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

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Abstract

Severe flooding events in China are a common cause of life losses. Many efforts have been carried out to understand flooding development and impact on the Yellow River. New approaches on modeling, specifically with the current development of the software modeling tool DFLOW-FM$^{\beta eta}$ gives the opportunity to enhance the understanding of the behavior of the Yellow River during extreme events. The modeling approaches based on discretization of the modeled domain in square and rectangular grids have a great importance in the management of rivers but usually they present two drawbacks: the required accuracy of the meandering of wide long rivers is not well represented, and the reduced speed in computational runtime due to the need of using many grid cells. A new tool, developed by Deltares, based on a flexible mesh discretization of the domain, presents the advantage that the two drawbacks can be overcome. The approach has the advantage of combining different grids, in order to properly represent the river and compute the flooding extent accurately. The method is checked and demonstrated on the Yellow River case. Along with the test of the new proposed modeling method new characteristics of the spatial flooding process in the Yellow River emerges and are presented in the paper, showing the capabilities of the software application tool in modeling such a complex environment like the one studied.

1 Introduction

Natural disasters, such as flooding events, on inland areas are the main factor of economic and life losses around the world. They do count for 40 % of the number of natural disasters and half of life losses worldwide (Balica et al., 2013; WMO, 2008).

Life losses, in Asia, ue to river flooding events, correspond to 40 % of the total world life losses (Jonkman and Kelman, 2005). The numbers showing the actual situation may be subject to uncertainties due to measurement approaches, however the order of magnitude is correct and shows that flooding is a common issue around the world.

Apart from life losses which are the most important impact of extreme flooding events, large losses occur in terms of economy and infrastructure as well.

China, is vulnerable to flood inundation, hence Chinese people have developed know how and learnt how to deal with floods, in an efficient manner since a very long time. The Yellow River is a particular example of the Chinese experience. Studies of ancient reports showed that since times dating pre-Qin dinasty (~ 400 BC), the river has overflowed 1590 times and changed its course 26 times; which correspond to a flooding event occurring two times every three years. Moreover every century there is on average one river course change. This trend caused a strong need for flood management for the Chinese government (Gao et al., 2011). In the 50 yr, the Yellow River Conservancy Commission (YRCC), has worked out the task of managing the river floods; while coping with the needs of several stakeholders, such as population, government and industry (Gao et al., 2011).

In order to achieve proper flood management, three completely different, but integrated levels of modeling of the river, have been developed in the last 30 yr, with the aim to look for new approaches in understanding the Yellow River behavior. The three levels of representation of the river are:

- the natural Yellow River, related to the control of the river structures and flow, based on the day to day operations;
- the scale river model, which is a set of physical models located at several YRCC laboratories. These scale models are used to simulate the behavior of the river in case of a planned construction of a large structure that may affect the natural evolution of the river; and
- the digital model, which refers to the mathematical computational model. This model includes the hydrologic and hydrodynamic models used for estimations and forecast of river flows, sediment and water quality. The model opens the possibility to link together the authorities and the stakeholders of the Yellow River.

The research presented herein focuses on the expansion of the digital model, using a new software tool and showing the difficulties in forecasting flooding events, from the point of view of understanding the spatial representation of the flood on floodplains, rather than looking at the magnitude of the peak discharges or the time of concentration of the flood peak.

The modelling approach uses the DFLOW-FM$^{\beta eta}$ software tool, to model the shallow water equations. The reason to use the tool was threefold; firstly because of the need of a complete bi-dimensional approach imposed by the special characteristics of the river; secondly because of the tool's ability to represent drying and wetting areas; and thirdly and most importantly, due to the capability of the tool to discretize the computational domain into curvilinear and unstructured grids simultaneously on the same computational grid. The approach has the advantage that it allows for a reduced number of computational cells, while preserving the accuracy in the modeling process, avoiding mass and momentum losses or additions. Compared with similar tools, previously used for modelling river floods (Dinh et al., 2012; Hartanto et al., 2011; Moya Quiroga et al., 2013; Van et al., 2012), this approach improves the computational speed, especially useful when studying multi-scenario responses. The particular case of the complex Yellow River system is used to demonstrate the concept.

The approach taken lies on several hypotheses. One hypothesis is that climatic variability is a reality (Milly et al., 2002; Stocker and Raible, 2005; Xu et al., 2011), and can not be measured just simply based on historical records. Model calibration for flooding events is typically done by using design hydrographs, that are based on flood frequency, however in case of climate variability these are losing their probability significance (Merwade et al., 2008; Jung and Merwade, 2012). A second hypothesis is the achieved level of intervention on the Yellow River. Nowadays there are a lot of dams (e.g. reservoirs) and lateral structures (e.g. dykes) build on the Yellow River, which makes it unrealistic to use flood design hydrographs for flood modelling. For a large river, as the Yellow River is, most often topographic data is not available, therefore the shape of the cross sectional configuration of the river in terms of length, width, sinu-

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osity, embankments and control structures has to be assumed from publicly available data. These kind of assumptions were previously used for different large rivers in the world, such as Missisippi in US or Tisza in Europe (Coustau et al., 2012; Gichamo et al., 2012; Muste et al., 2010; Quinn et al., 2010; Popescu et al., 2010; Poretti and De Amicis, 2011).

The research presented in the paper is not a deterministic or a probabilistic inundation mapping research, nor an uncertainty analysis of the quantities of historical flooding events. The study is a demonstration on how to account and model the non-linearities of extreme events, in case of highly modified streams like the case of Yellow River. The new application presented herein shows how several hydrographs can produce the same volume and inundation area in wide long rivers like the one studied.

The present paper presents the description of the Yellow River, its complexities and some of the flood management aspects in section two, followed by the presentation of the new modeling approach in section three. The results obtained by applying the new modeling approach, for different flooding events, are showed in section four, along with the integration of results for several input hydrographs. Finally in the last section the conclusions of the research are presented.

2 Case study: the Yellow River

This section presents the Yellow River physical characteristics of the three composing basins, corresponding to the upper, middle and lower reach of the river, and the structures that control the flow on the river, along with the applied flood management strategies in the basin.

2.1 Physical characteristics of the Yellow River

2.1.1 Yellow River

The Yellow River is the second largest river in China, in terms of the catchment size. It covers a vast area, 750 000 km^2, springs in the mountains in Qinghai province and discharges its water into the Bohai Sea. The Yellow River can be described in terms of geographical and hydrological characteristics using a subdivision in three basins; the upper, middle and lower basins (Fig. 1).

The upper river basin area is known for its complexity in relation to water and sediment volumes and has the largest watershed area (700 000 km^2). This area is located between the Yellow River spring and Hekouzhen. More than half of the Yellow River flow, 56 % of the water volume, originates from this area.

The middle river basin extends from Hekouzhen to Tao Huayu, which is a close location to the city of Zhengzhou. The largest part of the sediment volume, around 90 %, originates from this part or the Yellow River basin. The annual normal natural runoff of the middle basin is low 58×10^9 m^3, compared with other rivers in China, like Yangtze, 960×10^9 m^3. In terms of sediment volume, the annual average amount of the Yellow River is high 1.6×10^9 t, as compared with the Yangtze River, 0.53×10^9 t. The Yellow River–Yangtze ratio, is approximately 2/33 for the water volume, and 3/1 for the annual sediment volume (Li, 2013). The middle basin is characterized by the largest system of reservoirs in the stream, which serves mainly for flood control, irrigation, water supply and hydropower generation for the inhabitants living in the vicinity of the river.

The downstream river reach extends from Taohuayu to the river mouth, at Bohai sea. This part of the river has one special feature that makes it unique, the so called “hanging river” characteristic. In the downstream river reach the riverbed is higher than the nearby land surface, with 4–6 m on average. Protection of the river bed is done with summer dykes. The river floodplains, are enclosed by winter dikes. An example cross-section for this branch is illustrated in Fig. 2, around the city of Kaifeng, where the difference between the Yellow River bed and the floodplains is of approximately 13 m. The highest difference between the river bed and the land is 20 m at Xinxiang city.

2.1.2 Yellow River reservoirs

The Yellow River reservoir system is located on its middle reach (Fig. 3.) and it is composed of four reservoirs; three of them working in parallel (Guxian, Luhun and Xiaolangdi); and two of them in series (Sanmenxia and Xiaolangdi). These reservoirs are located along the Yihe and Yilohue tributaries and the main reach of the Yellow River, respectively. The planning of these large structures started since the beginning of the 20th century. The Xiaolangdi reservoir was designed to hold a volume of $10.1 \times 10^9\,\mathrm{m}^3$ of water, while the smallest one Guxian is having a volume of $1.11 \times 10^9\,\mathrm{m}^3$. The combined capacity of the system is amongst the largest hydro-systems in the world. The four main reaches, join together 70 km downstream of the reservoirs to form the main Yellow River reach. The main hydrological station that YRCC is using to assess the flooding downstream of the reservoirs is Huayuankou station, located 74 km downstream of the previous mentioned junction.

Nowadays, the smallest Yellow River bankfull discharge is approximately $4000\,\mathrm{m}^3\,\mathrm{s}^{-1}$. The conveyance of the downstream reach was obtained only by raising of the dykes and forming the “hanging river”. The large dyke system (1371 km long on both river banks) allows the development of the economy around the river. However in case of extreme flooding events it is almost impossible for the inhabitants inside the dyke area (1.97 million inhabitants) to relocate without incurring life losses (Li, 2013). In order to overcome this issue, YRCC authorities were looking for ways to increase the confidence in the built structures, and to cope with flooding events that have return period of 1/100 yr (e.g. discharges of $16\,000\,\mathrm{m}^3\,\mathrm{s}^{-1}$). One solution was to raise the outer dykes. Along the river, apart from the small dyke which created the “hanging river”, the farmers created small (informal) dykes to ensure the protection of their farmlands.

2.2 Flooding on the Yellow River

Flooding events occur along the Yellow River in the middle and downstream areas due to the accumulation of runoff. Rainfall events duration is ranging from a week, to more than one month, depending on the hydrological patterns and seasons.

An analysis of the flooding patterns on the Yellow River show that there are special characteristics of it that needs to be taken into account in case that a model of the flooding is built. When the first dykes, the ones of the “hanging river” are overtopped, water flows on the land until it reaches the outer dykes (the formal ones). The events are of intermediate magnitude because water flows towards downstream in meandering patterns. However such a feature is hard to be modelled using a modelling approach where classical rectangular grids are representing the terrain.

Yellow River has also two lateral flood detention areas; Beijingdi and Dongpinghu. The last one was originally a natural lake, but changed its character due to the structural interventions in the basin. With the raise of the outer dykes, YRCC avoids the operation of these storage areas.

The study presented in this paper is conducted for the middle reach of the Yellow River, due to the need of understanding the formation and propagation of flooding due to the operation of the upstream reservoirs. The river can be considered in this area as being a reservoir driven river, because its flows are not fully natural, but determined by the reservoir operation policies. No emphasis was made to include the effects of the sediment in the representation of the cross-sections of the river.

2.3 Flood management strategies

YRCC is daily faced with the issue of possibly managing evacuation tasks, because of potential flooding events. They have to determine and define the areas susceptible to flooding and the timeline of any flooding event (Li, 2013). Effort is made for development of software tools for flood management (Li, 2013), as well as for the improvement of the existing ones. An existing decision support system has been extensively used for the management of the complex reservoir system. the new approach of YRCC to involve stakeholders in the decision making process brings new challenges because of the number of issues posed by stakeholders, issued that needs to be taken into account in the decisions process, while having at the same time agreement on local policies. This task becomes quite complex, and negotiation should be made based on simple simulation approaches (Popescu et al., 2012b). Generally, the result of a decision is a response to a single simulation of a forecast flooding event, while the real outcome could be totally different. Present research trys to address these challenges by using a model that presents quick and accurate performance of several scenarios, and at the same time has the flexibility to add input data or extract results ready for analysis to stakeholders and decision makers (Jonoski and Popescu, 2012).

3 Flood inundation modeling using DFLOW-FM

In order to address the above mentioned challenges a new modelling approach has been tested. The approach uses an unstructured mesh model, that is accurate and flexible, to test different different adaptation strategies in case of extreme flooding events.

YRCC currently uses a 1-D-2-D structured grid based on rectangular discretization, to represent flooding extent in the downstream area of the reservoirs. The refinement of this model is a continuous process (Li, 2013). The computational engine of this existing model uses SOBEK 1-D-2-D software tool, developed by Deltares. DFLOW-FM$^{\beta eta}$ is a new modeling approach that uses the same modeling concept as SOBEK, but it implements a flexible unstructured grid approach that is more easy and flexible to be used.

The DFLOW-FM$^{\beta eta}$ modeling suite is based on a Finite Volume Method (FVM) numerical schematization solving the vertical integrated 1-D-2-D shallow water equations (Kramer and Stelling, 2008; Kernkamp et al., 2011). For the development of the grid an unstructured developer was integrated within the application. The tool converts between geographical and projected coordinates, which becomes useful in the phase of grids development. The DFLOW-FM$^{\beta eta}$ uses unstructured grid coverage of the computational domain.

Both software tools, SOBEK and DFLOW-FM$^{\beta eta}$, share the same numerical engine, the main significant difference being the discretization method, i.e. the way the grid is represented and developed. One of the advantages of using unstructured grids relies in the fact that narrow areas can be easily represented in a refined manner, while areas where no detail is required can be represented in a coarse manner (Kernkamp et al., 2011).

Another advantage of DFLOW-FM$^{\beta eta}$ is that in case of running several scenarios, the tools easily allows for considering or discarding the hydraulic structures in the model, which will lead to less input data requirements from the user of the model.

The built DFLOW-FM$^{\beta eta}$ hydrodynamic model of the Yellow River, represents a total area of 1936 km^2 for a river length of 240 km, between Huayuankou and Gaocun station (Fig. 1). The model uses topographical information obtained from freely available data of the Shuttle Radar Topography Mission (SRTM) (CGIAR-CSI, 2004) projected in UTM-50 system of coordinates. The use of this kind of information for wide long rivers have been previously tested for the Amazon river (LeFavour and Alsdorf, 2005).

The DFLOW-FM$^{\beta eta}$ Yellow River model does not include the storage areas of the most downstream part of the river, because they fell outside of the boundary of the model domain. Flood propagation develops only inside the dykes, on the middle part of the Yellow River.

The Manning roughness coefficient was set to match the data of the previous SOBEK model, 0.025, keeping the same value for both the river and lowland areas.

The discretization of the domain in the unstructured grid was done in two steps. First a curvilinear grid was defined in the main channel, based on a combination of the downloaded SRTM data and YRCC surveys. Second a triangular grid was adopted for the lowland areas. Figure 4 shows the meandering section, near Jiahetan station using the structured and unstructured grid discretization. It can be noticed that with the same number of computational nodes the unstructured grid gives a better representation of the river features (e.g. main river channel, dykes, etc.).

For the present study two different unstructured grids were developed, one raw and one fine, keeping the alignment and boundary domain the same, but increasing the number of grid cells for the later. In order to select one of the two grids, the orthogonality property was used to evaluate the wellness of the grid. Orthogonality is defined as the cosine of the angle formed between the line that joins the circumcenters of two adjacent cells and the common line of the two considered cells. Ideally, this measure has to be zero, as it is the case of structured square grids. The convention is, however, that values of the orthogonality that are less or equal to 0.05 are still acceptable. The limit value is selected in such a way that the computational diffusion of the numerical solution for mass and momentum equations, is reduced to minimum.

Both developed grids showed a good measure of orthogonality between cells and links along the whole domain, however the fine grid had a very small decrease in the value of orthogonality, as compared with the computational effort that would be needed to run a model with a very refined grid. Hence the raw unstructured grid was selected to perform flood simulations on the Yellow River.

The total number of cells of the raw unstructured grid is 18 236 (using only 11 700 nodes); while for the original structured square model, with a 300 m × 300 m resolution grid, the number of cells is 21 500 for exactly the same area. In case a higher resolution is required, for a structured grid of $90\,\text{m}^2 \times 90\,\text{m}^2$, a number of 239 000 cells will be needed to represent the modeling domain. This shows the advantage and the improvement in the total computational running time while using the unstructured grid approach.

The upstream hydrograph boundary condition is obtained from multiple scenario simulations of an inference model between the reservoir system and the hydrograph at Huayuankou. In total 339 flooding scenarios were selected as representative for the Yellow River behavior. The reservoir simulation model related the hydrographs obtained from operation of reservoir with the flooding volumes observed in the downstream. The selected 339 hydrographs are based on the fitness of it (Mean Square Error ±2 %) with respect to the observed flooding volumes at Huayuankou.

The downstream boundary conditions are set based on the rating curve at Gaocun hydrological station, which is obtained from field surveys. Verification of the model and determination of the initial state of the river was determined by running a steady flow simulation so that only the influence of the incoming hydrograph could drive flooding in the river. Each performed simulation was represented as a 100 days flooding process.

4 Results and discussion

Results are presented from two different points of view. Firstly, the resolution of the flooding mapping and differences in flooding patterns along the study area, are shown. A collection of six selected flooding events is presented. Secondly, all results are integrated and the flooding process nonlinearities are shown and discussed.

4.1 Flood maps comparisons

The results of the conducted flood simulations on the Yellow River are shown as spatial distribution of the flooding process in maps of flooded area. The post processing of the results is done by developing a code in Intel FORTRAN with the NetCDF (Rew and 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 5–9 show the the downstream Yellow River area that is flooded and the corresponding range of water depth (*h*).

The six selected scenarios are:

Scenario 01: Fast concentration time, fast flooding of the area, but minimum spatial coverage for this event (Fig. 5). The simulation shows that 28.4 % of the area is flooded.

Scenario 02: Slow concentration time, slow flooding of the area, but with low spatial coverage of the flooding (Fig. 6). The simulation shows that 37.8 % of the area is flooded.

Scenario 03: Maximum time of concentration, very slow flooding time, but medium to large spatial coverage (Fig. 7). The simulation shows that 71.7 % of the area is flooded.

Scenario 04: Slow concentration time, slow flooding in the area but with high spatial coverage (Fig. 8). The simulation shows that 91.1 % of the area is flooded.

Scenario 05: Fast concentration time, fast flooding of area and high spatial coverage (Fig. 9). The simulation shows that 88.3 % of the area is flooded.

Scenario 06: Intermediate concentration time, with intermediate to large spatial coverage (Fig. 10). The simulation shows that 68.3 % of the area is flooded.

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 1768 km^2; the time to flood a maximum area (FTA), which varies between 7 days and 8 h 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 h up to 41 days and 8 h. These ranges are presented in Fig. 11a–d.

In Fig. 11b it can be noticed that FMA has the largest frequency for the high values, showing the susceptibility of the Yellow River during flooding events to present large portions of area covered by water. In this case the populations living near the dykes are at risk.

In contrast, the FMV (Fig. 11d) shows that only several magnitudes of volume result in inundation, which can be explained due to the hanging river characteristic of Yellow River, which 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 and it is an interesting feature present in the area, during flooding events.

The variability in the obtained flooding processes in terms of and FMV is shown in Figs. 12 and 13. The figures show scatters that belong to every possible region of the space of the simulated variables. It can be concluded that it is not possible to develop a model that correctly predicts the flooded area and the flooded volume simultaneously.

A third comparison in the variability is shown in Fig. 14. It can be seen that FTA and FTV are not the same for each simulation, though the corresponding scatter plot of FMA vs FMV is highly correlated ($r = 0.968$). Both variables are not independent, but the interesting fact is the change in slope after a flooded area of 1550 km^2 (80 % of the total area). This shows a threshold of high impact of flooding in terms of both area and volume. Large volumes can cover the same area as smaller volumes, giving as a result a completely different water depth classification.

5 Conclusions

The DFLOW-FM$^{\beta eta}$ model for Yellow River is able to represent different scenarios of flooding inundation in wide long rivers, mainly driven by the operation of hydraulic structures. Rivers can be properly represented using DFLOW-FM$^{\beta eta}$ though only freely geographical information data, downloaded from the SRTM 4.1, was available.

A big advantage of using DFLOW-FM$^{\beta eta}$ is the reduction of the time of simulation. A computation time for each scenario takes between 4 and 8 h on a regular PC with Intel processors Core 2 Duo 3.00 GHz, and a 4Gb RAM, for a total runtime of 2030 h. If the square grid is used for the same hydrographs the total runtime process is ten times longer.

The results are stored in Network Common Data Format, NetCDF files, each two hours of time step, and can be up to 700 Mb per simulation. Interchangeability and transmission of data is ensured in a compressed binary file. Also the linkage with visualization libraries like f90gl is easily achieved.

There are three different characteristics of the flood modeling that needs to be addressed in future studies. First a connection with a hydrological rainfall runoff model is required due to the large area covered by the river (1936 km^2). This connection will serve to calculate the lateral discharge along the river reaches during every scenario, given that those scenarios are covering 100 days of simulations. Second, in the lowland areas, an integration with the infiltration process is advisable, because if the flooding area is large, then the infiltration process will affect the process of draining the water out of the modeled area. Finally sediment transport of the river was not included in the simulation of any scenario and it could be explored as well, due to its significance in the historical development of the river.

The new modeling approach is good to be incorporated in a Decision Support System that will not only be used for operation purposes but can serve as a tool to show the stakeholders what are the possible adaptation measures. Such a DSS will facilitate the involvement of the stakeholders in the flood management process and with nowadays technology can make them active players in the adaptive management (Jonoski and Popescu, 2012; Jonoski et al., 2012, 2013; Popescu et al., 2012a).

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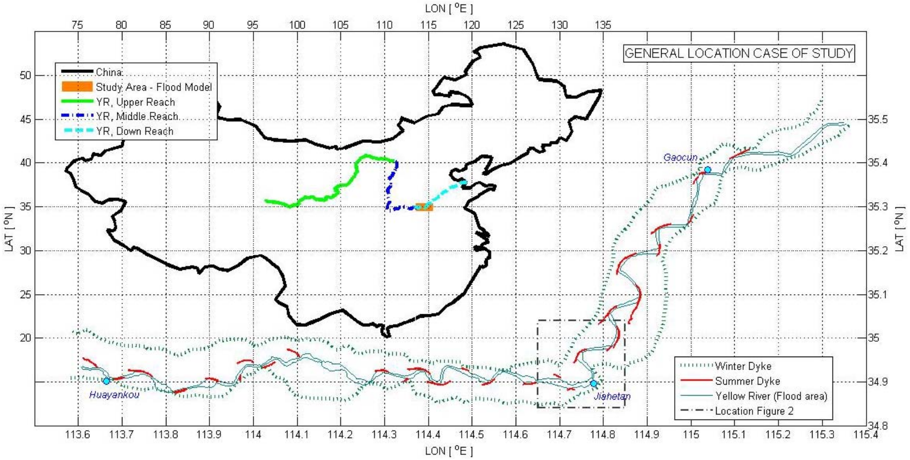

Fig. 1. Yellow River basin location and the study area.

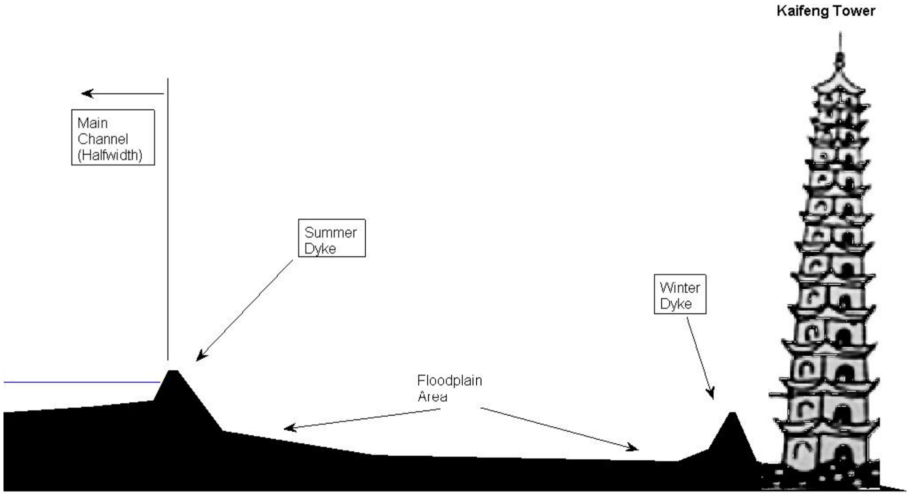

Fig. 2. Cross sectional view of the Yellow River at Kaifeng.

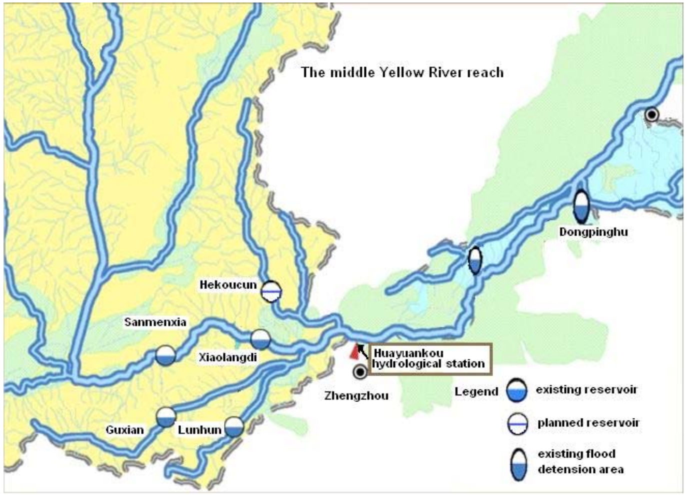

Fig. 3. Reservoirs of the Yellow River.

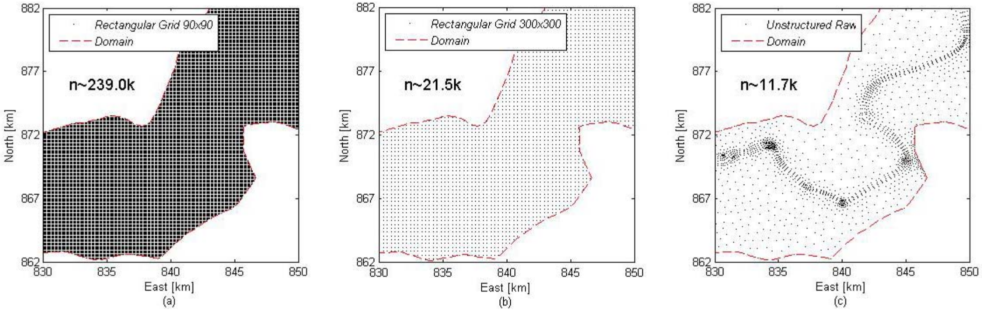

Fig. 4. Rectangular and unstructured grid discretisation at Jiahetan station.

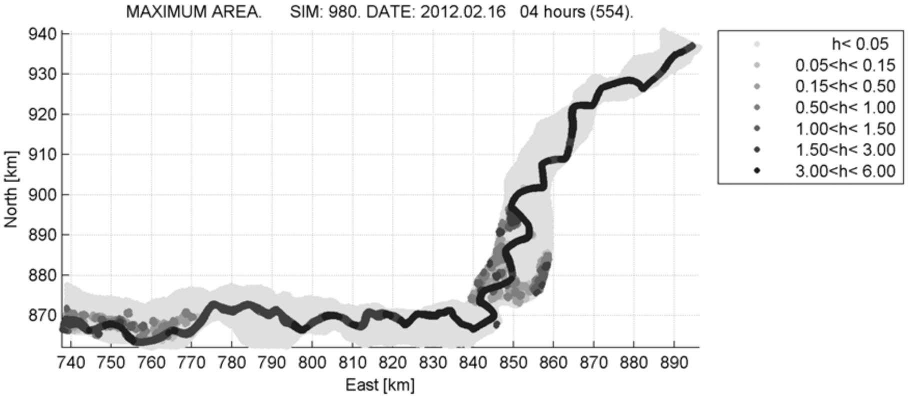

Fig. 5. Maximum flooded area in Scenario 01.

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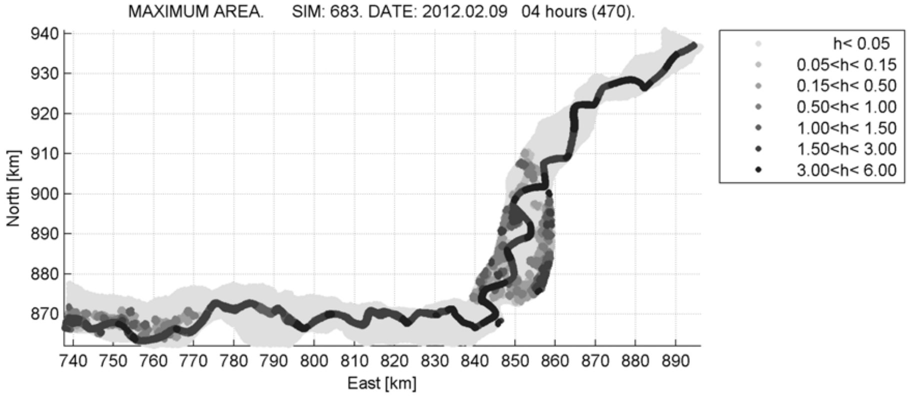

Fig. 6. Maximum flooded area in Scenario 02.

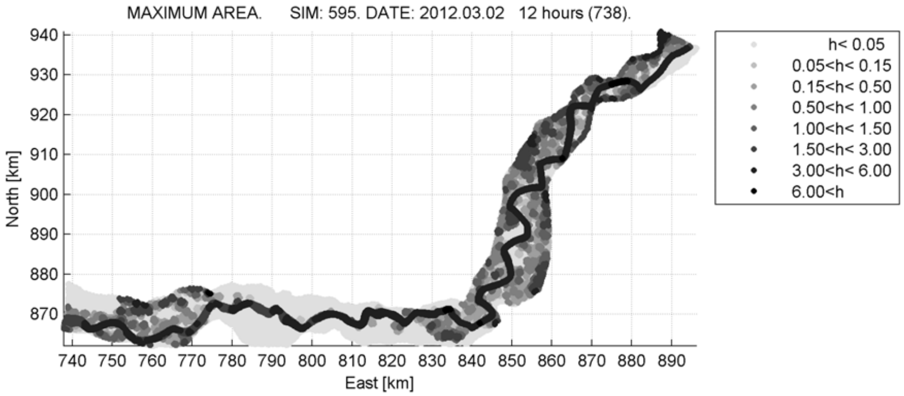

Fig. 7. Maximum flooded area in Scenario 03.

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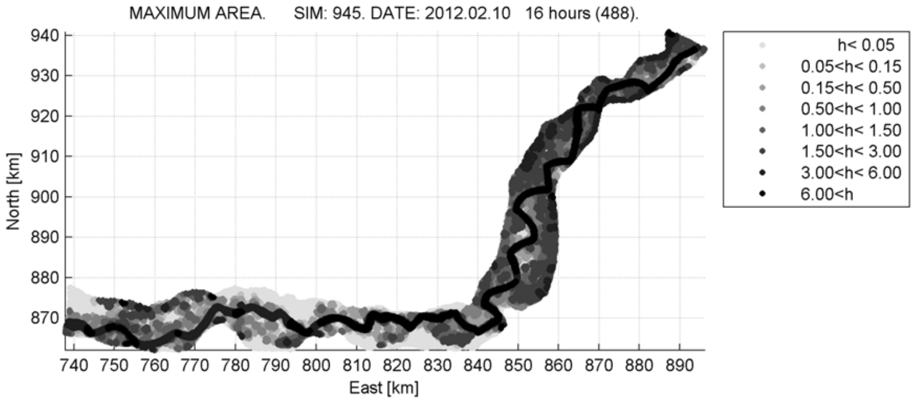

Fig. 8. Maximum flooded area in Scenario 04.

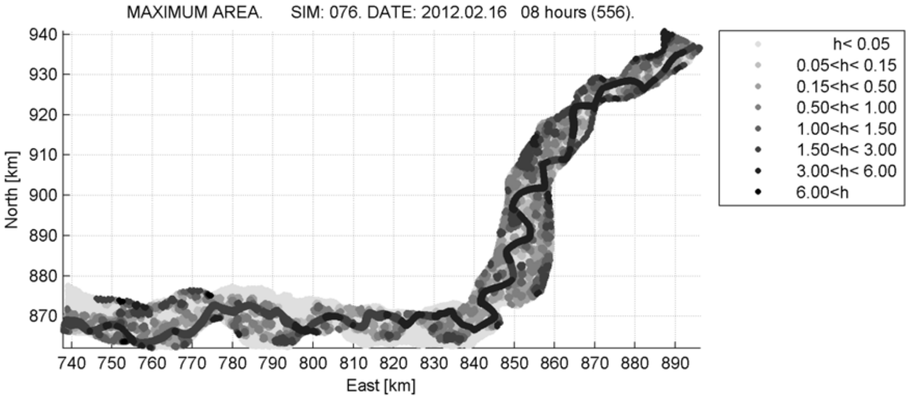

Fig. 9. Maximum flooded area in Scenario 05.

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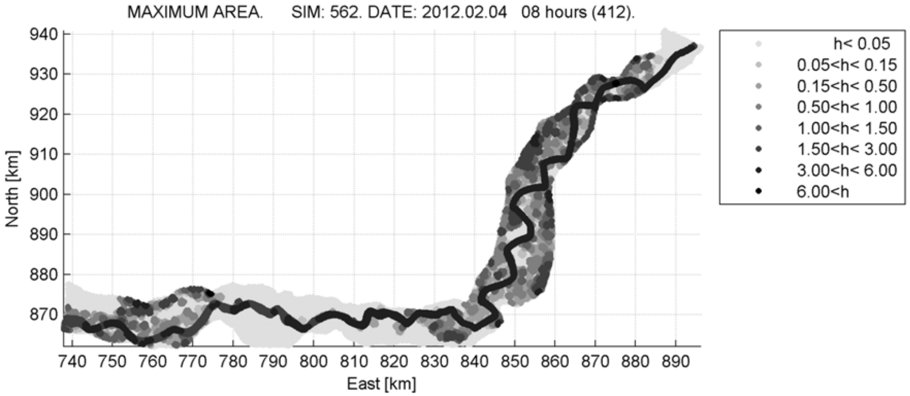

Fig. 10. Maximum flooded area in Scenario 06.

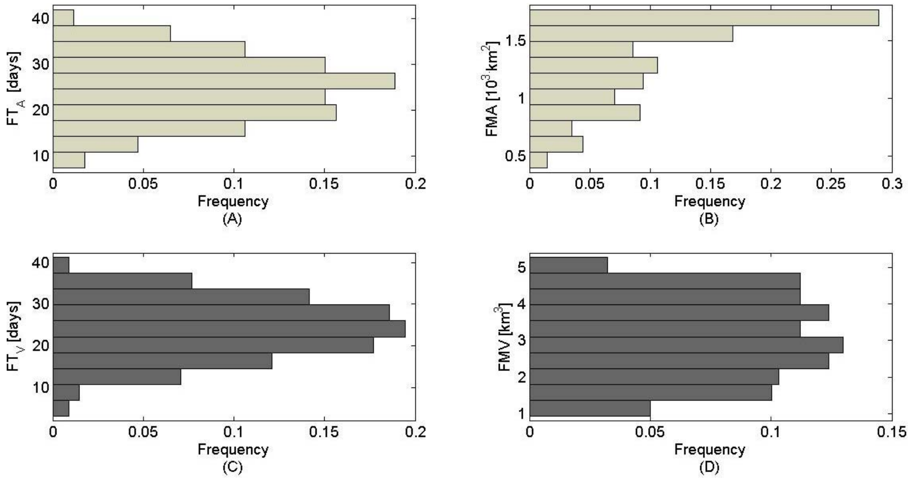

Fig. 11. Histogram for flooding variables.

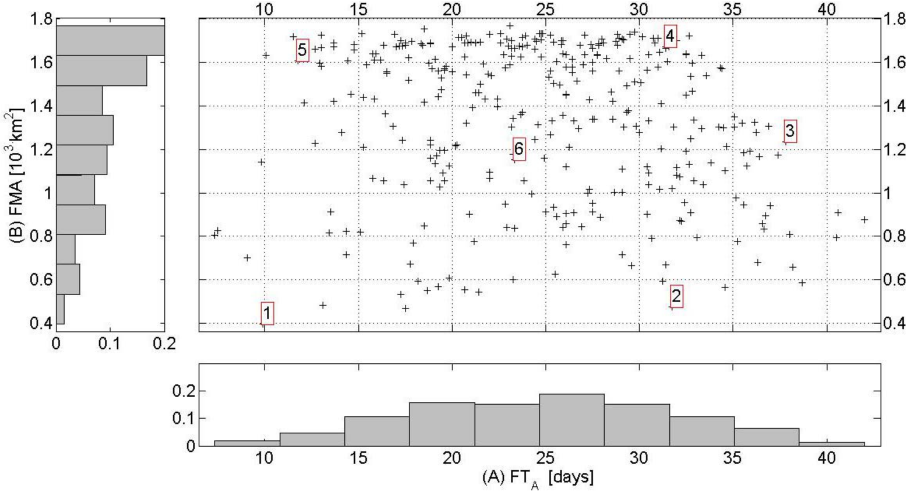

Fig. 12. Dispersion of FMA with respect to FTA.

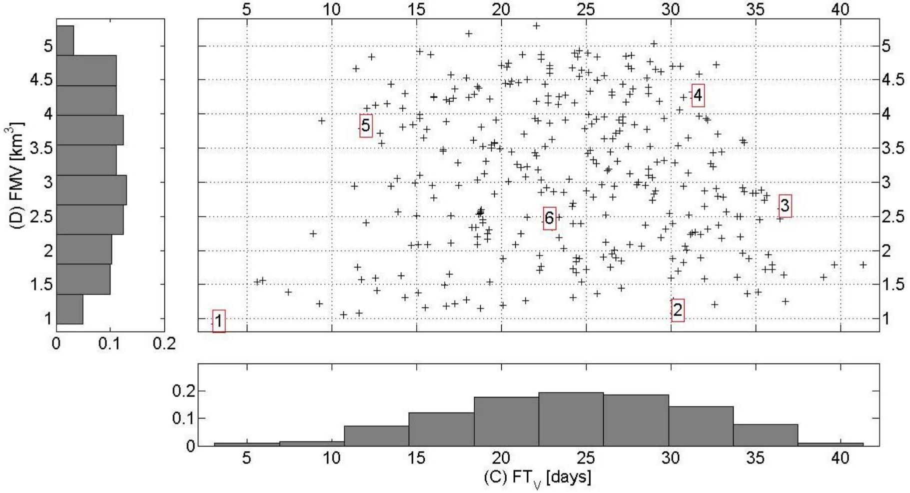

Fig. 13. Dispersion of FMV with respect to FTV.

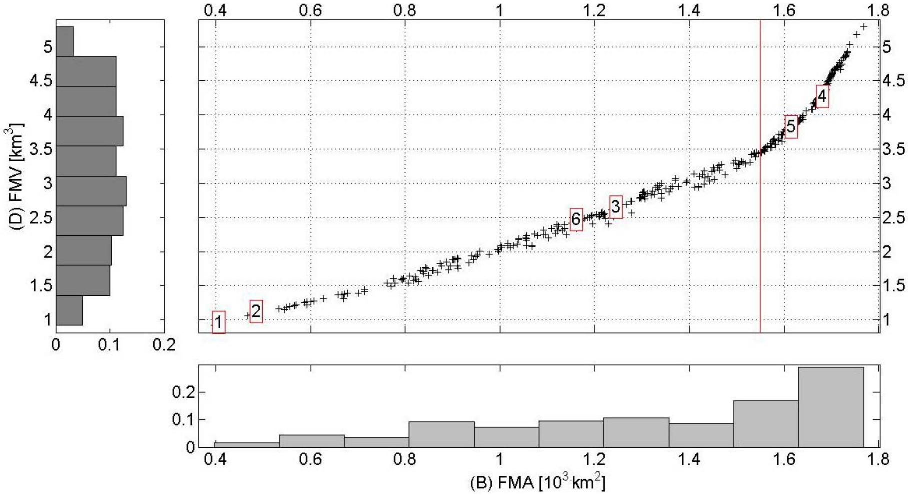

Fig. 14. Dispersion of FMV with respect to FMA.

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