Conversion of surface water coverage to water volume using satellite data

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Abstract:

This study analyzed the relationship between inundated area and actual water volume using data from satellites, including the Moderate Resolution Imaging Spectroradiometer (MODIS) and Gravity Recovery and Climate Experiment (GRACE) satellite systems. The results showed that using relatively simple assumptions for the flow of water, a clear relationship could be demonstrated between inundation ratio and water volume. In the Chao Phraya River basin, the spatial average of the converted data from MODIS showed good correlation with the water volume measured by GRACE. Since the method used in this study does not rely heavily on the characteristics of a specific region, it is expected the approach would be applicable on a global scale if the necessary data were available.

KEYWORDS inundation ratio; water volume; MODIS; GRACE; river network

INTRODUCTION

The International Panel on Climate Change (IPCC) has reported that flood damage is almost certain to increase due to climate change. As a result, knowledge about the mechanism of floods will become more and more important. Floods have been among the most common natural disasters in the period from 1985 to 2009, accounting for almost 40% of such disasters; half the victims of natural disasters are flood victims (Ferreira et al., 2011).

Since the launch of the first artificial satellite in 1957 [http://history.nasa.gov/sputnik/], satellites have been used for purposes such as weather forecasts, global positioning systems (GPS), and telecommunications. They are also used for validation of model simulations, with data from satellites serving as observations (Yamazaki et al., 2011). The products from these satellites are also varied, including measures such as land surface coverage, cloud mask, water volume, vegetation indices, temperature, etc. (Platnick et al., 2003).

A variety of research has been conducted using satellites for flood assessment. Prigent et al. (2007) used multiple satellites to estimate inundated areas on a monthly basis for the resolution of 0.25 degrees. Frappart et al. (2006) used satellite altimetry and imagery data to construct water level time-series for the lower Mekong river basin. They then used the calculated water levels to estimate variation of water volume. Most of the previous research has been conducted on a monthly or interannual scale due to the limitation of the data achieved from satellites. It is therefore difficult to analyze the direct relation between inundated area and existing water volume.

This study aims to show a link between inundation ratio and water volume by using data achieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) [http://modis.gsfc.nasa.gov/index.php] and the Gravity Recovery and Climate Experiment (GRACE) (Tapley et al., 2004). The inundation ratio of the surface is converted to water volume using multiple datasets, thereby revealing the relationship between inundation and water volume.

DATA AND METHODS

Study site

This paper focuses on the Chao Phraya River basin. The topography of the region surrounding the river basin is shown in Figure 1a; it is in Southeast Asia, and includes the Indochina Peninsula, Myanmar, Bangladesh, and some parts of China. The Chao Phraya River basin itself is located in central Thailand. In 2011, this river basin experienced the largest flood in the history of Thailand. The rivers in Thailand have a very gentle slope, with river gradients of around 1/10,000 to 1/15,000. This makes the Chao Phraya River basin very prone to floods (Komori et al., 2012).

Data

MODIS is carried on a satellite called Terra. It detects a wide spectral range of electromagnetic energy, from which it produces variables such as land surface cover, cloud mask, and precipitable water (Platnick et al., 2003). MODIS has a spatial resolution of 250–1,000 m, and measures the entire surface of the earth every day. Obstacles such as clouds, however, can prevent MODIS from measuring all land surfaces every day. Thus in order to obtain a complete data set, around ten days of data is thought to be necessary. The water spectral vectors in the MODIS images were estimated to identify the water-covered pixels at a resolution of 500 m (Sawada et al., 2013). After being identified, the water pixels were converted to inundation ratio at a resolution of 10 min (about 20 km). Figure 1b shows the inundation ratio derived from MODIS between October 1 and October 10, 2011. Ten-day composite data from 2009 to 2011 was used.

The GRACE twin satellites were launched on March 17,
2002, with the objective of producing high spatial resolution gravity models. The product available from these satellites provides global coverage of the gravity field. The GRACE data used in this study shows terrestrial water storage – which is the sum of soil moisture, ground water, surface water and snow/ice mass – in a temporal and spatial resolution of 10 days and 1 degree (about 111 km), respectively (Lemoine et al., 2007). Figure 1c shows the water equivalent height derived from GRACE for the period September 30 to October 9, 2011. Data from January 3, 2009 to December 28, 2011 are used with the exception of a few missing periods (December 24, 2010–February 1, 2011; June 12, 2011–July 1, 2011; and November 19, 2011–December 18, 2011). Data from GRACE was used as a means of verification for the conversion of inundation ratio to existing water volume.

Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales (HydroSHEDS) (Lehner et al., 2008) is derived from elevation data of the Shuttle Radar Topography Mission (SRTM) (Farr et al., 2007) and provides datasets such as stream networks and drainage direction. This study used topographical data and stream networks. The resolution of the data used in this study is 15 sec (about 500 m).

Method

This study proposed a method for using MODIS and GRACE data to convert inundation ratio to water volume. The original resolution, both spatial and temporal, of MODIS products is high, but MODIS can only measure the surface coverage. Meanwhile, GRACE can measure the water volume existing on earth, but has a coarse resolution. Usage of the proposed method in this study will enable the measurement of water volume in a high spatial resolution. Both GRACE and the converted MODIS are represented in water height equivalents. Water height equivalent is the height of water within a certain grid when it is assumed that the existing water is spread across a flat surface.

For the conversion, high resolution topography data from HydroSHEDS was used. Water generally flows from a higher to a lower elevation; as a result, the flow of water is largely influenced by the topography of a region. Figure 2 shows the ratio of times GRACE and the anomaly of the original MODIS showed the same signs of variability, that is, the ratio is higher if the data from GRACE and the anomaly of data from MODIS are both positive/negative for a given period. The white grids indicate places where the inundation ratio did not change in the data available for the study period. From Figure 2, the existence of rivers seems to have some impact on existing water volume, as the large rivers clearly have a high ratio of the same signs. The locations of rivers were also considered by using stream networks from HydroSHEDS. From the factors discussed above, the following two assumptions were used to develop inundation patterns:

1. Inundation begins in areas where rivers exist.
2. Inundation begins in areas with lower elevation.

The resolution of the topography and stream network data is extremely high, so that 40 × 40 grids exist within 1
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grid from MODIS. It was assumed that the ratio of water covered topographical grids was the same as the inundation ratio of each MODIS grid. This makes it possible to estimate the amount of water in each MODIS grid. The overall concept behind the method is shown in Figure 3. When the locations of rivers are not considered in the estimation of water volume (Figure 3a), the elevation within one MODIS grid is sorted from lowest to highest as follows:

\[ h = \{ h_1, h_2, ..., h_{1600} | \text{where } h_1 \leq h_2 \leq ... \leq h_{1600} \} \] (1)

The water height equivalent, \( H \), of a grid can be estimated with the following equation:

\[ H = \frac{\sum_{i=1}^{n} g_i A_i}{\sum_{i=1}^{1600} A_i} \] (2)

where \( n \) is the number of inundated topographic grids and \( A_i \) is the area of each topographic grid which is considered constant in this study. When the locations of rivers are considered (Figure 3b), the elevation within one MODIS grid is sorted from lowest to highest as follows:

\[ g = \{ g_1, g_2, ..., g_r | \text{where } g_1 \leq g_2 \leq ... \leq g_r \} \] (3)

\[ h = \{ h_1, h_2, ..., h_{1600-r} | \text{where } h_1 \leq h_2 \leq ... \leq h_{1600-r} \} \] (4)

where \( g \) is the elevation of grids with rivers, and \( h \) is the elevation of grids without rivers. The water height equivalent, \( H \), is estimated with the following equation:

\[ H = \frac{\sum_{i=1}^{n} g_i A_i}{\sum_{i=1}^{r} A_i + \sum_{j=1}^{1600-r} A_j} \quad (n \leq r) \] (5)

\[ H = \frac{\sum_{i=1}^{r} g_i A_i + \sum_{j=1}^{n} h_j A_j}{\sum_{i=1}^{r} A_i + \sum_{j=1}^{1600-r} A_j} \quad (n > r) \] (6)

where \( n \) is the number of inundated topographic grids, \( r \) is the number of topographic grids including river networks, and \( A_i \) and \( A_j \) are the area of each topographic grid which is considered constant in this study. The blue solid line in Figure 3b is the function curve for grids with rivers; the green dashed line is the function curve for grids without rivers.

Figure 3. The concept of the proposed method. The elevation profile of a certain grid when (a) rivers are not considered and (b) rivers are considered. The blue shaded area is where water is assumed to exist.

Figure 4. Standardized temporal variation of spatially averaged water height equivalent (Green dashed line: GRACE; Blue solid line: original MODIS). The period of the flood in the Chao Phraya river basin is shaded.

RESULTS AND DISCUSSION

Standardized comparison of original data from MODIS and GRACE

Figure 4 shows the temporal variation of water height equivalent from GRACE (green dashed line) and the original values of inundation ratio from MODIS (blue solid line), which was spatially averaged over the Chao Phraya River basin. Each variable in Figure 4 is standardized to allow direct comparison of variables with different units. The errors caused by using only three years’ worth of data for the standardization were ignored. Although the values of the original MODIS themselves did not coincide exactly with the values of GRACE, the peak timings were very similar. This implies that there is some relationship between inundated area and water volume, and that conversion of inundated area to existing water volume is possible.

Conversion of inundation ratio to water volume

Since the resolution of GRACE itself is quite coarse and contains uncertainties, verification on a grid scale remains a challenge. Figure 5 shows the temporal variation...
Figure 5. Temporal variation of the water height equivalent, which was spatially averaged for the Chao Phraya River basin. The values for GRACE (green dashed line), converted MODIS without rivers (red dotted line), and converted MODIS with rivers (blue solid line) are shown. The period of the flood in the Chao Phraya river basin is shaded (2009–2011) of the spatial average of water height equivalent of the Chao Phraya River basin. The values from GRACE (green dashed line), converted MODIS without considering rivers (red dotted line), and converted MODIS considering rivers and dams (blue solid line) are shown. For the dams, variations in the reservoir storage at the Bhumibol and Sirikit dams, both located in the Chao Phraya River basin, were taken into account. Little evidence of seasonality can be seen from the converted MODIS without rivers, and the range of fluctuations is obviously too small compared to that of GRACE. The areas with rivers were assumed to be the first places that water would exist. From the values of the converted MODIS with rivers, the representation of seasonality was improved significantly. Also, the 2011 flood (gray shaded area) was well described.

The results of standardization and of the converted MODIS without rivers seemed to demonstrate similar peak timing to the values from GRACE. This was simply due to the fact that the inundation ratio increases with flooding seasons. Although water tends to flow from places with higher elevation to lower elevation, the source of the water flow is mostly from rivers. By considering the locations of rivers, the distribution of water volume could be described more realistically. It is assumed that since the Chao Phraya River basin has a gentle slope, the impact of rivers overcome that of elevation differences.

CONCLUSIONS

This study attempted to quantify the relationship between inundation and water volume by converting the inundation ratio obtained from MODIS into water volume measures such as those gathered by GRACE. Topographical data, inundated area, and river network data were used to convert inundation ratio to existing water volume. The most suitable domain size and topographic features are issues that must still be solved, but the temporal variation of spatially averaged water height equivalent from the converted MODIS shows good correlation with GRACE data. The differences in peak timings are thought to be due to the lag time it takes for water to spread out over a certain region.

The main finding of this study was the importance of rivers in assessing the relationship between inundated area and existing water volume. Especially in regions with little variation in elevation, rivers play a large role in inundation. Additional analysis considering soil moisture and ground water, which are both included in the GRACE signals, may lead to a clearer understanding of the mechanisms of inundation and water spread.

The method proposed in this study is not limited to the study region. Given the necessary data, the proposed method would be applicable anywhere in the world. Some limitations remain, however. First, regions with major differences in elevation tend to produce overestimations of inundation owing to the fact that water volume is estimated using the elevation differences of a given grid. Second, the impacts of water existing underground, such as soil moisture, needs to be considered. The proposed method has the potential to measure the water volume of the Earth’s surface at a much higher resolution – both spatially and temporally – than existing methods.

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REFERENCES


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