Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2013.822638

52 (2014) 2700–2708
March

Geomatics-based water capacity monitoring for Quake Lake and its web service implementation

Jianzhong Lu[a,*], Xiaoling Chen[a,b], Xiaobin Cai[c], Lian Feng[a]

[a] *State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan 430079, China*
Tel. +(86)27 6877 8755; email: lujzhong@163.com
[b] *Key Laboratory of Poyang Lake Wetland and Watershed Research, Ministry of Education, Jiangxi Normal University, Nanchang 330022, China*
[c] *Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuhan 430077, China*

Received 12 July 2012; Accepted 12 June 2013

ABSTRACT

A novel geomatics-based dynamic lake or reservoir water capacity computing method is proposed for mountainous area, where the water surface curves with the slope of the topography. This water capacity monitoring framework supported by web service technology was designed and implemented for a geospatial processing service. A pixel-based method to model a three-dimensional water surface was created to monitor total capacity including the dynamic capacity. First, the upstream areas are extracted from geometrically corrected SPOT-5 satellite image. The riverbed digital elevation model was intersected with the upstream area to obtain the boundary consisting of a set of points with altitude values for the water body. Considering rationality and efficiency, an improved, pixel-based river segmentation algorithm was then developed and implemented. Taking Tangjiashan Quake Lake dammed by landslide sandstone after the Wenchuan Earthquake in China in 2008 as an example, an evaluation indicates that the improved pixel-based river segmentation algorithm has the advantages of higher computational efficiency and accuracy, useful for daily monitoring of lake or reservoir water capacity in mountainous regions. Finally, water capacity monitoring models were decomposed to atomic services, to support data sharing and service model interoperability by web service. The reusable atomic services were freely customized and combined to execute water capacity calculations for different data-sets. The web service implementation experiment demonstrated powerful interoperability and remotely processing between multiusers in this geomatics-based water capacity monitoring system, which can be implemented on interplatform. It provides a general mechanism to allow client to perform distributed geospatial processing in GeoSpatial Web Service.

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*Corresponding author.

Presented at the Second International Conference on Water Resources Management and Engineering (ICWRME 2012) Zhengzhou, China, 14–16 August 2012

Keywords: Dynamic water capacity; Water resource management; Web service; River segmentation; Quake Lake

1. Introduction

A lake/reservoir capacity is the water storage capacity below a certain water level. It lays the space between a lake/reservoir bottom and its top water surface and is surrounded by a spatially curved land surface and a water surface and can also be understood as “the largest volume that can be contained”. Therefore, the reservoir capacity is actually the largest volume of “the container” [1]. It is an important piece of information for water resource management, hydro-electric power usage, and hazard mitigation.

Many researchers have made great efforts on capacity monitoring. Mcmahon et al. used a global data set for 729 rivers to assess the adequacy of five techniques to estimate the relationship between reservoir capacity, targe draft and reliability of supply [2]. Furnans and Austin used numerical simulation to measure reservoir capacity and made a long time sequence analysis to account for water volume loss [3]. Foteinopoulos proposed a method using cubic splines to generate contours to estimate capacity [4]. In addition, some researches were focused on the capacity application in water distribution [5] and hydro-power [6]. Previous studies mostly focused on how to monitor water capacity mainly in the following three aspects. First, a lake or reservoir was divided into sections or blocks, and then the storage capacity was summed up from each section. Some of the studies using this method took the static water capacity as the total storage capacity [7]. To divide the lake into sections, some used the transect method [8], while others used contour lines [1], or a digital elevation model (DEM) [9]. Secondly, hydrological and hydraulic models were used to monitor the total storage capacity, including the dynamic capacity and instantaneous water storage capacity [10,11]. When dynamic capacity is considered, the lake/reservoir storage capacity is defined as the total water storage capacity between the upstream transect and the dam. As shown in Fig. 1, at a given water depth H in the front of the dam the water storage capacity can be expressed as the volume of the polygon ANDEFBC, which consists of static capacity Ws(ABC) and dynamic capacity Wd (NDEFB). The static storage Ws is a function of water depth H in the front of the dam or the elevation of the bottom of the spillway, while the dynamic capacity Wd usually needs to be calculated by complex hydrological and hydraulic models [12]. Thirdly, some studies have discussed how to apply geomatics to capacity monitoring [9,13–16].

Most methods of dynamic capacity calculation depend on simplifying the actual complex riverbed into a certain geometric shape. However, many boundary conditions and parameters in the model always cost much manpower and time to collect, and sometimes it is even impossible to access in the emergency situation following a serious disaster. The estimating algorithms are usually empirical, experimental, and approximate, which leads to unsatisfactory results under the emergency condition. Thus, it is a great challenge to design a rapid and accurate method to operationally monitor the lake/reservoir water capacity in emergencies. Monitoring of the storage capacity of lakes or reservoirs has been based on conventional land surveying, which is unable to meet the demands of data accuracy and updating frequency. With the development of remote sensing technology, it is possible to directly extract the exact upstream boundary from remotely sensed images and DEMs, which can then be used for the purposes of water resources conservation and flood prevention [17]. The combination of remote sensing and geographic information system (GIS) provides a method of monitoring lake capacity through dynamically calculating the water capacity curve quickly and accurately. In earlier studies, DEMs or digital maps were used to estimate lake capacity, but only the static

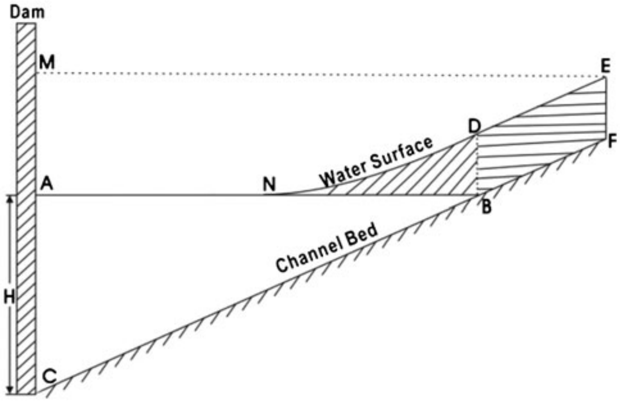


Fig. 1. Section for dynamic capacity of the reservoir. At given water depth H in the front of dam, the total water capacity can be expressed as the volume of the polygon ANDEFBC, which consists of static capacity Ws (ABC), and dynamic capacity Wd (NDEFB).

capacity was taken into consideration [13]. In other studies, remote sensing images were used to extract the water body area, and then the relationships between the area and capacity of the water body were analyzed, although the capacity was not calculated directly using remotely sensed images [14,16].

The water capacity monitoring models will never express their values unless applying to the real word with the aid of sharing techniques. The processing model sharing becomes highly desirable because it is of great cost saving and efficiency even though a web-based systems were established [18]. However, there are several issues for sharing and integrating geomatic models. It is difficult to adapt to the complex application requirements because of related limited resource utilization ability. Then, lack of consistent data exchange and model interoperability limits the model wide application. With the development of geomatical theories and technologies in past thirty years GIS has gone through single-tier and three-tiers to service-oriented architecture (SOA) [19]. SOA is better for interoperating among the different systems in the distributed network environment. The SOA-based geomatical model sharing is highly amenable to variant applications, including Browser/Server and Client/Server and distributed computing architectures.

In this paper, a method combining remote sensing and GIS technology is proposed to extract the water boundary for quake lakes in mountainous areas. A 3D water surface is then interpolated from the elevation points extracted from a DEM. In this method, not only the static and dynamic capacities are included, but the method is free from the constraint of riverbed shape. Based on Web Service technology, the water capacity monitoring model web service is constructed. It provides a new solution to monitoring lake water capacity dynamically, especially for the needs of rapid assessment of risks during emergencies.

1.1. Study area and data processing

On 12 May 2008, an earthquake of Richter magnitude 8.0 struck Wenchuan (latitude: 30˚45´–31˚43´N; longitude: 102˚51´–103˚44´E) in Sichuan Province, China, which directly caused fatalities and millions of people lost their homes. At the same time, the earthquake and the subsequent heavy rainfall led to landslides and debris flows, forming 37 large quake lakes in the region. The largest of them, Tangjiashan Quake Lake, is located 6 km upriver from Beichuan, most heavily damaged county in the earthquake. The city of Mianyang and other important cities in Sichuan Province are located downstream of the Tangjiashan Quake Lake, which threatened the safety of hundreds of thousands of people.

The Tangjiashan Quake Lake, formed by the blocked river, had a rock-accumulated dam approximately 800 m long and 610 m wide, with a dam height of 124 m in the highest area. Its volume can reach hundreds of millions of cubic meters, which is equivalent to a large reservoir. The main body of the dam is made of rocks and unconsolidated sediment. Therefore, the dam ran the risk of barrier bursting, as the water level was rising continuously. Monitoring data showed extremely high discharge rates flowing into the Tangjiashan Quake Lake from upstream, making the water level rise approximately two meters a day. With the flood season coming, the probability of heavy rainfall would further increase and flood waves from upstream may have caused the dam to collapse at any time.

Fig. 2 shows the drainage network of the Tangjiashan Quake Lake on the pre-disaster SPOT Image, which covers the part of the main body of the quake lake near the dam to demonstrate the monitoring procedure. As it is located in a mountainous area with the largest water head of over 60 m [20], there was an urgent need to develop a method to determine the lake capacity so the decision makers could monitor the condition of the Tangjiashan Quake Lake.

Experimental data included a 1:50,000 scale DEM with 25 m resolution from the national infrastructural geographic information database, and SPOT-5 images acquired on 16 May 2008 (shown in Fig. 2) after the Wenchuan Earthquake. The data covered the main parts of Tangjiashan Quake Lake from the end of the upstream to the dam of the Lake (but not the entire quake lake because of problems with data quality). The SPOT-5 images in the study area were firstly ortho-rectified to remove geometric distortions. Then, the water body polygon of the upstream area for the quake lake was extracted. The extent of the upstream was determined by the natural boundary on the SPOT image. The accuracy of the extracted upstream area depends on the spatial resolution and the quality of geometric correction. In this paper, an optical and SAR image processing software developed by Wuhan University was employed to ortho-rectify the SPOT-5 images based on the PRC (Rational Polynomial Coefficient) model. The accuracy within a 25-m DEM grid can satisfy the accuracy requirements of this study.

Secondly, the extracted water boundary was projected to the DEM longitudinally to obtain the intersecting points, which are discrete elevation points along the boundary of the water body. A spatial interpolation method based on a spline was implemented to create the 3D water surface. Then, the area of the

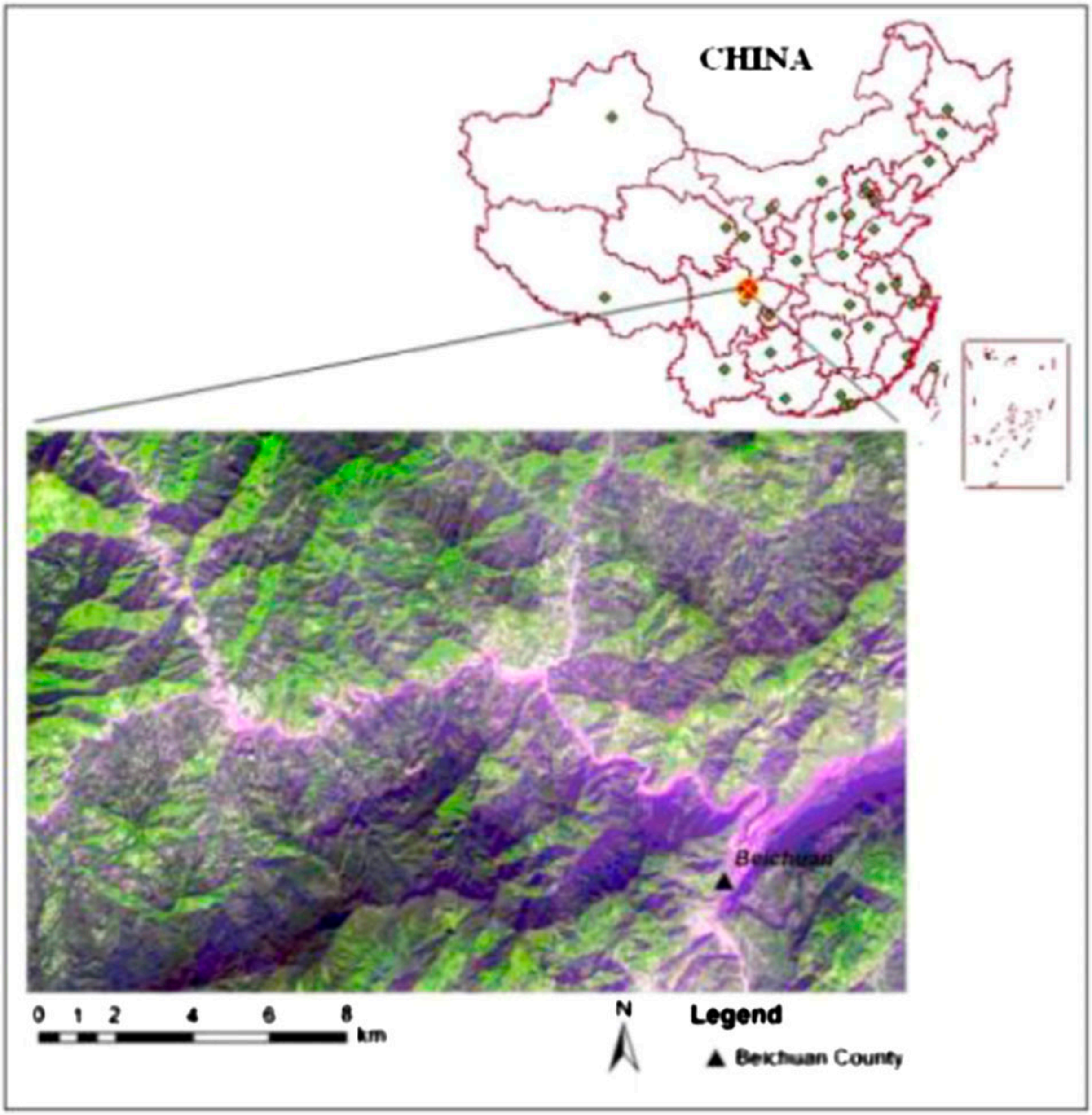


Fig. 2. Study areas. An earthquake of Richter magnitude 8.0 struck Wenchuan in Sichuan Province, southern China on 12 May 2008. This SPOT image was acquired before the earthquake on 10 May 2008. The Beichuan County locates downstream of the Tangjiashan Quake Lake.

water body was extracted by overlapping the water boundary. In this process, the pixel size of the riverbed DEM was transferred to the water surface DEM, so that the water surface DEM and riverbed DEM at a given location formed bottom-squared prisms for water capacity calculation. From the water surface DEM in Fig. 3, it can be seen that the water level varied greatly along the quake lake. Therefore, dynamic capacity must be taken into consideration to accurately calculate the total water capacity for the lake.

2. Methodology

2.1. Geomatics-based water capacity monitoring

In this study, a pixel-based curved water surface method based on geomatics is proposed to quantitatively measure the water capacity of the quake lake dynamically. Considering the characteristics of the long upstream distance and the great head of water in the mountainous rivers, how to accurately and rapidly calculate the dynamic water capacity is a big

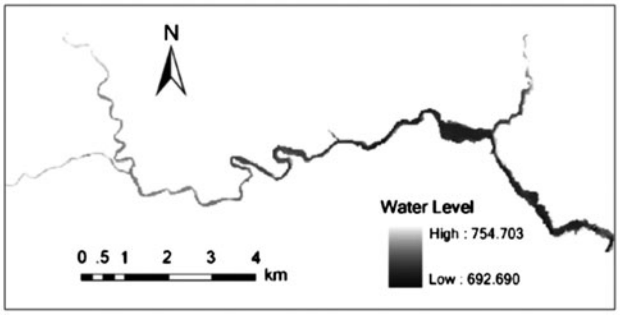


Fig. 3. DEM for water surface by interpolation. This water surface is interpolated from discrete points with water depths determined by the spline interpolation method. The difference in water level between upstream and the front of the dam is over 60 meters.

challenge, and the method proposed in this study should be a reasonable solution.

The water boundary was first extracted from the remotely sensed images and was overlapped with the DEM to obtain the boundary of the water body in the form of 3D spatial discrete points. Then a near-real water surface could be obtained by interpolating these discrete points with elevation values. Finally, water capacity was calculated in the area bounded by the water surface and the riverbed DEM. Fig. 4 shows the procedure of the data pre-processing used to calculate water capacity employing a pixel-based approach. As this algorithm has no special restrictions on the shape of the water body and configuration of the riverbed, it is feasible for use as a universal method for water capacity monitoring.

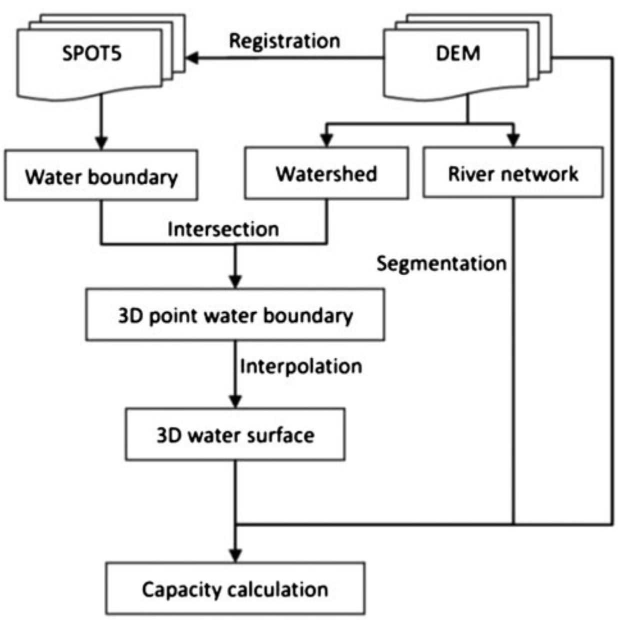


Fig. 4. Procedure of data processing.

The pixel-based sloped water surface forms the basis of the proposed method for water capacity monitoring. The maximal volume between the riverbed and the water surface is calculated by summation of the volume of individual bottom-squared prisms for all the water body pixels. When the water surface is considered as a continuous plane, the total capacity can be expressed as follows:

$$W = \int_{s} (H_W - H_T)\mathrm{d}s \tag{1}$$

where H_W is the pixel elevation on the water surface, and H_T is the pixel elevation on the riverbed.

When the water surface is considered as a pixel-based discrete surface, the mathematical model to calculate capacity can be expressed as follows:

$$W = \sum_{i=0}^{m} \sum_{j=0}^{n} (H_{Wij} - H_{Tij}) S_{\text{cell}} \tag{2}$$

where H_{Wij} is the elevation of the pixel at (*i*, *j*) on the sloped water surface, H_{Tij} is the elevation of the pixel at (*i,j*) on the riverbed DEM, S_{cell} is the area of the square pixel, and m and n are the numbers of columns and rows of the riverbed DEM, respectively. The calculation is limited to the regions where $H_{Wij} > H_{Tij}$, and the pixels calculated are the water body out of an $m \times n$ matrix of total image pixels.

2.2. Water capacity monitoring algorithm optimization

In the algorithm of pixel-based sloped water surface capacity monitoring, the number of pixels in columns and rows of the riverbed DEM are denoted by m and n, respectively. In this process, the time complexity of this algorithm is $O(m^2n^2)$, and thus very time-consuming. In practice, the algorithm has to process two nested circulations from 1 to m in width and from 1 to n in length. The first is to calculate the coordinates of each pixel with the number of rows and columns. In this iterative process, the other one is nested within it, to repeatedly retrieve the pixel on the water surface DEM with respect to each pixel on the riverbed DEM.

In order to improve the calculation efficiency of the algorithm, an optimized method employing a pixel-based river segmentation algorithm is proposed in this study. The optimized method only considers the slope of the water surface along the channel, which is segmented according to its ratio of slope

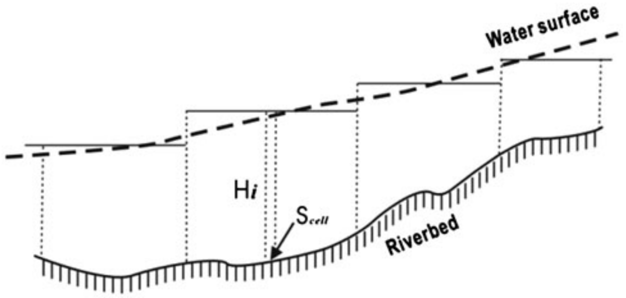


Fig. 5. Capacity calculation principle of pixel-based river segmentation. The whole Tangjiashan Quake Lake has been partitioned into a number of segments before manual calculation, and the water surface is regarded as a plane within each segment. The water level in each segment is an average value of pixel values of the discrete points falling into this segment. The pixel values in the same segment share the same value.

shown in Fig. 5. The whole Tangjiashan Quake Lake has been partitioned into a number of segments, and the water surface is regarded as a plane within each segment. The water level in each segment is an average value of the pixel values of the discrete points falling into this segment. The pixel values in the same segment share the same value, which dispenses with the procedure of retrieving corresponding pixels from one surface to another surface. Therefore, there is only one circulation for calculating the coordinates of each pixel with numbers of rows and columns in the process. The mathematical model can be depicted as follows:

$$V = \sum_{k=1}^{S} (H_{wk} - H_{Tk}) S_{\text{cell}} \tag{3}$$

where H_{Wk} is the average elevation of the sloped water surface at the k^{th} segment, H_{Tk} is the average elevation of the pixels in the riverbed under the k^{th} segment of the water surface, S_{cell} is the area of one pixel, S is the number of segments. The calculation is limited to the regions where $H_{Wk} > H_{Tk}$, If the number of river segments is denoted by S, the time complexity of the optimized monitoring algorithm is $O(mns)$. Generally, $S << mn$ and it is superior to that of the pixel-based sloped water surface model. The monitoring efficiency of the optimized algorithm can be greatly improved.

2.3. Results analysis for water capacity monitoring

In this study, ArcGIS desktop software by ESRI (Environmental System Resource Institute, Inc., USA) was selected as the platform for monitoring the water capacity of the Tangjiashan Quake Lake. Our proposed methods are compared with an ArcGIS method. The ArcGIS provides tools for 3D surface analysis. The surface volume is one of these tools to calculate the area and volume of a functional surface above or below a given reference plane. An experimental data block of 568 by 207 pixels was selected. Table 1 shows the comparison results.

The method in ArcGIS only considers the static capacity as the total capacity, which was calculated as 32.16 million cubic meters, less than the result calculated by the method employing the pixel-based sloped water surface algorithm. The underestimation is regarded as the difference between the dynamic and static capacities of the quake lake. As the water head is about 60 m between the upstream and downstream extents of the Tangjiashan Quake Lake, other factors, including the systematic error from DEM creation, non-channel areas with very high and very low elevation involved in the calculation, may also heavily impact on the calculation accuracy of the ArcGIS method. It makes the results significantly biased toward underestimating the true value. Therefore, the ArcGIS method is only suitable for calculating static capacity for horizontal water surfaces, even though its calculation speed is very fast, shown in Table 2.

The pixel-based sloped water surface capacity monitoring algorithm proposed in this study takes full consideration of the topographical features of the Quake Lake in the mountainous area, and confines the pixels used in the calculation to those of the water surface shown in Fig. 4. In the blank region, pixel

Table 1
Water capacity comparison for different methods

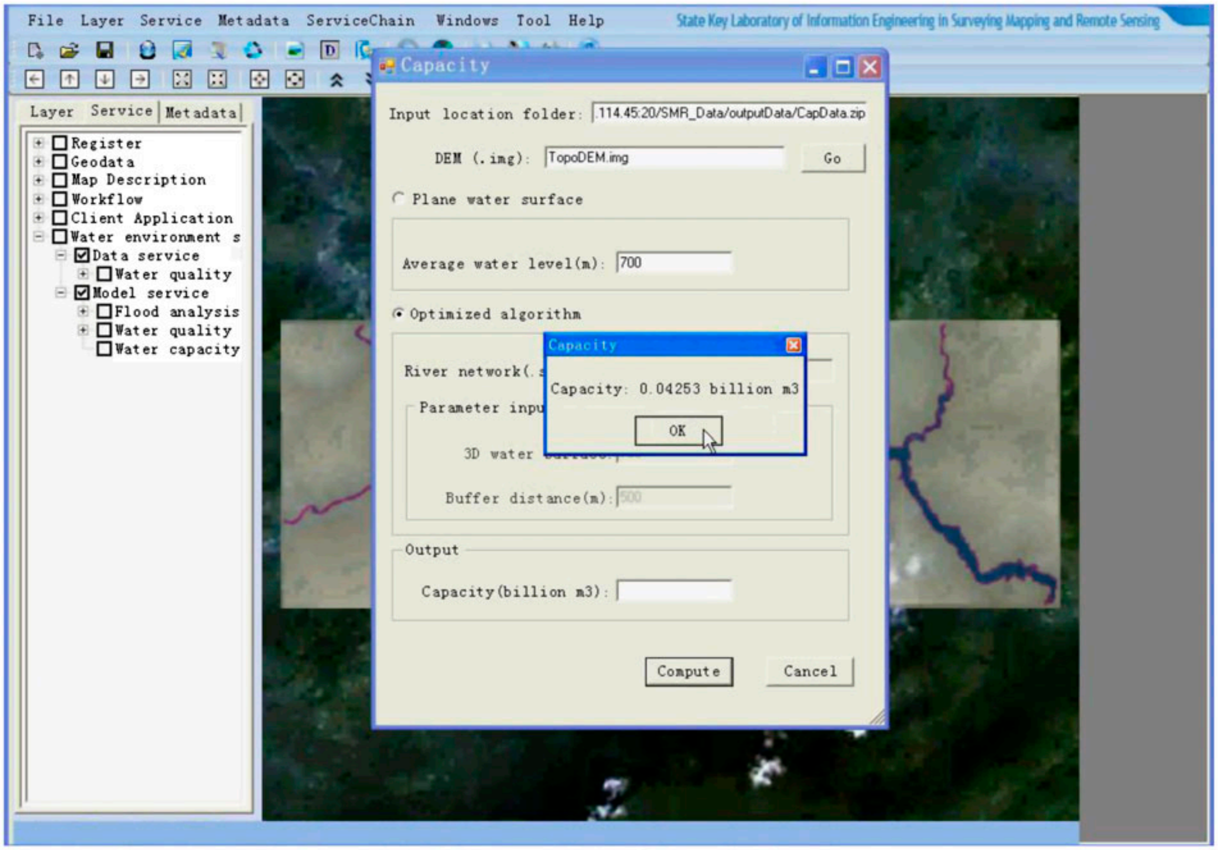
	Total capacity (million m^3)	Capacity subtracted from result of pixel-based 3D water surface method (million m^3)	Ratio of difference
The ArcGIS method	32.16	2.28	6.6%
Pixel-based 3D water surface method	34.44	–	–
Pixel-based river segmentation method	33.97	0.47	1.4%

Table 2
Comparison of calculation efficiency for different methods

	Total capacity (million m^3)	Time cost (s)
The ArcGIS method	32.1563	30
Pixel-based 3D water surface method	34.4398	312
Pixel-based river segmentation method	33.9748	98

values with NoData, pixels were only involved in the iteration for searching and were not involved in the calculation. Therefore, the impacts of the errors introduced by the DEM are considerably reduced, and the result of the method can be taken as close to the true total capacity. The result from the pixel-based river segmentation method is only 1.35% different from that of the pixel-based sloped water surface method and the computation speed was significantly increased. In addition, the pixel-based river segmentation algorithm does not rely on the shape of the river channels and the river boundary, and the calculation process is independent of hydrodynamic materials and meteorological parameters, and the assumptions for many simplifications that impact on the accuracy of water capacity monitoring are not required.

Table 2 shows a comparison of the efficiency using the three methods for water capacity calculation. Although the speed of the ArcGIS method is much faster than the other two, the result does not include dynamic capacity and may significantly underestimate total capacity in mountainous regions due to steep water surface gradients. The pixel-based sloped water surface capacity monitoring algorithm is theoretically sound, but it costs much time for its iterative searches of the water body pixels, which leads to lower efficiency. It may not be suitable for rapid monitoring for a large area when high-resolution DEMs are used for accurate results. The optimized algorithm based on river segmentation improves the calculating efficiency with a similar accuracy to the method proposed above. It should significantly improve calculation speed for massive volumes of data. As the optimized algorithm considers the theoretical rationality of the total water capacity calculation in mountainous areas, as well as the time consumption, it can be used widely.



Capacity

Input location folder: .114.45:20/SMR_Data/outputData/CapData.zip

DEM (.img): TopoDEM.img

○ Plane water surface

Average water level(m): 700

● Optimized algorithm

River network(.s

Parameter inpu

3D water

Buffer distance(m): 500

Output

Capacity(billion m3):

Capacity

Capacity: 0.04253 billion m3

Fig. 6. Results of water capacity monitoring service.

3. Web service implementation for water capacity monitoring

The data sharing and model interoperability of water capacity monitoring is implemented by geospatial information service based on web service, which can offer professional application model through service instead of system software to users. User sends the data to the remote server, and the server returns the results to the user directly. As a whole, the model processing service of water capacity monitoring is based on SOA, in which there are three participants interacting through three basically operation, such as publish, find and bind. Firstly, the service requester queries and discoveries model processing service for water capacity monitoring. The service provider, an interface of reusable subsystem, provides various atomic services of water capacity monitoring service. The service broker, a bridge between the service requester and provider for transferring data and processing service, generates service information published by the service provider.

The web service for water capacity monitoring is implemented on the platform of GeoGlobe, which is suitable software of global massive spatial data organization, seamless management and visualization, developed by Wuhan University. The platform was composed by three-tier architecture client, application server and data server, which support massive information querying service, attribution and graphics interaction querying service, and topographical analysis services.

The atomic services for water capacity monitoring are registered by UDDI (Universal Description, Discovery and Integration) and published by metadata. Then, the server returns the address of the results in the form of SOAP (Simple Object Access Protocol) message, by which the results will be downloaded to the client automatically. The water capacity result image displays in GeoGlobe viewer, and the computed results of water capacity are returned to the user, shown in Fig. 6.

4. Discussion and conclusions

A solution of total capacity monitoring for mountainous Quake Lakes is proposed by successfully applying geomatics to Quake Lake capacity monitoring in this paper. From algorithm design to implementation and algorithm optimization, spatial information technology has played an important role in the fast and accurate monitoring of Quake Lake capacity. Through comparison of the results from three methods, the proposed pixel-based method is proved to be feasible and rational. The optimized algorithm based on the river segmentation capacity monitoring algorithm can monitor the water capacity with a great water head. The dynamic water capacityfit in single columncan be calculated by RS and DEM and is most suitable for operation use in dynamically monitoring a disaster. Finally, the web service for water capacity monitoring is implemented on the GeoGlobe platform.

The accuracy of water capacity monitoring in the proposed method will be influenced by the resolutions of the remote sensing images and DEM. The water boundary extracted from high resolution images will be more reliable. The size of the DEM grid also directly affects the accuracy of the results. However, the size of the DEM grid has a direct impact on efficiency. How to get a good balance between accuracy and efficiency is an important issue for further research into the algorithm. In addition, the quality of pre-processed data is very important for the algorithm. Remote sensing images should be corrected with high geometric precision before extracting the boundary of the Quake Lake. Therefore, accuracy improvement in image geometric correction should be a key issue in applying this method to capacity monitoring.

The web service for water capacity monitoring is a service-oriented, open information sharing and model analysis service. Combining technologies of geomatic and web service, the whole water capacity monitoring service is divided into several atomic services to publish, which enable the user to freely assemble different services to a service chain for specified application. Therefore, the interoperation ability has been improved. Meanwhile, the service decomposition and atomic services assemble improve the service sharable and reusable.

Acknowledgements

This work was supported by The National Natural Science Foundation of China (Grant No. 41101415, 41071261), and the National High Technology Research and Development Program (863 Program) of China (Grant No. 2012AA12A304, 2012AA12A306).

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