Estimation of inundation depth using flood extent information and hydrodynamic simulations

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Abstract:

Inundation depth (or level) is the most basic information for flood risk assessment; however, its mapping suffers from lack of in situ data in many cases. The aim of this study is to propose a new method for estimating inundation depth and spatially distributed water level for a local-scale pluvial flood using a combination of flood extent information derived from remote sensing imagery and hydrodynamic simulations. The study assumes the location of the inundation area given by the remote sensing imagery is mostly, but not completely, reliable. The estimation error of ground surface area wetted by inundation water body (wetted area) is used as an index to determine the most likely distribution of inundation depth. The proposed method was applied to two study areas to examine the performance of the method for different topographic characteristics. It showed promising results with an estimation precision of 0.02 to 0.17 m. An additional experiment suggested that water level could not be correctly estimated without flood extent information, complementing errors of the ground elevation data, and furthermore, using different topographic datasets revealed that the performance was highly influenced by the ground elevation data.

KEYWORDS inundation depth; flood extent; hydrodynamic simulation; wetted area, pluvial flood

INTRODUCTION

Floods are frequent natural disasters that have significant negative impacts on social systems. Improving flood risk management is the key to making our society more resilient to these events; accordingly, the need for precisely assessing the flood risk of river basins is increasing. The inundation depth of past flood events is a simple and direct indicator of flood risk; therefore, assessing inundation depth is an important factor in better flood management. However, in reality, this process is considerably difficult because, in most cases, information on inundation depth is limited to high water marks and the memory of disaster-affected residents.

To overcome these observational difficulties, remote sensing imagery is often used as an alternative that can rapidly yield spatially distributed data over large areas. Over the last few decades, a number of approaches have been developed for determining inundation depth or level using remote sensing imagery. The primary idea is to develop an empirical relationship between the water levels in the river channel and inundation area (Imhoff et al., 1987; Overton et al., 1999), yet these empirical relations need to be calibrated and water levels for a record-breaking flood may exceed ranges of the relations.

Oberstadler et al. (1997) used satellite images to detect the land–water interface on a riverbank and overlaid it on ground elevation data to map river water levels along the river channel. This simple idea for retrieving water level often suffers from large errors, as is shown later, because its accuracy is completely dependent on the precision of detecting the land–water interface.

Matgen et al. (2007) and Schumann et al. (2007) used a similar approach to retrieve flood water levels using high-resolution synthetic-aperture radar (SAR) data and highly accurate digital elevation models (DEMs) for fluvial flood flow along a river segment with topographic gradient, and obtained relatively small errors by comparing estimated water levels with observed high water marks. Recently, many studies have attempted to combine satellite imagery and hydrodynamic models through data assimilation frameworks (e.g., Matgen et al., 2010; Giustarini et al., 2011).

In this study, a new method for estimating inundation depth for a local-scale pluvial flood is proposed using a combination of flood extent information derived from remote sensing image and hydrodynamic simulations. The proposed method uses the fact that flooding is very likely to happen in areas retrieved through remote sensing imagery of the water body. Land–water interfaces detected by remote sensing imagery are used to determine the boundary of the hydrodynamic simulations. This method does not directly use flood extent information to determine inundation level but instead treats the information as a location reference of the inundation areas. In this method, the land–water interface is determined from hydrodynamic simulations.

ESTIMATION METHOD

Basic idea of estimation

As discussed in the previous section, land–water interfaces detected by remote sensing imagery are often inaccurate. Using this information as fundamental data for water depth estimation is prone to errors. For example, a preliminary analysis based on the flood extent information and topography of a study area revealed a significant and unrealistic fluctuation of inundation level along the land–water interface: a variance of up to 7 m along a 2 km interface (Figure 1). This error is mainly due to insufficient precision of flood
extent information. If the quality of topographic information is low, the error may be exacerbated. Additionally, a relatively large fluctuation of inundation level along the flood extent boundary near mountainous regions was experienced in the preliminary study. These issues suggest that this method is more susceptible to dataset errors when used for hilly terrain.

Simply averaging the water level along the flood extent boundary to remove the unrealistic fluctuation may be sufficient in some cases, especially when the study area is small enough to assume that the spatial distribution of the inundation level is small. However, this correction has a limitation in that it does not work well in the case of large areas, in which the assumption of a level water surface may be violated.

A possible solution for overcoming the problems of the straightforward overlay operation between flood extent information derived from remote sensing imagery and ground elevation data is the introduction of a hydrodynamic model into the estimation framework, so that a more reasonable inundation depth can be obtained. Employing a hydrodynamic model for interpreting flood extent information and ground elevation, rather than using data-driven methods, such as a regression analysis, provides a consistent approach.

The newly proposed method estimates inundation depth and spatially distributed water level based on flood extent information and hydrodynamic simulations. Assumptions are made that flooding should have happened around the area retrieved through remote sensing imagery and ground elevation data while the detected flood extent boundary is not always sufficiently precise. The detected flood extent boundary serves as a boundary of the hydrodynamic simulation domain, preventing the water from flowing into and out of the flood extent, except through the outlets predetermined on the boundary (normally defined by visual investigations of the flood extent and geographical information). The land–water interface may be determined differently (but inside of the boundary) as a result of the hydrodynamic simulations, depending on the topography around the boundary.

Over the defined computational domain, a hydrodynamic simulation is performed using the simplified shallow water equations (given in the next subsection) with a constant and spatially uniform rainfall intensity until the spatial distribution of the steady state inundation depth is obtained. The wetted area error (given in the second next subsection) is calculated as the likelihood of the simulated inundation depth distribution.

Once a steady state spatial distribution of inundation depth and its wetted area error are obtained corresponding to the specified rainfall intensity, another simulation is performed with a different rainfall intensity to obtain a different steady state pattern of inundation depth as well as its wetted area error. This procedure is repeated until the inundation depth distribution that gives the smallest wetted area error is obtained, and this distribution is assumed the most likely estimation of the inundation depth.

Hydrodynamic model

The hydrodynamic model used in this study is a simplified shallow water equation, recently referred to as an inertial formulation of the shallow water equation (Bates et al., 2010):

\[
\frac{\partial H}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = r
\]

\[
\frac{\partial M}{\partial t} = -gh \frac{\partial H}{\partial x} - gn^2u \sqrt{\frac{u^2 + v^2}{h^{7/3}}}
\]

\[
\frac{\partial N}{\partial t} = -gh \frac{\partial H}{\partial y} - gn^2v \sqrt{\frac{u^2 + v^2}{h^{7/3}}}
\]

where \( t \) [T] is the time, \( h \) [L] is the water depth, \( x \) and \( y \) [L] are the spatial coordinates, \( M \) and \( N \) [L^2 T^{-1}] are the discharge per unit width in the \( x \)- and \( y \)-direction, respectively, \( r \) [LT^{-1}] is the rainfall intensity, \( H = h + z \) [L] is the water level, \( z \) [L] is the ground surface elevation, \( u \) and \( v \) [LT^{-1}] are the depth-averaged flow velocity in the \( x \)- and \( y \)-directions, respectively, \( g \) [L^{-2}] is the acceleration due to gravity, and \( n \) [T^{-1/3}] is Manning’s roughness coefficient.

This model is derived from the original shallow water equation by neglecting the advection term. In most cases of flooding flow, the advection term is negligible compared to other terms in the equation. Advantages of this model include simpler coding and reduction of computational burden. This equation is computationally efficient as a result of considering the local inertial term which is neglected in the diffusive wave equation (Yamazaki et al., 2015).

The model equations are discretized on a 2D staggered grid using an explicit finite difference formulation:

\[
M_{i+1/2,j}^{n+1} = M_{i-1/2,j}^{n} - gh_j \frac{\Delta t}{\Delta x} \left( H_{i,j}^{n} - H_{i-1,j}^{n} \right),
\]

\[
h_f = \max \left( H_{i,j}^{n}, H_{i-1,j}^{n} \right) - \max \left( z_{i,j}, z_{i-1,j} \right),
\]

\[
N_{i,j+1/2}^{n+1} = N_{i,j-1/2}^{n} - gh_j \frac{\Delta t}{\Delta y} \left( H_{i,j}^{n} - H_{i,j-1}^{n} \right),
\]

\[
h_f = \max \left( H_{i,j}^{n}, H_{i,j-1}^{n} \right) - \max \left( z_{i,j}, z_{i,j-1} \right).
\]
ESTIMATION OF INUNDATION DEPTH

\[ h_f = \max (H_{i,j}, h_{i,j-1}) - \max (z_{i,j}, z_{i,j-1}) \]  

\[ H_{i,j}^{n+1} = H_{i,j}^n + \Delta t \cdot r_{i,j}^n + \frac{\Delta t}{\Delta x} \left( M_{i,j-1/2,j}^{n+1} - M_{i+1/2,j}^{n+1} \right) \]

\[ + \frac{\Delta t}{\Delta y} \left( N_{i,j-1/2}^{n+1} - N_{i,j+1/2}^{n+1} \right) \]

where \( i \) and \( j \) denote the cell numbers in \( x \) and \( y \) directions, respectively, \( n \) denotes the time step, \( \Delta x \) and \( \Delta y \) are the cell sizes, and \( \Delta t \) is the time increment. The water depth \( (h) \) is calculated at the center of a cell and the discharge \( (M, N) \) between adjacent cells is calculated on the edges of the cells.

A spatially uniform water level is given as an initial condition; accordingly, no water movement is assumed at the beginning of the simulation. At the domain boundary (except the outlets), the flux is assumed to be zero. The water level gradient at an outlet is fixed as a boundary condition to the outlets), the flux is assumed to be zero. The water level simply cannot be trusted, as is shown in Figure 1.

The hydrodynamic simulation is iterated with changing rainfall inputs so that the simulated wetted area shows good agreement with that derived from the flood extent information. The most likely estimation of inundation depth is obtained from the simulation that gives the smallest wetted area error.

It should be noted that the two-dimensional surface area of inundation water body is not helpful in giving a reasonable estimation of the inundation depth. In the current estimation framework, the hydrodynamic simulations are repeated many times with different rainfall inputs. The two-dimensional surface area of the simulated flooding region can be small when a small rainfall input is used in the simulation, and it increases if a larger rainfall input is used. However, it reaches the maximum value (whole area of the target flood extent) once the target area is completely inundated, being constant no matter how large a rainfall input is given, because the simulated flooding area is restricted by the flood extent boundary. Therefore it cannot be used as an index for likely estimation.

**Study areas**

The Linh Cam area in the Ca River Basin (Figure 3) and the Dong Quan-Nhat Tuu area in the Nhue-Day River Basin, Vietnam (Figure 4) were selected as the study areas for testing the ability of the proposed method because they have different characteristics including the size of the inundation area and their topography. The Linh Cam area, located in the Ca River Basin, has a relatively small inundation area of 9 km² for the selected flood event and hilly topography. The Dong Quan-Nhat Tuu area, located in the Nhue-Day River Basin, has a large inundation area of 117 km² for the selected event in a low and flat region with a complex and meandering river channel network.

**Linh Cam area**

The Linh Cam area is located in the Ca River Basin. This river basin is one of the most flood-vulnerable regions in Vietnam, where flooding mostly occurs owing to monsoon rainfall events.

This study area continuously flooded twice during the short time from September 29 to October 19, 2010. The initial flooding occurred from September 29 to October 5 and a
subsequent flooding occurred from October 14 to 19. The record-breaking 7-day rainfall of 1127.6 mm was observed at the Hon Ngu station, which is comparable to 50–60% of annual rainfall of this region. Inundation extended to 182 of 243 communes. Unfortunately, 51 people were killed and 175 people were injured, and the economic losses exceeded 6 trillion VND (300 million USD) in Ha Tinh province.

In this study, a flood extent map provided by UNOSAT—the operational satellite applications program of the United Nations Institute for Training and Research (UNITAR, 2015)—was used for flood extent information. The original satellite image for the map was taken by the Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) (Japan Aerospace Exploration Agency, 2015) with a scale size of 1:198791 and 100 m spatial resolution at 22:23:20 on October 22, 2010, in local time (15:23:20 on October 22, 2010 in UTC time). This image missed the flood peak because the peak occurred three days before the image was captured. Figure 3 shows the target flooded area, which was selected because the river water level observed at a nearby gauging station was available for validation. The flood boundary line shown in Figure 3 was extracted from the flood extent map.

A point-based elevation dataset with approximately 250 m spatial resolution in VN2000 datum, National Coordinating System based on WGS84, provided by Department of Survey and Mapping Vietnam (DOSM), Ministry of Natural Resources and Environment was converted into a raster type dataset with 50 m resolution using a spatial interpolation method implemented in ArcGIS (“Topo-to-raster”), which employs a river channel dataset to generate a hydrologically-plausible raster type DEM. Figure 3 shows a topographic map created from the dataset, demonstrating that the flooded area captured by the satellite imagery extends over a relatively low elevation area along the river channel.

Figure 5 shows the water depth and level estimated by using the current method with 131.87 mm/h of constant rainfall intensity, resulting in a wetted area error of 0.04%. The water level gradient at the outlets used in the simulations was determined to be 0.0003 according to the topography around the outlets. A Manning’s roughness coefficient of 0.1 was used for the simulations. Note that in Figure 5b, water level is not shown for cells with negligible inundation depths (i.e., less than 0.0001 m).

The estimated water depth and level give a qualitatively reasonable match with the inundation situation seen from the flood extent information derived from satellite imagery, even replicating two dry areas located in the western part of the flooded region. However, several small dry areas in the eastern part were not reproduced in the estimation (Figure 5b) and a dry area that was not found in the flood extent information emerged in the estimation.

The river water level observed at the Linh Cam station (The Vietnam Institute of Meteorology, Hydrology and Environment) was used to validate the water level estimated by the proposed method because the station is located near the outlet of the target flooded area. The floodwater drained through this outlet to the river channel; accordingly, it is expected that the water level of the river is almost the same as that of the outlet. The difference of water level between the estimation (4.84 m) and observation (4.78 m) was 0.06 m, showing that the proposed method worked efficiently for this study area.

To discuss a possible reason why the proposed method
succeeded to replicate the water depth, an experiment without the flood boundary information derived from remote sensing imagery was performed; the simulation domain was enlarged and a new boundary condition that inundation water was drained into the surrounding river channels was used. The simulations were repeated so that the simulated flooding area matched with the flood boundary derived from remote sensing images as much as possible. Figure 6 shows the water depth and level estimated without the flood boundary information. The estimated water level of the outlet was 3.80 m; its difference with the observed water level (4.78 m) was 0.98 m, which was less accurate than that of the proposed method. Moreover, the simulated flooding area had a considerably different shape from the flood extent derived from remote sensing images (the red polygon in Figure 6). These findings suggest that the proposed method efficiently works because the flood boundary information derived from remote sensing images complements errors of the ground elevation data; it virtually represents locations of levees and/or banks, which are not well described in the elevation data.

**Dong Quan-Nhat Tuu area**

The case study in the Linh Cam area was validated against a single point observation. In order to support this weakness, another case study in the Nhue-Day River Basin is conducted where two water level gauging stations are available for better validation. The study area is located in a valley between the Nhue and Day rivers (Figure 4). The Day river plays an important role in sharing the floodwater with the Da and Red rivers. The Nhue river is the main component of the irrigation system in the surrounding area. The target event in this region is the rainfall that happened from October 30 to November 7 in 2008, causing a historical flood in Hanoi. The total amount of rainfall ranged from 350 to 550 mm, surpassing the largest record of 394 mm in 1984.

The flood extent information captured by ALOS PALSAR was used for the analysis. The acquisition time was October 7, 2008 (4 days after the flood peak). The point based elevation dataset in VN2000 datum (DOSM, 2015) was converted into a raster type dataset with 90 m resolution as in the previous application. The water level gradient at the outlets used in this case was determined to be 0.00005, and a Manning’s roughness coefficient of 0.1 was used for the simulations.

Figure 7 shows the estimated water depth and level in the target area, in which a stepwise change of water level over the domain occurs because of dikes along small channels. There are three river water level stations around the study area: Dong Quan, Nhat Tuu and Van Dinh. Among these stations, the Van Dinh station is not close to the flooded area; thus, it was eliminated from the validation candidates. The observed river water levels at the remaining two stations were used for validation. With a wetted area error of 0.0014%, the estimated water level at the Dong Quan station was 4.19 m, which was only slightly lower than the observed river water level of 4.21 m. The estimated water level at the Nhat Tuu station was 3.93 m, which gave a larger difference from the observed river water level of 4.1 m.

Another two topography datasets—the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global DEM (GDEM) ver. 2 (Japan Space Systems, 2015) and ALOS World 3D (NTT DATA ver. 2 (Japan Space Systems, 2015)) were used for further validation.
Corporation and RESTEC, 2015)—were also applied to similar analyses to investigate the possibility of using satellite derived topography data for estimating inundation depth. Figure 8 shows significant deterioration in the estimation, in which the water depth stood at 9 m, which was physically unreasonable. Obviously, inundation is strongly controlled by topography, so the quality of topographic datasets directly affects the estimation of inundation depth.

CONCLUSION

A method for estimating inundation depth using flood extent information and hydrodynamic simulations was developed to overcome the difficulties in retrieving water depth, which arise from the inaccuracy of remote sensing imagery. This method assumes that flooding is very likely to happen in the area retrieved by remote sensing imagery of the water body and uses a hydrodynamic model to estimate the steady state inundation depth with the land–water interface detected by remote sensing imagery being a boundary of hydrodynamic simulations.

The method was applied to two study areas having different topographic characteristics: one in a small region with hilly terrain and the other over a large plain. The differences between the estimated and observed water levels of the study areas ranged from 0.02 to 0.17 m, which exhibited the same degree of deviations in water level as the results of previous studies, suggesting the potential of the method being capable of working for pluvial floods, while a fair comparison of the current and previous studies is difficult because the current study focuses on pluvial floods but the other ones worked for fluvial floods, and the characteristics of the ground elevation datasets used in these studies are different. The additional experiment without flood extent information derived from satellite imagery suggested that the proposed method efficiently worked because the used extent information complemented errors of the ground elevation data. It should be noted that the accuracy of the proposed method depends upon the ground elevation datasets used in hydrodynamic simulations as the analysis employing satellite derived topography datasets revealed that the quality of topographical datasets played a critical role in estimating inundation depth with the proposed method.

The method developed in this study assumes that the inundation water does not go beyond the boundary specified by the land–water interface in the flood extent information (except through outlets), which always results in the estimated inundation area being either the same as or smaller than the flood extent used as the boundary. This assumption automatically leads to considerable errors in the estimation of inundation depth when the used flood extent information has low quality, e.g., coming from insufficient spatial resolution of satellite images. To overcome this difficulty, different ideas on setting boundary conditions need to be incorporated into the hydrodynamic simulations.

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