist may be relatively more hydrologically unstable. However, we note that though this some of this apparent instability at high elevations may be caused by noise in the ALPOD dataset, which is comparatively larger in areas with low lake density.

Pearson correlation analyses support these trends: elevation was moderately negatively correlated with variable water fraction ($r = –0.28$, $p < 0.001$), but showed a weak positive correlation with relative variability ($r = 0.09$, $p < 0.01$). Together, these results suggest that elevation governs the spatial distribution of dynamic lakes (with more variable water at lower elevations), but that instability per unit of water may be slightly greater at higher elevations.

Geologic substrate also influences surface water variability. ANOVA results indicate significant differences in absolute variability across geologic units ($F = 2.8$, $p = 0.025$), though relative variability differences were not statistically significant ($F = 1.8$, $p = 0.13$). Among the most hydrologically dynamic substrates were coastal deposits, which supported the highest amount of variable water (68.4%) despite only modest variability of total water (28%). Eolian silt and glaciomarine deposits also exhibited substantial relative variability (27.0% and 38.2%, respectively) and absolute variability around 2-5%, reinforcing the notion that fine-grained, unconsolidated materials are more susceptible to thaw, lateral water movement, and seasonal reorganization.

4.2.6 | River Connectivity

The presence of rivers within a grid cell significantly increased both absolute and relative surface water variability. Grid cells intersected by rivers had a higher variable water fraction (1.12%) than those without rivers (0.52%), indicating a highly significant difference ($t = 9$, $p < 0.0001$). This pattern held when variability was assessed as a proportion of total water: river-connected cells had an average relative variability of 30.6%**,** compared to 27.5% in non-river cells ($t = 3.7$, $p < 0.001$).

These results indicate that rivers enhance both the spatial extent and proportional instability of surface water, likely due to their role in lateral hydrologic connectivity. Rivers can link lakes through overbank flooding, subsurface exchange, and seasonal runoff pulses—mechanisms that introduce variability into adjacent lake systems not driven solely by climate or basin morphology. In fluvial corridors, lakes may gain or lose water depending on river stage, ice melt timing, and sediment transport dynamics, all of which create conditions for short-term lake fluctuation.

4.3 | *Interactions between Climate, Permafrost, and Landscape Features*

While individual environmental drivers offer important insights into the spatial structure of lake variability, Arctic-Boreal systems are shaped by interacting climatic and geomorphic forces. We focused specifically on interactions between permafrost extent and three core variables: actual evapotranspiration (AET), mean summer temperature, and median lake size. These variables were selected based on their relevance to thaw-driven hydrology and their prominence in existing literature on permafrost-climate feedbacks (Olefeldt et al., 2021; Webb et al., 2022).

4.3.1 | AET and Permafrost

Regression models reveal that AET alone is negatively associated with variable water fraction in continuous permafrost (coefficient = –0.05), suggesting that higher evaporative demand reduces spatial lake variability in stable, ice-rich zones. However, this effect reverses in thaw-prone regions: interaction terms for discontinuous (coef = +0.2, $p < 0.001$) and sporadic permafrost (coef = +0.1, $p < 0.001$) indicate that higher AET increases lake variability where permafrost is fragmented or degrading. This likely reflects the role of AET in accelerating thaw and altering subsurface water fluxes, thereby expanding or draining lakes in thermokarst-sensitive landscapes.

For variability of total water, AET again had a positive main effect (coef = +0.6, $p = 0.005$), suggesting that high moisture demand increases total water fluctuation. However, interaction terms with permafrost extent were not significant ($p > 0.05$), indicating that the AET–permafrost relationship is more relevant to spatial reorganization (extent) than volumetric fluctuation. This distinction reinforces the idea that surface water area is more climate-sensitive than volume in transitional Arctic landscapes.

While AET alone exerts only a moderate influence on lake variability, its interactions with permafrost highlight an important feedback loop: in regions where high evaporative demand (potential evapotranspiration) drives elevated AET, water loss amplifies hydrologic instability in thaw-prone landscapes. This pattern is more evident in variable water fraction than in relative variability, suggesting that AET primarily governs the expansion and contraction of lake area, especially where permafrost is unstable, rather than altering total water volumes. These dynamics reflect a climate–permafrost coupling where atmospheric conditions accelerate hydrological reorganization in thaw-sensitive terrain.

4.3.2 | Lake Size, Climate, and Permafrost

Regression models also reveal key interactions between lake size and permafrost. For variable water fraction, the interaction between lake size and temperature was significant (interaction coef = +0.1, $p = 0.035$), indicating that while larger lakes are generally more stable, this effect weakens in warmer climates. In contrast, for variability of total water, lake size and temperature both positively influenced variability, but with a significant negative interaction (interaction coef = –3.6, $p < 0.001$), suggesting that larger lakes are less sensitive to temperature-driven variability than smaller ones. This highlights a climate-modulated dynamic in which lake size buffers hydrologic instability—but less effectively under warming conditions.

Interactions with permafrost extent show a similar pattern. In continuous permafrost, larger lakes were significantly more stable (coef = –0.8, $p < 0.001$ for variable water fraction), but this effect weakened or reversed in thaw-prone regions, particularly isolated permafrost (interaction coef = +0.8, $p = 0.003$). For variability of total water, lake size exerted a strong dampening effect across most permafrost categories, with the largest effect observed in discontinuous zones (–15.7, $p < 0.001$), suggesting that larger lakes may buffer against hydrologic instability where thaw is already underway.

Together, these findings suggest that basins dominated by smaller lakes are more hydrologically unstable in both extent and proportion, contributing disproportionately to short-term surface water dynamics. While large-lake basins tend to exhibit more stable behavior, their stabilizing role is conditional; weakened in regions of elevated temperature or thawing permafrost. This positions lake size not just as a descriptive metric, but as a climate- and permafrost-sensitive predictor of where we might expect the greatest near-term hydrologic shifts under continued Arctic warming.

4.4 | *Interaction between Permafrost and Glaciation*

As a previous study using the static version of ALPOD found a strong relationship between lake fraction, permafrost, and glaciation history (Levenson et al., 2025), we also examined variability patterns across combinations of permafrost zones and glaciation history. The results reveal a consistent pattern: unglaciated landscapes exhibit substantially greater surface water variability—both in absolute and relative terms—across nearly all permafrost categories.

Across all permafrost zones, mean variable water fraction was consistently higher in unglaciated regions. For example, in sporadic permafrost, the variable water fraction reached 1.42% in unglaciated areas, compared to 0.50% in glaciated zones. Similarly, discontinuous permafrost showed 1.12% in unglaciated terrain versus just 0.24% in glaciated terrain. Even continuous permafrost, typically the most stable, exhibited a six-fold increase in variable water fraction when unglaciated (about 1% vs. 0.2%).

When variability was normalized by total surface water, this trend persisted. Relative variability was highest in isolated permafrost within unglaciated terrain (46.6%), followed by discontinuous (41.7%) and sporadic zones (37.6%). Glaciated zones, in contrast, exhibited relative variability values between 25% and 36%, suggesting a more stable hydrologic regime even in transitional permafrost classes. Unglaciated discontinuous and continuous permafrost zones also contributed the most variable surface water volume statewide. Although glaciated isolated permafrost accounts for a large share of total water area (28%), its surface water is comparatively stable.

Illustrated in Figure 7, glaciation history plays a crucial role in mediating how permafrost transitions affect lake behavior. In unglaciated terrain, fine-grained sediments, shallow gradients, and the absence of glacial scouring create favorable conditions for thermokarst formation and hydrologic reorganization. As a result, lakes in these regions are both more spatially dynamic and more proportionally unstable. In contrast, glaciated landscapes buffer against thaw-driven reorganization, likely due to coarser substrates, deeper basin morphology, and reduced soil ice content. These findings underscore that permafrost extent alone does not dictate surface water sensitivity—rather, it is the interaction with geomorphic legacy that governs the scale and intensity of lake change across Alaska's Arctic-Boreal landscapes.

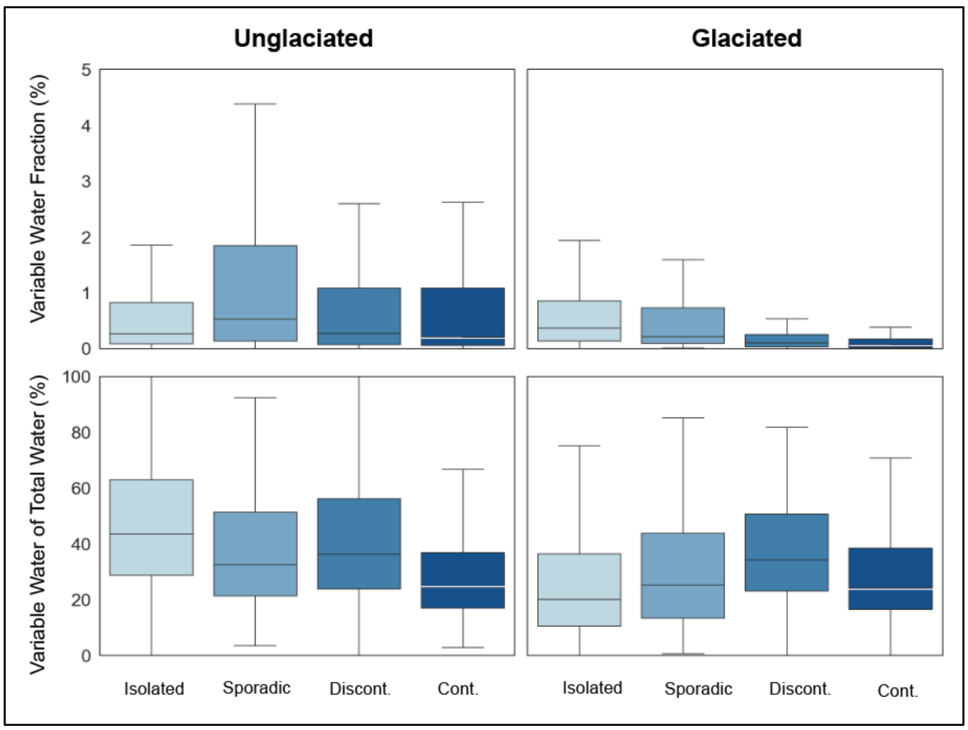

Figure 7. Boxplots illustrating surface water variability across permafrost zones (isolated, sporadic, discontinuous, and continuous) stratified by glacial history. The top row shows variable water fraction (%) relative to total land area, while the bottom row shows variable water as a percentage of total surface water, representing hydrologic instability. Unglaciated landscapes exhibit markedly higher variability, especially in sporadic and isolated permafrost zones, compared to their glaciated counterparts.

4.5 | *Dominant Predictors of Surface Water Variability Across Alaska*

Finally, to provide another method of disentangling drivers of lake dynamics, we assessed the relative importance of each environmental variable using permutation-based feature importance derived from HGBRT. Results reveal clear distinctions between the predictors shaping absolute versus relative measures of hydrologic variability. For the variable water fraction (%) the strongest predictor was geologic unit, followed by actual evapotranspiration (AET), and mean summer temperature. This ranking underscores the importance of landscape substrate and moisture fluxes in shaping surface water dynamics. Notably, geologic units such as eolian silt, glaciomarine deposits, and alluvial sediments may influence water storage and drainage potential, particularly in thaw-sensitive terrain.

Interestingly, permafrost extent ranked relatively low among predictors of absolute surface water variability. While permafrost processes are commonly cited as drivers of lake change, our results suggest that they may act more as secondary modifiers within a broader geomorphic framework. This finding does not contradict prior work highlighting permafrost's role but rather emphasizes that permafrost must be considered alongside geologic and climatic context to fully understand patterns of lake instability.

The relatively high importance of climate variables, like AET and temperature, suggests that evaporative demand and surface energy balance also modulate water presence, especially in marginal permafrost zones. Landscape characteristics collectively explained more model variance (permutation importance = 0.7 ± 0.02) than climate variables (0.5 ± 0.02), indicating that the landscape itself influences how much impact climate conditions have on hydrologic dynamics (Fig. 8).

For the relative measure of hydrologic variability, that is variable water as a percentage of total water, the dominant predictor was median lake size, followed by texture, geologic unit, and

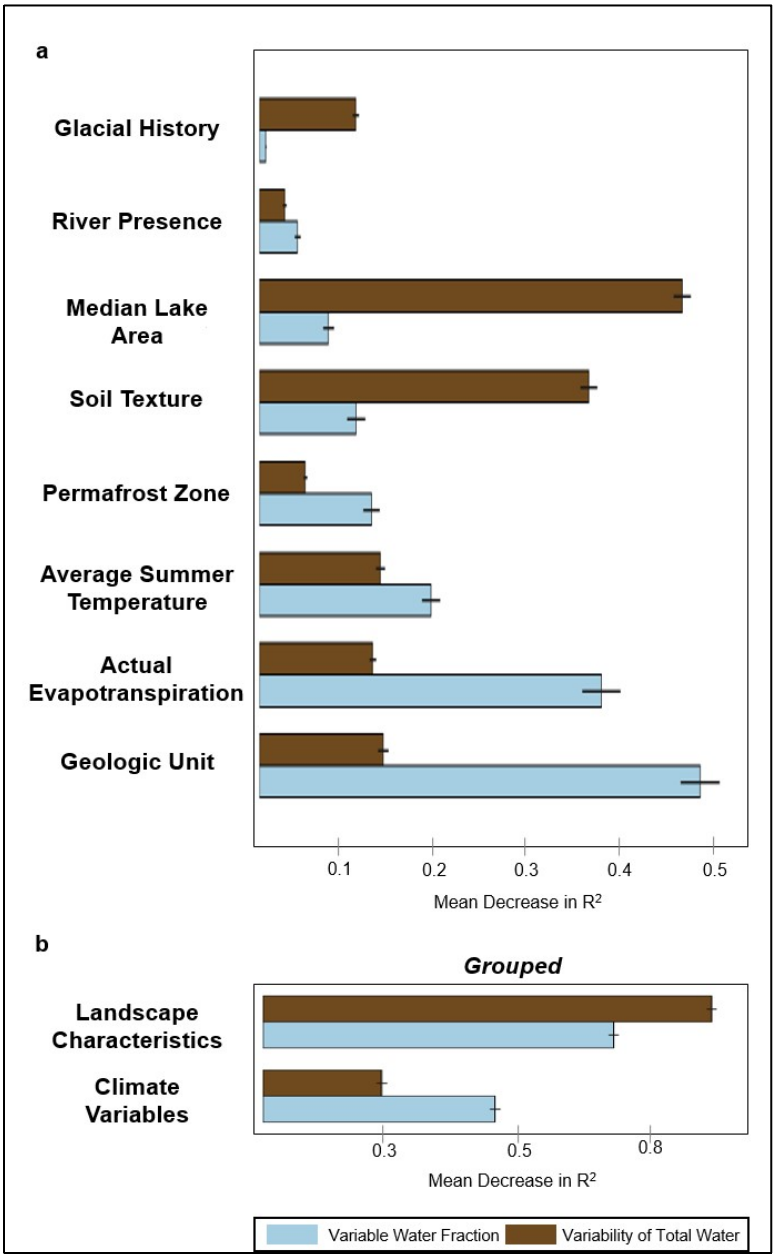

Figure 8. a) Permutation importance of environmental variables in predicating short-term surface water variability across Alaska. Bars represent the mean decrease in model performance (R^2) when each predictor is permuted, indicating its relative importance in modeling two hydrologic metrics: variable water fraction (blue) and variability of total water (brown). Results highlight the distinct yet overlapping drivers shaping different aspects of surface water dynamics. B) Grouped permutation importance of environmental predictors for modeling surface water variability in Alaska. Variables were aggregated into two categories: landscape characteristics (e.g., geology, lake size, permafrost, river presence) and climate variables (e.g., mean summer temperature and actual evapotranspiration). Bars represent the mean decrease in R^2 when each group is permuted, with higher values indicating greater importance.

mean temperature. This suggests that areas dominated by smaller lakes tend to have a greater proportion of variable water, reinforcing the idea that small lakes disproportionately contribute to interannual hydrologic instability. The strongest performance of texture (a composite of landscape slope and topographic roughness) reflects the importance of microtopography in governing drainage patterns and water retention.

While climatic variables such as AET and temperature were present, they were secondary to physical landscape traits. Overall, landscape characteristics (0.9 ± 0.02) were 274% more influential than climate variables (0.2 ± 0.01), affirming that geomorphic context—not permafrost alone—governs the sensitivity of lake systems to external forcings (Fig. 4). These results warrant a nuanced interpretation: permafrost plays a role but is likely part of a broader suite of interacting drivers, with surface geology and terrain characteristics taking precedence in shaping Alaska's short-term surface water variability.

5 | Discussion

5.1 | *Drivers of Short-Term Lake Variability*

This research constitutes of the most comprehensive fine-resolution, statewide investigations of short-term surface water variability in Alaska to date. By analyzing variability occurring in over 800,000 lakes over 2016-2021 using the Alaska Lake and Pond Occurrence Dataset (ALPOD; Levenson et al., 2025), we offer new insight into regional-scale seasonal to interannual lake dynamics. Through the integration of temporally resolved lake data with environmental variables, our findings reveal the uneven spatial distribution of surface water variability, with hydrologically dynamic regions clustering in low-elevation landscapes characterized by permafrost transition zones and unglaciated terrains. These regions tend to have fine-grained substrates, extensive wetland cover, and high fluvial connectivity, all of which enhance surface water sensitivity to climatic and seasonal forcing (Roach et al., 2011; Webb et al., 2022). The aggregation of these landscape traits creates hydrological hotspots; areas with both a large surface water footprint and elevated susceptibility to change. At the landscape scale, surface water variability was highest in low-elevation, wetland-dominated regions with small median lake sizes. Grid cells with smaller lakes (<0.54 ha) consistently exhibited both greater absolute and relative variability. The shallow depth and high perimeter-area ratio of these lakes likely enhance their sensitivity to thaw, precipitation variability, and evaporative losses. Additionally, landscapes with river presence and dynamic floodplain connectivity showed heightened variability, suggesting that lateral hydrologic connectivity amplifies short-term change. These findings are consistent with recent CubeSat-based work (Cooley et al., 2019), which observed that fine-scale shoreline dynamics in lake-dense terrains account for significant variability in lake area.

We find that permafrost appears to exert some control on short-term surface water variability, with variability increasing from continuous to discontinuous, sporadic, and isolated zones. Discontinuous and sporadic permafrost zones displayed the highest mean variability in both surface water variability metrics. While our results cannot conclusively isolate thermokarst-driven hydrologic variability, these findings of higher variability in these transitional areas align with earlier work by Roach et al. (2011) and Lantz & Turner (2015), which highlight permafrost degradation and talik development as key mechanisms for dynamic lake behavior.

Importantly, we find that the relationship between permafrost and short-term lake variability is strongest in unglaciated regions. Across all permafrost zones, unglaciated landscapes consistently exhibit higher lake variability than their glaciated counterparts. Variable water fractions were 2–5 times greater in unglaciated terrains, with isolated and sporadic permafrost zones showing especially high variability (up to 1.4%). When normalized by total lake area, these trends persisted: unglaciated zones exhibited up to 47% of water classified as variable, compared to just 25% in glaciated terrain. We attribute this finding to the fact that finer-textured, ice-rich substrates of unglaciated terrains are more subject to thaw sensitivity, thermokarst development, and surface water reorganization as compared to glaciated terrains. These results build on similar results for static lake distribution presented in Levenson et al. (2025) and further demonstrate the importance of considering glaciation history when analyzing drivers of surface water variability. We find that climatic conditions such as summer temperature and actual evapotranspiration (AET) contribute to changing lake behavior, often amplifying instability in thaw-prone zones. Warmer temperatures were associated with higher proportional surface water variability, particularly in marginal permafrost regions, consistent with concerns over nonlinear feedbacks between warming and permafrost degradation (Bring et al., 2016; Rantanen et al., 2022). Similarly, AET emerged as a significant, albeit moderate, predictor of surface water variability. High AET levels were associated with greater short-term variability, especially where permafrost is discontinuous or sporadic, where surface moisture deficits enhance evaporation and can also deepen active layer thaw, leading to further surface water variability (Webb et al., 2022). These findings suggest that while permafrost extent is an important structural control, climate acts as a powerful modulator, capable of intensifying instability under warming conditions.

Overall, this study demonstrates that short-term lake variability is spatially clustered, environmentally structured, and climatically sensitive. The novel integration of variable water fraction and variability of total water enables the detection of both the extent and relative instability of lakes across diverse terrain. Key findings reveal that transitional permafrost zones in unglaciated regions are hydrologic hotspots, strongly modulated by summer temperature, AET, and landscape morphology. However, our results also indicate that geologic unit is a dominant predictor of surface water dynamics, exceeding the explanatory power of permafrost in some contexts. These results reveal the need to consider substrate and geomorphic history alongside climate-permafrost interactions in predictive models. As Arctic warming accelerates, short-term lake variability will serve as a leading indicator of broader hydrologic and ecological transformation.

5.2 | *Limitations & Suggestions for future research*

While this study provides new insights into the spatial structure and environmental controls on short-term lake variability, several limitations remain. A first key limitation concerns the temporal structure of our dataset. While ALPOD captures seasonal and interannual changes across a six-year window, it does not isolate the temporal signature of water variable and thus cannot distinguish between types of variability–e.g., whether water loss occurs via seasonal drying, evaporative loss, or drainage. In most regions of Alaska, variability likely reflects a seasonal drawdown from the early summer snowmelt peak in June to a low in August, sometimes followed by a late season rebound in September as AET declines and precipitation increases. However, the timing and intensity of these changes vary regionally, and our results cannot disentangle these patterns. Future work should include more temporally explicit datasets and methods to capture intra-annual variability and assess the mechanisms of lake change. Finally, investigating how lake variability intersects with infrastructure risk, wildlife habitat use, and subsistence practices represents a critical next step for understanding the broader impacts of surface water change in Arctic and Boreal Alaska.

6.0 | Conclusions

This study provides a novel fine-scale, statewide assessment of short-term lake variability in Alaska, showing that surface water change is shaped by a combination of permafrost transitions, glacial history, climate forcing, and lake morphology. By integrating high-resolution hydrologic metrics with environmental drivers, we identify unglaciated, permafrost transitional, and relatively warm landscapes as hotspots of hydrologic instability. These findings highlight the importance of spatial context in understanding Arctic Lake dynamics and offer a framework for detecting early signs of landscape change. As warming accelerates, this approach can support more targeted monitoring, improve integration with Earth system models, and inform research on carbon feedbacks, habitat shifts, and climate adaptation in permafrost regions.

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