MEASURING RESERVOIR HEIGHTS VIA SATELLITE ALTIMETRY PRODUCTS FOR GLOBAL FLOOD MODELING

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ABSTRACT

Accounting for the regulation of water flow imposed on watershed drainage by dam operations is currently a major challenge in hydrological modeling for near real-time global flood forecasting. This water flow information is only available in areas where authorities are willing to release this data, leaving other regions, such as the developing world, without data access. Global flood models cannot provide accurate results and predictions for areas affected by dams without this necessary data, making these communities vulnerable to flood disasters. In order to compensate for the lack of data, a method must be developed in which altimetry data from satellites can be incorporated to account for the impact of dams on current flood models. By comparing near real-time satellite data to real-time in-situ water data, a change in reservoir heights can be observed and the relationship to discharge rates can be determined in order to monitor changes in water storage of downstream releases. The methods of this project can be used to adjust global flood models to properly account for the affects of dams on a watershed and predict future floods, preventing economic loss and ultimately saving lives.

INTRODUCTION

One major challenge in hydrological modeling for near real-time global flood forecasting is accounting for the regulation of water flow imposed on watershed drainage by dam operations. Currently, near real-time global flood models do not adjust lake levels and river flow rates to reflect the effects of dam operations (Cretaux and Birkett, 2006). Information on water flow regulation can generally be obtained in areas where authorities are willing to release this type of data, but it is not readily available for other regions, particularly in the developing world. This in turn provides incorrect data results from these models for areas affected by dams. Without this information, global flood models cannot provide the correct results for dam-affected areas, making these communities vulnerable to flood disaster.

This project investigates the use of near real-time satellite radar altimetry data to infer the dams' operation in order to overcome the regional and global hydrologic models' limitations (Birkett and Beckley, 2010). Data products collected from NASA and European Space Agency (ESA) satellites, specifically Jason-2 and Envisat, are used to measure the reservoir heights of dams (Altimetric Data Products, (<http://www.aviso.oceanobs.com/en/data/products/index.html>). By comparing this altimetry data to real-time in-situ water data collected from various agencies, such as the U.S. Army Corps of Engineers (U.S. Army Corps of Engineers, <http://www.nwd-mr.usace.army.mil/rcc/current.html>) and the United States Geological Survey (USGS) (National Water Information System, <http://waterdata.usgs.gov/nwis>), changes in reservoir heights can be observed and the relationship to discharge rates can be determined in order to monitor changes in water storage of downstream releases.

Selecting a primary study site serves to conduct this initial investigation in order to prove if satellite data is sufficient to use for measuring reservoir heights. Lake Sakakawea in North Dakota was chosen as the test site due to the large size of the reservoir and dam as well as the amount of data available (Corps Lakes Gateway, < http://corpslakes.usace.army.mil/visitors/projects.cfm?Id=G606400>). The selected dam also has available water release information to compare to the changes in reservoir gage height for the lake. If the method proves successful, the data will be incorporated into a regional hydrological model and can further be applied to other dam sites world-wide for further analysis.

The University of Oklahoma has partnered with NASA to develop the NASA-OU CREST Flood Model. This distributed hydrological model predicts the outcome of spatial and temporal variations of water fluxes through a cell-to-cell simulation (Hong, 2009). At the conclusion of this project, we will provide the results to the developers of the NASA-OU CREST Flood Model to present them with additional data in order to update their model.

The goal of this project was to develop a method in which satellite data from NASA satellites can be incorporated to account for the impact of dams on current flood models. Ideally, the methods of this project can be used to adjust global flood models to properly account for downstream releases and potentially avoid future floods. The Pacific Disaster Center benefits from this project as it will be the operational end-user for the developed model, which will provide the ability to more accurately monitor rivers and reservoirs while also predicting the possibility of future floods.

- Collect and compile altimetry data from NASA and ESA satellites
- Compare altimetry data to real-time in-situ water data
- Determine elevation accuracy of satellite data
- Establish a propagation of water flow due to dam filtration in study site
- Determine changes in reservoir gage heights
- Establish relationship between reservoir heights and discharge rates
- Determine water balance for study site
- Improve current global flood models

This project uses data from the Jason-2 NASA satellite and the Envisat ESA satellite (Altimetric Data Products, (<http://www.aviso.oceanobs.com/en/data/products/index.html>) in comparison to real-time in-situ water data collected from 2002 to the present. The focused three year time period will run from 2008 through 2010, in order to limit the amount of data collected and specifically include Jason-2 data.

Study Area

As part of the Missouri River system in North Dakota, Lake Sakakawea is the third largest man-made lake in the United States (Largest U.S. Reservoirs, <http://npdp.stanford.edu/damlarge.html>) (Figure 1). It covers about 368,000 acres and is 178 miles in length, giving it the capability of holding 18,110,000 acre-feet of water. Lake Sakakawea is the reservoir behind Garrison Dam, which is used for flood control, hydroelectric power, irrigation, navigation, and recreation (Lake Sakakawea State Park, <http://www.parkrec.nd.gov/parks/lssp.htm>). The dam project was completed in 1954 under the Flood Control Act of 1944 by the U.S. Army Corps of Engineers, who still manages the site today (Garrison Dam/Lake Sakakawea Homepage, <https://www.nwo.usace.army.mil/html/Lake_Proj/garrison/welcome.html>).

Figure 1. Google Earth Image indicating the Study Area: Garrison Dam on Lake Sakakawea, North Dakota.

METHODOLOGY

Data Acquisition

In order to select a proper study site, various lakes and reservoirs were considered globally. Research began by first establishing a criterion based on determined characteristics in order to find suitable sites. These pre-determined criteria for appropriate study areas include:

a) The water body must be a reservoir contained by a man-made dam
b) The reservoir must be of a considerable size (> 100 km^2)
c) The reservoir must be passed over by the NASA Jason-1 or Jason-2 10-day satellite altimeter and the ESA Envisat 35-day satellite altimeter
d) Satellite altimetry data must be available starting in 2002
e) In-situ data must be available from 2002 to the present
f) Specifically from 2008 through 2010

After significant background research, locations in the North American region proved to be the most useful for our project. While original study sites included Lake Diefenbaker (Canada), Lake Mead (US-Arizona and Nevada), Lake Mohave (US-Arizona and Nevada), Lake Oahe (US-South Dakota), and Tobin Lake (Canada), further analysis limited our research to one specific suitable study site. Ultimately, Lake Sakakawea in North Dakota, US, was chosen as the final study site as it best met the criteria listed above.

A compiled list of all lakes and reservoirs in Canada was cross-referenced with a list of available data from sites such as the USDA Crop Explorer, LEGOS, and ESA (see Table 1). Sites with sufficient data then had their location verified in relation to the satellite tracks by using path data from AVISO in conjunction with Google Earth. In-situ data was collected from Environment Canada, which is the Canadian equivalent to USGS but after attempting to work with the in-situ data, it was decided that these sites did not have enough suitable data to be selected. In addition, snow and ice cover created issues in the water balance calculations.

Table 1: Altimetry Datasets Used

Agency	Site	Website Address
USDA	Crop Explorer	http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/index.cfm
LEGOS	Altimetric Data Products	http://www.aviso.oceanobs.com/en/data/products/index.html>.
ESA	Water Themes and Data	http://www.eea.europa.eu/

To most accurately assess the use of satellite altimetry in measuring reservoir heights, a single study site was chosen that met all the require aspects listed above. By the process of elimination through our conducted research, Lake Sakakawea proved to be the most suitable site due to its large dam with a man-made reservoir which is monitored daily by the U.S. Army Corps of Engineers.

Data Processing

All in-situ data was obtained from the U.S. Army Corps of Engineers both through their websites and online sources and directly from the hydraulic engineer at the Missouri River Basin Water Management Division. Specific data variables were chosen in order to satisfy the water balance equation that ultimately determined the reservoir heights for the selected study area. All acquired in-situ data was originally in English units and therefore all units were then converted into International System of Units (SI) so as to maintain strict consistency of units. Additionally, all conversions were triple checked by hand calculations and conversion software calculations, thus insuring data accuracy.

In order to obtain satellite data, the process began by first downloading the Jason-2 IGDR (Interim Geophysical Data Record, near-real time) hydrology data from the Aviso website (Pass Locator, <http://www.aviso.oceanobs.com/en/data/tools/pass-locator/index.html>). Once the data for each relevant pass for the needed cycles had been downloaded, the files were able to be viewed using the Basic Radar Altimetry Toolbox (BRAT) program (Altimetric Data Products, <http://www.aviso.oceanobs.com/en/data/products/index.html>). Using BRAT, the satellite altimetry images can be pre-processed to derive surface heights and storage values. Therefore, in order to get the surface height in meters from a point on the ground above sea level, the Coastal and Hydrology Altimetry product (PISTACH) handbook instructs the user to use.

Equation (1) $\alpha = A - R - IC - DTC - WTC$

where:
α = Surface height
A = Altitude
R = Angle formed between reference spectrum and image spectrum
IC = Image spectrum
DTC = reference or target spectrum
WTC = reference or target spectrum

After the formula has been entered and the data parameters selected, the data is exported to a text document which can be imported into Microsoft excel. The data is represented by a series of heights per date. Once the data appears in the excel spreadsheet, it must be filtered to remove outliers and add a bias to the satellite data so that it can be compared it to the in-situ data. Data filtering was done through visual inspections of the height values, the mean and the standard deviation for the respective date. The bias was then computed by taking the average of the satellite data and subtracting that from the mean of the in-situ data over the same period of time. A bias was needed to compare the Jason-2 data and the gage data because the two sets of heights were taken relative to different zeros. With access to the GDR (Geophysical Data Record, delayed but fully validated) data, the same process was applied to obtain a workable set of heights. Although nearly identical, GDR was ultimately chosen over IGDR due to the fact that it is a fully validated product and has more precise and accurate values.

Data Analysis

The water balance shows the change in storage in the reservoir based on multiple factors. The picture below depicts the water cycle and the water balance is as follows:

Equation (2) $\Delta S - \Delta H$

where:
ΔS = □ + (ρ x Λ)
ΔH = ï + □ + (ε x □)

where:
□ = Streamflow
ρ = Precipitation
Λ = Area
□ = Discharge
ï = Infiltration
ε = Evapotranspiration
□ = Surface

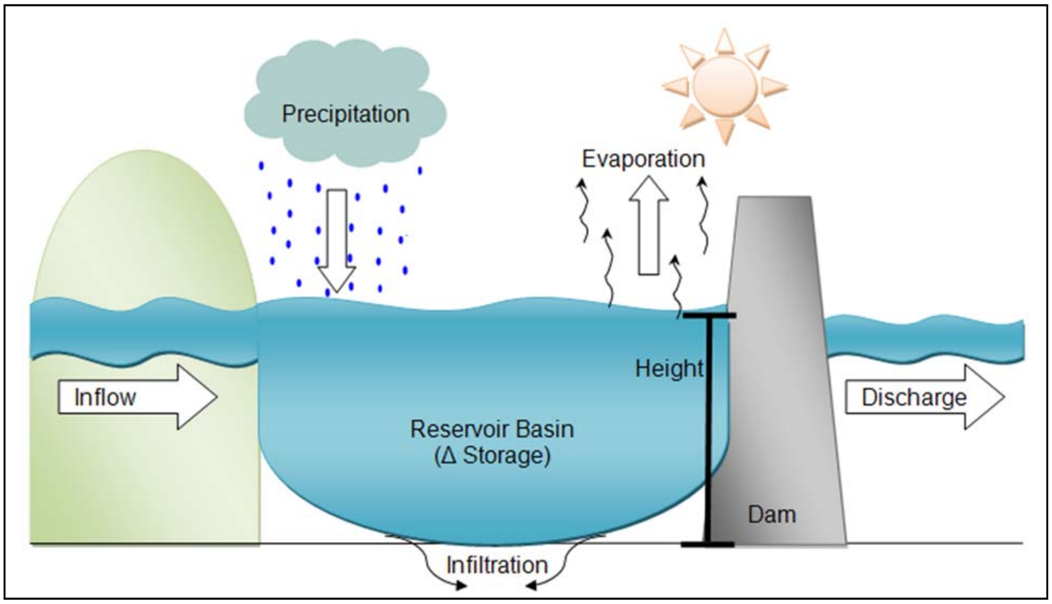

Figure 2. Water Balance Processes for Man-Made Reservoirs and Dams.

Additional data was obtained from the Atmospheric Science Data Center run by the NASA Langley Center (Stackhouse Jr. and Whitlock, 2010) in order to supplement the data from the U.S. Army Corps of Engineers (U.S. Army Corps of Engineers, <http://www.nwd-mr.usace.army.mil/rcc/current.html>). From all the in-situ data, graphs were created to visual display the data and explain different features about the study site, Lake Sakakawea at Garrison Dam. The raw data was further processed and calculated in order to find other variables pertinent to graphing a water balance.

RESULTS AND DISCUSSION

Comparisons of changes in heights (ΔH) and storage (ΔS) from the satellite, in-situ, and calculated data were graphed to show the relationships and validity of all data sources. In-situ data was available daily and satellite data from Jason-2 (GDR) was based on a 10-Day pass cycle. The water balance values were averaged based on the 10-day satellite observation dates. Time series of all datasets were collected over a three-year period from 2008 through 2010.

In-Situ Data

The in-situ data was provided from the U.S. Army Corps of Engineers and shows the changes in reservoir elevation due to variables such as inflow, outflow, evaporation, precipitation, and station water release. The parameters provided served as the source of data for the calculations in the water balance.

Satellite (GDR) Data

The satellite altimetry data was obtained from the NASA Jason-2 satellite and then processed through the BRAT program to obtain height and storage values. The satellite data was filtered to remove outliers and add a bias to the satellite data so that it could be compared it to the in-situ data.

Water Balance Calculations

Using satellite data in conjunction with in-situ data, a water balance for the selected study site was calculated and created. Calculations measure the change in storage volume of the permanent pool of the reservoir resulting from the total inflow minus the total outflow. The inflows consist of precipitation (P) and total inflow (Q-in) into reservoir whereas the outflows included evaporation (E) and total release (Q-out) from reservoir.

Equation (3) $\Delta V = \Sigma \text{ Inflow} - \Sigma \text{ Outflow}$

where:
ΔV = Change in storage volume of the reservoir (meters)
Σ Inflow = Sum of all inflows over a period of time (streamflow + precipitation)
Σ Outflow = sum of all outflow over a period time (discharge + evaporation)

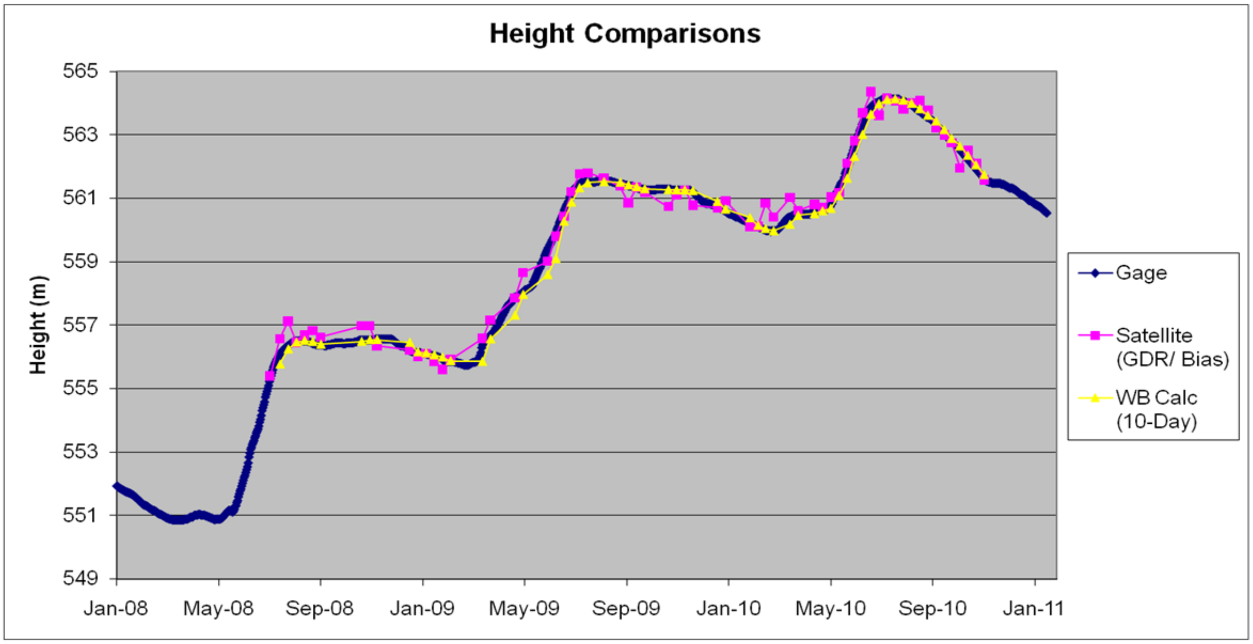

Figure 3. Time series of In-situ (gage), Jason-2 (GDR) Satellite, and Calculated Water Balance (10-Day Observations) elevation levels for Lake Sakakawea at Garrison Dam, North Dakota from 2008 through 2010.

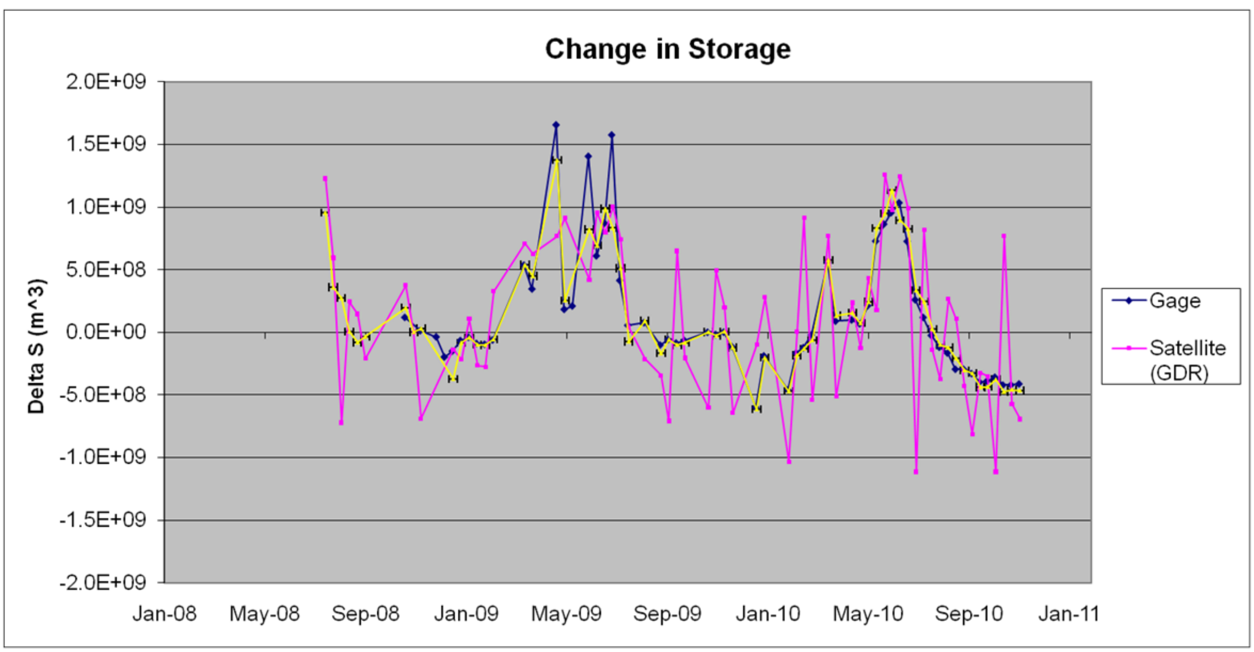

Figure 4. Time series of In-situ (gage), Jason-2 (GDR) Satellite, and Calculated Water Balance (10-Day Observations) changes in storage for Lake Sakakawea at Garrison Dam, North Dakota from 2008 through 2010.

RESULTS AND DISCUSSION

Analysis of Results

From the given data and analysis, a clear and general understanding can be grasped about the location of the Garrison Dam on Lake Sakakawea. A combination of satellite and in-situ data helps to understand the shape, characteristics, and general processes associated with the lake and dam. The gage height data also indicates that there are recorded changes in reservoir heights that can easily be compared to any processed satellite data during the selected time series. The processed data from the satellite altimeters have been analyzed and compared in order to conclude final results about their effectiveness in measuring reservoir heights. From the results generated, we were able to discern that satellite altimetry data could accurately estimate the height of lakes as accurately as the gage data. Therefore, satellite data can be used to complete water balance calculations where in-situ data is insufficient or missing. With the correct adjusted bias, satellite data can be as effective as collected in-situ data.

Errors & Uncertainty

All the in-situ data had to be converted into SI Units in order to be compatible world-wide. Converting the data between the two units may lead to some human calculation errors and small digit changes in the higher significant digits. Other significant implications in the in-situ data include the annual snow and ice cover that may alter the gage readings, thus creating false data points.

The satellite data proved to be more challenging than expected. It initially appeared that there was plenty data available online, but unfortunately it was not processed to our needs. Working with the BRAT program proved to be difficult considering the various variables that had to be considered just to obtain raw data. In addition, the raw data was not yet tailored to meet the needs of the project at hand and therefore required more analysis and manipulation before it could readily be used in order to measure reservoir heights. The satellite itself should only have approximately 1 cm or less of error when taking measurements based on previously conducted tests and studies.

Future Work

With these given results, a better understanding of watersheds with man-made reservoirs can be obtained. This data can then be incorporated into hydrological models to help improve forecasting and can also be turned over to partners to use for their own individual purposes. These results determine the satellite sensitivity which can be inferred from the graphs. Furthermore, this same process can now be applied to additional site locations to expand the geographic and temporal scope. Ultimately, these results can be used to calibrate both satellite and flood models for future natural disaster-flood mitigation.

CONCLUSION

Using satellite and in-situ data, a water balance was successfully calculated for the selected study site. These results prove that a calculated water balance can be completed using satellite altimetry data in order to compensate for missing data when in-situ observations are unavailable. Comparison of changes in heights (ΔH) and storage (ΔS) from satellite, calculated, and in-situ datasets shows the relationship between the data sources and the effectiveness of the data. With an adjusted bias, satellite altimetry data can be used to effectively measure reservoir heights from space.

The current results from this one study site can be expanded to study other reservoirs and river basins using this project as a model. Reservoir heights of dam locations without sufficient in-situ data can now be observed via satellite altimetry data products. The water balance calculated can also be applied to other reservoirs and further incorporated into flood models, such as the CREST Model. Further, results will be used to calibrate and improve global flood models, thus creating optimum results for flood prediction and potential socioeconomic gains from agricultural production to specific global regions.

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