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Application of the inundation area—lake level rating curves constructed from the SRTM DEM to retrieving lake levels from satellite measured inundation areas

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ABSTRACT

Remote sensing technology has great potential for measuring lake inundation areas and lake levels, and providing important lake water quantity and quality information which can be used for improving our understanding of climate change impacts on the global water cycle, and assessing the influence of the projected future climate change on the global water resources. One remote sensing approach is to estimate lake level from satellite measured inundation area based on the inundation area—lake level rating (IALLR) curves. However, this approach is not easy to implement because of a lack of data for constructing the IALLR curves. In this study, an innovative and robust approach to construct the IALLR curves from the digital elevation model (DEM) data collected during the Shuttle Radar Topography Mission (SRTM) was developed and tested. It was shown that the IALLR curves derived from the SRTM DEM data could be used to retrieve lake level from satellite measured inundation area. Applying the constructed IALLR curve to the estimated inundation areas from 16 Landsat Thematic Mapper (TM) images, 16 lake levels of Lake Champlain in Vermont were obtained. The root mean square error (RMSE) of the estimated lake levels compared to the observed water levels at the U.S. Geological Survey (USGS) gauging station (04294500) at Burlington, Vermont is about 0.12 m.

1. Introduction

Although water in lakes accounts for a small proportion of the Earth's water (i.e., about 0.013% of the total Earth's water in volume) (e.g., Maidment, 1993; Hornberger et al., 1998), it represents an important component of the global water cycle. The freshwater lakes hold about 0.26% of the Earth's fresh water and are considered to be the third largest reservoir of the Earth's freshwater (e.g., Maidment, 1993; Hornberger et al., 1998). The amount of water in lakes depends on the water balance between inflows and outflows. Inflows to lakes include precipitation, overland runoff, groundwater seepage, and tributary inflows. Outflows from lakes consist of evaporation, groundwater outflow, and surface water discharge for open-basin lakes. There is no surface water flow leaving closed-basin lakes. Since both inflows entering and outflows leaving lakes are related to climate, the fluctuations in lake levels indeed reflect climate change, and in turn can produce a feedback to climate (e.g., Street and Grove, 1979; Harrison et al., 1993; Mortsch and Quinn, 1996; Jones et al., 2001). Therefore, the information about lake levels is essential for understanding the impacts of climate change on the global water cycle and assessing the influence of the projected future climate on the global water resources.

Although we can easily measure lake levels through establishing and operating a lake gauging station, cost of installation and operation of gauging stations limits the number of lake gauging stations installed, especially in the developing countries. For example, the cost for the United States Geological Survey (USGS) to install a gauging station is between $20,000 and $35,000 and the annual operational cost is about $20,000 (e.g., Fekete and Vörösmarty, 2007). The actual cost of operating a water level station is less than $20,000/yr because the regular field surveys for calibrating the discharge gauge and establishing the stage-discharge rating curves are not needed for the water level station. Even in some developed countries, like the United States, the number of gauging stations has shown to be decreasing mainly due to a shortage of funding (e.g., Vörösmarty et al., 1996; IAHS Ad Hoc Committee, 2001; Bjerklie, et al., 2003; Hannah et al., 2011). For the ungauged lakes, we can periodically conduct ground survey (i.e., manual observation) of lake levels. However, such effort is time consuming and labor intensive. Furthermore,

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for those lakes located in the remote areas, it is virtually impossible to access them and not to mention to measure them. Therefore for the ungauged lakes, and especially those located in the remote areas, such as the lakes in the Tibetan Plateau, remote sensing probably is one practical approach.

Since the 1990s, significant progress has been made in remote sensing of lake level or river stage (e.g., Smith, 1997; Alsdorf et al., 2007; Schumann et al., 2009). The approaches of remote sensing of water levels in lakes or rivers generally can be classified into three types: (1) direct methods, e.g., altimetry radar or lidar point measurements of water surface elevation (e.g., Koblinsky et al., 1993; Birkett, 1995, 1998; Birkett et al., 2002; Coe and Birkett, 2004; Kouraev et al., 2004; Calmant and Seyler, 2006; Leon et al., 2006; Birkinshaw et al., 2010; Bhang et al., 2010); (2) indirect methods through estimating lake level (or river stage) using satellite measured inundation area (e.g., Smith et al., 1995, 1996; Hamilton et al., 1996; Pietronitro et al., 1999; Al-Khudhairy et al., 2002; Xu et al., 2004; Zhang et al., 2004; Brakenridge et al., 2005, 2007; Temimi et al., 2005; Ashmore and Sauks, 2006; Smith and Pavelsky, 2008, 2009; Bhang et al., 2010; Pan and Nichols, 2012); and (3) combination methods through integrating satellite observations with topographic data to determine water level (e.g., Brakenridge et al., 1998; Bjerklie et al., 2005; Matgen et al., 2007; Schumann et al., 2008a, 2008b).

Among the above three types of methods, the methods of the second type (i.e., the indirect approaches) were more commonly used than others. One possible reason is that unlike lake inundation area (i.e., lake water surface area), lake level is relatively difficult to measure directly from space with a high accuracy because of difficulty in eliminating the satellite orbital errors (e.g., Smith, 1997). However, to estimate lake level based on satellite measured inundation area, we need to use the inundation area—lake level rating (IALLR) curve. Smith (1997) demonstrated that the relationship between inundation area and water level is unique and can be used to estimate lake level. The problem associated with this approach, as pointed out by Smith (1997), is that we often do not have observed data to construct the IALLR curves. For ungauged lakes, lake level measurements are not available. For gauged lakes, lake level measurements may be available, but the lake level measurements may not have been made on the same days as the inundation area measured from space. Lack of data for constructing the IALLR curves directly hampers progress in retrieving lake level using satellite measured lake area or inundation area. To solve this problem, this paper presents a new method for remote sensing of lake level using the inundation area—lake level rating (IALLR) curves constructed from digital elevation model (DEM) data.

Our proposed method can be considered as an integrated approach combining the second type methods (i.e., using satellite measured inundation area) and the third type methods (i.e., integrating satellite observations with topographic data). The proposed approach first defines a polygon covering whole or a portion of a lake and then uses a DEM dataset to compute the "hypothetical" inundation areas at different "hypothetical" water levels in the predefined polygon (to be discussed in Section 3). The objective of this study is to develop a new, simple, and robust method that can be used to estimate lake level from space, regardless of whether the lakes are gauged or ungauged. Especially, we will address the following two questions: (1) How to construct the IALLR curves from the DEM data? (2) How to apply the constructed IALLR curves to estimate lake level from satellite measured inundation area? The arrangement of this paper is as follows. Section 2 introduces study area and data. Section 3 describes methods and results. Discussions and summary are presented in Section 4.

2. Study area and data

To describe and test the methods proposed in this study, Lake Champlain, located mainly within the borders of Vermont and New York and partially in Canada, was chosen as the study area (see Fig. 1). The location of the United States Geological Survey (USGS) gauging station (station ID is 04294500) at Burlington, Vermont (44°28′34″N, 73°13′19″W) is also marked in Fig. 1. This USGS gauging station has about 40-year measurements of

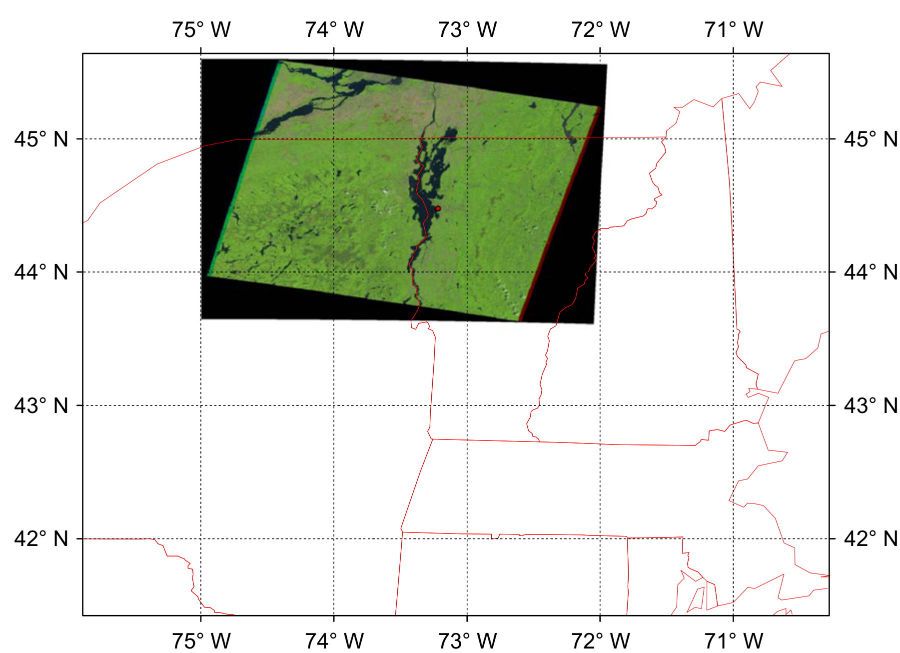

Fig. 1. Lake Champlain located mainly within the borders of Vermont and New York and partially in Canada. The United States Geological Survey (USGS) 04294500 gauging station at Burlington, Vermont (44°28′34″N, 73°13′19″W) is marked as a red dot. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)