Modelling extreme flood hazard events on the middle Yellow River using DFLOW-flexible mesh approach

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We would like to thank the Reviewer 1 for taking time in reading and suggesting modifications to the paper.

Answers to specific comments of the reviewer follow:

Comment 1:

The presented paper considers and describes numerical modelling of severe flooding events along the middle reach of the Yellow River in China by means of a flexible mesh approach that discretizes and solves the shallow water wave equations. A first aim is to highlight the capabilities of a new numerical tool for river flooding. The authors of the manuscript also claim to present new characteristics of the spatial flooding process. Although the addressed topic is generally of interest to the readership of the journal, the manuscript in its current form is very difficult to understand. The authors present a numerical model of the Yellow river that they use to simulate a large variety of event representations. In this regard, many questions remain unaddressed.

Authors' answer: We would like to thank the reviewer for evaluating the article as of interest for the journal audience and we are sorry for the unclearness that we will address hopefully in the answers to these comments, as well as in the improved version of the manuscript. We do address all the comments raised by the reviewer one by one below.

Comment 2: *How were the upstream boundary conditions generated and how do these represent the natural conditions? How is the overall model performance with respect to measured events? Calibration and validation of the elaborated model is completely missing. There is also no discussion on the quality of the underlying spatial data with respect to the modelling results.*

Authors' answer: Thank you for your questions. Indeed these issues were not detailed in the present paper due to its scope, and they are part of a research regarding the statistical inference of the input variables in surrogate models for reservoir operations. In the final version of the manuscript we will summarise these issues. The answers are as follows:

- The upstream boundary conditions are generated using a reservoir operations model which encapsulates the rules and behaviour of the reservoir system as defined by YRCC. The reservoir operation model generates synthetic Gamma function hydrographs.
- The overall performance with respect to measured events: present research focused on a set of 339 extreme events generated synthetically (as previously mentioned) and no measurements of such events are available yet.
- The methodology used for the calibration of a flooding event, is done based on the one currently applied at YRCC, looking at the behaviour of the Yellow River, in case of a flooding event of 4,000m^3/s. Calibration was performed by estimating the Manning roughness coefficient which guarantees that water is contained inside the main reach of the river for that specific flooding event.

Comment 3: *What is more, the language of the manuscripts greatly suffers from grammar, punctuation and spelling mistakes and it is advised to let the paper in a revised form be corrected by a native speaker before re-submission. With the above mentioned arguments I recommend to thoroughly revise the manuscript firstly. Yet, a re-submission based on the general content of the paper with substantial improvements regarding the main conclusions and discussion seems feasible.*

<u>Authors' answer</u>: The authors are thanking the reviewer for pointing out this important issue. We are currently checking once again the manuscript from grammar and punctuation point of view as well as explaining in a concise manner the content of the manuscript. This is done primarily by one of the authors whom happen to be a native English speaker. Taking very seriously the advice of the reviewer currently, as well, a specialist in Technical English writing is checking the paper. We hope that the revised manuscript, which will be submitted for the consideration of Reviewers and the Editor, at the end of the Interactive discussion will meet the requirements of the reviewer.

Comment 4: *Detailed comments (small and big):*

4.1. *- The abstract should be written clearer with respect to the main findings of the paper. The focus should more be on the methods and results than on mentioning "the new Deltares tool".*

<u>Authors' answer</u>: Thank you for the suggestion. We are proposing to rephrase the abstract as follows: "Severe flooding events in China are a common cause of life losses. Many efforts have been carried out by the Yellow River Conservancy Commission (YRCC) to understand the development of floods and their impacts on the Yellow River. The modelling approaches based on discretization of the modelled domain in square and rectangular grids are important when models are used in the river management, however they do present two drawbacks: the required accuracy of the meandering of wide long rivers is not well represented, and the speed in computational runtime due to the need of using many grid cells is considerably reduced. Present paper presents an approach on modelling flooding events using unstructured grids. The research suggests that the use of a flexible mesh discretization of the domain can overcome the two mentioned drawbacks. The approach of using unstructured grids for modelling flooding events on very wide rivers is applied on the Yellow River. While testing the unstructured grids new characteristics of the spatial flooding process of the Yellow River emerged and are presented as well in the paper. "

4.2. *p6062, l23: Typo "due"*

<u>Authors' answer</u>: Correction will be done accordingly.

4.3. *- The introduction seems rather long and content is widely known among modellers. There is substantial room for shortening the paper.*

Authors' answer: Thank you for the suggestion, the authors will reduce the introduction in several parts.

4.4. *- p6063, l5: No citation on the presented content (number of flooding events)*

Authors' answer: Correction will be done accordingly to the reference of Guoying (2010).

Guoying L. Ponderation and Practice of the Yellow River Control system. Volume 1. *Yellow river conservacy press*. ISBN 7-80621-727-4/ TV331, 2010.

4.5. *- 6063, l10: Section fully unclear to the reader. How is the history and task of the YRCC connected to the presented material?*

Authors' answer: ??

4.6. *- p6064, l1: How could a digital model be expanded by the use of a new (? reference) software tool? Unclear content.*

Authors' answer: The authors will clarify this by adding to the manuscript the detailed descriptions of the reservoir operation, as described in our answers to Comment 2.

4.7. *- p6064, l8: word: bi-dimensional?*

Authors' answer: Correction will be done accordingly, the correct wording is "two-dimensional".

4.8. *- p6064, l19: Unclear how the two approaches fit into the scientific message of the manuscript.*

Authors' answer: The paper intends to address two important modelling issues for the Yellow River flooding:

1) climate change affects the magnitude of flood design hydrographs; and

2) a large number of interventions had been implemented on the Yellow River during the last 50 years.

These two issues are addressed using an unstructured grid model. New spatial flooding characteristics are presented in the manuscript in section 4.1. In addition, section 4.2 shows that in case of a highly modified river, under climate change conditions, simulation of a single flooding event is not a good approach because multiple consecutive events can produce similar results in terms of flooding extent and volume.

4.9. *- p6065, l15: grammar "are showed"*

Authors' answer: Correction will be done accordingly.

4.10. *Fig. 1: The figure is meant to introduce the reader to the focus region and thus it is advised to work on the figure accordingly. Much more explanation has to be added in the figure label so that the reader is readily capable to understand what should be presented here. No explanation on the drawing on the lower and right side of the figure*

- *maybe this is a top view of river dikes and river training work?!*
- *- p6067, l3ff: Not all of the mentioned cities could be found in either of the figures. This is irritating to the readers.*

Authors' answer: Thank you for pointing this issue. Figure 1 was revised and changed and will be added to the new manuscript, after the discussion concludes. The new figure 1 is provided at the end of this answer.

4.11. *- p6067, l5: Here, a number of reservoirs are mentioned. This could be a starting point in discussion how the upstream boundary was generated. In addition, it should be much clearer highlighted how these reservoirs are managed in order to explain how the overall river system works.*

Authors' answer: Thank you for this important comment. As presented in the answer to *Comment 2* the upstream boundary condition was set based on the operation of Yellow River four main reservoirs. The full set of characteristics and reservoir operations are outside of the scope of the present paper, due to the length and extent, however, the new version of the manuscript will present the summary content in relation with the synthetic hydrographs used for this research, in order to make the paper clear.

4.12. *-p6068, l5-7: Sentence unclear.*

Authors' answer: Thank you for your comment. Indeed the sentence was unclear and will be rephrase as: "*An analysis of the flooding patterns on the Yellow River shows that there are special characteristics of it that requires special attention when a flood model is built to simulate its behaviour*" .

4.13. *-p6069, l1f: It is advised to clearly present the set of equations that is solved within the "new software tool" in order to allow for latter reproduction by other scientists. From the given information it is rather difficult to understand what was solved how. In addition, a concise comparison of the chosen method with methods using regular grids should be given.*

Authors' answer: Thank you for the comment, which shows to the authors that they have not stated clearly the objective of the research. The main focus of the presented research of the manuscript was to evaluate if DFLOW, an existing software tool developed by Deltares, is able to properly represent flooding events on Yellow River. The tool is solving the classical shallow water Saint Venant equations using an approach based on unstructured grids. The authors did not develop the tool, nor did they want to present the numerical algorithms implemented in DFLOW-FM, because they have been elaborated in two other articles, by the developers of the tool themselves. These two references are:

- Kramer, S., Stelling, G.,: A conservative unstructured scheme for rapidly varied flows. *International Journal of Numerical methods for fluids*, **58**, 183–212, 2008
- Kernkamp, H., Dam, A., Stelling, G., Goede, E.,: Efficient scheme for the shallow water equations on unstructured grids with the application to the continental shelf. *Ocean Dynamics*. **61** (8), 1175-1188, 2011

In the final version of the manuscript the authors will extend the text with a summary of the theoretical points regarding the numerical approach as presented in the two above mentioned papers, in order to make the paper clearer.

4.14. *With respect to Fig. 4 (which should also be redrawn and clarified), a table with results including i.e. run-time, mesh size, etc. should be added.*

Authors' answer: Please see at the end of this document the new proposed figure 4.

4.15. *- p6070, l9-11: It is unclear to me, how the model easily allows for considering or discarding hydraulic structures?*

Authors' answer: Thank you for pointing this misleading phrase. After a careful consideration authors concluded that the phrase is indeed unclear and will be removed from the manuscript without affecting the content of the manuscript.

4.16. *- p6070, l22: Here it is referenced to a previous SOBEK model, yet no reference is given.*

Authors' answer: Thank you for your comment on this omission. The reference to a previous Yellow river model existing at YRCC is given bellow to Tang (2009). The effort of modelling floods is done since a long time at YRCC.

Tang Y, : Integrated modelling of flood forecasting and multi-reservoir based operation in Yellow river basin, China. UNESCO-IHE. MSc.WSE-HI.2009-04, 2009.

4.17. *- p6071, l6: A mathematical description of the wellness of the grid should be introduced at that place.*

Authors' answer: Thank you for your comment. We will include the proper reference where the definition of orthogonality and its mathematical description is presented. In addition the orthogonality of the grid used for Yellow River is 0.04, which will be now included in the text.

4.18. *- p6072, l3-5: How was the downstream rating curve generated? More explanation is needed.*

Authors' answer: Thank you for your comment. The manuscript will be changed as follows: " The downstream boundary conditions are set based on the rating curve at Gaocun hydrological station, which is obtained by YRCC through field surveys and updated on a yearly basis. "

4.19. *p6072: Section 4 is meant to discuss und present the model results of the approx. 300 simulations, yet the section is very brief on presenting and discussion the many results. Besides, water levels, it could also be recommended to include analysis about spatio-temporal evolution of the flooding on the low-lying flood plains and how flow velocities evolve. In addition, no discussion is presented on which role the large content / concentration of fine sediments may play and how this could influence the flow behaviour.*

Authors' answer: Thank you for your comment, which helped the authors to reconsider the section and to provide new content. Section 4, as pointed by the reviewer, has been extended; in addition to the water levels of the six selected scenarios a zooming window for two particular areas of the river are selected to display the results of flooding extent; a figure of the time evolution of Scenario 5 is presented in which the water levels, near Jiahetan station, and the discussion about its meaning are presented accordingly; and presentation of velocities were added by including a figure of the time evolution of it for Scenario 5.

Please see the above mentioned figures at the end of this response letter. (Figure 12, for water depths and Figure 13 for velocities).

4.20. *- p6074, Sec. 5: In the conclusion section no additional content should be presented. The comments regarding the NetCDF development is obsolete and should either be removed or shifted the method section totally. Only few conclusions are drawn and it is advised to much deeper elaborate on the conclusions that could potentially be drawn here.*

Authors' answer: In the new version of the manuscript the sentences related to NetCDF development will be removed accordingly.

4.21. *- Fig. 5-10: Should be discussed in much more detail plus much more label text in order to understand the figures*

Authors' answer: As per suggestion new versions of the figures are made available at the end of this response letter, where names of cities Huayuankou, Jiahetan and Gaocun have been included. For two different sections of the river, detailed results are presented in zoom section. The discussion regarding the figures, in section 4.1 will be extended as follows:

"4.1 Flood maps comparison

The results of the Yellow River flood simulations are presented as maps of spatial distribution of the flooding process. The post processing of the results is done by developing a code in Intel FORTRAN with the NetCDF (Rew, R. K. and G. P. Davis, 1990) and the f90gl library (OpenGL, 2012).

The selected six scenarios are representative in showing the magnitude and concentration time of the flooding events. Figures 5 to 10 show the flooded downstream Yellow River area and the corresponding range of water depth (h). Each figure have two zoom windows to show the movement of water along the embankments, downstream of Huayuankou and in the area of Jiahetan.

The six selected scenarios are:

Scenario 1: Fast concentration time (9 days 22 hours), fast flooding of the area, but minimum spatial coverage for this event (Fig 5). The simulation shows that only 20.5% of the area is flooded. In this case, the area downstream of Huayuankou station shows a single branch of water that goes out of the main river reach and connects downstream on the opposite bank of the meander. The area near Jiahetan is flooded from the main river reach towards the banks (as can be seen in the zoom window in the right).

Scenario 2: Slow concentration time (31 days 18 hours), slow flooding of the area, but with low spatial coverage of the flooding (Fig 6). The simulation shows that only 24.5% of the area is flooded. The behaviour of this scenario as compared to scenario 1 shows many similarities in the extent of flooding, however the time concentration difference between the two scenarios is quite large (~22 days). This shows that due to the reservoir operations upstream of Huayuankou a different hydrograph can produce a similar flooding pattern.

Scenario 3: Maximum time of concentration (37 days 20 hours), very slow flooding time, but medium to large spatial coverage (Fig 7). The simulation shows that 63.82 % of the area is flooded.In the ziim window of the left its possible to visualize a water movement from the main channel, to the dikes and back to the main channel. This set of ramifications of flooding patterns in the Yellow River are a new concept that YRCC must take into account, when analysing flood hazard. In the zoom window of the right its possible to see how water accumulates outside of the main channel with ramifications to the dykes as before.

Scenario 4: Slow concentration time (31 days 10 hours), slow flooding in the area but with high spatial coverage (Fig 8). The simulation shows that 86.32 % of the area is flooded. This scenario displays the maximum flood extent obtained during simulations. It shows how the area between the dykes becomes almost completely covered by water. It is interesting that the largest percentage of flooded area (18.56%) ranked by water depth is 1.2 to 1.8 meters, but similar percentages are obtained also between 1.80 and 2.50 meters and between 2.50 and 4.00 meters. This means that in this scenario more than half of the area is covered by at least 1.2 meters of water. Another interesting feature is that the development of flooding branches downstream of Huayuankou (zoom window at the left) is more pronounced, while near Jiahetan (zoom window at the right) becomes less evident as the water just seems to flow directly along the dykes.

Scenario 5: Fast concentration time (11 days 18 hours), fast flooding of area and high spatial coverage (Fig 9). The simulation shows that 82.94% of the area is flooded. Scenario 5 is very similar in flood extent to scenario 4, however the concentration time of the former is much faster than the latter. The main difference is the decrease of area covered by water depths above 1.20 meters implying a reduction in the flood volume. Both zoom windows show that the flooding spreads from the main channel in the banks, to the dykes and back to the main channel of the Yellow river.

Scenario 6: Intermediate concentration time (23 days 8 hous), with intermediate spatial coverage (Fig 10). The simulation shows that 59.49 % of the area is flooded. This intermediate flood event shows that most of the area which gets not covered by water is located between the two zoom windows. For this scenario most of the area downstream of Jiahetan gets flooded until 15 km downstream of Gaocun."

The corresponding new figures are presented at the end of this response letter.

4.22. *- Fig. 11-14: See above comment for the other figures! More discussion is needed.*

<u>Authors' answer</u>: Thank you for your comment. The new discussion text of section 4.2 is

"*4.2 Analysis of flood events data*

At the finalization of all the simulations the value of the four variables related to the flooding events were determined as follows: the maximum flooded area (*FMA*) ranging from 397 km^2 to 1,768 km^2; the time to flood a maximum area (*FTA*), which varies between 7 days and 8 hours up to 42 days; the maximum volume of water inside the dikes (*FMV*), from 0.924 km^3 to 5.291 km^3; and the time to the maximum flooded volume (*FTV*) which is in the interval of 3 days and 2 hours up to 41 days and 8 hours. These ranges are presented in Fig 11 (A, B, Cc and D) as histograms of frequency for each flooding variable. In fig 11A it can be seen that the distribution of times for maximum flooded area is spread along the range with higher frequencies for times between 15 and 30 days. This range is known at YRCC as the forecast window for reservoir operations. In addition Fig 11C shows a similar behaviour for the middle range of frequencies, however low values of time for maximum flooding volume inside the dykes tend to present lower frequencies than for the case of maximum flooded area.

In Fig 11B it can be noticed that *FMA* has the largest frequency for the high values of covered area, showing the susceptibility of the Yellow River during flooding events to present large portions of area covered by water. It shows how inhabitants living near the dykes are at risk. However given that the treshold to account for flooding is 5cm as water table, almost every flood event spreads across teh middle Yellow river due to its "*hanging river*" characteristic.

In contrast, the *FMV* (Fig 11D) shows that several different magnitudes of volume result in inundation, again the hanging river characteristic of Yellow River, generates a complex flooding process. When large amounts of water overflow the summer dykes, flood is carried until it reaches the winter dykes. Then, slow moving waters are rapidly conveyed along the dykes with the topography developing a sub flooding process.

This feature has not been found anywhere else in the literature of the Yellow River (Guoying, 2010; Li, 2013) and it is an interesting feature present in the area, during flooding events. Figure 12 presents the evolution in time of the water depths of scenario 5, at times of 7.0, 8.5, 10.0, 11.75 (time of maximum flood extent), 20 and 40 days. It is possible to see flooding branches downstream of Jiahetan developing around the dykes in direction north. After 40 days most of the water has been routed downstream but some areas remain containing steady water. To explain this further figure 13 dysplays the evolution of the norm of velocity in each cell of the model for scenario 5, near Jiahetan, at times of 7.0, 8.5, 10.0, 11.75, 20 and 40 days. It is possible to see how higher values of velocity are present in the main channel of the Yellow River, with a maximum (obtained) of 4.0 m/s, while flooding branches around the dykes show lower velocities. It is noticeble that some areas near the main channel remain dry during the length of the event (Figure 13 at 10, 11.75 and 20 days). A combination of figures 12 and 13 shows that, for a time of 20 days some water is still moving to the north near the dykes. However its velocity is less or equal to 0.5 m/s. At a time of 40 days, the velocity of the water masses is almost zero everywhere, showing that the main flooding event has propagated in direction of Gaocun (North). A second analysis of flooding variables deals with the spread of variables between each other. To do this three scatter plots of the flooding variables are presented in Fig. 14, 15 and 16. Next to each axis the corresponding histogram of each variable is represented. In addition each of the selected scenarios (1 to 6) described in section 4.1 is located in the scatter for ease of identification.

The scatter plot of *FMA* versus its corresponding *FTA* is presented (Fig. 14). It is shown that almost every flooding extent can be covered at any time. This also shows the complexity in the management of the river given than several hydrographs can develop exactly the same flooding extent.

The spread of FMV versus its corresponding FTV is presented (Fig 15). A similar result as for the case of Fig 14 is obtained, in which several hydrograph can produce almost the same flooding volume inside the dykes. This is of particular importance given that the construction of the reservoirs in the main reach of Yellow river (Sanmenxia and Xiaolangdi) was based on flood and sediment control. In addition, it could be seen how the scenarios previously described are distributed along the feasible ranges of the flooding volume variables and are representative of different behaviour of the river.

It can be concluded that it is not possible to develop a model that correctly predicts the flooded area and the flooded volume simultaneously, however a third comparison in the dispersion of flooding variables *FMV* versus *FMA,* shown in Fig 14, shows a high correlation (r=0.968). Both variables are not independent, but records a change in slope after a flooded area of 1,550 km^2 (80% of the total area). This shows a threshold of high impact of flooding in terms of both area and volume."

Remark: All our responses to the questions raised by the referee will be included in the revised version of the manuscript.

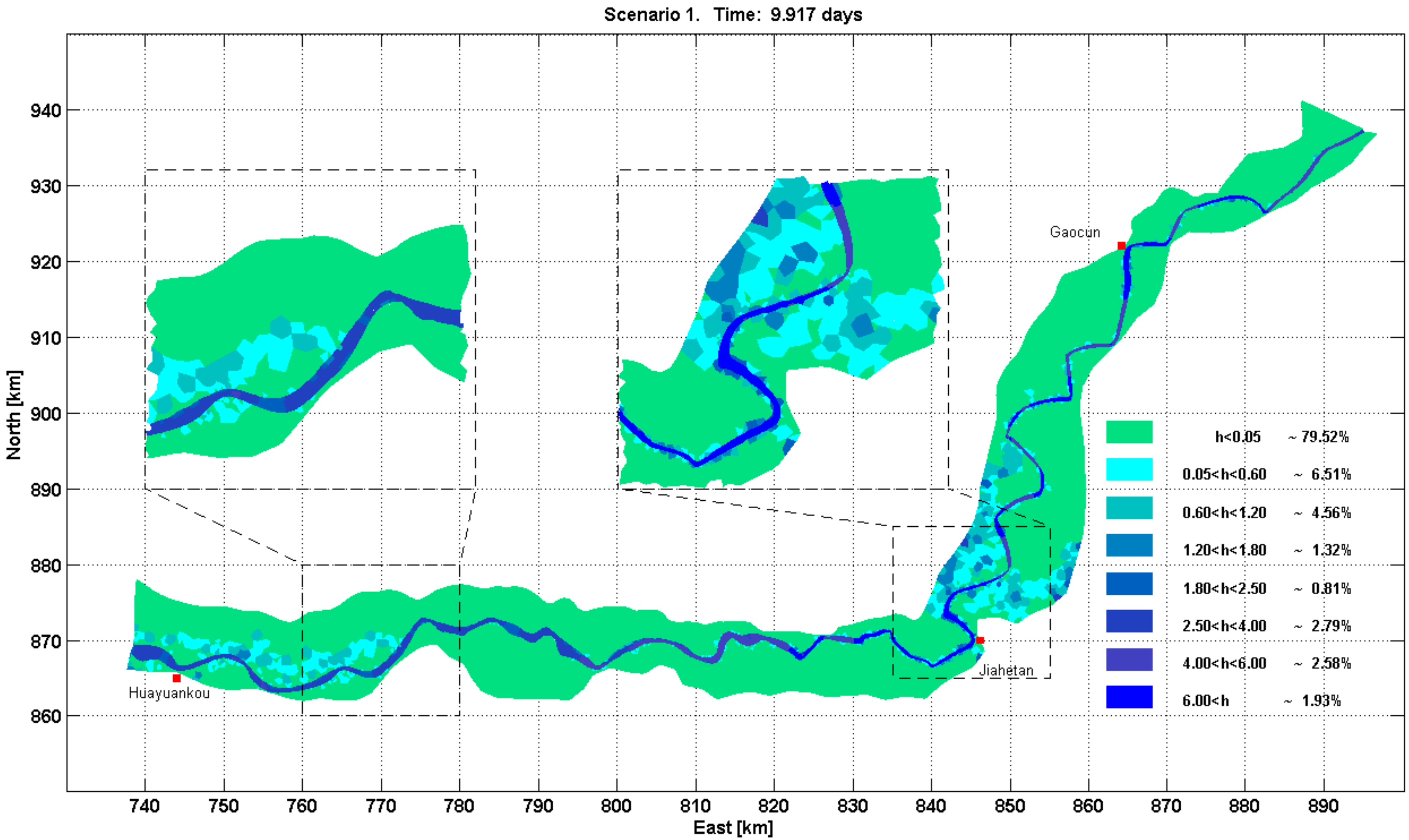


Fig. 5. Maximum flooded area in Scenario 1

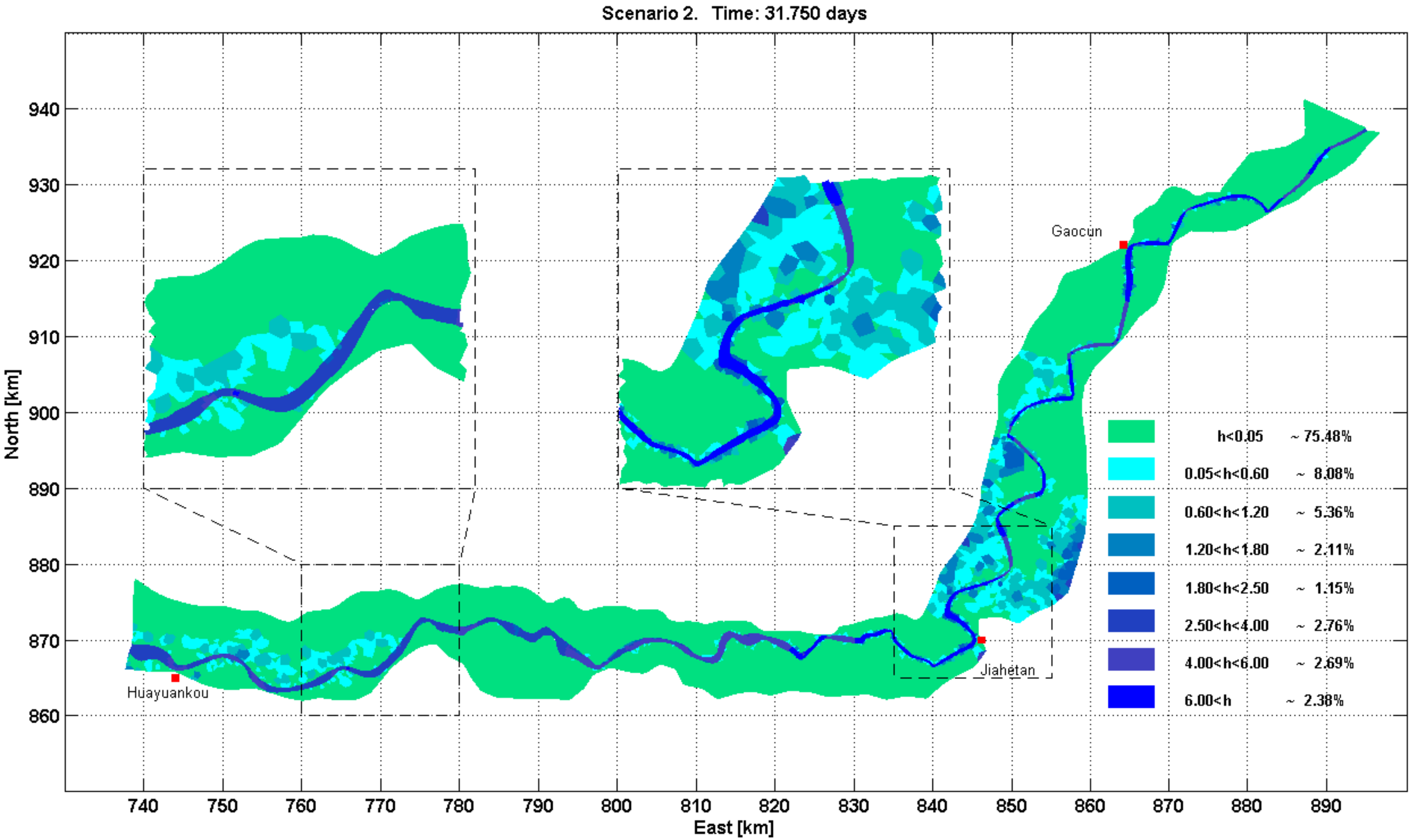
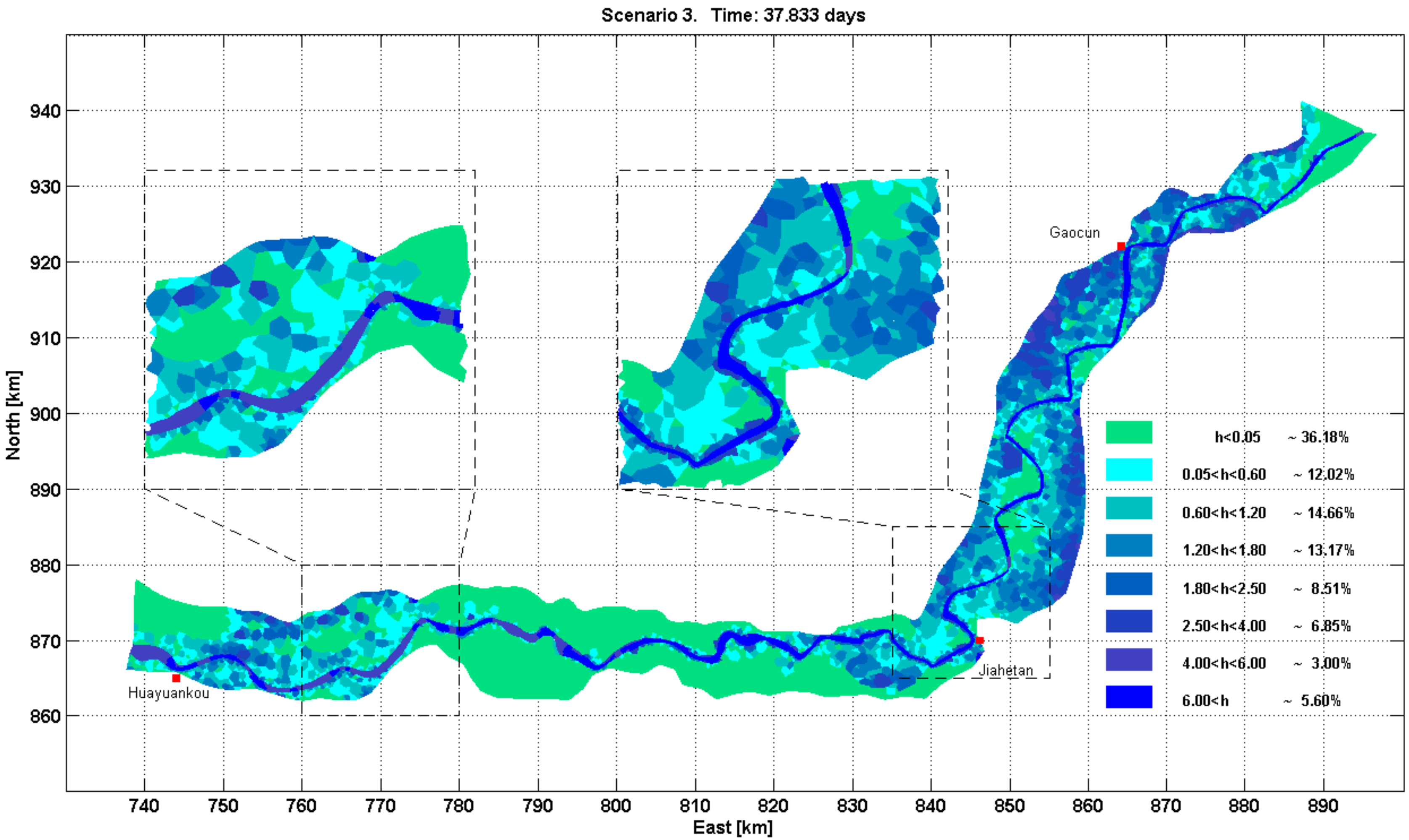


Fig. 6. Maximum flooded area in Scenario 2

1



2 **Fig. 7.** Maximum flooded area in Scenario 3

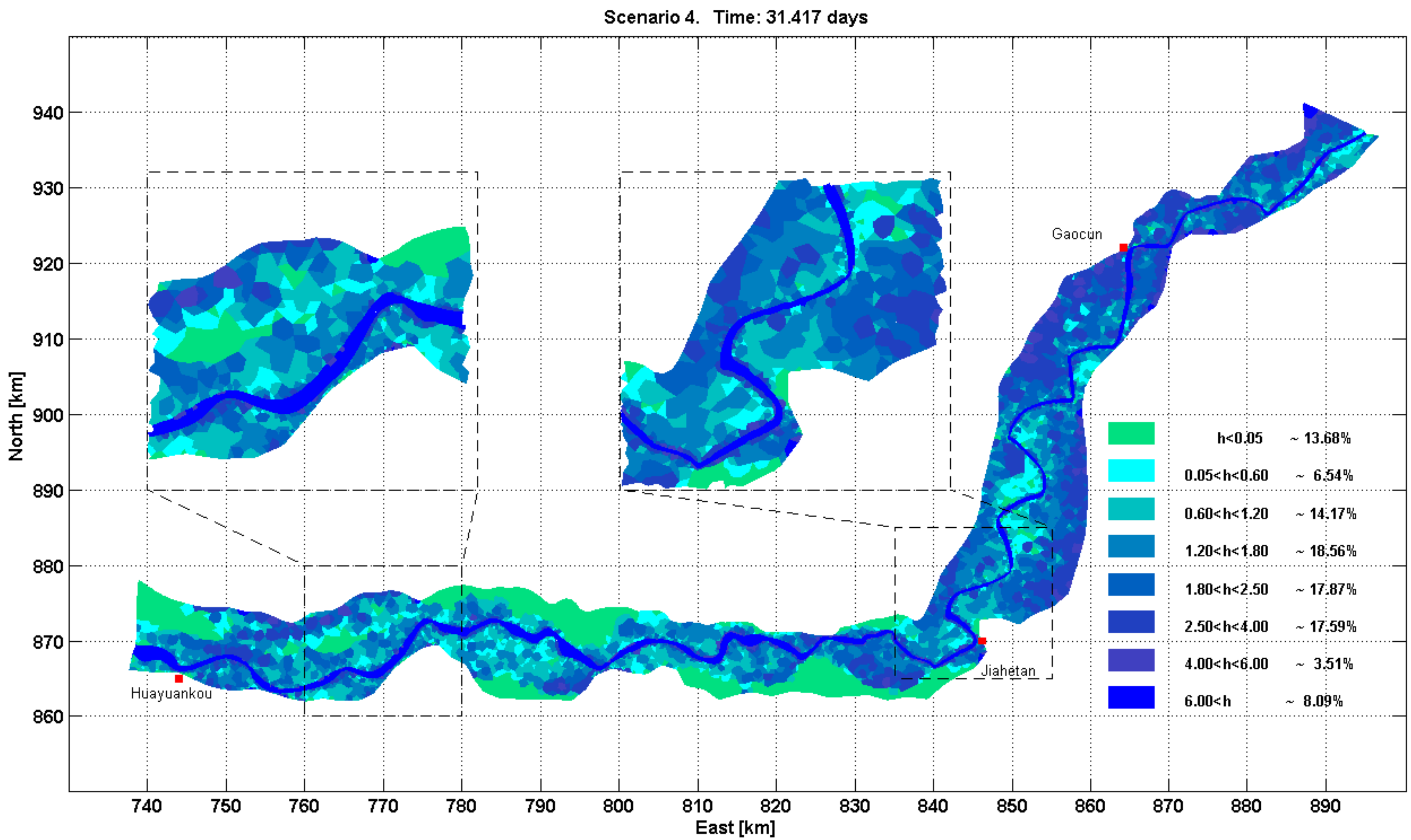


Fig. 8. Maximum flooded area in Scenario 4

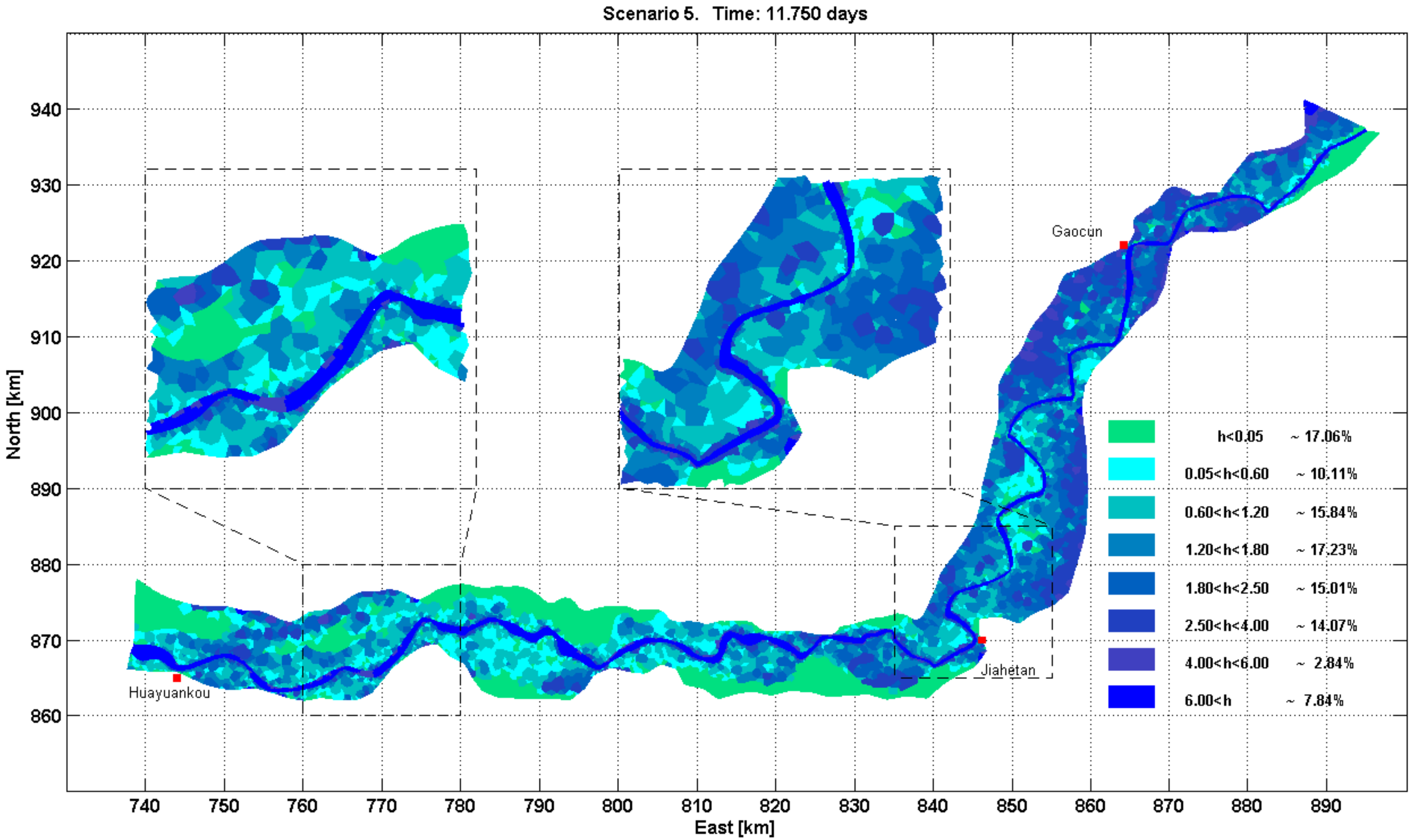


Fig. 9. Maximum flooded area in Scenario 5

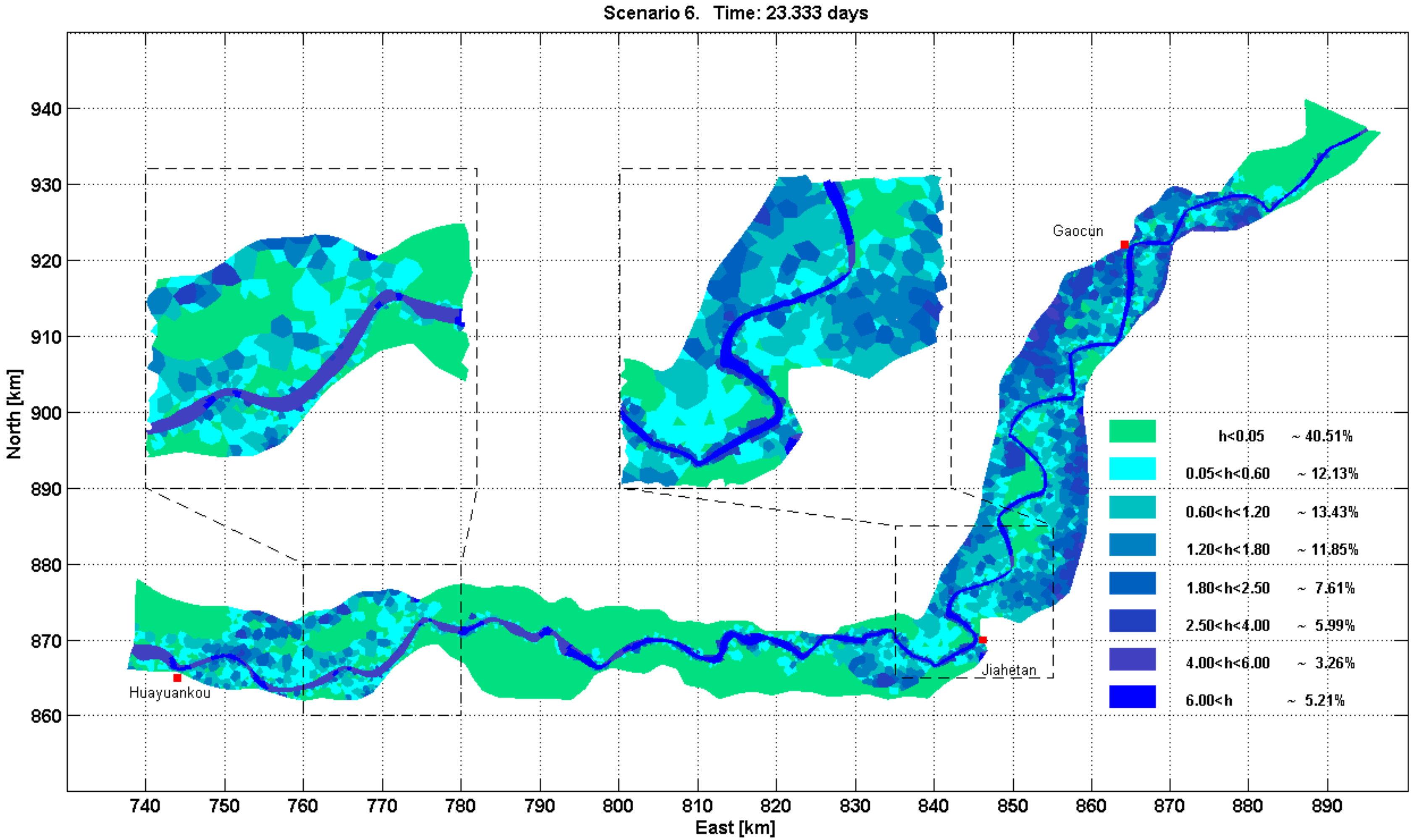


Fig. 10. Maximum flooded area in Scenario 6

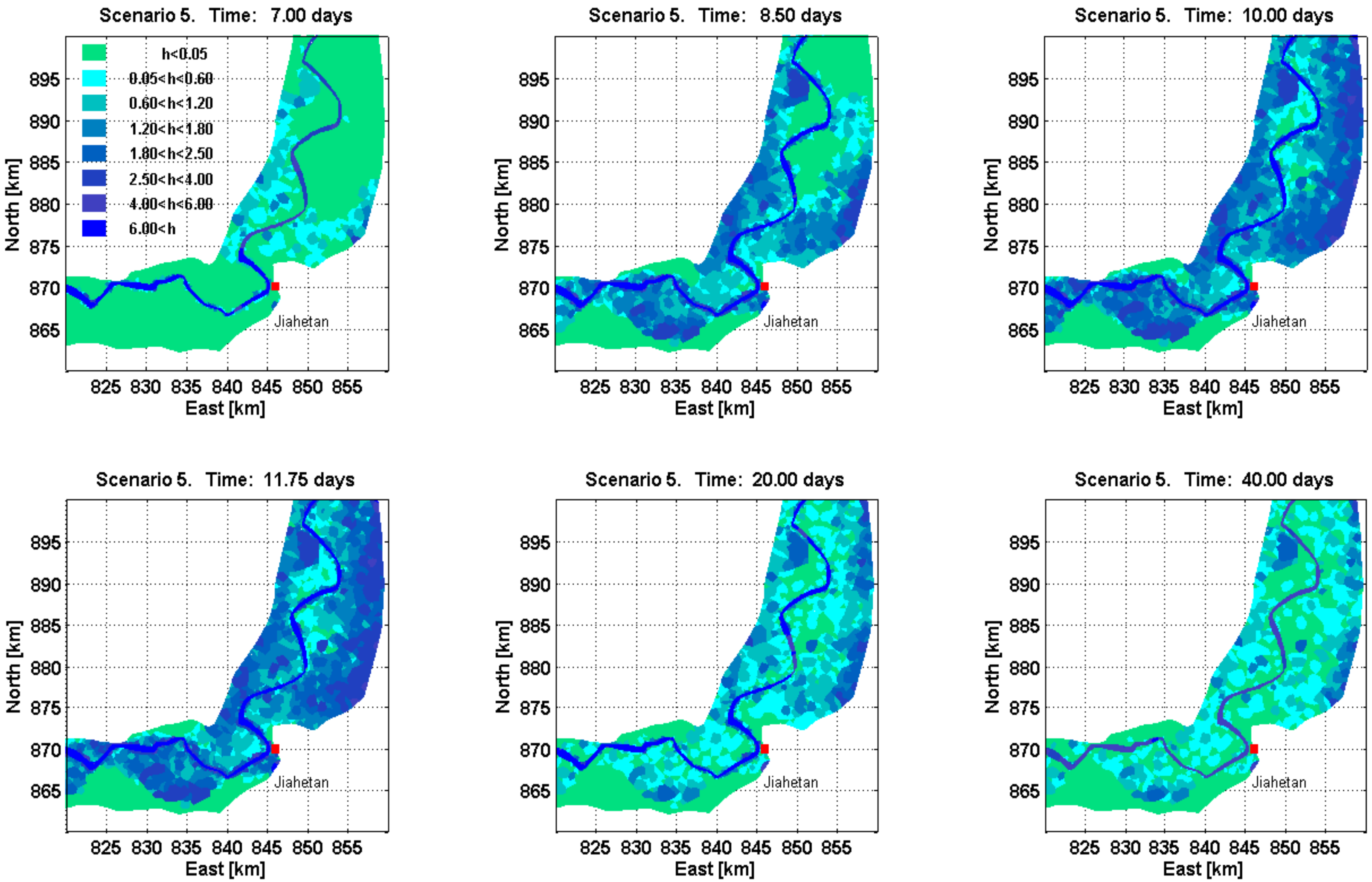


Fig 12. Water depths near Jiahetan in case of flooding scenario 5.

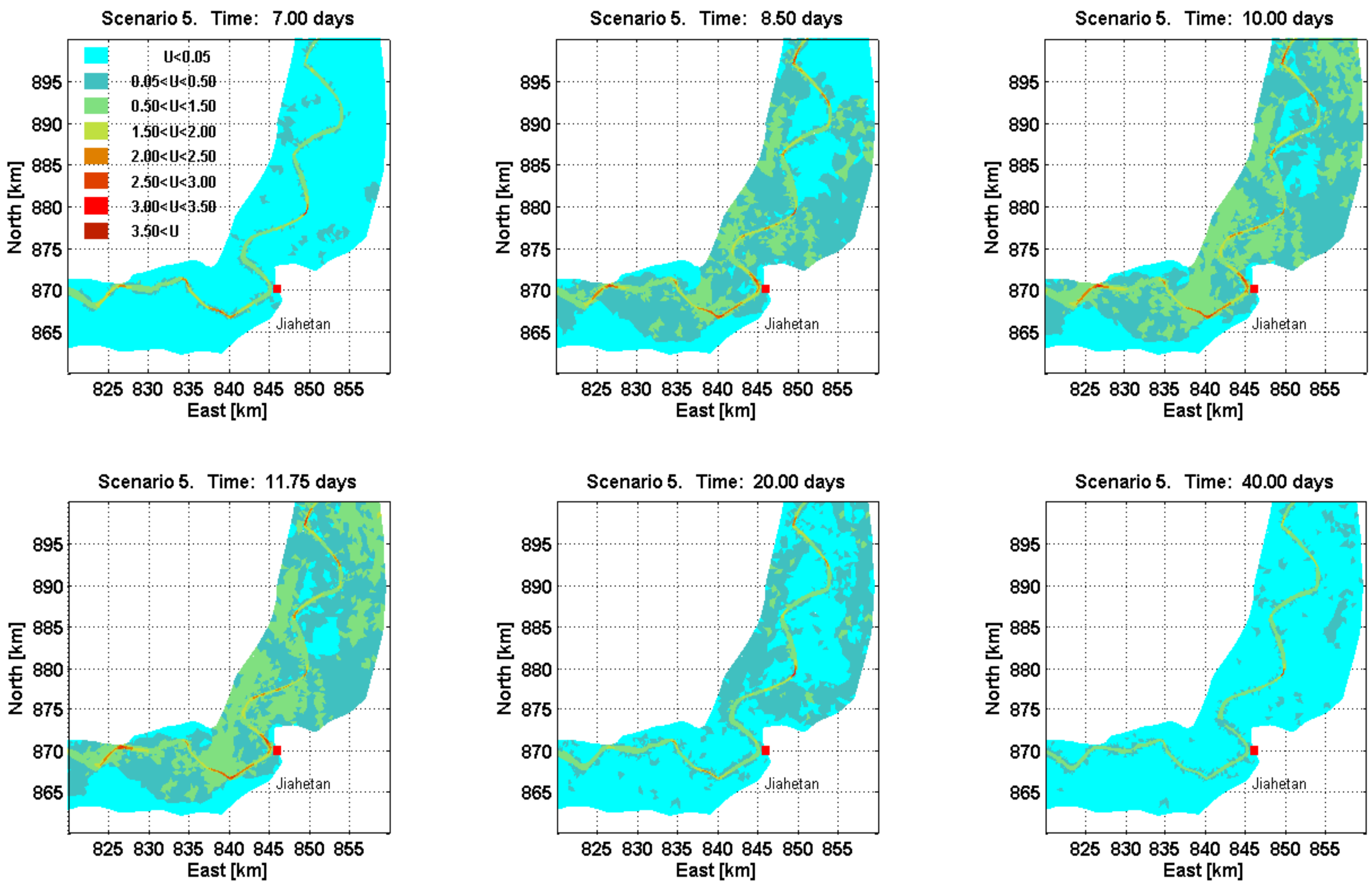


Fig 13. **V**elocity near Jiahetan in case of scenario 5.