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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.

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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:When the LiDAR data was acquired? With a lower water level in a year, nor not? The authors should explain it clearly because it may impact the accuracy of simulation results.

Responses: We captured the aerial photography data of our study area using airborne

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LiDAR sensor carried on “Shijiazhuang Y-5” from October 1st to October 8th, 2010. We have improved data capture and process-related contents in the revised manuscript. See in line 144-151.

We called the study area Gongshuangcha as a polder in the original manuscript, but this translation is not so accurate, and “detention basin” would be more appropriate than “polder”. A detention basin is an excavated area installed on, or adjacent to, tributaries of rivers, streams, lakes or bays to protect against flooding. These basins are also called “dry ponds”, “holding ponds” or “dry detention basins” if no permanent pool of water exists. Gongshuangcha detention basin will be used for flood storage only if a flood happens, so it will not be flooded unless there is a flood. That is why we didn’t mention the water level when LiDAR data captured. Besides, we have revised the description on study area’s basic situation in the revised manuscript. See in line 110-117 and 126-133.

2.Comments:This work employed the high-resolution LiDAR-derived DEM data to improve the accuracy of flood extent and depth. Its method is similar to the some previous similar works. And the authors should compared your method and results with other methods.

Responses: Just as Sanders mentioned in his paper, “At 1 m horizontal resolution, which is typical of aerial LiDAR surveys, detailed terrain features such as individual buildings can be resolved and researchers have begun to simulate flooding at this scale. Unfortunately, the computational cost of 2-D flood simulation at scales approaching 1 m is very high. ...... This translates into roughly 1012 operations per km2 per day, and it is not unusual to work with study areas of 100 km2 or more.” (Sanders et al., 2010). The under-utilisation of high-resolution topographic data is due, on one hand, to the exceptionally high computational requirements associated with fine-scale grids; and on the other, to the small time steps required by this type of model in order to achieve computational stability(Yu, 2010).

When high-resolution DEM data is used for 2-D flood simulation, finer topographic data are typically re-sampled to coarser meshes (Yu, 2010). For example, Moore resampled 1m-resolution DEM into 5m, 10m and 20m-resolution data for 2-D flood simulation (Moore, 2011).

However, such method has two main problems. Primarily, the dense coverage of the LIDAR data set leads to a large degree of data redundancy. Secondly, this redundancy is further compounded by the use of an unsophisticated interpolation method for the integration into the model of the data, whereby only a small number of topographic points (four per model node) are actually used to assign the elevation value to a given nodal point(Marks et al., 2000).

For the reasons above, we present our solutions in the manuscript. Starting with high-resolution DEM data, we constructed a comparatively coarse computational mesh and then constructed a 2-D hydraulic model. The results of the 2-D hydraulic model were interpolated into water level elevation data in DEM grid cell size. To obtain the actual flood area, two problems are needed to be solved here. One is how to process enormous DEM data efficiently, and the other is performing connectivity detection between DEM grid cells to remove false inundation areas. Thus, we processed enormous DEM data using run-length compressed encoding, and the connectivity issue of DEM grid cells was solved by run-length boundary tracing technology, in order to generate high-resolution flood extent and depth, and get better results.

According to the reviewers, our method is similar to the some previous similar works. However, previous works generally resampled high-resolution DEM into a comparatively coarse mesh, and construct a 2-D flood simulation model based on the mesh to simulate the floodplain flow directly. Just as Marks pointed out, this method didn’t take full advantage of DEM data’s topographic expression. We presented an improved method to obtain more accurate flood extent and depth, and to solve the problems on flood simulation using high-resolution DEM indicated by Marks.

Similar processing strategy is used in 1-D flood simulation models. In a 1-D model, watercourses are segmented by cross sections, and water level elevations of each sections for unique time points are calculated. In order to obtain accurate flood extent and depth, the results of 1-D models usually need to be overlaid with DEM to calculate the water level elevation of every DEM grid cells by interpolation (Werner, 2001; Merwade et al., 2008). During the process of interpolation, there can be many false inundation areas in the DEM grid because parts of the grid cells are interpolated despite not being inundated. To get rid of the false inundation areas, some connectivity detection methods of DEM grid cells are employed.

For example, Werner discussed the flood extent and depth extraction method using 1-D model, "An alternative is to determine stages in the river using a1-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"."

Nevertheless, the above-mentioned methods are not so suitable for 2-D models. Firstly, the interpolation strategies are different between 1-D and 2-D models. Known water level elevation points in 1-D models are distributed dispersedly on cross sections, while that in 2-D models are distributed within the entire study area. Secondly, the connec-

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tivity detection methods for DEM grid cells used for removing false inundation areas in 1-D models are difficult to be used to analyze enormous DEM.

According to the reviewers, our method and results should be compared with other methods. Current works on using high-resolution DEM for flood simulation usually resample DEM into comparatively coarse mesh and simulate flood on it, but seldom focus on how to further improve the accuracy of flood extent and depth. Besides, the 2-D flood model we built at first was based on coarse mesh generated from LiDAR-derived high-resolution DEM. The results of our method were compared with the results of 2-D flood model we built, and it is proved that our method performed inundation better.

Moore also presented a similar method that resampling 2-D flood simulation results into 1m resolution to improve the accuracy. "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 clarified, "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."

In Moore's researches, false inundation areas existed, whether IDW was performed on flood extent boundaries or water level elevations in flood extent were assigned to high-resolution DEM grid. Moore mentioned in his paper 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 removed the false inundation areas under enormous DEM data efficiently using run-length compressed encoding and run-length boundary tracing technology.

3.Comments:I think that authors can directly create the high resolution TIN based the high-resolution LiDAR data for the 2-D hydraulic model because the computational capability of the computer is power than ever and the parallel technology can be employed in the current time. The flood extent may be found based on the high resolution TIN and the flood depth may be represented by the contours made from the TIN.

Responses: The method proposed by reviewers is feasible in a relatively small study area. However, it may be hard to process in a big study area. Take our study area as an example, number of mesh cells will easily reach up to hundred millions if we generate TIN directly based on LiDAR, which is far beyond the calculation capability of 2-D models. In Moore’s researches, the study area covers 48.8 km2. It took more than 70 hours to calculate under a 5m-resolution grid and dual six-core 2.67 GHz Xeon processors with 12GB of RAM. Compared with 5m-resolution digital terrain, the numbers of grid cells of 1m-resolution digital terrain can be 25 times bigger. For the reasons above, Moore resampled 1m-resolution DEM data to build a 2-D model on comparatively coarse mesh as well.

In stand-alone application environment, the efficiency of multi-core processors-based parallel computation can be several times higher than that of single-core processors. However, this improvement on efficiency is still limited for enormous high-resolution DEM, though computer cluster-based parallel computation is able to solve the problems caused by high-resolution DEM data applied in 2-D flood simulation models (Sanders et al., 2010; Yu, 2010). One reason is parallel computation sets a higher request of 2-D hydrologic model programming, because some complex procedures need to be taken into consideration, such as data distribution, computer communication, model scheduling, etc. The other reason is computer cluster-based parallel process has a high requirement on computer software and hardware environment, so many relative researches are limited in laborites and are hard to promote its application. Actually, most of the existing flood modeling packages are designed to work on medium size desktop machines, which does not permit scaling to large size fine resolution domains. Our research provide the possibility of flood simulation using enormous high-resolution DEM under general computer environment.

4.Comments:This paper divided a large amount of DEM data, 8.36GB, into 5 strips spatially, and then each strip would be read at one time. I think this means is not so good to enhance the computational efficiency. If the database could be used to manage the larger data, it would make better results.

Responses: Given the enormous DEM data, we divided DEM data into strips and read each strip separately. According to the reviewers, this reading strategy is not so good to enhance the computational efficiency, and using database to manage data would make better results. Database technology can make a certain degree of improvement of computational efficiency. However, because DEM data is processed in memory, the computer memory allocation can be a bottleneck problem of data processing under large data. Thus, we using run-length compressed encoding to implement flood simulation and analysis under enormous DEM on general personal computer. The other reason why we choose DEM data files to process is that it is easy to program and port, and is common in existing flood modeling packages.

For the convenience of explaining our method, we described the principle of our method by dividing DEM into 5 strips. Actually, the number of strips can be changed to adjust the computer memory allocation, and it will be feasible as long as data of each strip can be read into memory. Because of the application of run-length compressed encoding and run-length boundary tracing technology, once a strip is read, it will be compressed to run-length data, which enables our method is able to deal with comparatively large

DEM data. Our method's capability of data processing is far beyond 8.36GB, because run-length compressed encoding has a quite high compression ratio on inundation raster data.

5.Comments:The sentence "What's more, the quality of mesh resolution has little effect on the results of 2-D hydraulic models" may be not appropriate. If the DEM is high-resolution in vertical, the results of 2-D hydraulic models would be better.

Responses: We have summed up the research status on flood simulation and rewritten corresponding contents in the revised manuscript. See in line 55-65.

6.Comments:The language should be checked carefully and the representation as well. For example, in page 3, "their methods still have weaknesses (Marks et al., 2000)", we are in 2015, any progress during this 15 years?

Responses: We have checked our original manuscript carefully and corrected or improved several expressions. In addition, we also have consulted some recent papers and added them in references, the review of relative researches has been revised. See in line 55-65 and 73-85.

Reference: Marks, K., Bates, P. Integration of high-resolution topographic data with floodplain flow models. HYDROLOGICAL PROCESS, 14, 2109-2122,2000.

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