Journal of Visual Languages and Computing 41 (2017) 89–99

Contents lists available at ScienceDirect

Journal of Visual Languages and Computing

journal homepage: www.elsevier.com/locate/jvlc

View Points

A visual analytics approach for flood risk analysis and decision-making in cultural heritage

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ARTICLE INFO

Article history:
Received 18 September 2016
Revised 16 April 2017
Available online 25 May 2017

Keywords:
Cultural heritage
Visual analytics
Flood risk analysis and decision-making
Simulation

ABSTRACT

World cultural heritage is the accumulation and essence of the development of human civilization, as well as the rare and irreplaceable treasures bestowed by history. However, cultural heritage is increasingly exposed to various risks caused by natural and man-made factors. Flood risk is the most common and the most devastating risk for cultural heritage. This study proposes a visual analytics method that supports the visual analysis of flood risk from multiple aspects, including predicted flood peak flow, flood propagation, flood impact, and vulnerability. The proposed method can also provide the required information from multiple scales, including the basin-, site-, multi-cave-, and single-cave-scale levels. The combination of the visualization techniques of flood risk analysis will enable the proposed method to support users to make decisions with respect to mitigation measures. Lastly, the proposed method is evaluated by water experts and cultural heritage site managers.

1. Introduction

Cultural heritage is one of the most precious treasures that resulted in the development of human civilization. Although cultural heritage is rare and irreplaceable, it is also frangible in most cases. The emergence of social development and deterioration of the natural environment have threatened cultural heritage due to an increasing number of natural or anthropogenic risk factors [1–5]. These threats can be classified into three categories, namely, natural hazard, anthropogenic factors, and relic deterioration. In general, the frequency and probability of natural hazards are relatively low, although such hazards are commonly sudden and occur in a short period. Moreover, natural hazards often lead to catastrophic consequences for cultural heritage sites. Flood hazard is undoubtedly a common and serious risk among all types of natural hazard risks for cultural heritage. Many world cultural heritage sites, such as the Ayutthaya of Thailand and the historic centers of Krumlov, Prague, Genoa, and Mogao, among others, are exposed to flood hazards. Climate change has also resulted in the considerable frequency of floods, the impact of which is rapidly increasing. Consequently, managers of cultural heritage sites have to closely consider and prepare against the threat of floods to cultural heritage.

In contrast to ordinary buildings and objects, cultural heritage sites have irreversible characteristics that can never be reproduced once they are destroyed. Therefore, the concept of preventive conservation is a primary focus in flood risk management for cultural heritage sites. Extensive studies have been conducted to realize preventive conservation. In recent years, risk management theory has been introduced in the flood management of cultural heritage, thereby guiding the application of this idea to improve the management system and process. Numerous devices have also been used to monitor flood-related indicators, such as precipitation and water level. In addition, information technology, such as computer simulation, is applied to predict flood hazard and assess impact and vulnerability.

Despite the aforementioned developments, many dilemmas still exist in the flood risk management of cultural heritage. Monitoring devices and information technology system for flood management generate a massive amount of heterogeneous data that indicate various aspects of flood risk. However, extracting the relevant and beneficial information for specific objects is still a challenging undertaking for domain experts. At present, the use of a flood risk map is a common and popular method in studying and representing flood risks [6]. However, the situation is considerably complicated for managers of cultural heritage sites. Thus, substantially detailed information is necessary to understand the impact of the risks to and vulnerability of important cultural relics (e.g., precious ancient artworks or buildings). Flood risk maps are

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http://dx.doi.org/10.1016/j.jvlc.2017.05.001
1045-926X/

unable to provide sufficient detailed information for conservators to support decision-making because these maps can only provide data on water levels at a coarse-grained level. Most significant and beneficial detailed information is often scattered among multiple heterogeneous data sources. Thus, managers of cultural heritage sites still have to process an entire set of heterogeneous data for several hours to collect the required information that will support decision-making. However, flood can only be predicted several hours in advance. To our knowledge, no visual analytics method or tool for the flood risk management of cultural heritage can process multi-sourced, heterogeneous flood-related data, as well as integrate all relevant information to provide to users in a convenient and intuitive manner.

This study uses the characteristics of cultural heritage as basis to propose a visual analytics approach that assesses and analyzes flood risks. Our approach also follows the risk management process of cultural heritage. Thus, the proposed method attempts to support the entire risk management process, which involves risk identification, assessment, analysis, mitigation, and decision-making support. Although we use the Dunhuang Mogao Grottoes as our study background, we believe that the proposed method is applicable to other similar world cultural heritage sites that are at risk of flood. The main foci of this study are summarized as follows.

- The risk management process is used as basis to propose a visual analytics method with multiple scales. This method will analyze flood risk to cultural heritage from multiple aspects, thereby supporting risk identification, analysis, and decision-making.
- Uncertainty-aware visualization of the predicted flood peak flow on a GIS map is designed to identify risk events.
- Software is designed and developed to manage and abstract the required information from the enormous pre-simulation data set.
- Visualizations of the flood propagation, flood impact, and vulnerability of cultural relics are proposed to support users analyze flood risk from diverse aspects on multiple scales, as well as make decisions regarding flood mitigation.

2. Related work

2.1. Flood risk management and cultural heritage

Flood is a common natural hazard risk for many cultural heritage sites [7–9]. Accordingly, flood can damage cultural heritage sites in a variety of manner. Moreover, flood results in devastation by directly damaging materials and structures that come in contact with the flowing surface water, as well as by destroying the basic infrastructure of architectural heritage sites [10]. Siedel [11] demonstrated that water saturation caused by flood events damages the ashlars and stone sculptures in cultural heritage sites. Flood can also damage the diverse components of immovable cultural heritage sites, such as individual structures, buildings, and artistic objects, through various forces and actions during flood situations [12]. Consequently, appropriate and effective flood risk management is becoming considerably crucial due to the increasing number of flood events and extensive damage caused by flood.

Risk management has been employed in the preventive conservation of cultural heritage sites [13–15]. Considerable effort is exerted to improve risk management models to suit the affected cultural relics [16]. Paolini and Tamayo [17] developed a risk management model and attempted to apply this model in the preventive conservation of an immovable cultural heritage site in Amman. The European Union (EU) flood directive initiated the crucial task of assessment and management of flood risks to mitigate the potential loss of cultural heritage sites [18]. The current study considered over 3500 cultural monuments, museums, and archives, among others, within the risk planning process. Flood risk is assessed based on the probability of floods and the vulnerability of each object in this research. In addition, emergency response plans are considered.

2.2. Data visualization of flood risk

Visualization of flood-related data has been applied in ordinary flood management. The most common and traditional visualization technique for flood hazard is the use of a risk map [19–21]. However, many novel visualization and visual analytics methods have been presented in recent years. An online application [22] visualizes the evacuation zones on a GIS map, which users can use to conveniently find the nearest shelter. Cornel et al. [23] proposed a visual analytics method based on the extraction of relevant information from a large collection of pre-simulated flooding events; this method focuses on addressing vulnerability to flood-related hazards for a specific building. Konev et al. [24] demonstrated a visual analytics approach to explore a complex, multidimensional parameter space of flood response plans. Waser et al. [25] presented an integrated visual analytics solution that combines multidimensional ensemble simulations and logistics computations with interactive visualizations. This system aims to assess response plans by conveying the details of the execution method of such plans. These novel approaches are remarkable and impressive but only a few of them are applicable to cultural heritage sites. A risk map is one of the few visualization technologies applied to cultural heritage sites. Wang [6] attempted to create a set of cultural heritage risk maps to analyze present heritage preservation strategies and the feasibility of a few flood mitigation measures.

Extensive effort has been focused on ordinary flood management. However, such undertakings fail to consider the characteristics of cultural heritage; hence, they fail to address the concerns of managers and conservators of cultural heritage sites. To our knowledge, no visual analytics method supports risk event identification, analysis, and decision-making for the flood risk management of cultural heritage sites.

3. Method and design

3.1. Overview of the method and design

Risk management theory [17] states that risk management involves risk identification, assessment and analysis, as well as the identification and implementation of risk mitigation strategies and measures. The flood risk management of cultural heritage sites follows this theory. In the flood risk management of cultural heritage sites, managers initially deploy the appropriate monitoring devices to observe key flood-related indicators, such as the amount of precipitation. To achieve "preventive conservation", flood risk alerts must be provided as early as possible. Experts process monitoring data to develop a flood prediction model that can calculate flood peak flow in advance. Thus, flood risk events can be identified in advance. Moreover, these experts analyze the flood impacts to and vulnerability of cultural relics based on the information from the risk events. Subsequently, site managers identify and evaluate risk mitigation strategies to guide their decision on the manner of treating risk events.

In addition, the flood management of cultural heritage sites has distinct features compared with ordinary flood management. Preventive conservation is the first principle of the flood management of cultural heritage sites because of its irreversible nature. Apart from the casualties and economic losses caused by floods in cultural heritage sites, experts and workers are also concerned regard-

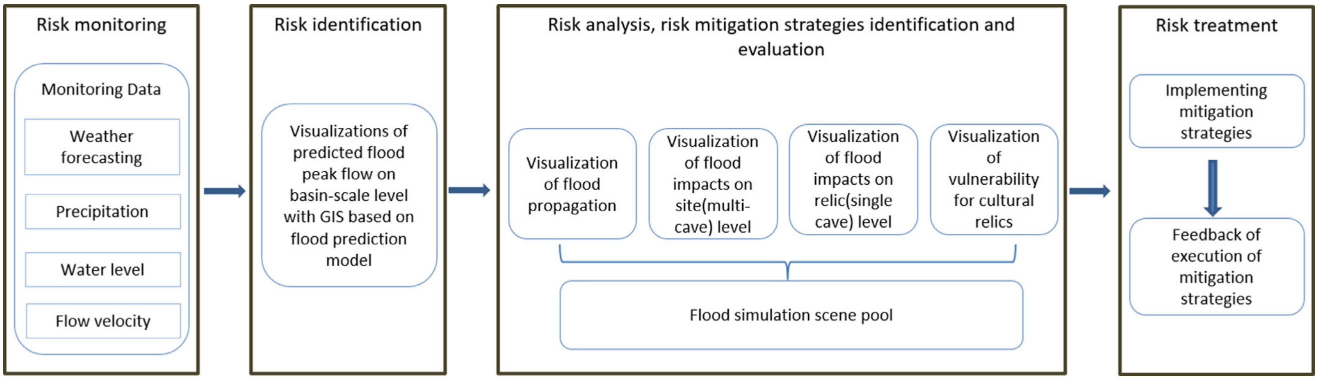

Fig. 1. Overview of the proposed visual analytics method for flood risk analysis and decision-making in cultural heritage sites.

ing the loss of historical relics, damage to these sites, and even changes in the historical landscape. On the one hand, site managers need considerably detailed information for a particular object for decision-making related to risk mitigation measures. On the other hand, historical relics in various sites are key protected objects; thus, site managers must select the appropriate mitigation measures to reduce or avoid damage. Therefore, risk mitigation measures should be judiciously selected within a limited time based on the evaluations of risk impact and vulnerability on a fine-grained level.

The design goals of the visual analytics method for flood risk management in cultural heritage sites can be summarized as follows. First, the proposed method should follow risk management theory and practices in cultural heritage, as well as support all processes of risk management (i.e., from risk identification to treatment). Second, this method should effectively manage a large, multi-resource, and heterogeneous data set, as well as extract beneficial information. Third, flood risk must be conveniently analyzed from different aspects, such as flood propagation, impact, and vulnerability. The other equally important point is to provide sufficient fine-grained information (e.g., impact or vulnerability of a selected relic) in an intuitive manner to analyze flood risk, thereby enhancing decision-making within a limited time.

Fig. 1 shows our approach, which implements the aforementioned goals based on the complete consideration of the distinct characteristics of cultural heritage sites, as well as supports flood risk identification, assessment, analysis, and treatment in an intuitive and convenient manner. Our visual analytics approach comprises two parts and three scales. The first part is the visualization of the predicted flood peak flow on the basin-scale level based on the flood prediction model. This part represents the temporal distribution of the predicted flood peak flow of the river cross-sections in cultural heritage sites. The second part is the visualization of flood propagation based on flood simulation results to analyze impact and vulnerability on a fine-grained level on the site- and relic-scales. The overview of all visualizations is shown as Fig. 2.

3.2. Visualization of the predicted flood peak flow

The first step in flood risk management is to identify a risk event, which is the basis of risk analysis and treatment. To identify risk events and buy time to take risk mitigation measures, the flood peak flow must be predicted as early as possible. Fortunately, experts have developed a prediction model that forecasts the flood peak flow of river cross-sections near cultural heritage sites based on the precipitation of basins. This prediction model is based on the geographical location and topography of the entire basin. A basin can be divided into several runoff sections based on its topography. Topographical features, such as rainfall conditions, precipitation, and runoff, are used as basis to develop a prediction model that calculates the relationship between precipitation and flood peak flow [26]. In our case study, the entire river basin (i.e., from north to south) is divided into three sections in light of different geographical locations and topographies in the prediction model. Flood experts studied the flood peak flow discharge of the three sections by principally employing an instantaneous unit hydrograph method [27] and a rational formula method of small watershed flood peak discharge [28] accessorily. Thereafter, the correlation between flood peak flow discharge and rainfall is obtained by data fitting combined with the history of rainfall data since 1951 from local meteorological monitoring stations. In general, the correlation between flood peak flow discharges exhibits an exponential function. In the current study, the correlation between flood peak flow discharge and rainfall evidently exhibits a linear function. The main reason for this result is that the spatial distribution of rainfall in the basin is extremely uneven. Another cause is that the terrain slopes gently in the middle section, where substantial rainfall infiltration is observed. Consequently, the formula between flood peak flow discharge and rainfall is $y = ax + b$, where y is the flood peak flow discharge of the cross-section near a cultural heritage site and x is the amount of rainfall of a section. Parameters a and b take different values for the different sections. One monitoring station will be established in each section to collect the rainfall data. Data on precipitation and time of collection are used as input data for the aforementioned formula. By contrast, the flood peak flow of a river cross-section near a cultural heritage site is calculated as the output of the prediction model. In addition, the predicted arrival time of the flood peak flow can be calculated. In the prediction model, the flow velocity of a river is assumed constant and equal to the maximum velocity of the river flow. Thus, the fastest predicted arrival time is obtained by dividing the distance from the section to a cultural heritage site by the velocity of the maximum flow.

Another significant note is that the prediction model presents relative uncertainty. The flood peak flow is decided by rainfall and substantially influenced by the temporal spatial distribution of rainfall. The flood peak in the downstream cross-section is equal to a superposition of the peak flows of all upriver sections. Rainfall from the upper to the lower reaches results in a considerably larger flood peak flow than that from the lower to the upper reaches. Rainfall from the upper to the lower reaches evidently leads to significant superposition at the downstream cross-section. However, the type of rainfall cannot be identified because the rainfall season is not entirely over. Consequently, the superposition of the flood peak flow at the downstream cross-section is uncertain when the model predicts the flood peak flow. Therefore, the model provides two formulas to predict the worst and normal situations.

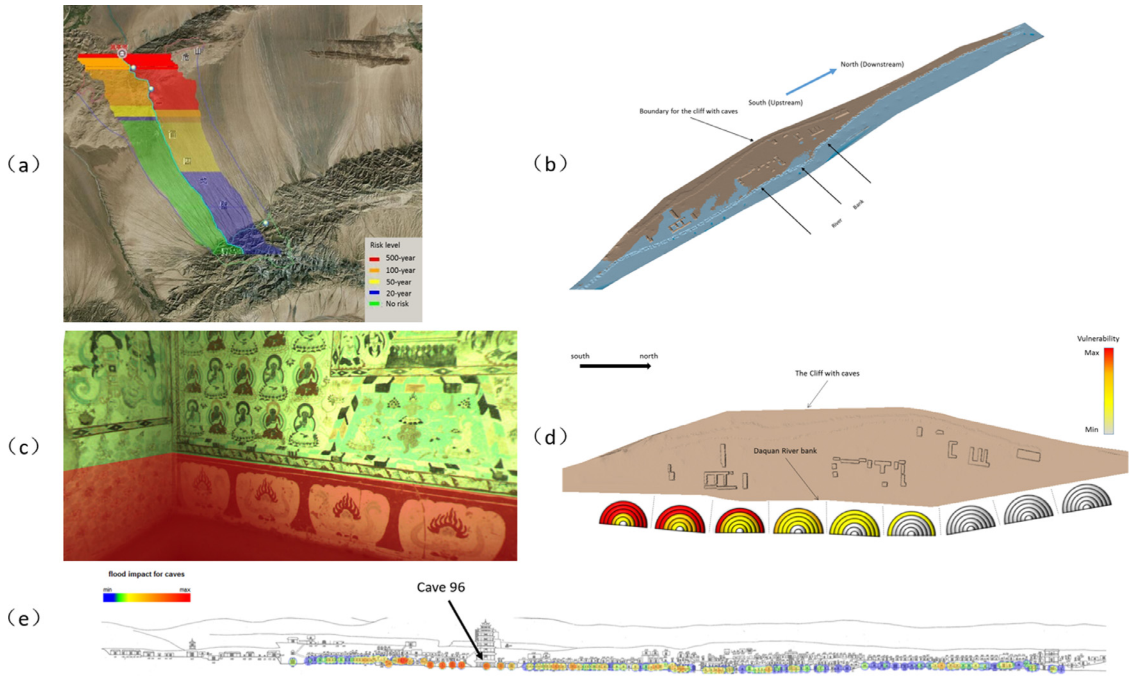

Fig. 2. Overview of all visualizations in the proposed visual analytics method. (a) Visualization of predicted flood peak flow based on GIS and aggregated bars. (b) Visualization of flood propagation based on 3D terrain model and color map. (c) Visualization of flood impacts to flood on cave level by panorama view. (d) Visualization of vulnerability based on concentric half rings plot. (e) Visualization of flood impacts on multi-cave level based on heat map.

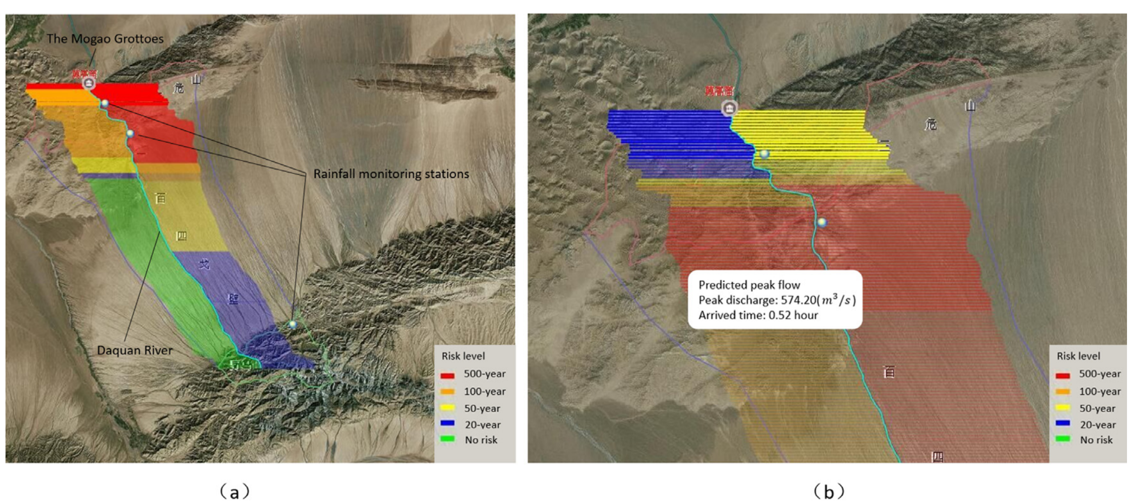

Fig. 3. Uncertainty-aware visualization of the temporal distribution of the predicted flood peak flow based on GIS on the basin scale. (a) Overview of the flood peak flow visualization. (b) Zoom-in view to show the horizontal aggregated bars.

Visualization of the predicted flood peak flow is designed to depict the peak flow and its uncertainty. Flood peak flow for every moment is visualized through the aggregated bars, which are two horizontal bars that are in opposite directions to each other. These bars share the same starting point in the river (see Fig. 3 (b)). In Fig. 3(a), three white points on the GIS map represent the rainfall monitoring stations for the three sections; the cyan ployline in the middle of the GIS map represents the river. The bars on the right and left sides of the river represent the worst and normal situations, respectively, which are calculated by the proposed model. We did not select the box plot to express uncertainty because we believe that the current design can visually compare the worst and normal situations. The length of the bar represents the amount of peak flow discharge. Risk levels are encoded using different colors. In the present case study, the flood risk level is divided into four levels, namely, ordinary, relatively serious, serious, and extremely serious. The thresholds for the risk level of the flood peak flow are evaluated based on the extent of damage to cultural heritage sites due to historical flood, as well as the experiences of experts. The thresholds are defined in terms of flood frequency, that is, different flood frequencies correspond to varying amounts of river flow discharge. For the Mogao Grottoes in our case study, 500-, 100-, 50-, and 20-year frequency floods correspond to flow discharges of 510, 330, 230, and 139 m^3/s, respectively. Flood with a peak flow under a 20-year frequency poses no risk and is encoded in green. Flood with a peak flow between 50- and 20-year frequencies is at the ordinary risk level and encoded in blue. Flood with a peak flow between 100- and 50-year frequencies is at the relatively serious risk level and encoded in yellow. Flood with a peak flow between 500- and 100-year frequencies is at the serious risk level and encoded in orange. Lastly, flood with a peak flow beyond a 500-year frequency is at the extremely serious risk level and encoded in red. For consistency with the conventions used by experts, flood frequency is used in the legend to express risk level instead of risk severity. All bars are rendered along the river on the GIS map. Each bar represents a specific flood peak and the position of the bar can be considered the geolocation of the flood peak flow in the river. Thereafter, the distance from the position of the specific flood peak flow to a cultural heritage site can be measured automatically by GIS. In addition, the flow velocity of the river is 6–8 m/s. For security reasons and simplicity of calculation, flood experts assume that the flow velocity is constant and equals the maximum velocity of 8 m/s. Accordingly, the arrival time of a specific flood peak can be calculated by dividing the distance from the current position to the site by the maximum flow velocity. Moreover, the distance from the upstream area to the site is fixed because the river channel is fixed. If the flow velocity is considered constant, then the arrival time for the peak flow from the upstream area is a fixed value. In this case, the arrival time from upstream to the site is approximately 2.5 h. Thus, the bar in the start location of the river represents the flood peak flow after 2.5 h, whereas that in the middle represents the flood peak flow after 1.25 h, and so on. Hence, this design represents the geolocation distribution of flood peak flow and interprets the temporal distribution of flood peak flow by geographical information based on arrival time. In practice, site managers can conveniently estimate the arrival time through the geolocations of flood peaks because they are generally familiar with the geographical situation around the cultural heritage sites. From the aspect of arrival time, all bars along the river aggregate to a colored ribbon that represents the temporal distribution of flood peak flow in the next several hours (see Fig. 3 (a)). When the mouse is moved over the bar, a pop-up message box is displayed to show detailed information.

3.3. Design of the simulation scene pool

The second part of the visualization of flood propagation, impact, and vulnerability is based on the simulation results. The pool is a large database of pre-simulated flood scenes, which are calculated using a hydrodynamic 2D flood simulation engine. In the current study, the MIKE21 hydrodynamic model [29] is used to simulate the flood water level change process in cultural heritage sites. The MIKE21 hydrodynamic model has been applied in numerous studies as a general numerical modeling system to simulate water levels and flows in bays, estuaries, and coastal areas. In this model, the alternating direction implicit (ADI) technique and finite difference method are employed to solve the equations for mass and momentum conservation in the space–time domain. Terrain data and hydrodynamical boundary conditions are the main input data for this simulation model, whereas water surface elevation, flow velocity, and the direction of each grid are calculated as output data.

Our case study of the Mogao Grottoes, which illustrates the design of the flood simulation pool, yielded three types of flood risk events for this site: dike overflows, dike breaches, and heavy rains. The model features and input boundary conditions of each type of risk event are varied to build various flood scenarios. The design of the pool is shown in Fig. 4. Given that the flood peak flow have four risk levels, the maximum, average, and minimum values of the thresholds for each risk level are selected. Five event durations are selected based on historical records and from the experiences of the experts. Consequently, 12 possible flood peak flows and 5 overflow durations are selected to simulate the dike overflows. For dike breaches, the 1 km-long river bank of the Mogao Grottoes is divided into 10 sections. Thus, 10 breach positions and 5 possible breach widths are selected to simulate 12 flood peak flows and 5 breach durations. For heavy rains, 12 different precipitation rates and 5 heavy rain durations are simulated. A total of 3120 different pre-simulated flood scenes are included in our pool. The parameters of the flood scene mainly define the hydrodynamical boundary conditions as the input data of the simulation model. Another input data, namely, terrain data, are decided by simulation scope. The simulation scope in this study is limited within cultural heritage sites. Thus, an entire cultural heritage site is partitioned into over 270,000 triangular meshes. The mesh mode is also provided to the simulation model as input data.

3.4. Visualization of the flood propagation

Flood disaster cannot be avoided; thus, we can only reduce its impact by taking the proper and timely measures. For cultural heritage sites, managers must opt for the most cost-effective measures to protect significant historical relics on account of the limited time and sources. Thus, managers must know the key points or weak locations for flooding in the site when they make decisions. Thus, a tool to intuitively analyze the flood propagation process is necessary.

This study opts to aggregate the color map of the water level onto the 3D terrain model of cultural heritage sites to visualize the frames of the time step of flood propagation (see Fig. 5). Given the predicted flood peak flows as input conditions, the water surface elevations for each time step in the site can be obtained through pre-simulation. Thereafter, the cells of the 3D terrain model of cultural heritage sites are rendered in different colors to express water levels based on the different water surface elevations of each cells vertices. The blue areas represent those that have been inundated, while the shades of blue represent the depth of water.

Users can realize each time step of spatial distribution of the water level in the site to explore the flood propagation process through user interaction by operating the timeline scrollbar. The frame-by-frame display through animation enables users to understand the possible dynamic process of floods inundating a site. Moreover, users will be able to determine the key points or weak locations by exploring the flood propagation process. This type of information is beneficial for site mangers in formulating emergency response plans and measures.

3.5. Visualization of the flood impacts

Flood impact on cultural relics is another significant factor that site managers should consider when they assess, analyze, and treat flood risks. The impact of flood is considered the damage inflicted by flood water inundating historical relics. In a few emergency situations, a cultural heritage site can be partially submerged but with minimal damage to significant cultural relics. However, managers should completely assess the impacts on each important relic prior to making their decisions. Our method provides visualization tools to assess and analyze the flood risk impact for relics at the fine-grained level from two different scales. In this study, ancient caves and mural paintings on their walls are the most precious history relics of the Mogao Grottoes. Thus, we take caves as the unit of cultural relics for risk impact assessment.

Our method provides two scales with which to visually analyze the impacts. The first scale is the visualization of flood impacts on the multi-cave level. In this level, our method employs a heat map to visualize the impacts of flood on multiple caves given the relative position of each cave (see Fig. 6). The heat map view uses the orthophoto map of the cliff facade as the base map. The dots with different colors on the base map represent the flood risk impacts of caves, while the colors of the dots indicate the degree of damage. The orthophoto map is long and narrow; thus, focus + context

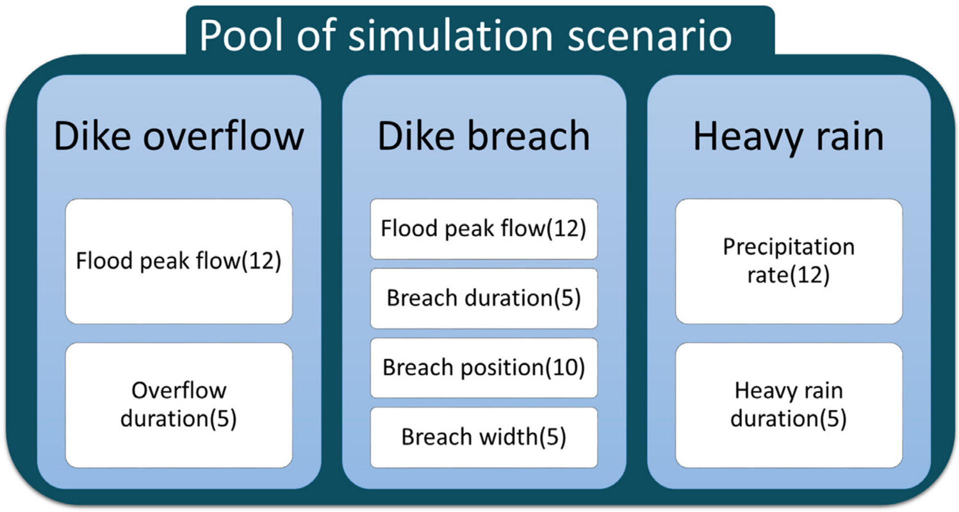

Fig. 4. Design of simulation scene pool.

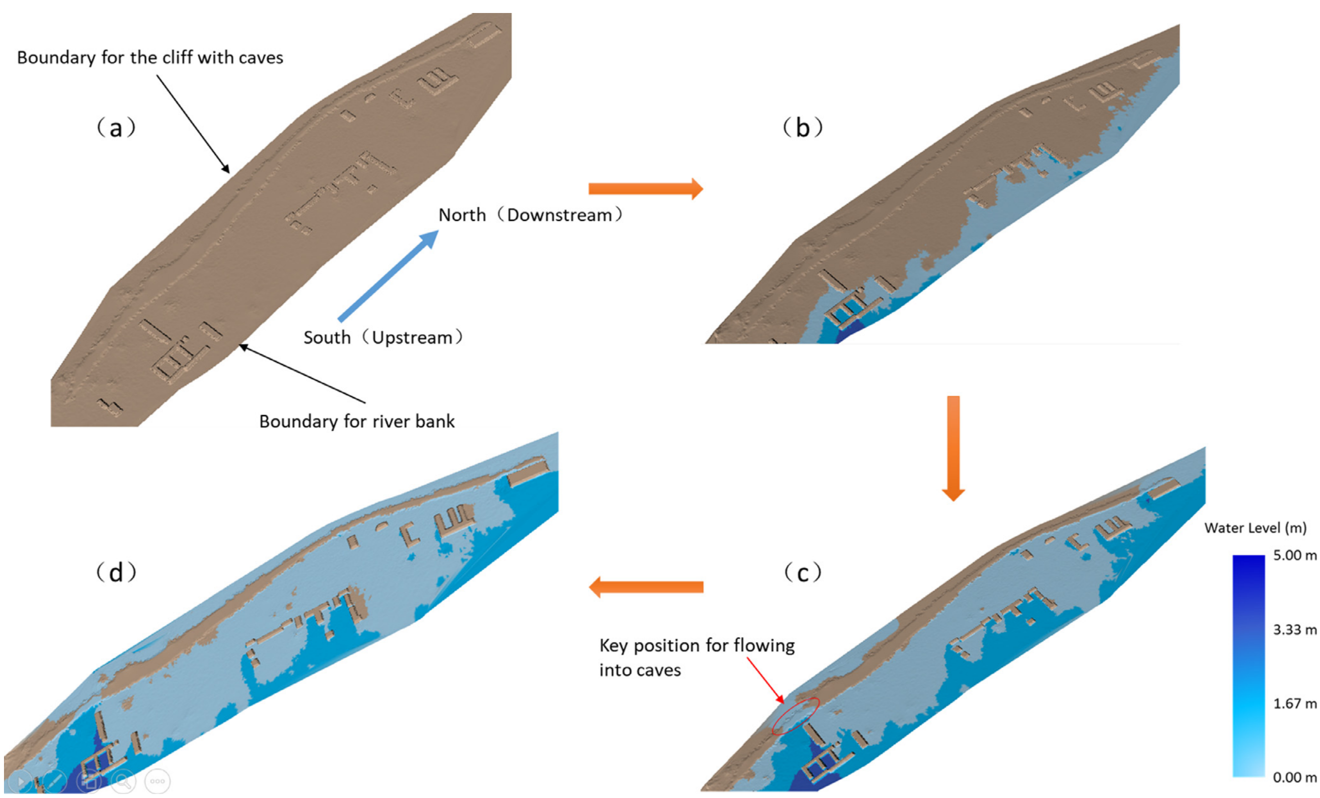

Fig. 5. Visualization of the flood propagation on the site level. Users can view the spatial distribution of water levels in the site for each time step to explore the flood propagation process through user interaction. (a) 3D terrain model for the cultural heritage site without water. (b) Water level distribution of the cultural heritage site after a 500-year frequency level flood that lasts 0.5 h. (c) Water level distribution on the site after a 500-year frequency level flood that lasts 1 h. (d) Water level distribution on the site after a 500-year frequency level flood that lasts 1.5 h.

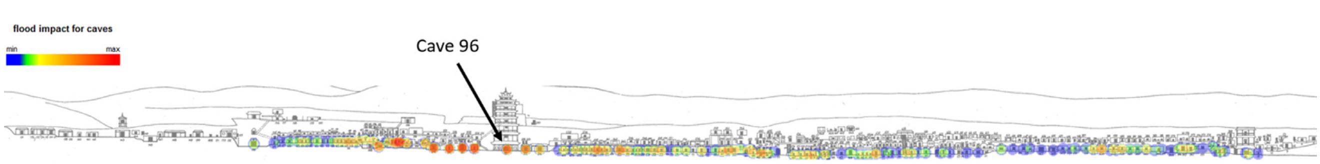

Fig. 6. Visualization of flood impacts at the multi-cave level. Impact to each cave is visualized on a heat map that uses the orthophoto map of the cliff facade as a base map.

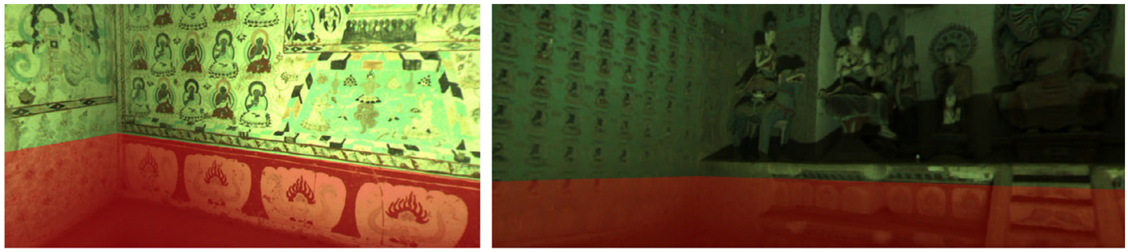

Fig. 7. Visualization of flood impacts to flood on the cave level. Users can understand the internal inundating situation for each cave through an immersive manner. (a) Internal submerging situation of cave 351. (b) Internal submerging situation of cave 356.

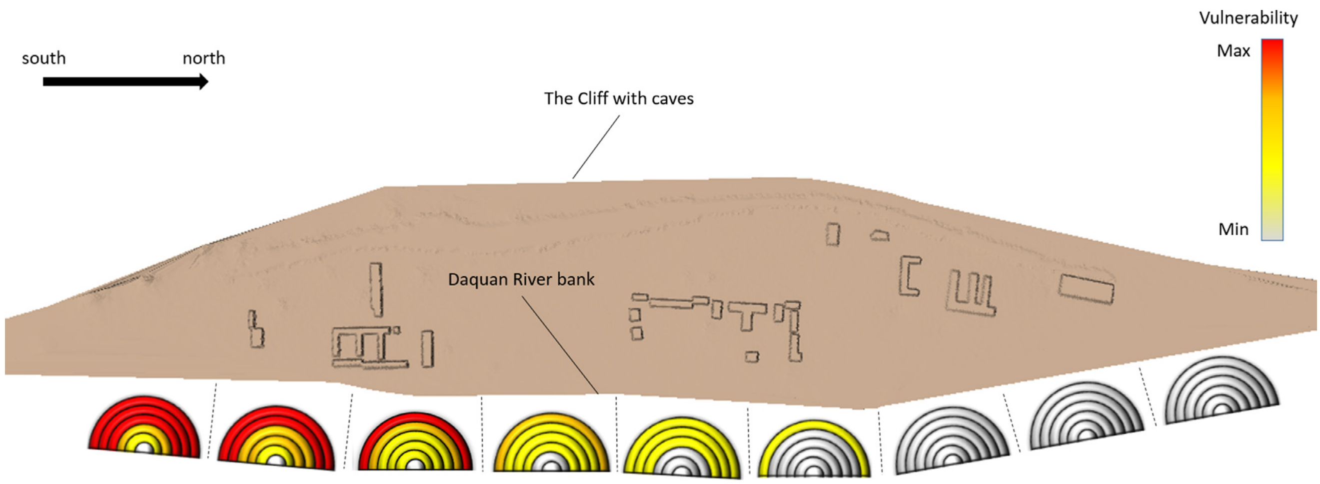

Fig. 8. Visualization of vulnerability to dike breaches. For a selected cultural relic (e.g., selected cave with mural paintings), the vulnerability to different breach positions and widths is visualized through the concentric half ring plot.

visualization is also applied in the heat map view to provide users with detailed information with the context information.

The heat map view can only provide relatively coarse information on flood impact for a single cave. However, every cave and its mural paintings is different; thus, the value of each cave is different. The value of mural paintings on different walls or positions is likewise different. Therefore, site managers should know substantially detailed information on the damage of a specific cave. In our method, the detailed information of flood impact for a single cave is visualized through a cave-level panoramic view (see Fig. 7). The submerged areas of the walls are marked by red in the panoramic view based on the water level of the cave. Users can explore the panoramic view to realize which mural paintings on the walls will be damaged by flood. Through panoramic visualization, users can accurately and intuitively assess the impacts for the caves of interest. This visualization technique can be relied upon for decision-making.

3.6. Visualization of the vulnerability of cultural relics

Vulnerability is another significant aspect of flood risk analysis. Vulnerability is defined as the degree of exposure to flood risks. Vulnerability analysis will enable us to obtain information with respect to which level of flood risk can threaten a selected object. This study focuses on visualizing the vulnerability of cultural relics to dike breaches. Accordingly, visualizing vulnerability to dike breaches is represented by a plot of concentric half rings along the actual river bank in the 3D site model (see Fig. 8).

In this visualization, the possible breach widths for every possible breach position are visualized along the side of the river bank by using the concentric half ring plot. Each half ring of a concentric half ring corresponds to a breach with varying breach widths in the same breach position. The diameter of the half ring corresponds to the width of the breach. The breach position corresponds to the positions of the concentric half rings. The orientation of the concentric half rings follows the actual contour of the river bank at the corresponding positions. The vulnerability of a selected relic to particular breach widths and positions is represented by the color of the corresponding half rings.

4. Case study

4.1. Study background

Our study context focuses on the Mogao Grottoes, also known as the Mogao Caves or Caves of the Thousand Buddhas. This World Heritage site is located 16 miles southeast of the center of Dunhuang, an ancient oasis city located at a religious and cultural crossroad on the Silk Road in Gansu Province, northwest China. The Mogao Grottoes is distinguished by its exquisite murals and sculptures of Buddhist art spanning a period of 1000 years. This site was built and rebuilt from the period of the Sixteen Kingdoms to the Qing Dynasty after the first caves were built in 366 CE. At present, 735 caves are found in the Mogao Grottoes, as well as 45,000 m2 murals and 2415 painted sculptures.

The Daquan River flows by the front of the Mogao Grottoes from south to north. This river is a small inland river that originates from the southern side of the Qilian Mountain. Given that the geographical location and topography of the entire Daquan

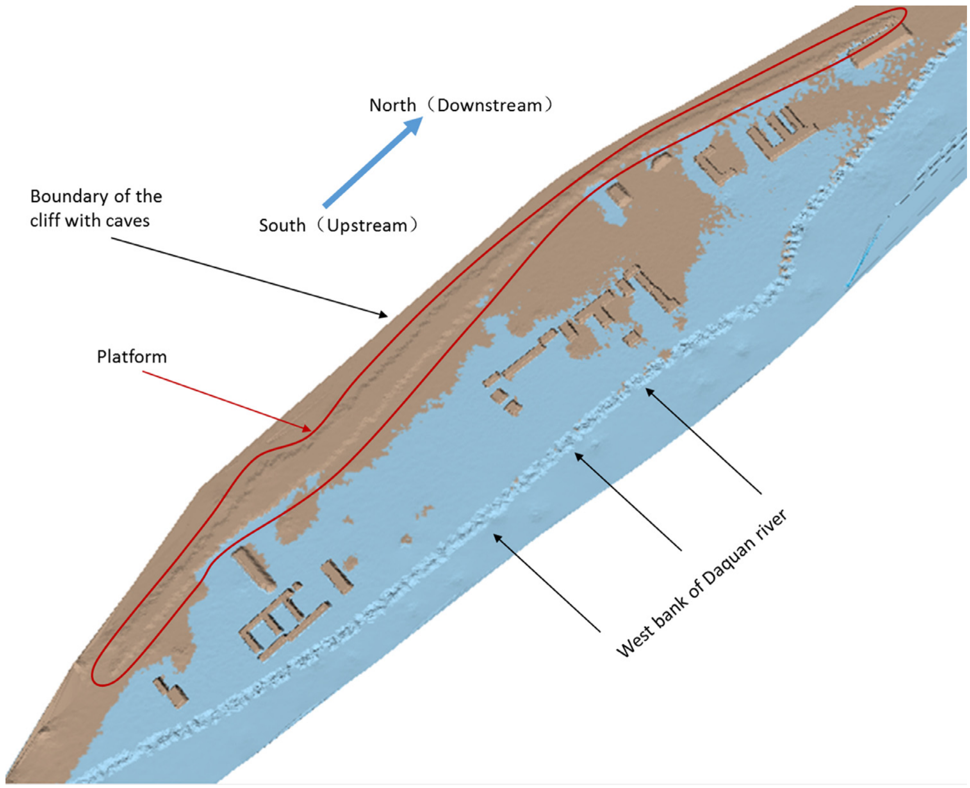

Fig. 9. Flood impact analysis of cultural relics. The Daquan River spills over its bank and water begins to flow into the site when flood exceeds the 100-year frequency level. However, the flood cannot affect the caves because the platform prevents the water from flowing in. The platform is marked by a red line in the figure.

River basin are special, the distribution of annual rainfall on the basin is extremely uneven, and the amount of precipitation shows an evidently decreasing pattern from south to north. The basin can be divided into three runoff sections from south to north. The southern section is the source of the basin, which belongs to the Yema Mountain. In this section, the amount of rainfall is high but evaporation is low. In addition, vegetation is poor and the area is dotted with high mountains and steep slopes. The middle section of the basin is in the Yibaisi Gobi Desert. The amount of rainfall is relatively low and vegetation is normal. The terrain gently slopes in this section. The northern section downstream of the basin is in the Sanwei Mountain. Rainfall in this section is limited but evaporation is strong. Vegetation is poor and the terrain is relatively steep. The superposition of all peaks of the three sections is the total flood peak in the cross-section of the Mogao Grottoes in the Daquan River.

4.2. Flood impact and cave vulnerability analysis for the Mogao Grottoes

Flood risk analysis for cultural heritage involves two aspects. First, the impact on cultural relics is analyzed. Through the visualization of simulated water surface elevations, we know that flood in the 100-year frequency level does not threaten the cultural relics of Mogao because flood cannot spill over the dike of the Daquan River. However, if flood exceeds the 100-year frequency level, then water will spill over the river dike and flow into the cultural heritage site. Fortunately, the cliff where the caves with mural paintings is located is dozens of yards away from the bank of the Daquan River. In particular, a long platform along the cliff has been built to prevent flooding. This platform is only 60–80 cm high, but it can effectively prevent water from reaching the caves. Thus, flood does not threaten the caves and mural paintings even if water flows into the site (see Fig. 9). If flood reaches the 500-year or above frequency level, then a significant amount of water will reach the site and inundate the top of the platform. The water flow into the caves and their mural paintings will be damaged by flood water. Theoretically, water should not flow into the caves above the second floor. By contrast, the impact for every cave on the bottom floor is different because of the geographical positions of the caves. In general, the entire terrain of the Mogao Grottoes site tilts from south to north. The cliff undulates based on the terrain and winds along the river. The heat map (see Fig. 6) shows the impacts of the caves on the bottom floor for the flood scenario at the 500-year frequency level and 2.5 h duration. The heat map shows that the impact distribution is inconsistent with the upstream to downstream orientation. The caves that suffer considerable damage are mostly located south and middle of the cliff. In particular, several caves on the south side of cave 96 are the most severely damaged caves. By exploring the cave-level panoramic views (see Fig. 7), most parts of the wall paintings of these caves will be damaged due to submersion in flood water. One reason for this result is that the elevation of the terrain surface of the area near cave 96 is lower than the other terrains around this area. In addition, careful observation of the relative position of the caves from the heat map will reveal that the position of these caves is extremely near the ground.

Another aspect of risk analysis is vulnerability. For a selected cave, the vulnerability to different breach positions and widths is different. This difference is mainly due to the relative positional relationship between the cave and breach position. For a selected cave located in the middle of the cliff, the breaches located on the south of the river bank are evidently dangerous to the cave, whereas those on the north of the river can hardly threaten the selected cave (see Fig. 8).

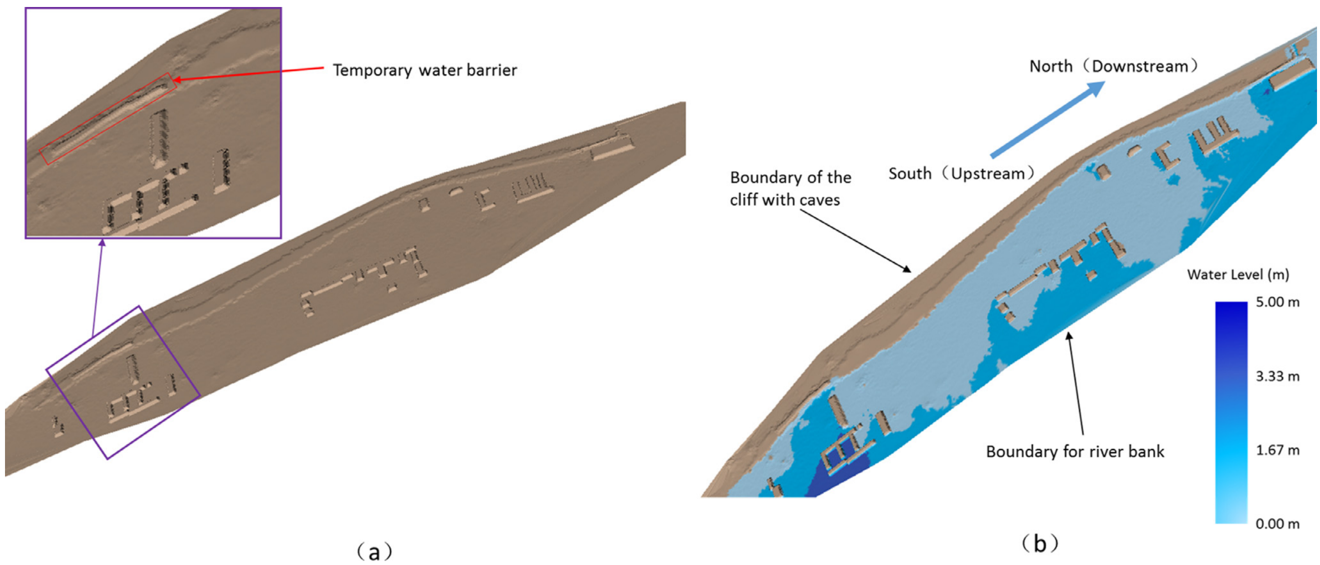

Fig. 10. Decision-making support to flood risk mitigation. (a) Temporary water barrier is added on the key position as a risk treatment measure. (b) Water level distribution on site after the 500-year frequency level flood that lasts for 3 h by implementing the risk treatment measure.

4.3. Decision-making support to flood risk mitigation

The risk of flooding is unavoidable; thus, selecting the appropriate measures within a limited time is significant. Our method can facilitate the process of formulating emergency response plans and measures. By utilizing the visualization of the water level with the color map, users can determine several key positions by exploring the flood propagation process. If the flood risk is at the 500-year frequency level, then water crosses the platform and flows into the caves after flooding that can last for 1 h (see Fig. 5 (c)). However, note that water only spills over the platform in one specific position (the key position is marked by a red circle in Fig. 5 (c)). Fig. 5 (d) shows that the entire area on the northwest side of the platform has been inundated completely after flooding that can last for 1.5 h . This result means that water has flowed into all bottom caves and directly damaged the wall paintings. However, most parts of the platform have yet to be inundated at this time. Water can only spill over the platform and access the caves through the aforementioned key position. Thus, building temporary water barriers at this position may be a sensible risk treatment measure. We reassess the effectiveness of this measure by adding an 80 cm-high water barrier at the key position on the platform (see Fig. 10 (a)). Fig. 10 (b) shows the water level distribution on site after a 500-year frequency level flood that lasts for 3 h by implementing the treatment measure. The temporary water barrier can definitely prevent water from flowing into the caves for over 3 h in the case of the 500-year frequency level flood. The mean flood duration is 3 h based on the historical records of flooding in recent decades. Thus, this mitigation measure can generally avoid the direct impact caused by the 500-year frequency level flood. Site mangers can formulate substantially effective response plans to build optimized water barriers at the proper positions. During the decision-making process, users can also assess the effects of the measures of response plans through the visualizations of flood impact and cave vulnerability if they need additional detailed information.

5. Evaluation

The proposed method is developed based on the requirements of experts through a series of dedicated workshops. Accordingly, they identified the significant historical relics to be protected. They also developed the flood prediction model and provided the terrain and building data of the cultural heritage site. These experts comprise two specialized teams: one team comprises managers of cultural heritage and the other is composed of water experts. These experts participated in the evaluation as well.

The first step of the evaluation is to introduce our visual analytics method to the experts. Thereafter, they are asked to evaluate the proposed method from seven aspects, namely, visual design, aesthetics, interaction, understandability, usability, functionality, and decision support. The evaluation results is shown in Fig. 11. The bar chart shows the average scores of the seven aspects for all visualizations. The average score for the understandability of the flood peak flow visualization is very low because site managers consider such visualization process difficult to understand. They explain that this process is considerably complicated for non-professionals; thus, the visual design should be simplified. Nevertheless, the water experts can correctly interpret the visualization and understand the encoded uncertainty of the peak flow. Moreover, the visualization of flood propagation using the 3D terrain model is regarded as a substantially valuable tool for decision-making. The experts can analyze the flood propagation process in an intuitive manner and determine the key or weak positions to formulate considerably effective response plans, thereby reducing or avoiding damage to the caves and mural paintings. Moreover, the visualization of flood impact and relic vulnerability is considered practical and beneficial when the experts need detailed visual evidence to make decisions. However, visualization obtains a relatively low score on the interaction aspect. Most experts thought that the interactive nature of our method should be more functional and additional interactive options in the method should be provided.

In summary, all experts agree that all visualizations in our method are appropriate and comprehensible with the exception of the uncertainty-aware visualization of the flood peak flow, which is challenging for non-professional users. Moreover, two teams of experts consider our method beneficial for risk analysis and decision-making. Compared with the traditional risk map method applied in cultural heritage sites, our method is a systematic and integrated system that can support all processes of risk management, provide detailed and comprehensive risk information, and is considered a powerful risk analysis function to risk managers.

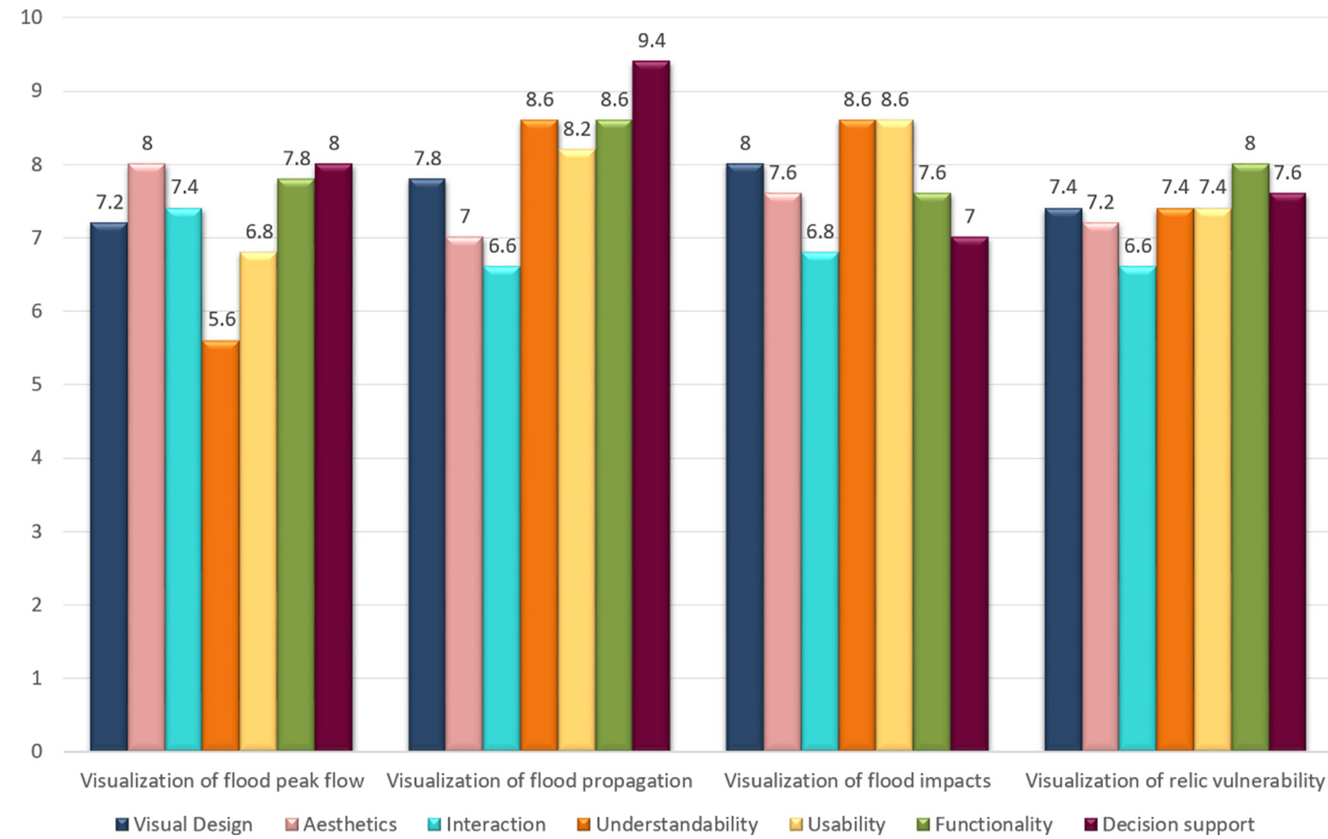

Fig. 11. Evaluation results. Bar chart shows the average scores of the seven aspects for all visualizations in the method.

6. Conclusions

This study proposes a visual method to support flood risk identification, analysis, and risk mitigation for decision-making. Visualization of flood peak flow is presented to analyze the temporal distribution of peak flow on the GIS map based on the flood prediction model. Our method also provides visualization of flood propagation using a colored map aggregated on the 3D terrain model, which is beneficial in formulating emergency response plans. Visualizations of flood impact and relic vulnerability provide users with the ability to assess the risks on a fine-grained level. In addition, two case studies demonstrate that our method is available and valuable for flood risk analysis and decision-making related to cultural heritage sites. Lastly, water experts and site managers analyzed the proposed method and provided us several beneficial comments and recommendations.

Acknowledgments

The authors thank Mingming Wang for discussing with us. We also appreciate Xudong Wang, Bomin Su, Xiaowei Wang, Qinglin Guo, Wanyu Zhu, Zongren Yu, Shujun Ding, Tianxiu Yu and all the Dunhuang Academics. They not only provide us the flood prediction model, monitoring data but also give us helpful suggestions and comments. We also thank the anonymous reviewers in that their suggestions and comments are really constructive for our work and paper. This research was sponsored in part by the Chinese National Science and Technology Support Program through grants 2013BAK01B05.

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