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Global Characterization of Inland Water Reservoirs Using ICESat-2 Altimetry and Climate Reanalysis

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Key Points:

- We present a first assessment of ICESat-2 altimetry for investigating changes in global freshwater reservoirs
- High accuracy of ICESat-2 surface water retrievals is demonstrated through comparison with in situ reservoir gauges
- Distinct regional patterns in reservoir levels are identified, many of which can be explained by water availability and reservoir function

Supporting Information:

- Supporting Information S1

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Abstract Accurate, transparent knowledge of global reservoir levels is a prerequisite for effective management of water resources. However, no complete database exists because gauge data are not globally available and the current generation of satellite radar altimeters resolves only the world's largest reservoirs. Here, we investigate water level changes in global reservoirs using ICESat-2, National Aeronautics and Space Administration (NASA)'s new satellite laser altimetry mission. In just the first 12 months of the mission, we find that ICESat-2 accurately (±14.1 cm) retrieved water level changes for 3,712 global reservoirs having surface areas ranging from <1 to >10,000 km^2. From this new global data set, we identify distinct regional patterns in reservoir level change that can be attributed to both water availability and management strategy. Our findings demonstrate that ICESat-2 will form a crucial component of any global reservoir level inventory and enable new insight into how reservoir management responds to climatic variability and increasing human demand.

Plain Language Summary Freshwater reservoirs provide critical services (e.g., hydroelectricity generation, irrigation, and water supply) to societies around the world. However, global knowledge of reservoir water levels is limited because reservoir gauge data are often proprietary, difficult to access, or nonexistent, and the current generation of satellite radar altimeters can only resolve the world's largest reservoirs. Here, we demonstrate the potential of ICESat-2, National Aeronautics and Space Administration (NASA)'s new laser altimetry mission, for accurately and transparently characterizing global reservoirs. We find high accuracy (±14.1 cm) of ICESat-2 surface water observations as compared with 195 in situ reservoir level gauges. Next, we identify distinct regional patterns in global reservoir levels, many of which can readily be explained by reservoir function (e.g., hydropower generation). Our findings emphasize the critical role that humans have in regulating water flow across large areas of the Earth and demonstrate the potential of a new satellite technology for characterizing global reservoir response to climatic variability and human water demand.

1. Introduction

The impoundment of water in reservoirs enables societies around the world to irrigate crops, produce electricity, store drinking water, and prevent flooding. In the last few decades, the volume of water contained in reservoirs has exponentially increased as new dams are constructed to meet increasing global water and energy demands (Lehner et al., 2011; Timpe & Kaplan, 2017; Zarfl et al., 2014). Yet much of this water is shared between nations (De Stefano et al., 2010; Gleason & Hamdan, 2017; Smith, 2020; Subramanian et al., 2014), and inequities in downstream water transfers are a well-documented source of domestic (Böhmelt et al., 2014) and international tension (De Stefano et al., 2010; Gleick, 1993). Overexploitation of water resources, for instance, may lead to water scarcity downstream, while insufficient impoundment may lead to flooding hazards. Effectively managing transboundary reservoir storage in a sustainable and equitable manner is therefore a major global challenge (Vörösmarty et al., 2015).

A prerequisite for effective transnational water management is accurate, transparent knowledge of global reservoir water levels. However, no such complete database exists because reservoir levels are gauged at national or subnational levels, and these data are often proprietary, difficult to access, or entirely absent (De Stefano et al., 2010; Gleason & Hamdan, 2017). Due to this lack of transparency, researchers have attempted to provide global reservoir levels using satellite radar altimeters (Birkett, 1995; Crétaux et al., 2011; Gao et al., 2012; Schwatke et al., 2015). However, large ground footprints, narrow swath widths, and wide spacing of orbital tracks restrict such observations to a few hundred of the world's largest lakes and reservoirs having surface areas >100 km^2. The U.S. Department of Agriculture (USDA)/National Aeronautics and Space Administration (NASA) G-REALM program (Birkett et al., 2011, 2017), for example, currently tracks water levels in 292 lakes and reservoirs, accounting for only 4% of reservoirs in the Global Reservoir and Dam (GRanD) database (Lehner et al., 2011). Water level data and the primary function of thousands of smaller reservoirs around the world therefore remain unavailable to the international scientific and management community.

The recent launch of NASA's Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) on 15 September 2018 provides new opportunities for observing global reservoir levels across international boundaries. ICESat-2 carries the Advanced Topographic Laser Altimeter System (ATLAS) a lidar capable of detecting a laser reflection at the single-photon level (Neumann et al., 2019). While the mission's primary science objectives are to measure surface elevation change in the cryosphere (Markus et al., 2017), the ATLAS instrument has several advantages over previous spaceborne radar and laser altimeters that make it uniquely equipped to investigate the surface hydrology of the Earth's temperate and tropical regions. First, ATLAS splits a single laser pulse into six beams (three pairs), providing much denser ground coverage than its predecessor, the Geoscience Laser Altimeter System (GLAS) onboard ICESat-1, which was deactivated in 2010. Second, ATLAS's single-photon sensitive detection strategy is capable of providing much higher vertical accuracy and precision than satellite radar altimeters (Neumann et al., 2019). Third, ATLAS has a small ground footprint (17-m diameter) enabling retrieval of water surface heights in small (surface areas <10 km^2) lakes and reservoirs. During the first year of the mission ICESat-2 retrieved water level change for 3,712 (51%) reservoirs in the GRanD database, representing a first opportunity to observe changes in water storage in reservoirs of all sizes across the world.

Here, we demonstrate the feasibility of ICESat-2 altimetry for characterizing global reservoir storage, hydroclimatic sensitivity, and purpose (function). First, we demonstrate high accuracy of ICESat-2 inland surface water retrievals through comparison with in situ reservoir level gauges. Next, we quantify subseasonal reservoir level change during the first full year of operation (October 2018 through November 2019) by intersecting ICESat-2 data with the GRanD database (Lehner et al., 2011), which contains spatial attributes for 7,250 reservoirs ranging in size from <1 to >10,000 km^2. By comparing remotely sensed reservoir level changes with seasonal water balance (approximated as precipitation [P] minus evapotranspiration [ET]), we explore global and regional patterns of reservoir level change and investigate the extent to which humans are regulating the natural climatic water cycle. Finally, using only remotely sensed reservoir level adjustments and water balance, we investigate the extent to which reservoir function and global water resource resiliency to drought can be inferred from space.

2. Materials and Methods

2.1. Acquisition of Reservoir Levels From ICESat-2

We generated a global reservoir level change data set using the second release (14 October 2018 to 16 November 2019) of the ICESat-2 L3A Land and Vegetation Height product (ATL08). This product provides mean terrain height, as well as other statistics, in 100-m segments based on geolocated point cloud data from ATLAS, known as ATL03 (Markus et al., 2017). More details about the ATL08 algorithm can be found in Neuenschwander and Pitts (2019) and the Algorithm Theoretical Basis Document (ATBD) for Land and Vegetation Data Products (ATL08) (Neuenschwander et al., 2019). We used ATL08 instead of the Inland Surface Water Height product (ATL13) (Jasinski et al., 2019) because the current version of ATL13 does not include lakes and reservoirs with surface areas <10 km^2. Given that many reservoirs are smaller than 10 km^2, the use of ATL08 therefore substantially increases our sample size. When we compared water level changes retrieved by ATL08 with ATL13 (see supporting information [SI]), we find almost no difference between the two products ($R^2 = 0.998$; RMSE = 10.4 cm; Figure S1).

We determined the water surface elevations of known global reservoirs by intersecting the ATL08 product with the GRanD database, which currently contains georeferenced shorelines for 7,250 global reservoirs (Lehner et al., 2011). For each reservoir, the water surface elevation was computed as the median of along-track ICESat-2 elevation retrievals. We chose the median because it is robust against outliers caused by falsely classified water pixels in the GRanD database. To further ensure that ICESat-2 retrievals over water only were retained, we also excluded retrievals that were within 100 m of the reservoir shoreline. Finally, to remove spurious water surface elevations in reservoirs having three or more observations, we excluded retrievals that had *Z* scores higher than 2. We then determined reservoir level change by differencing pairs of water surface elevations in consecutive seasons, defined as winter (December, January, and February), spring (March, April, and May), summer (June, July, and August) and autumn (September, October, and November).

2.2. Reservoir Hydroclimate

To investigate the extent to which reservoir levels track climatic conditions (as opposed to human regulation), we computed the water balance (approximated as P − ET) for each reservoir in the GRanD database from the ERA5 atmospheric reanalysis. Water balance was averaged across the reservoir's upstream watershed between consecutive pairs of water surface elevation retrievals. The upstream watershed was delineated using the HydroBASINS data set (Lehner & Grill, 2013) and Pfafstetter coding scheme (Verdin & Verdin, 1999). We present our findings by grouping reservoir levels and associated water balance at a national and regional level, as defined by the United Nations Geoschemes (Figure S2).

2.3. Validation of ICESat-2 Products

We assessed the uncertainty of ICESat-2 water surface elevation retrievals using continuously operating lake level gauges maintained by the U.S. Geological Survey (USGS) (http://waterdata.usgs.gov/nwis/). These gauges are located in hundreds of lakes and reservoirs across the United States and measure water surface elevation in a stilling well using either a float, pressure, optical, or acoustic sensor. The measured surface elevation or stage is recorded every 15 min and transmitted to the web database every 1 to 4 hr. During our October 2018 to November 2019 study period, we identified 195 lakes and reservoirs in the contiguous United States that were monitored with USGS gauges and had at least one pair of ICESat-2 retrievals. These gauged reservoirs provide an invaluable resource for performance assessment of ICESat-2 over surface water.

2.4. Machine Learning of Reservoir Function

We tested a random forest classifier (Breiman, 2001) for automatically detecting reservoir function using the GRanD database, which contains attributes for primary and secondary reservoir function, as a training data set (Lehner et al., 2011). We trained the classifier with nine predictor variables, namely, seasonal water level change (i.e., winter, spring, summer, and autumn), seasonal water balance, and water level variability, which was defined as the standard deviation of seasonal water level change. We evaluated our model using *k*-fold cross validation ($k = 5$), which involves randomly dividing our data set into five groups of equal size. Training is performed on four groups (80% of samples) with one group held out for validation (20% of samples). This step is repeated until all groups have been validated. The advantage of this technique is that it enabled us to predict the function of every reservoir with seasonal (i.e., four) ICESat-2 water surface elevation retrievals during our study period. The accuracy of our predictions, defined by the F1 score (where 1 is *best* and 0 is *worst*), allowed us to investigate the extent to which reservoir function can be inferred from space.

3. Results

3.1. ICESat-2 Accuracy and Coverage Assessment for Global Reservoirs

In comparison to in situ reservoir level gauges, we find that ICESat-2 measures water level changes with a root-mean-square error (RMSE) of 14.1 cm (Figure 1). This RMSE likely overestimates ICESat-2's uncertainty because the gauges are rarely located directly under the ICESat-2 ground track and reservoirs can have slight slopes due to wind and differences in outflow and inflow. The small RMSE also demonstrates that even though some of the instrument's green (532 nm) laser may penetrate water (Jasinski et al., 2016; Parrish et al., 2019), ICESat-2 is able to detect water surface elevations with high accuracy (Figure 1).

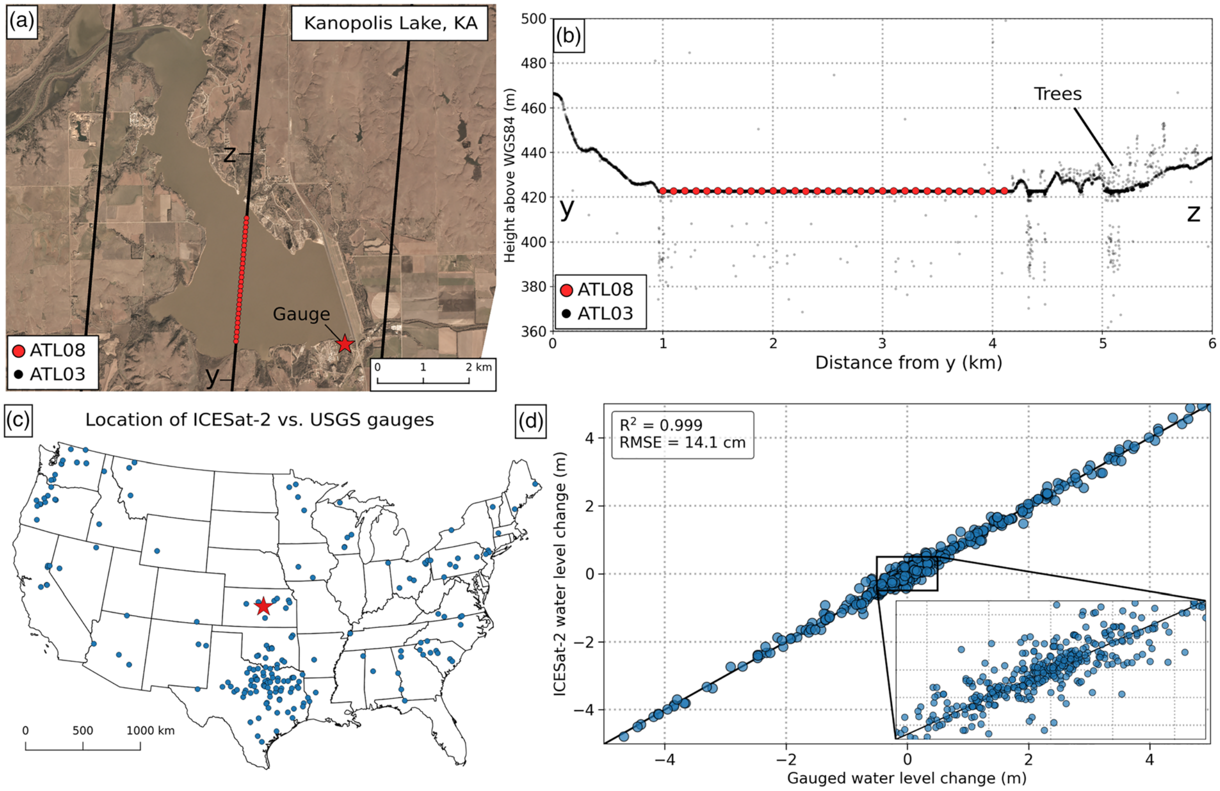

Figure 1. Accuracy assessment of ICESat-2 water surface elevation change retrievals. (a) Example of three ICESat-2 beams across Kanopolis Lake, KS, in October 2018. (b) ICESat-2 profile across Kanopolis Lake showing the filtered ATL08 land and vegetation product overlaid onto the ATL03 geolocated photon product. (c) Location of Kanopolis Lake (star) and the 195 lakes and reservoirs that contained both USGS lake level gauges and repeat ICESat-2 water level retrievals between October 2018 and November 2019 (blue dots). (d) In comparison to the lake level gauges, we find that ICESat-2 measures water level change with a RMSE of 14.1 cm ($n = 653$), demonstrating high accuracy.

In the first year of the mission, between the period October 2018 to October 2019, we find that 5,199 reservoirs in the GRanD database (72%) had a least one ICESat-2 observation and 3,712 reservoirs (51%) had two or more observations (Figure S2). Many of these reservoirs have surface areas much smaller than 100 km^2, the minimum required for accurate water surface retrieval with satellite radar altimeters. For example, we observed reservoir level changes for 3,260 reservoirs smaller than 100 km^2 and 1,667 reservoirs smaller than 10 km^2. The smallest reservoir observed was Lago di Morasco in Italy, which has a mean surface area of 0.38 km^2 and experienced a 2.5-m decrease in water level between 24 February and 26 May 2019. By quantifying surface water elevation changes in these small reservoirs, ICESat-2 increases the number of reservoirs that can be routinely observed from space by an order of magnitude.

Reservoirs with larger surface areas receive more ICESat-2 observations than smaller reservoirs (Figure S2). On average, reservoirs between 1 and 10 km^2 receive ~2.0 observations per year, reservoirs between 10 and 100 km^2 receive ~4.2 observations per year, reservoirs between 100 and 1,000 km^2 receive ~12.3 observations per year, reservoirs between 1,000 and 10,000 km^2 receive 39.0 observations per year, and reservoirs larger than 10,000 km^2 receive 107.7 observations per year (Figure S2). During our study period, 27 reservoirs in the GRanD database were observed by ICESat-2 at least once per month. These reservoirs have a mean surface area of 7,304 km^2 and include some of the largest on Earth (e.g., Bratsk Reservoir, Lake Nasser, and Lake Volta). While the exact timing of reservoir level retrieval may vary in the future due to the mission's off-pointing mapping strategy in the Earth's middle and low latitudes (Markus et al., 2017), these statistics may be useful for planning research activities with ICESat-2.

3.2. Global Patterns of Reservoir Level Change

Reservoir levels exhibit marked seasonal fluctuations over our October 2018 to November 2019 study period. Between autumn and winter, winter and spring, and summer and autumn, reservoir levels observed by

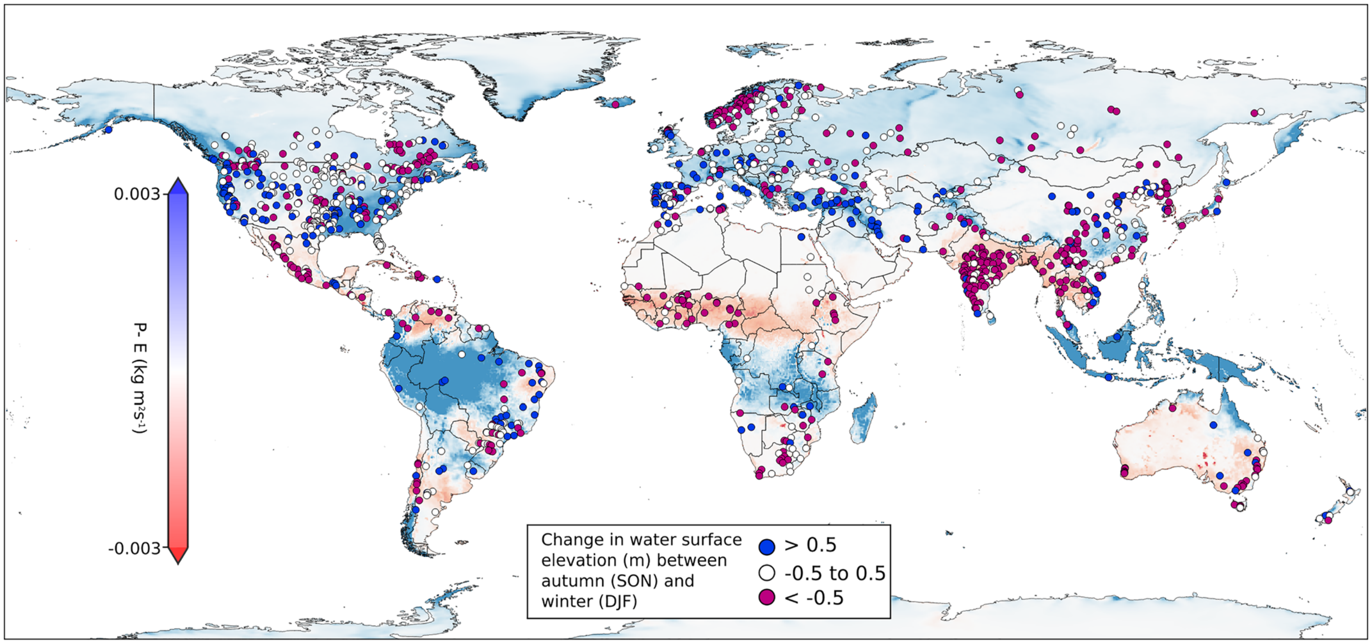

Figure 2. Global patterns of reservoir water level change between autumn (SON) and winter (DJF) in comparison to water balance (P − ET). Circles show water level changes derived from repeat ICESat-2 overpasses for 1,163 reservoirs in the Global Reservoirs and Dams (GRanD) database. Background map shows water balance derived using P − ET data from ERA5 atmospheric reanalysis. See SI for reservoir level changes in other seasons (Figures S4–S6).

ICESat-2 decreased by an average (standard deviation [std]) of 0.47 m (±1.11 m), 0.32 (±1.57), and 0.46 m (±1.32 m), respectively. Between spring and summer, reservoir levels increased by 0.23 m (±1.37 m). These statistics, however, conceal strong regional patterns (e.g., Figures 2 and S4–S6). Between summer and autumn, reservoir levels in Western Asia (see Figure S3 for definition) decreased by 2.66 m, on average but increased by 3.86 m between autumn and winter (Figure 2). In contrast, reservoir levels in northern Europe increased between summer and autumn by 0.64 m, on average, and decreased between autumn and winter by 1.32 m (Figure 2). These regional patterns reflect not only climatic conditions but also human regulation of water resources and can be further investigated through comparisons between reservoir level change and seasonal water balance.

In most regions, reservoir level adjustments closely track seasonal water balance (P − ET; Figure 3). The clearest examples are Central America (Figure 3b), western Africa (Figure 3i), western Asia (Figure 3(m)), and southern Asia (Figure 3o) where correlation coefficients (*r*) between mean water balance and mean reservoir levels are +0.79–0.99. These regions are characterized by climates with pronounced variability in seasonal precipitation. During the wet season, reservoir levels increase as water managers store water in preparation for dry season. In Western Africa, ICESat-2 observed a 2.46-m increase in average reservoir levels during the wet season (autumn). If managers release too much water during the dry season and/or if the wet season is delayed, water resources in these regions are placed under pressure. In southern Asia, ICESat-2 observed a synchronous decline of reservoir levels by an average of 1.62 m during the dry season (winter and spring). This caused severe water shortages in Chennai, India where several reservoirs emptied (https://www.bbc.com/news/world-asia-india-48672330).

However, reservoir levels in at least two regions clearly oppose seasonal water balance. In northern Europe (Figure 3d) and eastern Europe/Russia (Figure 3g), for example, the correlation coefficients between mean regional water balance and mean reservoir levels are −0.96 and −0.66, respectively. Reservoir levels in northern Europe increased by an average of 2.98 m during the driest season (summer) and decreased by 2.94 m during the wettest season of the year (spring). The loss of water in these regions coincides with peak energy demand, indicating that many of these reservoirs were artificially lowered to produce hydroelectricity. Alternatively, the reservoirs may have been lowered in anticipation of the spring flood pulse.

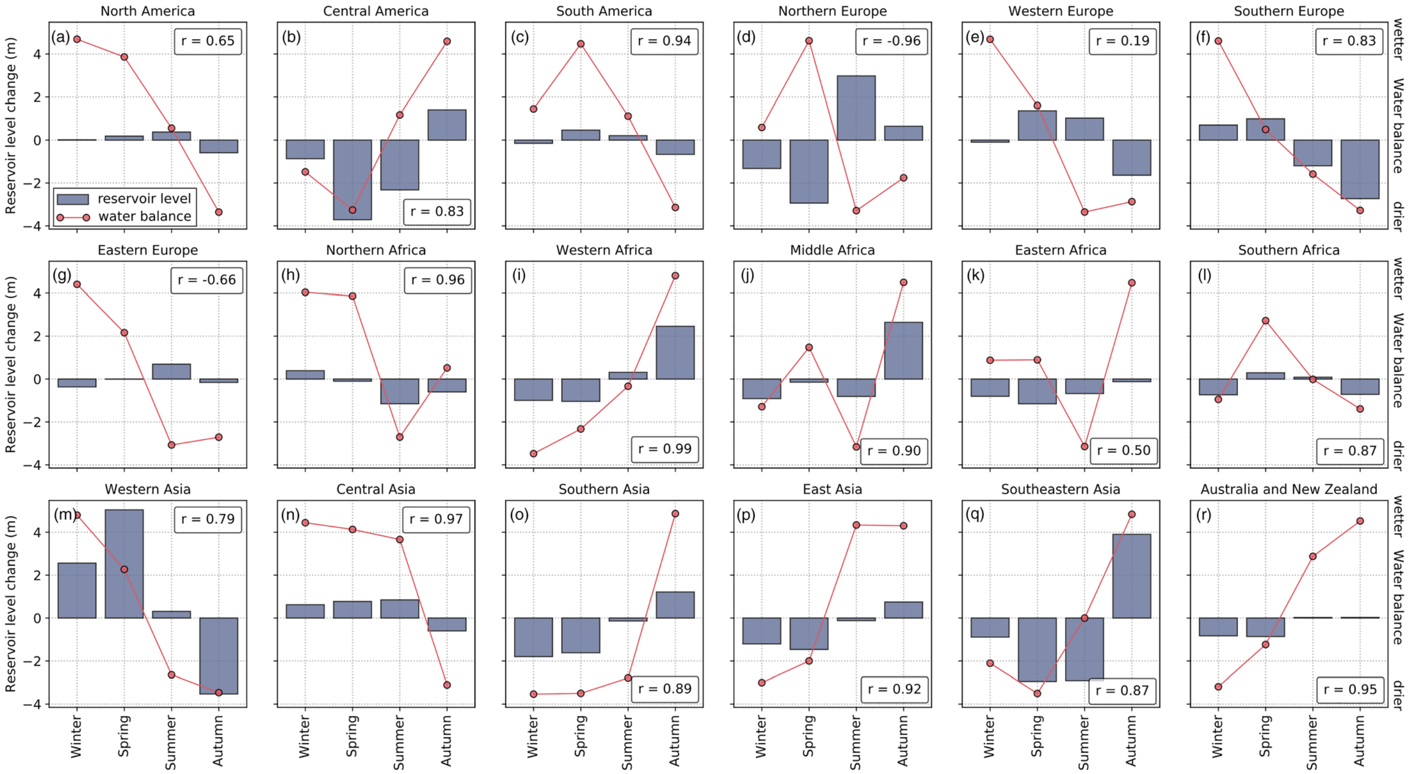

Figure 3. (a–r) Regional patterns of reservoir level response to water balance (P − ET). Blue bars represent mean regional reservoir level change, red lines represent mean seasonal water balance in the reservoir watersheds, and the *r* value represents the correlation coefficient between the two. In most regions (e.g., Central America, western Africa, and western Asia), reservoir levels closely track seasonal water balance. In other regions (e.g., North America and western Europe), reservoir levels are not strongly correlated with seasonal water balance. In two regions (northern and eastern Europe), reservoir levels strongly oppose seasonal water balance.

In some regions, reservoirs levels exhibit a diverse response to seasonal water balance. These regions usually contain linked river reservoir systems. The clearest example of this behavior is North America, western Europe, Brazil, and China where we find both water level increases and decreases in reservoirs that are part of the same watershed (Figures 2 and S3–S5). In sum, the contrasting responses of reservoir levels to seasonal water balance reflect the critical and varying influence that humans have in regulating water flow across large parts of the Earth, often in opposition to climate.

3.3. Remote Insights Into Reservoir Management Strategy

We find that primary reservoir function, as defined by the GRanD database, is revealed through straightforward comparisons between human-induced adjustments in reservoir levels and seasonal fluctuations in water balance (Figures 4 and S6–S8). Water levels in reservoirs used for primarily for irrigation tend to follow seasonal water balance, whether in a positive or negative direction (i.e., lower left or upper right quadrant, Figure 4a). Reservoir levels decrease in dry seasons, as irrigation demand outpaces supply, and increase in wet seasons, as excess water is impounded (Figures 4a, S6, S7a, and S8a). Reservoirs used for irrigation therefore tend to display large fluctuations in water level that also track water balance. In contrast, water levels in many hydroelectric reservoirs fell during winter and spring, in opposition to water balance (lower right quadrant, Figure 4b). This phenomenon is readily apparent in northern Europe and eastern Europe/Russia where reservoir levels were lowered markedly in winter (despite having strongly positive P − ET, Figures 3d, 3g, 4b, and S6b) due to peak energy demand for heating. The water levels in reservoirs used for flood control are relatively subdued between autumn and winter (Figure 4c) but rapidly increase between winter and spring (Figure S7c) to reduce the effects of flood waters. Between summer and autumn, water levels in these reservoirs decrease in preparation to for the following winter/spring flood pulse (Figure S9c). The seasonal fluctuations of navigation, recreation, and water supply reservoirs are far more

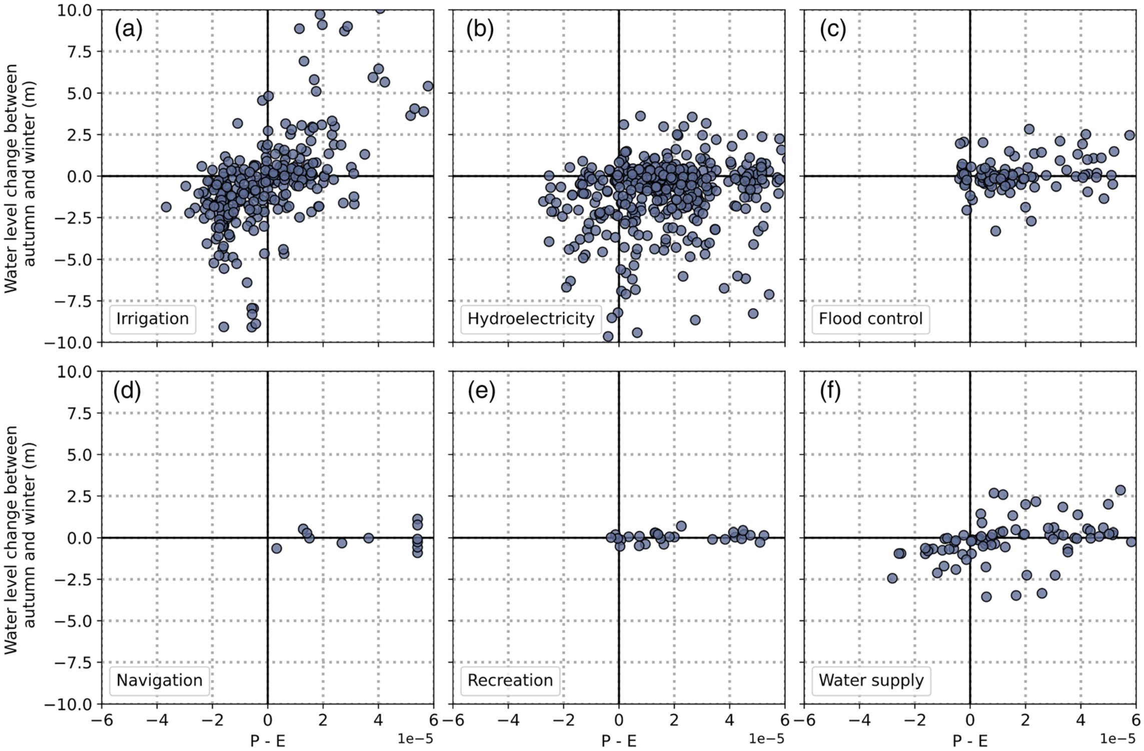

Figure 4. (a–f) Water level response to seasonal water balance (P − ET) for different reservoir functions between autumn and winter. These characteristic signatures both authenticate reservoir level changes derived from ICESat-2 and demonstrate the possibility of remotely identifying reservoir function from space. See SI for reservoir level changes in other seasons (Figures S7–S9).

subdued than either irrigation, hydropower or flood control reservoirs (Figures 4c–4f, S7c–S7f, S8c–S8f, and S9c–S9f), consistent with their primary functions, which demand maintaining relatively stable water levels. The observed distinctions between remotely sensed reservoir water level changes, seasonal water balance, and reservoir function suggest strong potential for inferring water management strategies and reservoir function from space.

Predicting reservoir function solely from remotely sensed fluctuations in reservoir level and ERA5 water balance demonstrates promise. For the 404 reservoirs having seasonal water level observations, the overall accuracy of our random forests classification was 0.64 (Figure S10 and Table S1). The classifier was more successful at identifying hydroelectric reservoirs (F1 score = 0.76) than irrigation and navigation reservoirs (F1 score = 0.59 and 0.48, respectively; Table S1). This is not that surprising as hydroelectric reservoirs form a distinct cluster in Figure 4b (lower right quadrant). As ICESat-2 retrieves more water levels, including those separated by time periods longer than annual, it may be possible to predict reservoir function even more accurately in the future.

The observed response of reservoir water management to seasonal water balance also offers insights into potential water resource vulnerabilities and resiliencies. In regions having abundant water resources (e.g., northern Europe and eastern Europe/Russia), for example, we find evidence of water managers lowering hydroelectric reservoirs during the wet season, knowing that they will refill the following summer when electricity demand is lower (Figures 3d and 3g). Similarly, in regions having linked reservoir systems (e.g., North America, western Europe, South America, and central/eastern Asia) we find evidence of water managers lowering water levels in one reservoir, knowing that the water will be recaptured in a different reservoir downstream. This yields a heterogeneous response of regional water levels (e.g., Figure 2), with some reservoirs lowering and others filling. Plentiful water availability and extensive infrastructure thus allow countries in these regions to defy climate, ranking them as some of the least water stressed in the world. According to the World Resources Institute's Aqueduct water risk framework (Hofste et al., 2019), Norway, Brazil, Canada, Russia, United States, and China, rank as the 153rd, 112th, 108th, 94th, 71st, and 56th least water-stressed countries, respectively.

In regions with less abundant water resources and/or reservoir infrastructure, we identify highly homogeneous reservoir level responses to water balance. In western Asia, water levels in all reservoirs dramatically increased during the wet season, indicating that these countries are hoarding water in expectation of the dry summer season (Figure 3m). Similarly, in southern Asia, water levels in almost all reservoirs decreased during the dry season, indicating that water demand is, at least temporarily, outpacing supply (Figure 3o). This observed homogeneity of reservoir response suggests that these regions are less independent of climate and may be more vulnerable to hydroclimatic variability. It follows that countries in these regions are ranked as some of the most water stressed in the world. According to the Aqueduct water risk framework (Hofste et al., 2019), Iran, India, Pakistan, Turkey, and Iraq rank as the 4th, 13th, 14th, 32nd, and 42nd most water-stressed countries, respectively.

4. Discussion and Conclusions

This study demonstrates that ICESat-2 can provide accurate, transparent tracking of reservoir water levels globally. In just the first 12 months of the mission, we find that ICESat-2 accurately (±14.1 cm) retrieved water level change in 3,712 reservoirs around the world (51%), with surface areas ranging from <1 to >10,000 km^2. This is an order of magnitude increase in the number of reservoirs observed by the current generation of satellite radar altimeters. As the mission continues, the number of reservoir level change retrievals will continue to grow due to ICESat-2's off-pointing mapping strategy in the Earth's middle and low latitudes (Markus et al., 2017). ICESat-2 data will thus form a crucial component of any inventory or synoptic assessment of global reservoir levels. Together with the incorporation of data from other satellite missions, such as the upcoming Surface Water and Ocean Topography (SWOT) mission (Biancamaria et al., 2016), these remote sensing observations will fill gaps where gauge data are proprietary, difficult to access or nonexistent.

Our findings demonstrate good potential for inferring reservoir function from space. From just 1 year of ICESat-2 data, we identify distinct regional patterns in reservoir level change (Figures 2 and 3). Some of these patterns appear entirely attributable to climate (e.g., western Africa and western and southern Asia), whereas others can only be explained by active human management policy (e.g., North America and northern and eastern Europe/Russia). We found that hydroelectric reservoirs, in particular, display unique responses to climate as compared to irrigation reservoirs, and both differ from the more stable water levels required for navigation and flood control reservoirs (Figure 4). These signatures are so distinct that we were able to correctly identify 76% of hydroelectric reservoirs solely from remotely sensed observations, climate reanalysis and machine learning. We found that determining other reservoir functions was more challenging over our 1-year study period. This is likely due to ICESat-2's 91-day repeat cycle, which reduces the probability that we capture reservoir response to short-term, flashy events. However, as more ICESat-2 data are accumulated over multiple years, data gaps will be eventually filled and remotely identifying complex reservoir management strategies including those that are managed for multiple purposes should become more feasible.

Looking forward, our study lays the foundations for detection of global water resource vulnerabilities and resiliencies from space. By comparing seasonal reservoir level adjustments to water balance, our findings already corroborate regional water management policies and previously published national-level water stress indices. ICESat-2 therefore represents the start of a new era of remote sensing in which water resource stresses and resiliencies associated with built reservoir infrastructure systems can be observed in near-real time. We conclude that remotely sensed water level retrievals, in combination with the techniques outlined in this study, have the potential to substantially improve our understanding of global water resource response to increasing hydroclimatic variability and human demand.

Conflict of Interest

The authors declare that they have no competing interests.

Data Availability Statement

Our reservoir level data set is available for download at Zenodo (https://zenodo.org/record/3981328). Other data needed to evaluate the conclusions of this study can be accessed online: ICESat-2 data from https://nsidc.org/data/atl08 and https://nsidc.org/data/atl13 maintained by the National Snow and Ice Data Center (NSIDC) at the University of Colorado Boulder Cooperative Institute for Research in Environmental Sciences (CIRES); lake level gauge data from https://waterdata.usgs.gov/nwis/rt, maintained by the U.S. Geological Survey (USGS); ERA5 data from https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=overview, maintained by the Copernicus Climate Change Service (C3S); GRanD data from GDW (http://globaldamwatch.org/data/#core_global).

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