Method for satellite monitoring of water storage in reservoirs for efficient regional water management

JUN MAGOME
University of Yamanashi, Takeda 4-3-11, Kofu 400-8511, Japan
j.magome@ccn.yamanashi.ac.jp

HIROSHI ISHIDAIRA & KUNIYOSHI TAKEUCHI
Graduate School of Engineering, University of Yamanashi, Takeda 4-3-11, Kofu 400-8511, Japan

Abstract Efficient use of water resources, at the basin-wide or regional scale, is the most important subject in integrated water resources management. For this purpose, it is necessary to monitor the variation of water storage in reservoirs within the region. We propose new methods of estimating water storage in reservoirs from satellite observations and digitized topographic data. These methods are applied to the Volta Lake of the Akosombo dam in Ghana. In this application, seasonal and inter-annual variations of reservoir storage are estimated, and the possibility of monitoring water storage is demonstrated.

Key words Digital Elevation Model; reservoir storage; satellite altimeter; satellite image; Lake Volta

INTRODUCTION

According to ICOLD (1998), worldwide more than 41,413 dams over the height of 15 m were in operation in 1996. The efficient use of reservoirs in a region is the most important part of integrated water resources management; the regional monitoring of water storage in reservoirs and especially the understanding of seasonal variations are key issues for strategic risk management. Ground observations of reservoir storages are often unavailable due to a lack of proper information transmission networks as well as, in some cases, administrative barriers.

It is desirable to develop the technology to monitor reservoir storage by the use of satellite remote sensing techniques. A number of studies using satellite remote sensing have been made on the monitoring of land surface hydrological conditions, including detection of water surfaces using satellite images (e.g. Harris, 1994) and variation of stage height for large lakes and rivers using satellite radar altimetry (e.g. Birkett, 1998). However, the remote sensing of land surfaces can only provide the area of the water surface, and/or the water level, but the volume of water storage cannot be observed directly. Therefore, a method of transforming the area of water surface and water level, obtained through remote sensing, into the volume of water storage should be investigated.

In this study, we propose new methods of estimating water storage in reservoirs based on satellite observations and digitized topographic data. The proposed methods are applied to the Volta Lake (Akosombo dam) in Ghana to verify the possibility of monitoring seasonal and inter-annual variation of water storage in reservoirs.
METHOD FOR MONITORING RESERVOIR STORAGES

Basic concept

Figure 1 shows the basic concept for monitoring reservoir storage using satellite observations. The change of reservoir storage can be estimated from the expansion/shrinkage of the area of water surface and the rise/fall of the water level. In this study, the satellite-derived area of water surface and water level is used to estimate the change of reservoir storage based on the following ideas.

The first method is the combination of the area of water surface ($A$) extracted from satellite images and changes in water level ($dH$) measured by satellite altimeter. The change in water storage ($dV$) for a certain period (time $t = t_0 \sim t_1$) is calculated as follows:

$$dV = A_{\text{ave}} \times dH$$  \hspace{1cm} (1)

where $A_{\text{ave}} = (A_0 + A_1)/2$, $A_0$ and $A_1$ are the area of water surface at $t = t_0$ and $t = t_1$, respectively.

The second method is the combination of relationships between water level ($H$), area of water surface ($A$), and reservoir storage ($V$), i.e. the $A$–$V$ curve, $H$–$V$ curve, and $H$–$A$ curve, and satellite data. If the $A$–$V$ or $H$–$V$ curves are available, satellite measured $A$ or $H$ can be directly translated into $V$. In the case of using the $H$–$A$ curve, $dV$ can be obtained as follows:

$$dV = \int_{H=H_0}^{H_1} A(H) dH$$  \hspace{1cm} (2)

Table 1 shows the practical methods for estimating the reservoir storage. The methods are classified into two types based on the data required for their application.
Method for satellite monitoring of water storage in reservoirs

Estimation from satellite observations alone (Type 1) In the first approach, (methods a, b and c), change of reservoir storage can be estimated from satellite observations alone. The method a requires a pair of satellite images and altimeter data observed at the same periods, and $\Delta V$ is calculated by equation (1). Methods b and c provide $\Delta V$ from the $H-A$ curve, which is estimated by satellite observations, and satellite observed $H$ or $A$. Once the $H-A$ curve is established, methods b and c are applicable even if only either satellite image or altimeter data is obtained.

Combination of satellite observations and DEM (Type 2) Methods d, e, f and g require topographic data (DEM) in addition to satellite observations. In these methods, the $A-V$ curve, $H-V$ curve and $H-A$ curve are established from the DEM, and combination of the curve and satellite observations ($H$ or $A$) provides $\Delta V$. In some cases, satellite observations cannot be obtained due to a coarse sampling interval (for the altimeter) or cloudiness (for visible and near-infrared sensors). However, the Type 2 method is applicable if DEM and either satellite images or altimeter data can be used.

The method for measuring the area and height of the water surface from the satellite and the procedure for establishing the $H$, $A$, and $V$ relations are discussed next.

Extraction of the water surface area from satellite images

In this study, multi-spectral images (TERRA/MODIS) and Synthetic Aperture Radar images (JERS-1/SAR) are applied for the detection of the water surface area ($A$). For the TERRA/MODIS images, band 5 (1230–1250 nm) reflectance, which is 500 m resolution, is used to identify the water surface. All pixels in the images are classified into two categories (water surface and others) according to a certain threshold value, and the mask filter is applied to remove the pixels of water surface that are not connected to the water surface of the reservoir. For JERS-1/SAR images, the image enhancement and histogram equalization, spatial filtering is applied to eliminate speckle noise (Magome et al., 2002). The pixel size is 12.5 m for level 2.1 products, and 100 m for the mosaic image. All pixels in processed images are classified into water surface and others according to a certain threshold value. The area of the water surface is calculated as the sum of the areas of the pixels with water surface.
Measurement of water level by satellite altimeter

Satellite altimetry measures the altimeter range, which is the distance from the satellite to the surface of the Earth. The altimetric height is determined by the difference of the satellite orbit and altimeter range:

\[ H' = Alt - R_{cor} \]  

where \( H' \) is with respect to a mathematical reference ellipsoid, \( Alt \) is the satellite orbit, \( R_{cor} \) is the altimeter range corrected for the atmosphere's influence on the altimeter radar pulse. Consequently, the water level \( (H) \) is calculated and used for the water level of the reservoir:

\[ H = H' - H_g - T_e - I_B \]

where \( H_g \) is the Geoid height, \( T_e \) is the earth tide effect, \( I_B \) is the inverse barometer. All the above values are derived from TOPEX/POSEIDON MGDR-B data. The spatial sampling is about 6 km along the tracks, and spacing between parallel tracks at the equator is 315 km.

Relation between \( H, A, \) and \( V \) for the reservoir

If the relationship between water level \( (H) \), area of the water surface \( (A) \) and storage volume \( (V) \) of the reservoir \( (H-A \) curve, \( H-V \) curve and \( A-V \) curve \) are available, change of water storage \( (\Delta V) \) can be estimated from satellite observations. However, it is difficult to obtain equivalent observed values, which are generally established from topographic contour maps or specific reservoir basin surveys. In this study, the \( H-A \), \( H-V \) and \( A-V \) curves are estimated from a DEM using the method of Magome et al. (2002). The \( H-A \) curve is also estimated from satellite observations. Based on previous studies (Takeuchi, 1997), the relation between \( H, A \) and \( V \) of the reservoir is expressed as follows:

\[ A = \alpha \cdot H^\beta \]  

\[ V = \gamma \cdot H^\eta \]  

\[ V = a \cdot A^b \]

where \( \alpha, \beta, \gamma, \eta, a, b \) are the parameters of the power relationships for the \( H-A, H-V, A-V \) curves.

CASE STUDY

The study area is the Volta Lake of the Akosombo dam (Fig. 2), which is one of the largest reservoirs in the world. The dam was built on the lower reaches of the Volta River (western Africa, Ghana) in 1965. The principal purpose of this dam is hydro-power generation. When full it has a water surface of 8482 km\(^2\), which is the biggest in the world, and the gross storage capacity of the reservoir is 148 km\(^3\).

Twenty-five scenes of TERRA/MODIS images for 2000 to 2002, four scenes of JERS-1/SAR level 2.1 images collected from 1995 to 1996, and a JERS-1/SAR mosaic
image for 1996.2–3 were collected for the study area and used in this study. Satellite altimeter data was obtained from TOPEX/POSEIDON MGDR-B data archived in PO DAAC/NASA. The temporal resolution of the altimeter data is about 10 days, and data for 1992–2002 were used in this study. The GTOPO30 (USGS) DEM was used for the topography data to estimate the $A-V$, $H-V$ and $H-A$ curves (Fig. 3); the spatial resolution of this grid-based DEM is about 1 km and the vertical resolution is 1 m.

The water storage in Volta Lake was estimated for the period of 1992 to 2002 using the proposed methods. Figure 4 shows the results for estimating the change of water storage $dV$, where $dV$ is the water storage difference from the water storage at the water level $H = 76$ m. It was found that all the proposed methods are able to
Fig. 4 Results of estimating the change of reservoir storage ($dV$) by methods a–g. $dV$ is the difference of water storage from the water storage at the water level $H = 76$ m.
Table 2 Comparison with each result.

<table>
<thead>
<tr>
<th>Method</th>
<th>Type</th>
<th>RMSE (km$^3$)</th>
<th>dV (km$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>1</td>
<td>0.9</td>
<td>61.8</td>
</tr>
<tr>
<td>b</td>
<td>1</td>
<td>11.9</td>
<td>61.3</td>
</tr>
<tr>
<td>c</td>
<td>1</td>
<td>-</td>
<td>60.4</td>
</tr>
<tr>
<td>d</td>
<td>2</td>
<td>10.2</td>
<td>65.5</td>
</tr>
<tr>
<td>e</td>
<td>2</td>
<td>2.3</td>
<td>51.6</td>
</tr>
<tr>
<td>f</td>
<td>2</td>
<td>8.6</td>
<td>44.0</td>
</tr>
<tr>
<td>g</td>
<td>2</td>
<td>0.4</td>
<td>59.9</td>
</tr>
</tbody>
</table>

RMSE: Root Mean Square Error (period: 00/12 ~ 02/5)
dV: V(00/12) - V(02/5)

monitor the seasonal variation of water storage in the reservoir, i.e. water storage increased in winter (dry season) and decreased in summer (rainy season). In addition, the long-term decreasing trend from 2000 to 2002 was also represented by all methods, and it implies that the methods are suitable for monitoring of the inter-annual variability of water storage.

The differences between the estimates for each method are shown in Table 2, where the results from method c are used as “reference", and the difference is the discrepancy of estimates from the reference. In the case where both $A$ and $H$ are obtained from satellite observations (Type 1), method a gives relatively similar estimates to the reference; on the other hand, the differences for method b are larger. When either $A$ or $H$ is obtained from satellite observations (Type 2), results from altimeter $H$ (methods e and g) are close to that of method c. However, the differences for methods d and f are larger than for e and g. This implies that errors in extracting the area of the water surface (e.g. caused by cloudiness) would more directly affect the estimation of the reservoir storage than observation errors in $H$.

Since the TOPEX/POSEIDON altimeter data are available for a longer period than TERRA/MODIS satellite images, methods e, e, and g are able to provide longer term estimates of water storage (Fig. 4). In comparison with the Volta River Authority report, in which the change in water storage for the calendar year was reported as 27.89 km$^3$, the errors of methods c, e and g were 4%, 17% and 2%, respectively.

DISCUSSION

The causes of error in the proposed algorithm can be separated into three parts: errors in water level ($H$) derived from altimeter data, errors in the extraction of water surface ($A$), and errors of the modelled $A-V$, $H-V$, and $H-A$ curves. In this application, the accuracy of $H$ obtained from altimeter data is considered higher than the accuracy of $A$ from satellite images, and the influence of errors in $A$ is more apparent than other errors. Therefore, it is necessary to improve the accuracy of $A$ to give more accurate estimates. For the methods b–g, the estimates are also affected by errors in the $A-V$, $H-V$, and $H-A$ curves. Since the resolution of the DEM is considered to have a significant influence on the accuracy of these curves, it is desirable to use a higher
resolution and accurate DEM. Fortunately, a high resolution DEM for the total land area of the world will be provided in the near future (e.g. by the Shuttle Radar Topography Mission, SRTM), and it will be applicable to estimation of these curves.

Data availability is also a problem in the practical application of the proposed methods. Altimeter data cannot be obtained for all reservoirs, because the flight passes of the satellite are wide (315 km at the equator) and the data sampling interval is coarse (about 6 km). On the other hand, satellite images can be obtained for everywhere on the globe. Therefore, even though altimeter data cannot be used, water storage can be estimated by methods d and f. For Yagisawa dam (Japan), where the altimeter data is not available and surface area is 5.67 km² (at maximum storage), variations of water storage were detected correctly using method d (Magome et al., 2002).

**CONCLUSION**

In this study, methods for estimating reservoir storage from satellite data are proposed. The results of a case study of Lake Volta (8482 km²) shows that the proposed methods can provide seasonal to inter-annual variability of reservoir storage from satellite observations and DEM data. Each method has its advantages and limitations depending upon the availability of data, reservoir scale and location, etc. However, these methods have potential for use in monitoring reservoir storage without *in situ* observations, and they could be applied to ungauged or data poor basins. Furthermore, satellite altimetry missions applicable for inland water monitoring (e.g. HYDRA-SAT) are being planned, and the data required for the proposed methods will be obtained with higher spatial and temporal resolution in the future.

For practical use of the algorithms we need to improve the accuracy of extracting the water surface area from satellite images. The automation of procedures to extract the water surface area is also one of the important issues for the application of the methods proposed in this paper to monitor regional reservoir storage.

**REFERENCES**


