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# *Interactive comment on* "Integration of 2-D hydraulic model and high-resolution LiDAR-derived DEM for floodplain flow modeling" *by* D. Shen et al.

**D. Shen et al.**

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We appreciate the suggestions and comments provided by the reviewer. In the revised version of our manuscript, the modifications have been made according to the reviewers' comments.

1.Comments:The authors use a special method to identify confined depressions of the relief where the calculated water amount flows to. However, actually inundation of these depressions is impossible taking into account detailed analysis of the relief and the authors suggest excluding these areas and volumes of inundation from consider-

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ation. But if any volume of water doesn't reach a certain area, then due to the law of conservation of mass it should be redistributed over the remaining territory, which would lead to a change in areas, volumes, and depths of inundation at the other parts of the modeled area. This issue is not considered in modeling (to a lesser extent this may refer to stationary problems, but floods are never stationary).

Responses: The problem reviewers indicated is widespread in 2-D flood simulation using high-resolution DEM. The error of flood extent and depth generated from flood simulation on mesh is unavoidable, because the mesh used in 2-D flood simulation models, which is resampled from high-resolution DEM, simplifies terrain further. 2-D flood models are sensible to terrain, and any changes on digital terrain can cause the changes on flood process, as well as the changes on flood extent and depth. For 2-D flood simulation models, the changes of flood under more detailed terrain is hard to be taken into consideration once the computational mesh is defined. That is, it is hard to use coarse mesh to construct 2-D models while considering the influence of fine-granularity terrain on flood in order to improve accuracy of simulation. A common way to solve these problems is to construct 2-D models directly on high-resolution DEM. However, it is usually time-consuming. Since flood risk analysis results are required to be given within a short time under flood emergency decision, a compromise proposal between model computation time and accuracy has a significance here.

One solution is presented. 2-D flood simulation models based on comparatively coarse mesh can be considered as a fluctuant dynamic water level covering the study area. At any time point, accurate flood extent and depth can be obtained by subtracting high-resolution DEM elevation value from water level value and extracting actually flooded and connective DEM grid cells. The flood level elevations are at central point or node point of each element in 2-D flood simulation models. Therefore, these water level elevations can be considered as points dispersedly distributed over the study area. And then, flood level raster data in the same grid cell size as high-resolution DEM can be generated by interpolation. When overlaying flood level with high-resolution DEM,

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there are some DEM grid cells called false inundation area exist with high possibility, whose water level is higher than terrain elevation but is not flooded. It is the key to generate high-resolution flood extent and depth that removing these false inundation areas efficiently.

There is a method that assume or analog calculate a flood level, compare it with DEM, and then extract flood extent and depth based on flooded grid cells connectivity detection principle. This method is widely applied in flat-water model (Poulter et al., 2008) and 1-D model (Werner, 2001; Merwade et al., 2008).

The flat-water model assumes that water level is a horizontal plane. In this method, flooding of coastal areas due to rise of water level can be modeled relatively easily. Poulter introduced the principle of this model: "Three approaches to modelling hydrological connectivity were developed to simulate inundation of both the 6- and 15-m-resolution lidar DEMs. The first approach was a simple 'bathtub' approach (referred to as a 'zero-side rule') in which a grid cell became flooded if its elevation was less than the projected sea level. The 'zero-side rule' does not consider surface connectivity at all between grid cells and is the approach used in previous studies of sea-level rise (Moorhead and Brinson 1995, Titus and Richman 2001). The second and third approaches specified that the grid cell was flooded only if its elevation was below sea level and if it was connected to an adjacent grid cell that was flooded or open water...... The appropriateness of different connectivity rules is related to our ability to accurately resolve surface flow connections."

1-D hydraulic models divide watercourses into cross sections and get the water level of cross sections for unique time points. To get accurate flood extent and depth, 1-D models need to be overlaid with DEM and calculate each grid cell's elevation along watercourses by interpolating between cross sections (Werner, 2001; Merwade et al., 2008). During interpolating, there can be many false inundation areas in the DEM grid because parts of the grid cells with flood level higher than grid elevation are not flooded actually. These areas need to be removed.

Werner stated the method for extracting flood extent and depth applying 1-D model in his paper. “An alternative is to determine stages in the river using a 1-D flow model and subsequently interpolating these to create a flood map using GIS based techniques. Many authors give examples of coupling results of 1-D flow models with GIS. The methods described differ substantially, ranging from application of geostatistical interpolation routines through neighbourhood analysis to methods that calculate the interception points of water levels in the cross section profile and subsequently map these interception points. ......The interpolation methods result in a water level surface that after subtracting elevations from a digital elevation model (DEM) of the area yields a map of flood depths. One of the difficulties of this straightforward routine is that areas not directly connected to the main channel at the given stage (e.g. local depressions) are considered as flooded because the terrain elevation lies under the interpolated water level surface. The method introduced here for estimating flood extent maps using a simple Inverse Distance Weighted Interpolation easily avoids this problem by using an algorithm based on "cost distance mapping”.”

For 2-D models, Moore presented a similar solution (Moore, 2011). “Simulation results were re-sampled to improve inundation resolution, as shown in Figure 5.1. A buffer distance of 15 m was used to isolate the cells on the perimeter of the inundation extent. The raster cells on the perimeter were then converted to water surface elevation points. An inverse distance weighted spatial algorithm was used to extrapolate water surface elevation from the perimeter water surface elevation points to adjacent dry cells. This ensured that the inundation extent was not under-predicted when the DEM was subtracted from the water surface. The extrapolated water surface elevation data was then combined with the original water surface elevation raster. The high-resolution (1m) DEM was then subtracted from the combined water surface elevation to create a new, high-resolution depth raster. Disconnected pools, artificially created by the IDW algorithm, were removed from the depth raster.”

Just as the author said, “The primary advantage of the re-sampling tool is the ability to use a lower resolution mesh to achieve results that are comparable to using a higher resolution mesh. The potential time savings of decreasing resolution are substantial."

However, in Moore's research, water lever inside inundation areas was assigned directly to high-resolution DEM grid, while interpolation was mainly applied on flood boundaries. For how to solve the problem of flooded grid connectivity, the author mentioned that "disconnected pools, artificially created by the IDW algorithm, were removed from the depth raster", but methods for removing these disconnected pools were not given. In our research, we applied run-length compressed encoding and run-length boundary tracing to implement the exclusion of these false inundation areas.

2.Comments:Even more serious problems arise when flooded territories are crossed by roads elevated over the average relief of the area, as well as by rivers, which channels are below the average topography level (see, for example, Figure 6 of the paper). If these linear objects (and also bridge span) are not approximated accurately enough in the applied 2D hydrodynamic model (they should be separated on the grid in a certain way), then the general character of flow, inundation zones and depths will not be described by the model.

Responses: When resampling high-resolution DEM data into a comparatively coarse 2-D flood simulation mesh, no changes in micro topography but only some large artificial structure (like large levees in Figure 4) can be taken consideration into. Just as previously discussed, A common way to solve these problems is to construct 2-D models directly on high-resolution DEM. A compromise proposal was given in our paper. Like the method for extracting flood extent and depth in 1-D hydraulic model, we generate flood level using 2-D hydraulic model and overlay it with high-resolution DEM.

3.Comments:Interpolation of high-resolution topography onto the 2D model computational mesh having much larger cells should be done by area averaging of all points of the elevation matrix that fall into a computational cell. Then inundation volumes at a certain water level calculated using the elevation matrix and computational mesh of the hydrodynamic model will coincide.

Responses: In high-resolution DEM, flood level value of each grid cell is generated from that of 2-D model using Inverse Distance Weighted Interpolation, and false inundation areas in computational mesh are removed. That is why the two inundation volume results are different.

4.Comments:The authors get more precise values for only inundation extent and depth, but don't deal with the problem of specifying flow velocity. If the average velocity in a certain cell of the computational mesh is calculated for a certain bottom level averaged over this cell, then when applying a larger scale, the bottom elements within the cell would have different elevations, and therefore, local velocities would be different. To get the correct local flow velocities, we need to re-calculate 2D model for a denser mesh.

Responses: Our research mainly targets to the application in assessment of potential loss from flooding events and flood disaster risks, where to obtain inundation graph is crucial. Hence we pay more attention to the extraction of flood extent and depth in flood simulation.

5.Comments:The method presented in the paper doesn't give more accurate results of numeric 2D simulation of hydrodynamic parameters of inundation of floodplain territories, if we're talking about specification of inundation levels (marks), flow velocities, distribution of discharges indifferent cross sections, etc. The method only gives more precise description of flood extent and depth, and moreover, with some assumptions. The results obtained using the suggested method show inundation boundaries and depth more clearly (which is definitely useful); however this approach should be rather considered as post-treatment of the simulation results.

Responses: In our method, to extract more accurate flood extent and depth can be considered as post-processing. The process first builds 2-D flood simulation model on comparatively coarse computational mesh, then generates high-precision inundation data based on the model combined with high-resolution DEM. Our main consideration

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of choosing this method is computational efficiency of flood simulation models, and it keeps the balance between model computing time and accuracy. The aim of our research is not to build a more accurate 2-D flood simulation model, but to generate more precise inundation data by combining 2-D flood simulation model and high-resolution DEM, which is indicated in the test that comparing our results with 2-D modeling results.

6.Comments:For local interpolation of simulated water levels into nodes of the elevation matrix, the authors use Formulae 6, 7, 8. As the practice of numerical simulation of stream flow shows, this method gives poor results when used for interpolating the marks of bottom topography into nodes of computational mesh. This method doesn't satisfy the major requirements for methods of interpolation on arbitrary sets of points. Interpolation methods that have this ability are described in [1-4].

Responses: As previously discussed, for the computational efficiency of 2-D models, computational mesh is usually resampled from high-resolution DEM. In order to limit the loss of flood simulation precision to the minim, we assume 2-D modeling results as spatial discrete point set regular distributed in study area, and then calculate water level of grid cells' central points by interpolation. At last, flood extent and depth are generated by overlaying water level with DEM. IDW has been applied in several previous researches on water level interpolation in 1-D and 2-D model (Werner, 2001; Moore, 2011), so we choose IDW as well.

We really appreciate the recommendation of these papers, where some more superior interpolation methods were presented. Because our research mainly targets to the application in assessment of potential loss from flooding events and flood disaster risks, the interpolation method we used can meet the application requirement. Besides, we will take trial on using these method for water level interpolation. We have also referred these methods recommended by reviewers, and improved related contents on flood water level interpolation methods in the revised manuscript. See in line 269-274.

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