Dear Dr. Xing Yuan

We are grateful for the constructive comments from the referees, and for your encouragement to revise this manuscript to be considered for publication in Hydrology and Earth System Sciences. We believe that this paper makes important novel contributions to the modeling of dynamic exposure to floods in city-regions and is of interest to the hydrological and geographical community. All comments from you and the referees are fully addressed point by point as listed below, and all of the changes are tracked in the main manuscript. The tracked manuscript is attached at the end of this document.

If any further information is needed, please don't hesitate to contact us.
Yours Sincerely

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Reply to Editor

Comments:

Point 1: To have this work more impactful, please provide solid evidences (or added values) on the necessity of using high-resolution dynamics exposure model, this could either be addressed in the introduction, or the result and discussion sections.

Reply: We have revised the manuscript to highlight the importance of using high-resolutions dynamic exposure simulation on urban disaster risk management. The following texts have been added in the manuscript:

"Urban flooding exposure is generally investigated with the assumption of stationary disasters and disaster-bearing bodies during an event and thus cannot satisfy the increasingly elaborate modeling and management of urban floods."

"With respect to spatial considerations, the currently implemented method for estimating disaster exposure adopts administrative boundaries of socioeconomic data, which are organized as research units (Yin, 2009). Natural elements with higher spatial resolutions are compromised due to the lower spatial resolution of human elements, such as population (Yang et al., 2013). Consequently, a comprehensive and sophisticated geographic research unit has not been established, resulting in simulation results applicable only to macro planning and decision making. The estimation of disaster exposure therefore needs to incorporate greater spatial heterogeneity and resolution."

"At the micro timescale, disaster-causing factors and disaster-bearing bodies represented by populations vary constantly. On one hand, spatiotemporal changes in disaster-causing factors (e.g., rainfall) result in corresponding dynamic changes in the characteristics of urban flood disasters (e.g., water depth and velocity). On the other hand, daily travel activities of urban residents, such as commuting between residential and work or study areas, cause a dynamic spatiotemporal distribution of the population. Exposure to urban flooding changes dramatically over a short period of time. To avoid or reduce disaster risks, casualties, and property losses, different individuals are likely to adopt different adaptive behaviors, such as delaying or canceling travel plans, whereas the government is likely to adopt organizational actions such as issuing warnings and evacuating residents (Wan and Wang, 2017; Parker et al., 1995). The dynamic simulation of exposure therefore requires dynamic space–time simulation of variations in the disaster event, disaster-bearing bodies, and their interactions."

"This study presents the first fully formulated method for dynamic urban flood exposure simulation with high spatiotemporal resolution. The quantitative results of this study can provide fundamental information for determining urban flood disaster vulnerability, assessing socioeconomic losses, managing urban disaster risk, and establishing emergency response plans."

"*Exposure simulation is a useful tool for estimating disaster vulnerability and assessing losses, and the quantitative results under different scenarios of this study are likely to benefit relevant government agencies in assessing risk, issuing warnings, and planning emergency responses to urban natural disasters. In particular, considering the dynamic distribution of the population during a flood disaster, a more reasonable migration measure can be taken to minimize casualties.*"

"*The method proposed can provide the government with high resolution dynamic exposure of the population, roads and buildings to flooding as well as information for urban vulnerability and loss assessment, and can support government disaster risk management. It could further provide effective reference information for residents' travels.*"

Point 2: For those comments you have not addressed directly, please try to add discussions in the manuscript, e.g., uncertainty in the model or method, the implication of the results.

Reply: The previous reply to referees has been further improved to clearly address or discuss all referees' comments. Specifically, the possible uncertainties associated with this model were introduced in the conclusions. Please refer to Point 10 in reply to Referee 2. As for the implication of the results, please refer to Point 1.

Point 3: Please check the clarification of models/methods and proofread the manuscript carefully, and ask for help from senior authors if necessary.

Reply: We have added the clarification of models in Sections 3.1, 3.3, and 4. Efforts were also made to improve the readability of the paper. Spelling errors were corrected and the references were updated. We believe this manuscript has made significant improvement compared with the previous edition.

Reply to Referee #1

Comments:

Point 1: The modeling results (e.g., in lines 17-21) are very usual. They can even be obtained from intuitive reasoning, without building the complicated model as presented in this paper. I would suggest the authors present the modeling results that could really support the unique contribution of this paper (e.g., high resolution, dynamics exposure), especially those that cannot be obtained without high resolution model. Otherwise, we cannot see the benefit of building such model.

Reply: The agreement of the modeling results and the intuitive reasoning is not the weakness of the model, but an indication that the model's soundness. It would be a concern if the model's results are against the intuitions. The strengths of the model lie in the quantitative analysis of the disasters and exposure under different scenarios for risk assessment and management. Considering the dynamic distribution of population, a more reasonable migration rescue measure can be taken to minimize casualties. Figures 13 and 14 show dynamic exposure results, which cannot be derived by intuition alone.

The following text has been added at the beginning of Section 4.3:

"*The spatial and temporal resolutions of the modeling results could be adapted to the study area. The area of the minimum block was 2731.64 m2. The temporal resolution of the results was 30 minutes, which could be set to 10 minutes or even 1 minute according to need.*"

Point 2: Line 39, the term "disaster-pregnant environment" is rarely used in English scientific publications. Please change it to some commonly used term. It would be better to let some native English speakers proof read the paper before resubmission.

Reply: Agreed and amended. The term "*disaster-pregnant environment*" has been changed to "*disaster-prone environment*".

Point 3: Lines 46-47, what is "index method"? Please provide some details.

Reply: Agreed and the following text and reference have been added in the introduction:

"The exposure index method is to select the natural, social, economic and other evaluation indices from the characteristics of the disaster-bearing bodies to establish the evaluation index system, determine the index weights by the analytic hierarchy process and expert scoring method, construct the evaluation system by using mathematical model, and obtain the exposures of the disaster-bearing bodies (Nasiri et al., 2016)."

Reference: Nasiri, H., Mohd Yusof, M.J., and Mohammad Ali, T.A.: An overview to flood vulnerability assessment methods. Sustain. Water Resour. Manag., 2: 331, https://doi.org/10.1007/s40899-016-0051-x, 2016.

Point 4: The daily routine is generated from survey. But the paper does not provide an introduction to the survey itself, such as how many people participated in the survey, the responders' age distribution and professions, etc. Please add some text to detail the survey in the paper.

Reply: Agreed and the following text has been revised in the manuscript:

"The datasets used in this study included a digital elevation model and river, road, building, population, and observation data consisting of river discharge and water level. Travel survey data were used to determine daily routines. Additionally, traffic flow and water accumulation data were used for validation. Table 1 describes the sources and uses of the datasets.

We randomly selected 500 residents in the study area to participate in a questionnaire survey on daily activities. We collected data on their social characteristics to distinguish population types. There were 100 people under 18 years of age, 300 middle-aged people (18-60 years), and 100 elderly people (>60 years). Employed people and males accounted for 55% and 50%, respectively. Lastly, 14% of the population had received higher education. The distribution of the above social characteristics was close to the actual population distribution in the study area."

Point 5: Section 3.2 reviews ABM in detail. The paragraph seems to be better fit in "introduction" section, instead of methodology section.

Reply: Section 3.2 and Section 3.1 are juxtaposed to introduce ABM for population distribution simulation and flood model respectively. Section 3.2 mainly introduces the current commonly used modeling technology, the concept and application of ABM, which shows ABM is suitable to the

modeling in this paper. Specific modeling method is described in Sections 3.3 and 3.4. Therefore, no modification or adjustment will be made for the time being.

Point 6: Line 211, classification of activities is confusing. What is the difference between leisure, recreation, and rest? Are there any literatures to justify this classification?

Reply: We have revised the manuscript to remove this confusion. "Recreation" refers to the activities in leisure places, away from the residential area (home). "Rest" is changed to 'at-home'. The following text has been revised in Section 3.3:

"*Activities were classified as work, study, recreation, shopping, at-home, and travel.*"

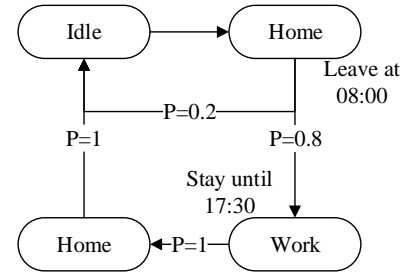
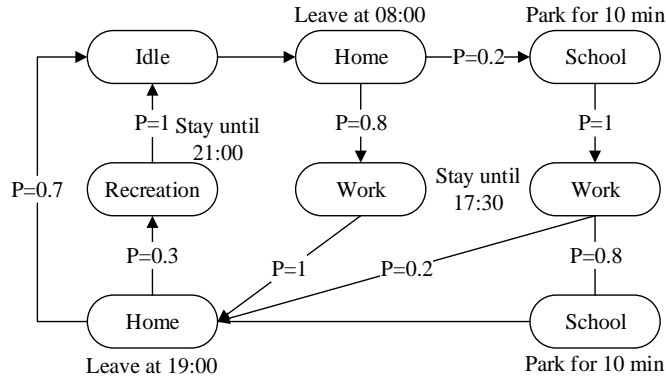
Point 7: Figure 4 emphasizes the daily routines for unemployed woman. Why these unemployed women go to school to drop children off?

Reply: This part of the probability is used to represent some unemployed women (housewives) who are responsible for taking their children to and from school. According to the survey, many housewives send their children to school, and then go shopping in supermarkets before going home. According to Point 8, we have changed it to adult male's daily routines.

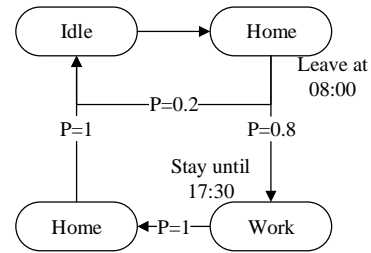
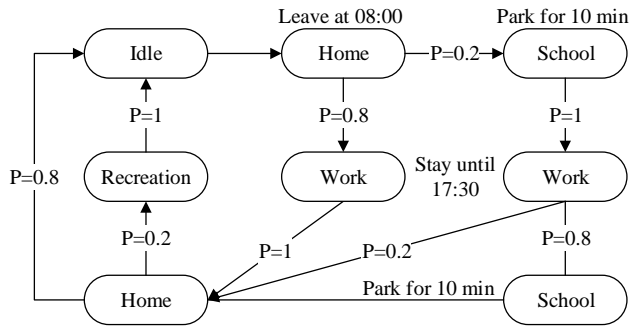
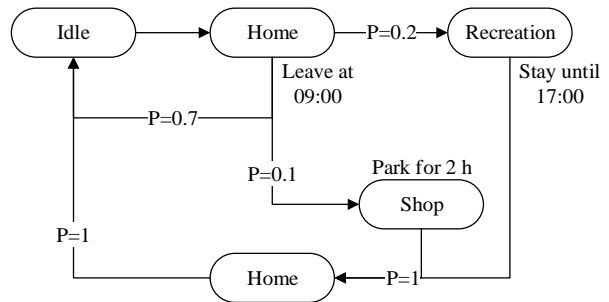
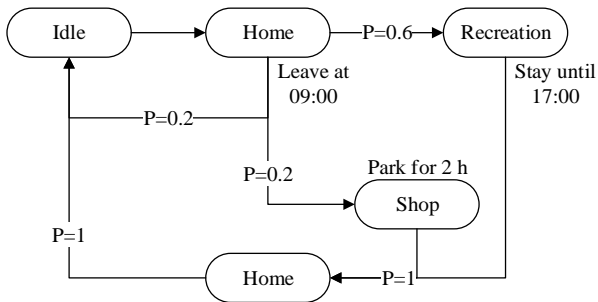
Point 8: The paper never mentioned the daily routine for unemployed man and employed person. However, it might be more important to talk about employed person, than unemployed women as in Figure 4.

Reply: Agreed and the following texts and figures have been revised in the manuscript:

"*Figure 4 presents an example of the synthetic daily routine of an agent with the following demographic characteristics: male agent, aged 18–60 years, and employed. In this example, the agent started the day at 8 am on a weekday and had a 0.8 probability of going straight to work, going home, and so on.*"

"*Figure 5 indicates activity patterns during different disaster scenarios for employed adult men who had received higher education.*"

(a) Activity on weekdays

(b) Activity on weekends

Figure 4. Synthetic daily routine generated from the travel survey and census data for an employed male agent aged 18–60 years.

(a) Bad weather (weekday)

(b) Warning (weekday)

(c) Bad weather (weekend)

(d) Warning (weekend)

Figure 5. Activity patterns for a highly educated, employed male agent aged 18–60 years during disaster scenarios.

Point 9: Please provide some introduction how the probability of agents' daily activities is generated (e.g., Figure 4).

Reply: During the survey, residents and activities were grouped into eighteen types (refer to Fig. 8 (a)) and six categories (refer to Point 6). We estimated the probabilities of all the activities of the population groups under investigation. For example, in Figure 4 (a), about 20% of people send their children to school before going to work, based on the survey data of the employed adult males.

The following text has been added in Section 4.1:

"*The probabilities of agents' daily activities were generated based on the travel survey. We estimated the probabilities of all the activities of the population groups under investigation.*"

Point 10: For agents' route choices (start from line 232), minimizing travel time does not mean the agents will choose the shortest path, because too many people choosing the same path might cause traffic jam. In addition, travel time also depend on number of driving ways on road and traffic condition.

Reply: Agree. At present, a simple but effective shortest path method is used in the porotype system. We will improve the human movements on roads in future.

The following text has been revised in Section 3.3:

"*Here, a simple but effective shortest path method was used. The classical Dijkstra algorithm is a single-source shortest path algorithm that provides trees of minimal total length and time in a connected set of nodes (Dijkstra, 1959).*"

Point 11: Figure 8 lists some daily scenarios and disaster scenarios. They are confusing. For example, scenarios 2, 5, 8, 11, 14 and 17 are all about traveling by car. Are there are any differences? If they are different, then what are the differences? If not, why they are classified as different scenarios?

Reply: We have revised the manuscript to clarify this part. The following texts have been revised in Section 4.1:

"*To reduce the number of agent types, only a limited number of agent classes were used. The distribution of population characteristics for Liandu District is shown in Table 4. The agents were divided into 18 types for daily (non-disaster) scenarios (S1, S2, S7, and S8) and 24 types for disaster*

scenarios (all other scenarios) based on the influence of education level on individual disaster response behavior (Fig. 8)."

"Figure 8. Agent types for daily and disaster scenarios. Daily scenarios refer to S1, S2, S7, and S8 and the rest are disaster scenarios."

Point 12: I do not see how you model agents' moving process on road. Are there any traffic models to simulate this process? How do you simulate the agents' moving from one place to another during floods?

Reply: We have revised the manuscript to clarify this part. The following texts have been added in Sections 3.3 and 4.3, respectively:

"We obtained the departure and destination block of each stage according to the activity patterns, and then calculated the shortest path consisting of a series of road sections. At each moment, the block in which the agent was located was calculated, e.g., if an agent was on the road, according to the variation in speed of its walking or riding on a bus or in a car, the road section where it was located was calculated. The same was done during flooding, except that the activity patterns were different."

"Additionally, no accurate traffic model was used to simulate agents' movements on roads. On one hand, it was for improving efficiency. On the other hand, we did not pay attention to high temporal resolution human movements (e.g., with precision to 1 minute or 1 second). We only focused on the population distribution for a specific period of time, and the temporal resolution requirement of human activities was therefore low."

Point 13: The first part of "Results" section, subsection 4.1, introduces model implementation and parameter setting. However, this subsection seems to fit better in methodology section since they are not related to modeling results.

Reply: Section 4.1 mainly introduces the block and agent generation results and exposure threshold. The results of the block and agent generation correspond to Sections 3.3 and 3.4, which vary according to the different study area and data. The block is the result of data processing in the early stage of modeling, and it is an important input data unit. The agent type and exposure threshold are parameters to be set. Therefore, the above three parts are listed separately in Section 4.1 of the result.

Point 14: Section 4.5 Validation is very confusing. Usually model validation appears in the first section of modeling results, to tell readers that the model/method has been calibrated and is reliable. I am not sure why the authors put it at the end of results section. Please explain this arrangement.

Reply: Agree. We have divided the original validation (Section 4.5) into two parts, one is the validation of flood simulation and the other is the validation of population distribution. We have placed them behind the corresponding simulation results (Sections 4.2 and 4.3).

Point 15: The results section simply introduces the modeling results, without telling us the insights. In other words, what information we can obtain after reading your figures/data? Can the results justify your claiming of the contribution of this paper?

Reply: We have revised the manuscript to clarify this part. The following texts have been added in Section 5:

"Our study focused on an explorative method, whereas the results were an application case. Due to the limitation of the study area and data, the current results were general and preliminary. The proposed method has many areas in need of improvement, such as the ABM design. Therefore, future studies should focus on optimizing the proposed method and practical case studies, which may produce more informative results."

"The method proposed can provide the government with high resolution dynamic exposure of the population, roads and buildings to flooding as well as information for urban vulnerability and loss assessment, and can support government disaster risk management. It could further provide effective reference information for residents' travels."

Reply to Referee #2

Comments:

Point 1: In the title, the authors mention "high-resolution". But I didn't see any high resolution descriptions in the manuscript. Do you mean spatial resolution or time resolution?

Reply: We mean both spatial and time resolutions. Previous studies have generally focused on the macro-scale of a region, in which the most refined scale is at the community level, and there are few dynamic studies. The time resolution of our study is half an hour and can be set to even finer time intervals. Spatially, irregular vector units are used, and the area of the minimum block is 2731.64 square meters. Please refer to the Point 1 in reply to Referee 1.

Point 2: The authors used the well-known LISFLOOD-FP as the flood model. However, many details are missing about this model. For example, what are the spatial and temporal resolutions of this model? How was this flood model calibrated and validated?

Reply: In the flood simulation, the time resolution is unified with other output results for half an hour. Spatially, it is based on the most refined topographic data which are regular square grids with a 5 m resolution in the study area. We indirectly validate the simulation results by using water accumulation points (refer to Section 4.1).

The following texts have been added in Section 4.2 and Table 1, respectively:

"*The temporal resolution of the flood simulation results was unified with other output results for 30 minutes.*"

"*The flood simulation results were indirectly validated by actual water accumulation points.*"

"*regular square grids with a 5 m resolution*"

Point 3: I don't understand why the authors used synthetic rainfall data for the 2014 flood. If the authors used synthetic rainfall data, how can the flood model be validated? This kind of synthetic rainfall generation method is often used for urban planning. I propose the use of actual rainfall data.

There are too many assumptions behind this synthetic rainfall generation method. For example, is Chicago hyetograph valid in this region? Is the rainfall from 6am-12 pm reasonable?

Reply: The hypothetical rainfall data is used because we only have the daily precipitation data at that time in the study area, and there is no hourly rainfall observation data. The total volume of the hypothetical rainfall is fitting to the actual rainfall estimate at the coarser resolution. Flood model results are indirectly validated by water accumulation points. The Chicago hyetograph is applicable to this region as it has been used by Hangzhou Municipal Planning Bureau who provided the relevant parameters. Rainfall duration is designed according to the flood information in 2014.

The following texts have been added in Section 3.1:

"*Due to the lack of hourly rainfall observation data, we used designed rainfall data for pluvial flood simulation.*"

"*To simulate the 2014 flood, we fixed r at 0.2 based on the assumption that the peak is located at the one-fifth point of the design hyetograph. Additionally, the rainfall duration was 6 hours (6 am to 12 pm), and the accumulated rainfall was nearly 148 mm. The parameters A, b, c and n were estimated from the rainstorm intensity formula for Lishui City obtained from the "Zhejiang City Rainstorm Intensity Formula Table" published by the Hangzhou Municipal Planning Bureau (Table 2).*"

Point 4: Actual flow and water level data in 2014 were used. Then why synthetic rainfall data?

Reply: Please refer to Point 3.

Point 5: Line 151: what is "r" here? I didn't find this variable in the equations. Please explain.

Reply: The "r" does not appear in the formula, but is one of the input parameters in simulating rainfall data. We have revised the manuscript to clarify this part. The following text has been added in Section 3.1:

"*The "r" value refers to the relative rainfall peak time, i.e., a value from 0 to 1, where 0 means the maximum rainfall at the beginning of the rainfall event, and 1 means the maximum rainfall at the end of the rainfall event.*"

Point 6: Line 162-163: please provide references to these methods.

Reply: The value of r was set according to the related news reports of the flood in 2014. Please refer to Point 3 and Point 5.

Point 7: Line 165-167: please provide evidence to this sentence "ABM is considered most suitable to address challenges associated with simulating the complexity and dynamic variability of population exposure to flooding due to its capacity to capture interactions and dynamic responses in a spatial environment".

Reply: The following text has been revised in the manuscript:

"*ABM is considered most suitable for addressing challenges associated with simulating the complexity and dynamic variability of population exposure to flooding because of its capacity to capture interactions and dynamic responses in a spatial environment (Dawson et al., 2011).*"

Reference: Dawson, R. J., Peppe, R., and Wang, M.: An agent-based model for risk-based flood incident management. Natural hazards, 59(1), 167-189, https://doi.org/10.1007/s11069-011-9745-4, 2011.

Point 8: Line 222-223: please specify the GIS tools or software the authors used in this study.

Reply: Intersection and editing tools of the ArcGIS software are used in block generation. As shown in the following figure, the centerlines of the rivers and main roads are applied to split the study area into cells with the GIS intersect tools. Second, the cells obtained by the first step are subdivided or modified by the boundaries based on land use data. Finally, the cells obtained by the second step are modified by the boundaries based on buildings.

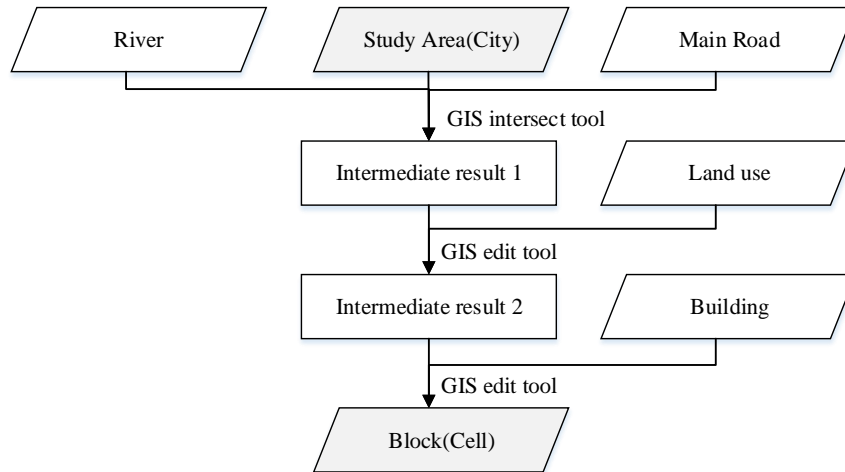



Figure 1. Spatial discretization based on geographic information system (GIS) techniques.

The following text has been revised in Section 3.3:

"*The study area was discretized into several blocks to improve the spatial resolution of the exposure results. The major factors that affect the flood exposure included rivers, roads, land use, and buildings. The discretization procedure was conducted with GIS tools (intersection and editing tools of the ArcGIS software) (Lü et al., 2018).*"

Point 9: I didn't see many details of the agent model the authors used. Is this only a meta model or kind of simulation model? I expect more details about this model.

Reply: We developed the prototype system with the agent model concept as shown in Section 4.1, using the Visual Studio Code software and Python programming language.

Point 10: There are many assumptions and simplification when the authors assess the dynamic exposure. Therefore it is also very difficult to verify the model the authors set up.

Reply: Indeed. We mainly validate the model using indirectly ways. We have added discussion about this in conclusions. The following text has been added in Section 5:

"*It should be noted that there is no comprehensive way of verifying the proposed method. This is because parameters of human behavior and psychological processes are difficult (or, to some extent, impossible) to obtain. In this study, the proposed method was verified indirectly. Actual traffic data for each road intersection were collected and compared with the simulated population results. Data*

for actual water accumulation points were also compared with the simulated water accumulation results. Nonetheless, the study had some limitations, e.g., considerable uncertainties regarding the use and design of the ABM. These included differences in the responses of residents of the same type to disasters in the same scenario. Therefore, this study simply attempted to reflect reality. Based on the survey data, we designed simplified activity patterns, which were consistent with the actual situation of the study area. Simplification of the behavior patterns and disaster responses of residents was inevitable, resulting in differences between the simulation results and reality. Our study focused on an explorative method, whereas the results were an application case. Due to the limitation of the study area and data, the current results were general and preliminary. The proposed method has many areas in need of improvement, such as the ABM design. Therefore, future studies should focus on optimizing the proposed method and practical case studies, which may produce more informative results."

Point 11: Many details of the agent model are referred to the experiences of other countries. Can the authors add discussion about this? Are these experience applicable in China?

Reply: There are also many relevant studies based on the agent model in China. Kang et al. (2012) proposed an agent-based urban population distribution model. Huang et al. (2015) proposed a multi-agent-based theoretical model for dynamic flood disaster risk assessment. Ling (2014) and Guo et al. (2015) carried out flood disaster risk simulation research and population risk dynamic assessment research based on an agent model respectively. We also refer to the above literatures when designing our agent model. Based on the survey data, we designed simplified activity patterns, which are consistent with the actual situation of the study area. The classification of agent types is based on several main social characteristics. In the future, we will also conduct more surveys in the study area in order to make the modeling results more realistic.

We have added texts to introduce the travel survey data (refer to the Point 4 in reply to Referee 1) and their applications (refer to Referee #1 Point 9 and the following text added in conclusions).

"Based on the survey data, we designed simplified activity patterns, which were consistent with the actual situation of the study area."

They can all prove that our model is applicable for the study area.

References: Kang, T., Zhang, X., Zhao, Y., Wang, Y., and Zhang, W.: Agent-based Urban Population Distribution Model. Scientia Geographica Sinica, 32(7): 90-797, https://doi.org/10.13249/j.cnki.sgs.2012.07.003, 2012.

Huang, H., Fan, Y., Yang, S., Li, W., Guo, X., Lai W., and Wang H.: A multi-agent based theoretical model for dynamic flood disaster risk assessment. Geographical Research, 34(10):1875-1886, https://doi.org/10, 1875-1886, 10.11821/dlyj20151006, 2015.

Ling, H.: Simulation of Flood Disaster Risk based on Multi-Agent. University of Science and Technology of China: Hefei, China, 2014.

Guo, X., Li, W., Wang, H., Lai, W., Shi, Y., and Sun, B.: Population Risk Dynamic Simulation for Rainstorm Flood Disaster Based on ABM and ABS. Computer Systems & Applications, 24(12):10-17, 2015.

Point 12: Again, I didn't understand why the authors use the traffic data of 2017 for validation of the agent model instead of those of 2014?

Reply: This is due to the lack of traffic data during the flood period in 2014. The available data are the traffic flow of four intersections, which lasted for two weeks, from June 24 to July 7, 2017.

The following text has been revised in Section 4.3:

"*The reliability of the simulation of the spatiotemporal population distribution was indirectly verified by using traffic flow data. Due to the lack of data for 2014, we used traffic flow data from June 24 to July 7, 2017. The simulated total number of residents passing the four intersections (such as the junction of the Liqing and Huayuan roads) and the actual measured traffic flow at the intersections during the morning and evening peak hours on weekdays and weekends are shown in Fig. 14. The traffic flow data in Fig. 14 are multi-day average results.*"

Point 13: How was the flood model validated?

Reply: Please refer to Point 2.

Modelling the high-resolution dynamic exposure to flood in city-region

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Abstract: Urban flooding exposure is generally investigated with the assumption of stationary disasters and disaster-bearing
10 bodies ~~within~~ during an event~~,~~ and thus cannot satisfy the increasingly elaborat~~e~~ive modell~~l~~ing and management of urban flood~~s~~. In this study, a comprehensive method was developed to simulate dynamic exposure to urban flooding considering residents' travel behavior. First, a flood simulation was conducted using the LISFLOOD-FP model to predict the spatio-temporal distribution of flooding. Second, an agent-based model was used to simulate residents' movements during the ~~period of~~ urban flooding period. Finally, to study the evolution and patterns of urban flooding exposure, the exposure of the population, roads,
15 and buildings to urban flooding was simulated using Lishui, China~~,~~ as ~~the~~ a case study. The results indicated evident spatio-temporal variations in urban flooding and population distribution. ~~Additionally, t~~The exposure increased with increasing rainfall and flooding severity. The urban area near the Oujiang River was the most severely flooded and indicated the highest~~largest amount of~~ exposure of the population, roads, and buildings. Furthermore, the impacts of flooding on roads were greater than those on the population and ~~on~~ buildings. This study presents the first fully formulated method for dynamic urban
20 flood exposure simulation ~~at~~with high spatio-temporal resolution. The quantitative results of this study can provide fundamental information ~~baseline data~~ for determining urban flood disaster vulnerability, assessing socioeconomic loss~~es~~ ~~assessment~~, managing urban disaster risk ~~management~~, and ~~for~~ establishing emergency response plans.

~~**Keywords:** urban flooding; resident travel behavior; agent-based model; dynamic exposure~~

1 Introduction

25 Storm flooding has become increasingly frequent and severe with the intensification of climate change~~global warming~~ and the rising frequency of extreme weather events (*Dankers and Feyen, 2008*; *Hammond et al., 2015*). Urban floods ~~have become~~are major natural disasters in many cities around the world and ~~have created~~ serious~~ly~~ threat~~ens to~~ human life and social and economic activities (*Gain et al., 2015*). Effectively coping with floods and their adverse effects is an important part of disaster prevention~~, and~~ mitigation, and~~as well as disaster~~ risk management (*Atta-Ur-Rahman, 2014*). Non-engineering measures, such
30 as exposure assessment, are currently the main way of managing urban flooding risk (*Chen et al., 2015*). Exposure refers to

the presence of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in ~~places~~ areas that could be adversely affected by natural disasters (*IPCC, 2012*). Urban flood disasters ~~are caused by~~involve the adverse effects of heavy rain and other factors on ~~the~~ city system~~s~~ in ~~certain~~ disaster-~~prone~~egnant environments. These events consist of three ~~parts~~elements: ~~the~~ disaster-causing factors, ~~the~~ disaster-~~prone~~egnant environment~~s~~, and ~~the~~ disaster-

5   bearing bodies (*Shi, 1996*).

Exposure has ~~obvious~~ dynamic characteristics because of the dynamic evolution of urban floods and disaster-bearing bodies. Therefore, the characteristics of flood disasters and building environments~~,~~ as well as~~and~~ the distribution of population and socio-economic resources are the key factors ~~for~~in evaluating urban flood exposure. The methods for evaluating exposure to urban flooding at a certain time or period vary due to changes in ~~the~~ disaster-bearing bodies, study areas, and data acquisition

10   methods, ~~etc~~among others. (*Röthlisberger et al., 2017*). Index-based methods are commonly used for comprehensive exposure evaluation (*Mahe et al., 2005*; *Mansur et al., 2016*; *Guo et al., 2014*). The exposure index method is to select the natural, social, economic and other evaluation indices from the characteristics of the disaster-bearing bodies to establish the evaluation index system, determine the index weights by the analytic hierarchy process and expert scoring method, construct the evaluation system by using mathematical model, and obtain the exposures of the disaster-bearing bodies (*Nasiri et al., 2016*). Statistical

15   methods based on historical disaster data are also ~~utilized~~ used (*Moel et al., 2011*).

With respect to spatial considerations, the currently implemented method for estimati~~ng~~on ~~of~~ disaster exposure adopts ~~the~~ administrative boundaries of socioeconomic data, which are organized as research units (*Yin, 2009*). ~~Consequently, n~~Natural elements ~~that have~~with higher spatial resolutions ~~must be~~are compromised due to the lower spatial resolution of human elements~~,~~ ~~like~~such as population (*Yang et al., 2013*). ~~Therefore~~Consequently, a comprehensive and sophisticated geographic

20   research unit has not been established, ~~thus~~ resulting in simulation results applicable only to macro planning and decision making. ~~Hence, t~~The estimation of disaster exposure therefore needs to incorporate greater spatial heterogeneity and resolution. Besides enhancement of the spatial scale, dynamic temporal simulation of disaster exposure has gained increasing attention. Specifically, the dynamic evolution of disaster exposure at the macro time-scale considers exposure distribution ~~as well as~~and its variation during different development periods (*Weis et al., 2016*). ~~Therefore, t~~This method is relatively mature and has ~~led~~

25   ~~to~~yielded abundant research results. At the micro time-scale, disaster-causing factors and disaster-bearing bodies represented by populations ~~are~~ vary constantly~~varying~~. On ~~the~~ one hand, spatio-temporal changes in disaster-causing factors (~~e.g.,~~ rainfall) result in corresponding dynamic changes in the characteristics of urban flood disasters (~~e.g.,~~ water depth and velocity)~~of urban flood disasters~~. On the other hand, daily travel activities of urban residents, such as commuting between residential and work or study areas~~learning spaces~~, cause a dynamic spatio-temporal distribution of the population. ~~At the same time, the e~~Exposure

30   to urban flooding changes dramatically over a short period of time. To avoid or reduce disaster risks, casualties, and property losses, different individuals are likely to adopt different adaptive behaviors, such as delaying or cancel~~l~~ing travel plans, ~~while~~ whereas the government is likely to adopt organizational actions such as issuing warnings and evacuating residents (*Wan and Wang, 2017*; *Parker et al., 1995*). ~~Thus, t~~The dynamic simulation of exposure therefore requires ~~the~~ dynamic space-~~–~~time simulation of variations in the disaster event, disaster-bearing bodies, and their~~as well as~~ interactions~~between them~~. Modeling

of the temporal and spatial changes in natural disasters mainly uses the disaster system simulation method, and ~~the typical representative used is a~~ hydrological or hydrodynamic model~~s are typically used~~ to simulate flood disasters (*Werren et al., 2016*). The change simulation of the disaster-bearing body (e.g., the population) can use the method based on individual space-time mark data (*Liang et al., 2015*) and the agent-based ~~method~~ model (ABM) (*Kang et al., 2012*). Although the former can

5 acquire ~~the~~ human position and moving track data, it ~~is difficult to~~cannot identify the purpose of human activities, and human disaster response behavior cannot be simulated. The ~~agent-based model (~~ABM~~)~~ can simulate not only ~~simulate~~ the population distribution but ~~can~~ also ~~simulate~~ the interaction among the population (as ~~the~~ disaster victims), ~~the~~ hazard factors, and ~~the~~ disaster-prone~~gnant~~ environments (*Yin, et al., 2016b*). ~~Current~~ Previous ~~research~~ studies ha~~ve~~s used the ABM to simulate human responses to disasters, which, in turn, have been used in natural disaster risk research (*Johnstone, 2012*; *Huang et al.,*

10 *2015*). Nevertheless, the simulation results do not reflect the exposure characteristics of the disaster-bearing bodies and their dynamic changes (*Dawson et al., 2011*).

Therefore, the objectives of this study were to develop a novel method using the LISFLOOD-FP model ~~(Sect. 3.1)~~ and an ABM ~~(Sect. 3.2)~~ to simulate the exposure of urban populations, roads, and buildings to flooding under varying conditions and ~~subsequently~~ to implement the method as a ~~pilot~~ case study in a real city. Several scenarios, including diverse flooding types

15 and various responses of residents to flooding, were considered in this regard. Additionally, dynamic features of the real world were incorporated to improve the micro exposure analysis. ~~This method was subsequently applied to an urban area as a case study.~~ Exposure simulation is a useful tool for estimati~~ng~~on ~~of~~ disaster vulnerability and assess~~ing~~ment ~~of~~ losses, and the quantitative results under different scenarios of this study are likely to benefit ~~the~~ relevant government agencies in assessing risk, issuing warnings, and planning emergency responses to urban natural disasters. In particular, considering the dynamic

20 distribution of the population during a flood disaster, a more reasonable migration measure can be taken to minimize casualties.

2 Study area and data sources

~~In this study,~~ Lishui City ~~in,~~ Zhejiang Province, China, was ~~considered~~ used as the study ~~region~~ area because of the availability of the required data and flooding history. The urban district of Lishui is a largely hilly and mountainous area, and the Oujiang River traverses its southern and eastern parts. The study area is located in the central district of Lishui, covers an area of 43.4

25 km^2, and has a ~~large~~ population of ~~about~~ approximately 71,673 (Fig. 1). The frequenc~~y~~ies of heavy rainstorms and persistent concentrated rainfall events rise~~s~~ sharply in May and June during the Meiyu flood period, which often results in flood disasters. On August 20, 2014, a heavy rainfall event lasting a few days produced a 50-year flood in Lishui and caused considerable loss of property.

The datasets used in this study included a digital elevation model and ~~data for~~ river~~s~~, road~~s~~, building~~s~~, population, and

30 observation data consisting of river discharge~~flow~~ and water level. Travel survey data were used to determine daily routines. Additionally, ~~T~~traffic flow and water accumulation data were used for validation. Table 1 describes the sources and uses of the datasets.

We randomly selected 500 residents in the study area to participate in a questionnaire survey on daily activities. We collected data on their social characteristics to distinguish population types. There were 100 people under 18 years of age, 300 middle-aged people (18-60 years), and 100 elderly people (>60 years). Employed people and males accounted for 55% and 50%, respectively. Lastly, 14% of the population had received higher education. The distribution of the above social characteristics was close to the actual population distribution in the study area.

3 ~~Methodology~~Methods

This study comprised three aspects: disaster simulation, human activity simulation, and dynamic exposure assessment (Fig. 2). The first step included fluvial and pluvial flooding simulation based on the LISFLOOD-FP model. The simulation of human activity ~~utilized~~ subsequently used ABM to obtain the spatio-temporal distribution of the population under different scenarios. Finally, the developed model was combined with the results of the previous two steps to assess the dynamic exposure of the population, roads, and buildings to urban flooding.

3.1 Flood models

There is ~~A~~a wide variety of existing hydrological or hydrodynamic models ~~are available~~ that are capable of simulating fluvial or pluvial flooding, including the Storm Water Management Model (SWMM) (*Rossman, 2015*), LISFLOOD (*Bates and De Roo, 2000*), MIKE-SHE (*DHI, 2000*), MIKE-11 (*Havnø et al., 1995*), MOUSE (*Lindberg et al., 1989*), HEC-RAS (*Brunner, 2008*), and HEC-HMS (*Charley et al., 1995*). LISFLOOD-FP (*Bates et al., 2013*) is a coupled 1D/2D hydraulic model based on a raster grid and was designed for research purposes at the University of Bristol, United Kingdom. LISFLOOD-FP uses a square grid as the computational grid to simulate ~~one dimensional~~1D river ~~hydraulic changes~~ and ~~two dimensional~~2D floodplain hydraulic changes. The applicability of the model has been verified by several studies (*Horritt and Bates, 2002*; *Bates and De Roo, 2000*). Therefore, the LISFLOOD-FP model was chosen for the simulation of fluvial and pluvial flooding in this study.

Floodplain flows were described in terms of ~~the~~ continuity and momentum equations discretized over a grid of square cells, which allowed the model to represent 2D dynamic flow fields for the floodplain. It assumed that the flow between two cells was simply a function of the free surface height difference between ~~those~~ these cells:

$$\frac{dh^{i,j}}{dt} = \frac{Q_x^{i-1,j} - Q_x^{i,j} + Q_y^{i,j-1} - Q_y^{i,j}}{\Delta x \Delta y}, \tag{1}$$

$$Q_x^{i,j} = \frac{h_{flow}^{5/3}}{n} \left(\frac{h^{i-1,j} - h^{i,j}}{\Delta x}\right)^{1/2} \Delta y, \tag{2}$$

where $h^{i,j}$ is the free surface height of water at node (*i,j*), Δx and Δy are the cell dimensions, *n* is the effective grid scale Manning's friction coefficient for the floodplain, and Q_x and Q_y describe the volumetric flow rates between the floodplain cells in the x and y directions, respectively. ~~Q_y is defined analogously to Q_x.~~The flow depth, h_{flow}, represents the depth

through which water can flow between two cells, and d is ~~defined as~~ the difference between the highest free surface height of water in the two cells and the highest bed elevation.

The types of flooding simulated in this study included pluvial and fluvial floods. Due to the lack of hourly rainfall observation data, we used designed rainfall data for pluvial flood simulation. Synthetic rainfall data for a return period of 50 years ~~used for pluvial flood simulation~~ were simulated using the Chicago hyetograph method (CHM) (*Cen et al., 1998*). The rainfall data were determined using the rainstorm intensity formula (Eq. (3)), rainfall duration time (T), and peak position (r).

$$i = \frac{A(1 + c \log P)}{167(t+b)^n}, \hspace{4cm} (3)$$

where i is the rainfall intensity (mm $/$min^{-1}), P is the return period, and t is the time. The parameters A, b, c and n are ~~parameters~~ related to the characteristics of the local rainstorm and need solutions. A is the rainfall parameter, i.e., the design rainfall (mm) for 1 min~~ute~~ at a ~~10~~ 10-year return period, c is the rainfall variation parameter (dimensionless), ~~and~~ b is the rainfall duration correction parameter, i.e., the time constant (min~~utes~~) that can be added to convert the curve into a straight line after logarithmic calculation of the two sides of the rainstorm intensity formula, and n is the rainstorm attenuation index, which is related to the return period. ~~The rainfall duration was 6 hours (6 am to 12 pm), and the accumulated rainfall was nearly 148 mm.~~ The "r" value refers to the relative rainfall peak time, i.e., a value from 0 to 1, where 0 means the maximum rainfall at the beginning of the rainfall event, and 1 means the maximum rainfall at the end of the rainfall event. To simulate the 2014 flood~~Here~~, we fixed r at 0.2 based on the assumption that the peak is located at the one-fifth point of the design hyetograph. Additionally, ~~T~~the rainfall duration was 6 hours (6 am to 12 pm), and the accumulated rainfall was nearly 148 mm. The parameters A, b, c and n were estimated from the rainstorm intensity formula for Lishui City obtained from the "Zhejiang City Rainstorm Intensity Formula Table" published by the Hangzhou Municipal Planning Bureau (Table 2). The rainfall simulation results are shown in Fig. 3(a). The ~~flow~~ river discharge and water level input data for fluvial flood simulation ~~utilized~~ used observational data from Lishui's 50-year flood in 2014, provided by the Liandu Hydrological Station (Fig. 3(b)). The ~~flow~~ river discharge data for the Daxi and Haoxi rivers on August 20, 2014 were obtained from the Xiaobaiyan and Huangdu stations, respectively, and the observational data for water levels at the outlets were those for the Kaitan Dam.

3.2 ABM

Several modeling techniques, often collectively referred to as social simulation, have been successfully used to represent the behaviors of humans and organizations. These include event and fault trees, Bayesian networks, microsimulation, cellular automata, system dynamics, and ABMs. Research methods based on ABMs have been gradually introduced in~~to~~ the field of natural disaster risk assessment. ABM is considered most suitable ~~to~~ for address~~ing~~ challenges associated with simulating the complexity and dynamic variability of population exposure to flooding ~~due to~~because of its capacity to capture interactions and dynamic responses in a spatial environment (*Dawson et al., 2011*).

An ABM is a computational method for simulating the actions and interactions of autonomous decision-making entities in a network or ~~a~~ system to subsequently assess their effects on the system as a whole. Individuals and organizations represent

agents. Each agent individually assesses its situation and makes decisions based on a set of rules. Agents may execute various behaviors appropriate for the system component they represent for example e.g., producing production or consuming consumption. Therefore, an ABM consists of a system of agents and the relationships between them. Even a simple ABM can exhibit complex behavior patterns, because a series of simple interactions between individuals may result in more

5   complex system-scale outcomes that could not have been predicted just by aggregating individual agent behaviors.

The ABM was developed as a concept in the late 1940s, and substantial applications were realized with the emergence of high-powered computing. Such applications include those in the political sciences (*Axelrod, 1997*), management and organizational effectiveness, and social network the behavior of social networks (*Sallach and Macal, 2001*; *Gilbert and Troitzsch, 2005*). In recent years, it has been introduced to the geosciences and other fields to provide novel ideas for the study of modern geography,

10 including land use simulation and planning as well as residential choice and residential space differentiation (*Benenson et al., 2002*). The urban flood disaster system is a typical complex "natural and social" system. The introduction use of ABM to simulate space -time distributions of populations is expected to quantify the dynamic exposure of populations to urban flood disasters. For example, *Dawson et al. (2011)* proposed a dynamic ABM for flood event management to evaluate population vulnerability under different storm surge conditions, dam break scenarios, flood warning times, and evacuation strategies.

15 **3.3 Spatio-temporal simulation of population distribution**

The iIndividual travels were simulated using ABM by defining the activity patterns of different types of residents to subsequently obtain the distribution of the population at each moment. The ABM of residents' travels established in this study included two core elements of agents and activities, and two basic elements of blocks and networks. The travel survey data were used according to the demographic properties of the agent to generate synthetic daily routines.

20 Residents were independent individuals with subjectivity. This study abstracted them as agents. Only a limited number of agent classifications were used to reduce the number of agent types. The types of agents were classified according to the social characteristics of the residents. Age and gender characteristics mainly affect the ability of people to respond to disasters. The self-help abilities of the minors under 18 years of age and residents older than 60 years are generally poor. In the event of natural disasters, they are generally categorized as the objects of help. The middle-aged group (18–60 years old) generally has

25 greater physical strength with a better ability to cope with disasters. Unemployed people are more vulnerable to natural disasters. On the one hand, their living environments and resistance to disasters are poor; on the other hand, their economic conditions are limited, which impedes recovery after the disaster and seriously affects their daily life in the short term. Education level is related to the possibility of an individual receiving early warning information by the individual. Individuals with higher education levels are more likely to respond to early warning information and are more aware of disasters than

30 others those with low education levels are (*Terti et al., 2015*; *Shabou et al., 2017*). Additionally, different travel modes have different effects on the activity patterns of people as well asand on exposure levels when disasters occur. Therefore, the agent types were divided according to age, gender, employment status, education level, and travel mode.

Activities were classified as work, study, recreation, shopping, at-home, and travel.~~Activities were classified as work, learning, leisure, recreation, shopping, rest, and travel.~~ An activity pattern consisted of a series of activities to describe the spatio-temporal distribution of the agent. The location and scope of an agent were restricted to blocks and networks. Different types of agents ~~indicated~~ had different activity patterns, and the same agent type could also ~~indicate~~ have different activity patterns in different scenarios. The travel survey data were used according to the demographic properties of the agent to generate synthetic daily routines. To capture the variability in the travel survey and the uncertainties in behavior, synthetic daily routines were described in probabilistic terms. Figure 4 presents an example of the synthetic daily routine of an agent with the following demographic characteristics: ~~fe~~male agent, aged 18–60 years, and ~~un~~employed. In this example, the agent started the day at 8 am on a weekday~~. The agent then~~ and had a 0.8 probability of going straight to work~~traveled by a school to drop the children off~~, ~~subsequently~~ going home~~had a 0.8 probability of shopping~~, and so on.

The study area was discretized into several blocks to improve the spatial resolution of the exposure results. The major factors that affect the flood exposure included rivers, roads, land use, and buildings. The discretization procedure was conducted with ~~geographic information system (~~GIS~~)~~ tools (intersection and editing tools of the ArcGIS software) (*Lü et al., 2018*)~~, and several factors, including rivers, roads, land use, and buildings, were considered~~. Blocks were activity places for agents and represented the smallest unit of exposure. This study divided ~~the~~ blocks into five categories: residential area, school, company, recreational area, and others. Additionally, ~~the~~ residential areas were subdivided into classes I, II, III, and IV ~~classes~~ according to the type of building.

In this study, the network referred to roads and restricted the spatial travel scope of an intelligent agent. Rural roads, highways, and urban roads (including main roads, sub-trunk roads, and their~~its~~ branches) were included in the network. The route selection criteria were defined once the different activities from each individual's schedule were located, and road section attributes were specified. Although various factors are involved in the route choice process, several studies have indicated that minimizing travel time is the principal criterion for selecting routes (*Papinski et al., 2009*; *Ramming, 2001*; *Bekhor et al., 2006*). Here, a simple but effective shortest path method was used. ~~Therefore, t~~The classical Dijkstra algorithm is~~,~~ a single-source shortest path algorithm that provides trees of minimal total length and time in a connected set of nodes~~, was selected in this study~~ (*Dijkstra, 1959*). The activity pattern attributions concerned only the starting times and durations of the activity sequences, thus indicating that the travel duration for each individual was computed based on the distance between the different activity locations. Therefore, the implemented schedules may be distorted compared to the assigned schedules in terms of travel duration~~s~~ (*Terti et al., 2015*). We obtained the departure and destination block of each stage according to the activity patterns, and then calculated the shortest path consisting of a series of road sections. At each moment, the block in which the agent was located was calculated, e.g., if an agent was on the road, according to the variation in speed of its walking or riding on a bus or in a car, the road section where it was located was calculated. The same was done during flooding, except that the activity patterns were different.

3.4 Impacts of disasters on ~~anthropogenic~~ resident activities

This study accounted for the adaptability or adjustment behavior of residents to a ~~disasters~~ during the disaster event. The type of activity and its sensitivity to disaster affected the residents' disaster response behavior. Recreation and shopping activities were easier to cancel and postpone than work and study were ~~learning~~ (*Cools et al., 2010*). The sensitivities of residents to

5   disasters depended on their socioeconomic characteristics and risk factors such as disaster ~~(flood)~~ related (i.e., flood-related) knowledge and experience. People with higher education levels are more knowledgeable about disasters and are more likely to receive early warning information and take effective measures (*Terti et al., 2015*). Additionally, it is easier for workers to ignore the risks of a disaster (*Ruin et al., 2007*; *Drobot et al., 2007*). Therefore, this study accounted for the impacts of education level on the response behavior of residents to disaster events.

10   The impacts of a disaster on population distribution were determined by defining different activity patterns and their changing probabilities. Figure 5 indicates activity patterns during different disaster scenarios for ~~un~~employed adult ~~wo~~men who had received higher education ~~during different disaster scenarios~~. The "bad weather" scenario was similar to the "daily activity" pattern. For instance, ~~the~~ changes in travel probability during "bad weather" due to a rainstorm reflected the adaptive behavior of residents. The "warning" scenario assumed that the government had issued early warning information at ~~eight~~ 8 a.m., the

15   schools had suspended classes ~~during the~~on weekdays, and the resident responses were stronger than those to the "bad weather" scenario, ~~thereby~~ resulting in ~~a~~ greater differences in activity patterns.

3.5 Dynamic exposure assessment

~~The d~~Dynamic exposure was calculated based on the simulations of spatio-temporal distributions of the population and flooding. Therefore, the exposure at each moment was calculated according to the population distribution and flood data at

20   that time. Based on the data availability ~~of data~~, this study focused only on three types of disaster-bearing bodies, ~~i.e.,~~ namely population, roads, and buildings.

~~(i) Population~~

Population exposure generally refers to the population exposed to the impacts of disaster events and is characterized by regional population size or population density. This study selected the exposed population and accounted for vulnerable groups

25   and road users. Among these, age was the primary factor impacting ~~the~~ vulnerability. Specifically, the young (people under the age of 18 years) and the elderly (people over the age of 60 years ~~old~~) were the vulnerable groups.

~~(ii) Roads~~

As the basic skeleton of a city, roads are not only the media for daily travel of passengers and freight transportation but also disaster-bearing bodies (*Yin, et al., 2016a*), as they are vulnerable to flood disasters. This study selected the number and lengths

30   of exposed roads to reflect road exposure.

~~(iii) Buildings~~

Finally, ~~T~~the aggravation of urban flooding has made ~~building~~ flooded buildings more common in urban areas, ~~thus~~ resulting in loss of internal property and construction structure. ~~Additionally, t~~The dynamic state of building exposure is related to the safety of both the building ~~as well as~~and the nearby population. In this study, the area of the exposed building and ~~the~~ depth of accumulated water in the building were considered ~~to be the~~ building exposure.

3.6 Scenario design

The daily behaviors of people are characterized by certain patterns with regard to daily, weekly, monthly, and annual cycles. ~~The r~~Rainstorm ("bad weather") and disaster response measures adopted by ~~an~~the organization ("warning") are likely to affect people's daily behaviors. Therefore, 12 scenarios, representing different flooding types and human activities, were designed in this study (Table 3). S1, S2, S7, and S8 were control groups that indicated human activity with no rain and no warning, while the rest of the scenarios were experimental groups.

4 Results

4.1 Model implementation and parameter setting

As an important spatial data management and analysis technology, GIS plays a~~n important~~ crucial role in the dynamic exposure analysis of urban floods. Because of the simplicity, readability~~,~~ and extensibility of the Python programming language, an increasing number of research institutes are adopting it for development. Therefore, the model was developed using the Visual Studio Code software (*Visual studio code, 2018*) and Python programming language (*Python, 2018*). The development of the graphical user interface (GUI), GIS module, and drawing module was realized by Qt (*Qt, 2018*), Geopandas (*Geopandas, 2018*), and Matplotlib (*Matplotlib, 2018*), respectively.

~~(i)~~4.1.1 Block generation

Blocks are irregular vector units whose size represents spatial resolution. Therefore, the spatial resolution of the results is related to the study area and data. In this study, the study area was divided into 237 blocks based on the method introduced in Sect. 3.3, with a minimum area of 2731.64 m^2.~~In this study, the study area was divided into 237 blocks based on the method introduced in Sect. 3.3.~~ The block types and their spatial distributions are shown in Figs. 6 and ~~Fig.~~ 7, respectively. Most of the blocks in the study area were categorized as residential area~~s~~, ~~while~~ whereas blocks of recreational areas and others (which indicated rivers) were few and concentrated.

~~(ii)~~4.1.2 Parameter setting

To reduce the number of agent types, only a limited number of agent classes were used. The distribution of population characteristics for Liandu District is shown in Table 4. The agents were divided into 18 types for daily (non-disaster) scenarios

(S1, S2, S7, and S8) and 24 types for disaster scenarios (all other scenarios) based on the influence of education level on individual disaster response behavior (Fig. 8).

Since tThe census did not identify individuals according to addresses, and at the start of each simulation, an agent population with the same distributions of age, gender, employment, education level, and travel mode was therefore randomly located within the residential area for the case study. The synthetic daily routines were described in probabilistic terms to capture the variability in the travel survey and uncertainties in behavior. The probabilities of agents' daily activities were generated based on the travel survey. We estimated the probabilities of all the activities of the population groups under investigation. Additionally, to reduce the number of agent types, only a limited number of agent classifications were used. The distribution of population characteristics for Liandu District is shown in Table 4. The agents were divided into 18 types for daily (non-disaster) scenarios and 24 types for disaster scenarios based on the influence of education level on the individual disaster response behavior (Fig. 8).

(iii)4.1.3 Exposure threshold

Although flood fatalities can occur throughhave a number of mechanismscauses, such as physical trauma, heart attack, or electrocution, drowning accounts for two-thirds of the such fatalities (*Jonkman and Kelman, 2005*). Previous research has established that the probability of death or serious injury as a result of exposure to flooding is dominated by floodwater depth and velocity (*Abt et al., 1989*; *Karvonen et al., 2000*; *Lind et al., 2004*; *Jonkman and Penning‐Rowsell, 2008*) is dominated by (1) the depth of floodwater and (2) the velocity of floodwater. Additionally, the rate of water level rise can also play an important role in this regard. However, other factors, such as age, fitness level, height, and weight of the individual, are also important for determining their vulnerability to disasters. A comprehensive review of the flood-related casualty data and methods to for assessing the risk of death or serious harm to people caused by flooding is provided by the *Department for Environment Food and Rural Affairs and Environment Agency (2003)* and *Jonkman and Penning‐Rowsell (2008)*. In this study, rather than predicting mortality (which is subject to random factors as well asin addition to those mentioned previously), exposure to floodwater depths of 25 cm or greater under relatively fast flowing (2.5 $m\ s^{-1}$m/s or greater) conditions was established as the threshold for the most vulnerable people (*DEFRA and Environment Agency, 2003*). This provided a conservative estimate of individuals vulnerable to floodwater rather than an estimate of mortality (*Dawson et al., 2011*).

Since building steps (thresholds) exert a blocking effect on shallow flooding, they are likely to reduce the degree of flooding by restricting the flood water to the outside of the building, thereby reducing the exposure of the building. Therefore, this study assigned the height of building steps heights to corresponding block types according to the Chinese architectural design standards of China and the actual conditions of the study area (Table 5). It should be noted that the block type "Other" constituted rivers and did not contain buildings. Therefore, the exposure of the buildings was determined according to the depth of the flood and the height of the building steps. The depth of the water entering the building was the difference between the depth of the flood and the height of the steps.

4.2 Flood simulation

The temporal resolution of the flood simulation results was unified with other output results for 30 minutes. Figure 9 indicates the accumulated water depths and velocities of pluvial and fluvial floods in the study area. As is evident, tThe pluvial and fluvial floods exerted significant impacts, and the urban area near the Oujiang River was the most severely flooded area. Additionally, water isWater also accumulated in the inner areas of the city, mainly on roads, in the case of pluvial flood disasters. The variations in water depths and velocityies for eight severely flooded areas (including blocks and roads) are presented in Fig. 10. As indicated, evident sSpatio-temporal variations in flooding were observed. Figures 9 and 10 indicate show that water depth was the main factor causing that caused life and property losses, whereas water velocity had little or no effect.

The flood simulation results were indirectly validated by actual water accumulation points. During the 50-year flood in 2014, the city had 10 flooded roads and 18 water accumulation points. The actual hydrological points selected according to the study area and urban flooding results simulated by the prototype system are indicated in Fig. 11.

To avoid overlap with the simulated water accumulation results for roads, the actual flooding points in the figure only included road junctions, and the entirety of Gucheng road (the Lutang to Dayou Street section) and Liyang Street (which connected the senior middle school to the Sanyan temple section) was represented by corresponding intersection points. Figure 11 indicates that both the simulation results and actual water accumulation points were mainly distributed along the river. The simulated water accumulation area (Fig. 11(a)) included roads in the center of the city and was larger than the actual flooding area. This difference could be attributed to different definitions of "water accumulation." The simulation results presented in Fig. 11 included all areas where the accumulated water depth during the flooding period was greater than 15 cm. The actual water accumulation point was defined as one experiencing rainfall of greater than 50 mm over a 24-hour period. Additionally, it was characterized by the water accumulation depth of the road reaching 15 cm (the meteorological department issued a blue rainstorm warning at this level), the water withdrawal time reaching 1 hour, and the water accumulation scope value being greater than 50 m^2. Certain gaps existed between the observational data and the actual river discharge since the observation station was far from the study area. Hence, the results indicated that the simulated water accumulation area during the fluvial flood (Fig. 11(b)) was smaller than that of the actual situation.

4.3 Simulation of the spatio-temporal population distribution of population

The spatial and temporal resolutions of the modeling results could be adapted to the study area. The area of the minimum block was 2731.64 m^2. The temporal resolution of the results was 30 minutes, which could be set to 10 minutes or even 1 minute according to need. Additionally, no accurate traffic model was used to simulate agents' movements on roads. On one hand, it was for improving efficiency. On the other hand, we did not pay attention to high temporal resolution human movements (e.g., with precision to 1 minute or 1 second). We only focused on the population distribution for a specific period of time, and the temporal resolution requirement of human activities was therefore low.

The spatio-temporal distribution of the population was simulated based on six scenarios: (1) daily, weekday (S1, S7), (2) daily, weekend (S2, S8), (3) bad weather, weekday (S3, S9), (4) bad weather, weekend (S4, S10), (5) warning, weekday (S5, S11), and (6) warning, weekend (S6, S12). Figure 12 indicates the population variation for blocks and roads for the six scenarios. Figure 12(a) shows that, among the three weekend scenarios, the population in the playground (Block 77) changed more than that in the company (Block 113). Figure 12(b) indicates that the population on the roads was volatile, and the morning peak hour over the weekend was delayed by 1 hour in comparison to that on weekdays. The population distribution in the study area is shown in Fig. 13. The population was unevenly distributed and concentrated in recreational and residential areas over the weekend. However, the population distribution on weekdays was relatively uniform. The concurrent population distribution for the six scenarios changed significantly over the weekend, whereas the distribution on weekdays changed little.

Figures 12 and 13 indicate that the population change patterns were different for different blocks types. The daily routines of several people started from the residential area (home) in the morning, was followed by school or company blocks on weekdays and recreational areas over weekends, and concluded with a return to the residential area at night. During the occurrence of rainstorms or the reception of warning messages, different types of people reacted differently (continuing, postponing, or cancelling routine activities). Vulnerable people, such as the elderly and children, and sensitive people (such as the homeless) were more likely to cancel travel plans. Additionally, recreational activities were more likely to be cancelled than were study and work activities.

The reliability of the simulation of the spatiotemporal population distribution was indirectly verified by using traffic flow data. Due to the lack of data for 2014, we used traffic flow data from June 24 to July 7, 2017. The simulated total number of residents passing the four intersections (such as the junction of the Liqing and Huayuan roads) and the actual measured traffic flow at the intersections during the morning and evening peak hours on weekdays and weekends are shown in Fig. 17. The traffic flow data in Fig. 17 are multi-day average results.

In theory, the simulated value should be much larger than the measured value since the former indicates the number of people, whereas the latter represents the number of cars and buses. However, as indicated in Fig. 17, the simulated value was close to the measured value. This could be attributed to the assumption that the study area was closed and the simulated population was the number of permanent residents, excluding the migrant population. In reality, the number of migrants in the urban area during the daytime is large owing to its geographical location. This study simplified human activities when simulating the spatiotemporal distribution of the population, resulting in a small number of pedestrians on the road. However, both the simulated and measured values were essentially similar with regard to changes in their trends. Therefore, the simulation method for the spatiotemporal distribution of the population is feasible, and the results are reliable.

4.4 **Dynamic E**exposure assessment

Figure ~~13~~15 presents the population exposure variation for two selected areas. The difference between pluvial and fluvial flood scenarios could be attributed to differences in the changes and degrees of water accumulation. Figure 15~~3~~(a) indicates that population exposure was the highest for the daily scenario, followed by the bad weather ~~scenario~~ and minimum warning scenario**s**. However, as indicated in Fig. 15~~3~~(b), the population was most exposed to both weekend and weekday warning scenarios. This is attributed to the assumption that the disaster response behavior adopted by residents was to reduce travel, i.e., the refuge of residents was the residential area. ~~Additionally, t~~The response was not based on the exposure of the residential area. Therefore, when residential areas, such as Block 6, were exposed to floods, the residents chose to reduce travel, ~~thus~~ resulting in an increase in the population ~~of~~ in residential areas and consequently increasing the population exposure. According to the analysis of the 12 scenarios, the government departments can carry out disaster prevention and mitigation measures for areas with ~~large amounts of~~high population exposure, such as evacuation prior to the disaster~~,~~ and ~~initiate~~ initiation of key rescue operations during the disaster. The method proposed in this study can ~~also~~ help to determine vulnerable populations and road users in the exposed blocks. Because we ~~had~~ considered vulnerable people and road users when we constructed the population groups (agents), we ~~can~~ could ~~get~~obtain similar information from the results of vulnerable populations and road users in the exposed blocks, ~~like~~ such as the exposed population. Such information is of great practical significance.

Figure 16~~4~~ presents variations in the road and building exposures of two selected areas with serious flooding. The road and building exposures for the study area are presented in Fig. 17~~5~~. It can be concluded that road and building exposures during pluvial and fluvial floods also varied with ~~the~~ flood depth. ~~Additionally, t~~The exposed road length of the block ~~was fluctuant~~ fluctuated, ~~while~~ whereas the building was either entirely exposed or not exposed. Furthermore, the area of the road affected by pluvial and fluvial floods was greater than that of the buildings. As indicated in Fig. 17~~5~~, exposed buildings were present in only ~~in~~ a few areas (blocks), ~~while~~ whereas roads were affected in several areas. ~~Additionally, b~~Buildings were least exposed due to high thresholds or the number of building steps designed and built in recent years, ~~while~~ whereas roads and population were severely affected by floods.

~~4.5 Validation~~

~~The flooded urban roads and locations in Lishui during the 50-year flood in 2014 were as follows: the city had 10 flooded roads and 18 water accumulation points. The actual hydrological points were selected and combined with the urban flooding results simulated by the prototype system. The water accumulation distribution is indicated in Fig. 16.~~

~~To avoid overlapping with the simulated water accumulation results for roads, the actual flooding points in the figure only included road junctions and the entirety of Gucheng road (the Lutang Street to Dayou Street section), and Liyang Street (which connected the senior middle school to the Sanyan temple section) was represented by corresponding intersection points. Figure 16 indicates that both the simulation results and the actual water accumulation points were mainly distributed along the river.~~

The simulated water accumulation area (Fig. 16(a)) included roads in the center of the city and was larger than the actual flooding area. This difference could be attributed to different definitions of "water accumulation". The simulation results presented in Figure 16 included all areas where the accumulated water depth during the flooding period was greater than 15 cm. The actual water accumulation point was defined as one experiencing rainfall greater than 50 mm over a 24 hour period.

5 Additionally, it was characterized by the water accumulation depth of the road reaching 15 cm (the meteorological department issued the blue rainstorm warning at this level), the water withdrawal time reaching one hour, and the water accumulation scope value being greater than 50 m^2. Certain gaps existed between the observational data and the actual flow since the observation station was far from the study area. Hence, the results indicated that the simulated water accumulation area during the fluvial flood (Fig. 16 (b)) was smaller than that of the actual situation.

10 The reliability of the simulation of the spatio-temporal population distribution was indirectly verified by utilizing the traffic flow data from June 24 to July 7, 2017. The morning and evening peak hours on weekdays and weekends, the simulated total number of residents passing the four intersections (such as the junction of the Liqing and Huayuan roads) during peak hours, and the actual measured traffic flow at the intersections are shown in Fig. 17. The traffic flow data in Fig. 17 are multi-day average results.

15 In theory, the simulated value should be much larger than the measured value since the former indicates the number of people while the latter represents the number of cars and buses. However, as indicated in Fig. 17, the simulated value was close to the measured value. This could be attributed to the assumption that the study area was closed and the simulated population was the number of permanent residents, excluding the migrant population. In reality, the number of migrants in the urban area during daytime is large owing to its geographical location. Moreover, this study simplified human activities when simulating 20 the spatio-temporal distribution of the population. Therefore, the number of pedestrians on the road was small. However, both the simulated and measured values were essentially similar with regard to changes in their trends. Therefore, the simulation method for the spatio-temporal distribution of population is feasible, and the results are reliable.

5 Conclusions

Urban flooding considerably impacts the daily lives of residents and not only affects commuting but also causes casualties and 25 traffic congestion. This study proposed a method for ~~obtaining~~ determining high-resolution dynamic exposure to urban flooding. First, the spatio-temporal distributions of pluvial and fluvial floods were simulated by the LISFLOOD-FP model. Second, the responses of residents to bad weather and government measures (warnings) were incorporated to develop an ABM to simulate residents' activities during flooding. Finally, urban exposure during different flood scenarios was comprehensively simulated and was based on the population and hydrological simulation results, road and building data, and the case study of 30 the Lishui urban district.

The method proposed can provide the government with high resolution dynamic exposure of the population, roads and buildings to flooding as well as information for urban vulnerability and loss assessment, and can support government disaster

risk management.~~developed could predict floods as well as the exposure of buildings, roads, and the population at different times and locations. Additionally, i~~It could further provide effective reference information for residents' travels ~~and urban disaster management. In summary, t~~This study ~~had~~ comprised four main elements. First, different spatio-temporal distributions of water depth and velocity predictions were obtained using the LISFLOOD-FP model. Second, an ABM was ~~utilized~~ used to simulate the spatio-temporal distributions of the population. Third, the impacts of pluvial and fluvial floods on buildings were found to be small, ~~while that~~ whereas those on roads and the population ~~was evident~~were greater. Finally, if residents ~~simply~~ reduced their travels (i.e., stayed at home), the exposure of the population in ~~the~~ exposed residential areas increased.

It should be noted that there is no comprehensive way ~~to~~of verify~~ing~~ the proposed method. This is because parameters of human behavior and psychological processes are difficult (or, to some extent, impossible) to obtain. In this study, the proposed method was verified indirectly. ~~The a~~Actual traffic ~~information~~ data for each road intersection w~~ere~~as collected and compared with the simulated population results. ~~Additionally, the information~~Data for actual water accumulation points w~~ere~~as also compared with the simulated water accumulation results. ~~However~~Nonetheless, the study had some~~a few~~ limitations~~, persist. For instance~~ e.g., considerable uncertainties regarding the use and design of the ABM ~~exist~~. These include~~d~~ differences in the responses of residents of the same type to disasters in the same scenario. Therefore, this study simply attempted to reflect reality. Based on the survey data, we designed simplified activity patterns, which were consistent with the actual situation of the study area. ~~Moreover, s~~Simplification of the behavior patterns and disaster responses of residents ~~i~~was inevitable, ~~thus~~ resulting in differences between the simulation results and reality. Our study focused on an explorative method, whereas the results were an application case. Due to the limitation of the study area and data, the current results were general and preliminary. The proposed method has many areas in need of improvement, such as the ABM design. Therefore, future studies should focus on optimizing the proposed method and practical case studies, which may produce more informative results.~~In addition, the investigation of different durations and intensities of the rainstorm is also relevant. However, the inclusion of other factors was beyond the scope of this research. Therefore, future studies should focus on optimizing the proposed method and incorporating the effects of different durations and intensities of rainstorms.~~

Data availability

The geography, hydrological observation, and traffic flow data in Lishui city were provided by Lishui City Housing and Urban-Rural Construction Bureau, Liandu Hydrological Station, and Lishui City Transportation Bureau, respectively. These data are not publicly available because of governmental restrictions. The 1 km grid population data are available online at http://www.geodata.cn (last access: March 2019). The population profile are available online at http://tjj.lishui.gov.cn (last access: March 2019). The water accumulation points are available online at http://www.zjjs.com.cn (last access: March 2019). Data provided by the local government and other model simulated data in this paper are available from the authors upon request (zhuxuehong816@163.com).

Author contribution

Xuehong Zhu and Qiang Dai were responsible for setting up the experiments, completing most of the experiments, and writing the manuscript. Dawei Han and Shuliang Zhang principally conceived the idea and design of the study and provided financial support. Lu Zhuo performed the flood simulation. Shaonan Zhu was responsible for the development of the model.

5 **Competing interests**

The authors declare that they have no conflict of interest.

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Figure captions

Figure 1. Location of the study area in Lishui City (left) and a digital elevation model (DEM) indicating ~~the specific~~ details of the study area (right).

Figure 2. Overview of the dynamic exposure simulation ~~to~~of urban flooding.

Figure 3. Rainfall simulation results based on the ~~CHM~~ Chicago hyetograph method, and observational data used for fluvial flood simulation.

Figure 4. ~~A s~~Synthetic daily routine generated from the travel survey and census data for an ~~un~~employed ~~fe~~male agent aged 18–60 years.

Figure 5. Activity patterns for a~~n~~ highly educated, ~~un~~employed ~~fe~~male agent aged 18–60 years during disaster scenarios. ~~(a) Bad weather (weekday) (b) Warning (weekday) (c) Bad weather (weekend) (d) Warning (weekend).~~

Figure 6. Number of different block types.

Figure 7. Spatial distribution of blocks in the study area.

Figure 8. Agent types for daily and disaster scenarios. Daily scenarios refer to S1, S2, S7, and S8 and the rest are disaster scenarios.

Figure 9. Maps of ~~A~~accumulated water depths and velocities. "T" ~~mean~~indicates time ~~here~~.

Figure 10. Changes in the surface water depth~~s~~ (dep) and velocit~~yies~~ (vel) for eight severely flooded areas. ~~The "dep" indicates water depth, and "vel" indicates water velocity.~~

Figure 11. Map of the flooded area indicating the flooding simulation and real flood in 2014. Data for the flooded area were provided by Lishui City Housing and Urban-Rural Construction Bureau.

Figure 12~~1~~. Population changes in blocks and roads for the six scenarios.

Figure 13~~2~~. Population distribution for the six scenarios. "T" ~~mean~~indicates time ~~here~~.

Figure 14. Traffic flow and population simulation results during peak hours on weekdays and weekends. Traffic flow data were provided by the Lishui City Traffic Bureau. Real means measured value. LQ is Liqing Road, KF is Kaifa Road, HY is Huayuan Road, ZJ is Zijin Road, and LT is Lutang Street.

Figure 15~~3~~. Changes in ~~the~~ population exposure of two blocks for the 12 scenarios. Block 168 was a recreational area, and Block 6 was a residential area.

Figure 16~~4~~. Changes in road and building exposure~~s~~ in severely flooded blocks. ~~The e~~Exposed road length and building area represent road and building exposure~~s~~, respectively.

Figure 17~~5~~. Map of road and building exposures. "T" ~~mean~~indicates time ~~here~~.

~~Figure 16. Map of the flooded area indicating the flooding simulation and the real flood in 2014. The information for the flooded area was provided by Lishui City Housing and Urban-Rural Construction Bureau.~~

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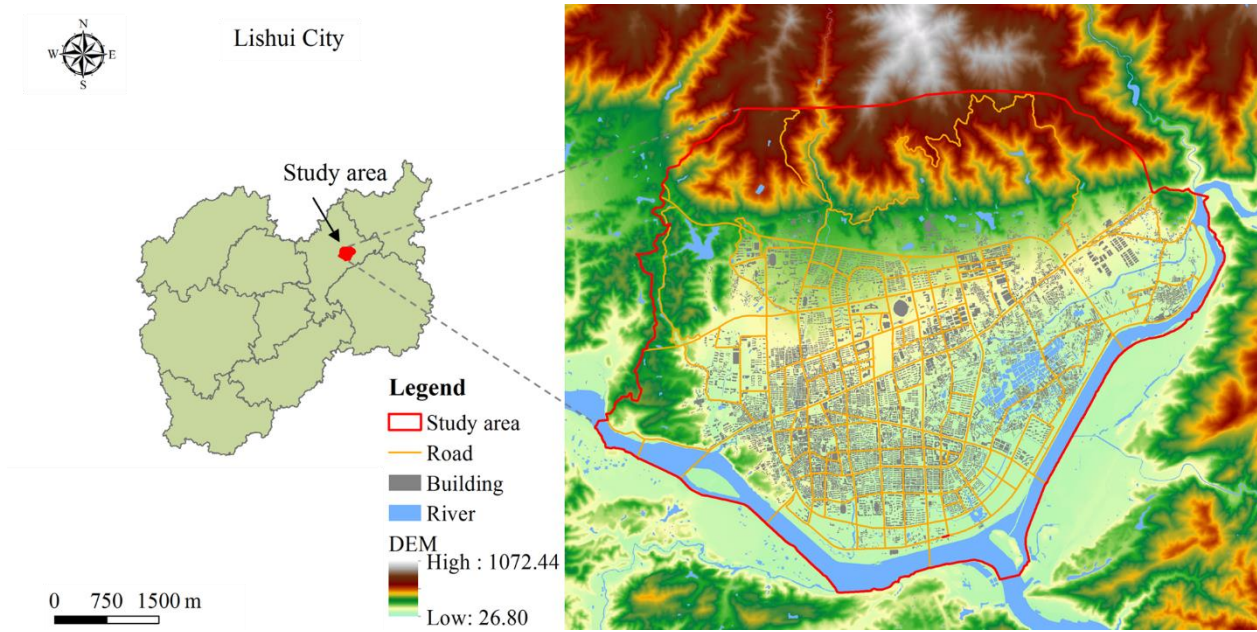


Figure 1. Location of the study area in Lishui City (left) and a digital elevation model (DEM) indicating <s>the specific </s>details of the study area (right).

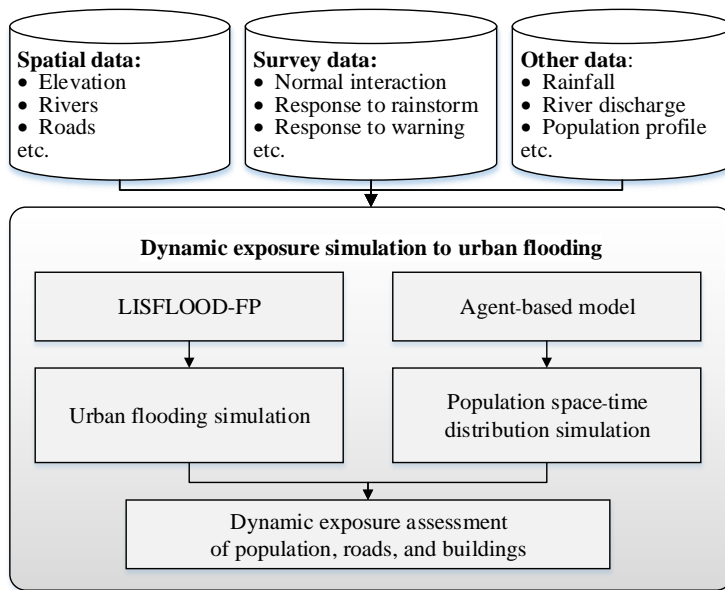
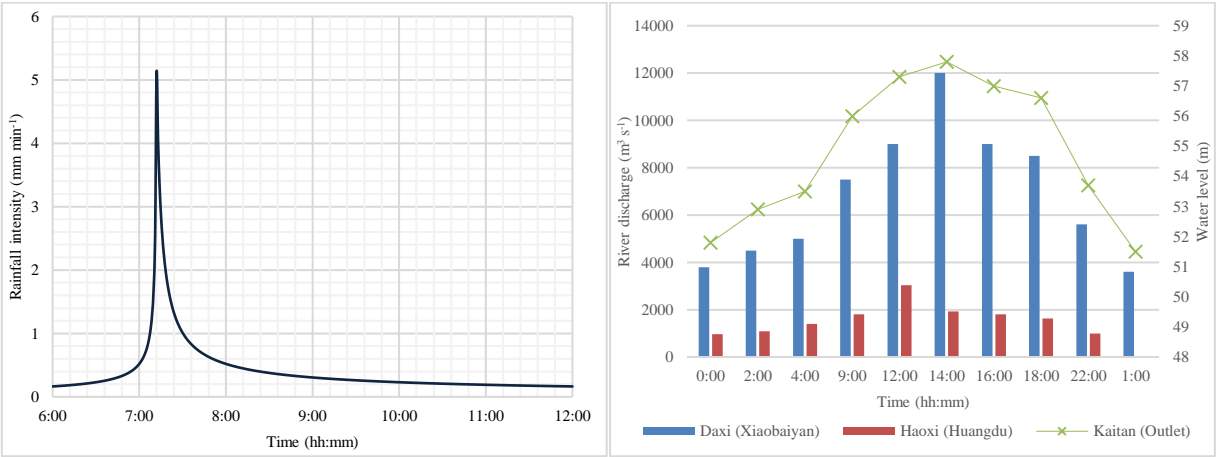
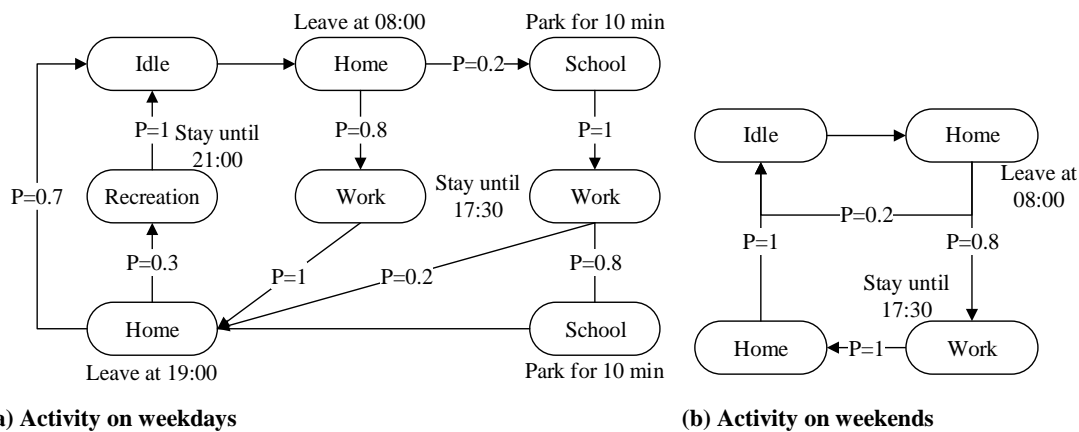
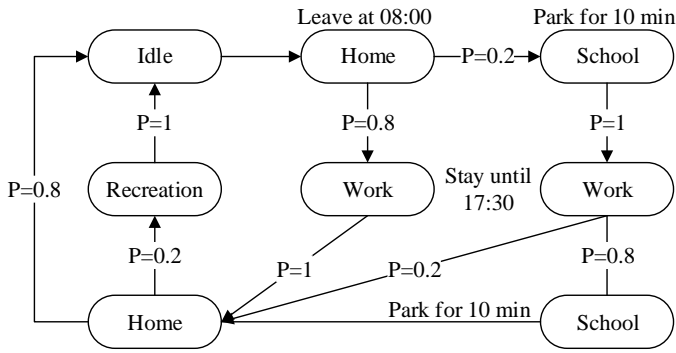
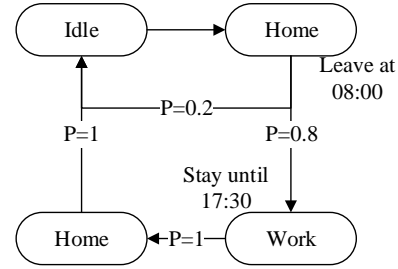
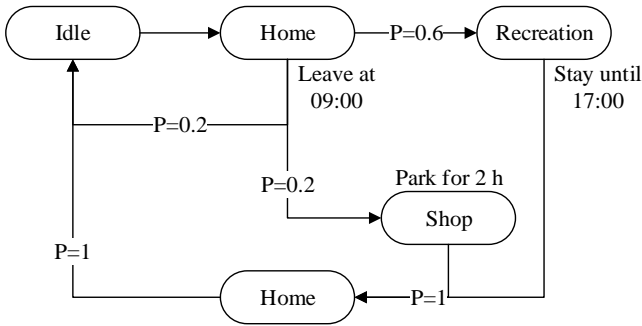



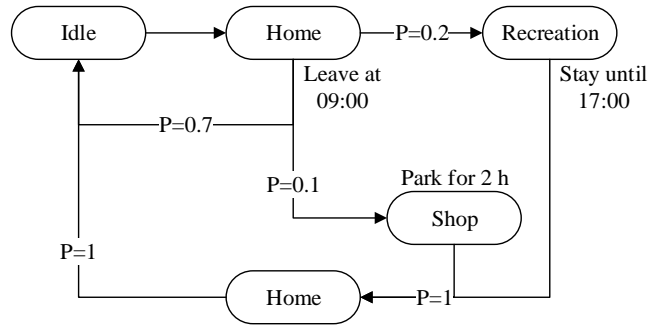
Figure 2. Overview of the dynamic exposure simulation ~~to~~**of** urban flooding.

(a) Rainfall simulation data

(b) Observational data

Figure 3. Rainfall simulation results based on the Chicago hyetographHM method, and observational data used for fluvial flood simulation.

(a) Activity on weekdays

(b) Activity on weekends

Figure 4. ~~A s~~Synthetic daily routine generated from the travel survey and census data for an ~~un~~employed ~~fe~~male agent aged 18–60 years.

(a) Bad weather (weekday)

(b) Warning (weekday)

(c) Bad weather (weekend)

(d) Warning (weekend)

5   **Figure 5. Activity patterns for a~~n~~ highly educated, ~~un~~employed ~~fe~~male agent aged 18–60 years during disaster scenarios. ~~(a) Bad weather (weekday) (b) Warning (weekday) (c) Bad weather (weekend) (d) Warning (weekend).~~**

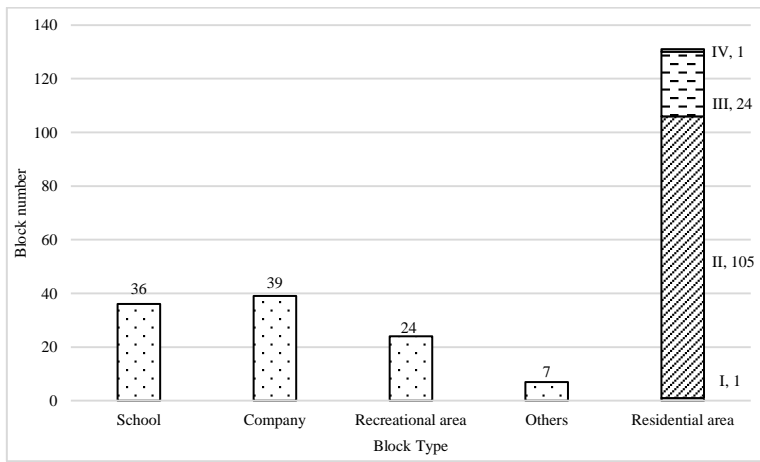



Figure 6. Number of different block types. I–IV represent the type of building.

Legend

Block type
- ■ School
- ■ Company
- ■ Recreational area
- ■ Residential area (I)
- ■ Residential area (II)
- ■ Residential area (III)
- ■ Residential area (IV)
- ■ Others

0   750 1500 m

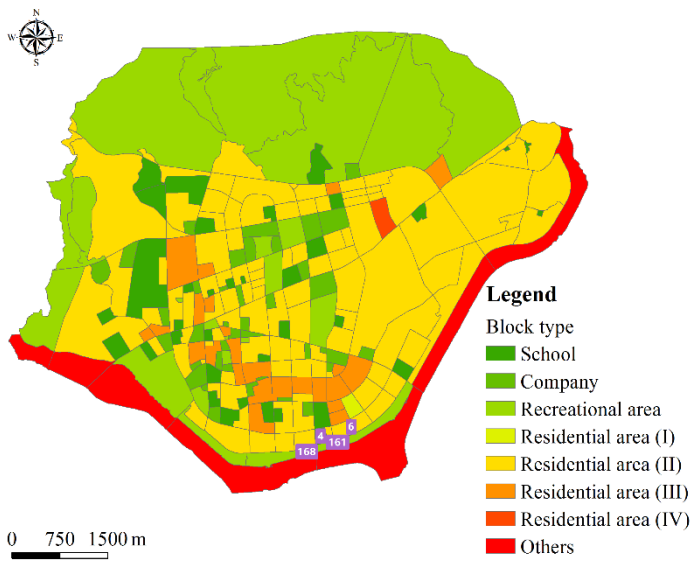



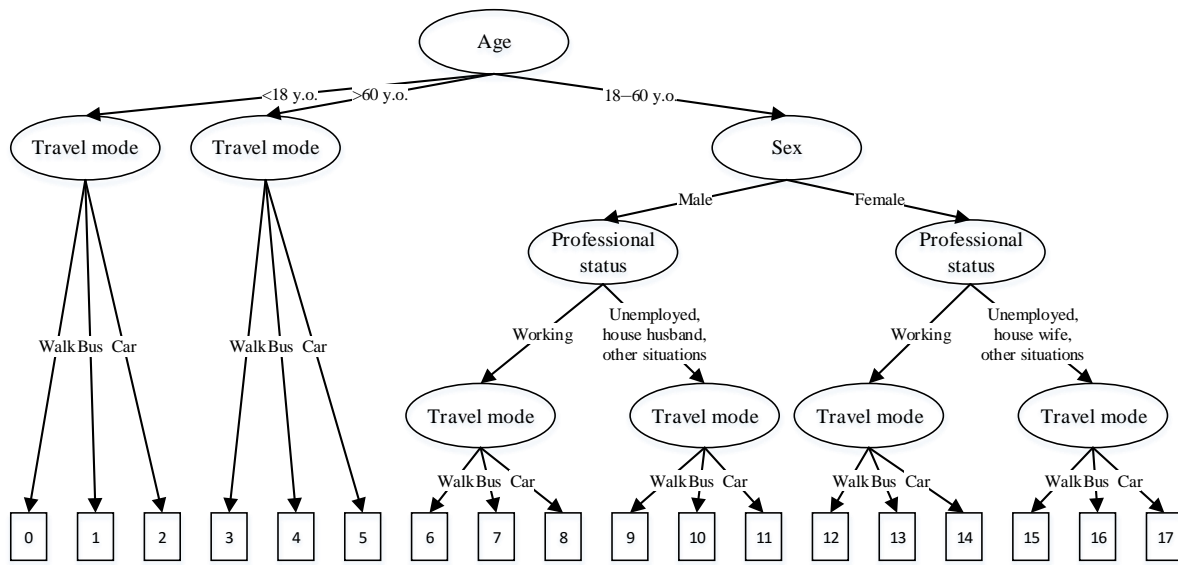
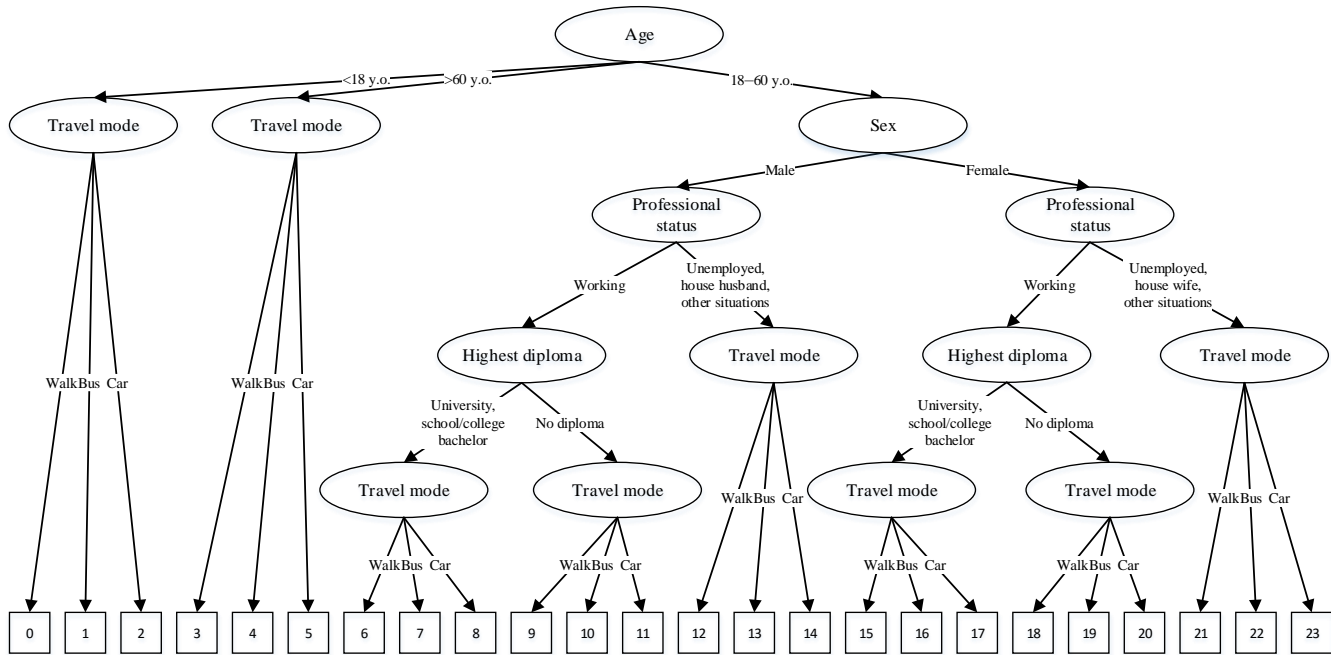
Figure 7. Spatial distribution of blocks in the study area.

(a) Agent types for daily scenarios

(b) Agent types for disaster scenarios

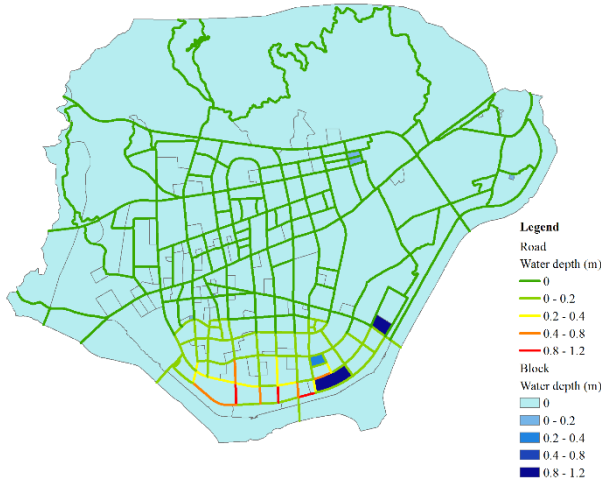
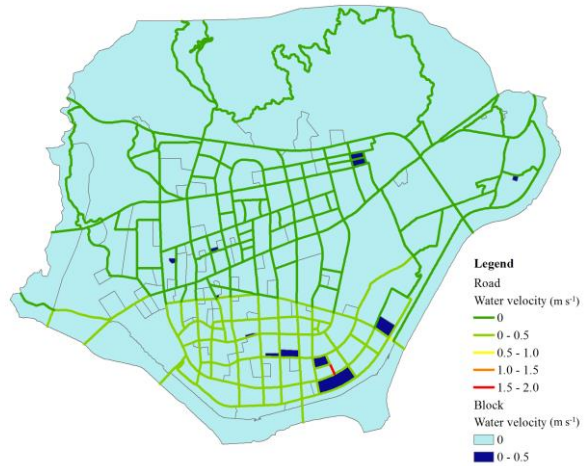
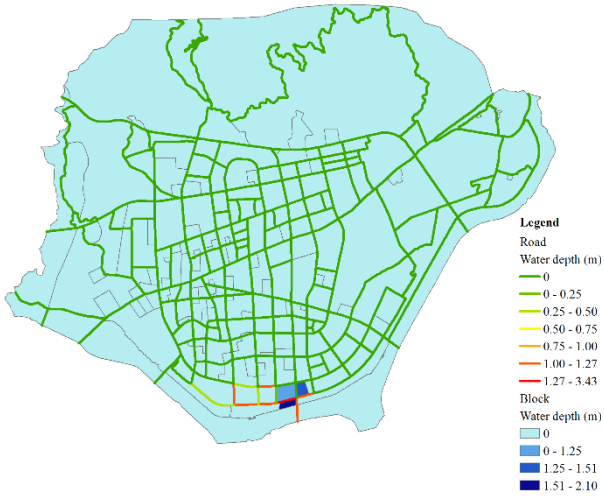
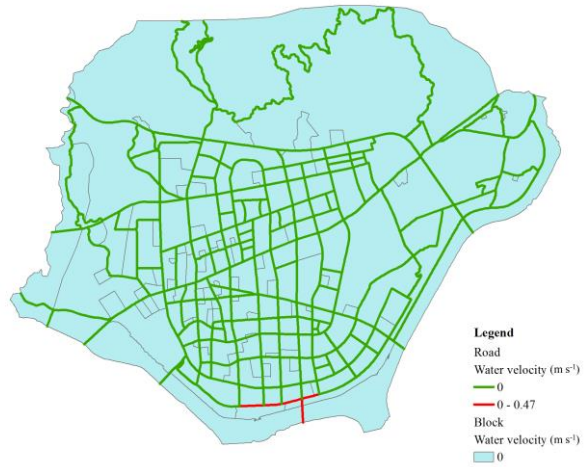
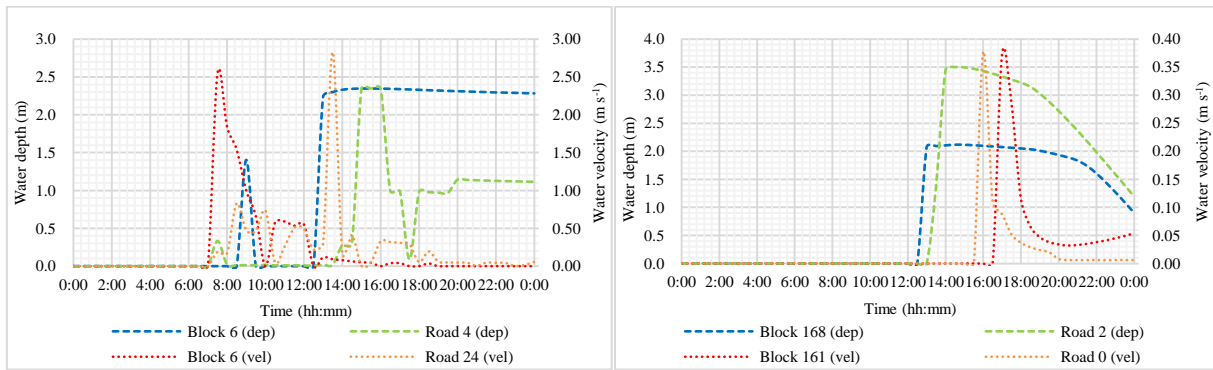
Figure 8. Agent types for daily and disaster scenarios. Daily scenarios refer to S1, S2, S7, and S8, and the rest are disaster scenarios.

(a) Water depth (pluvial flood, T = 15:00)   **(b) Water velocity (pluvial flood, T = 08:00)**

(c) Water depth (fluvial flood, T = 16:00)   **(d) Water velocity (fluvial flood, T = 16:00)**

5   **Figure 9. Maps of Aaccumulated water depths and velocities. "T" meanindicates time here.**

(a) Pluvial flood   **(b) Fluvial flood**

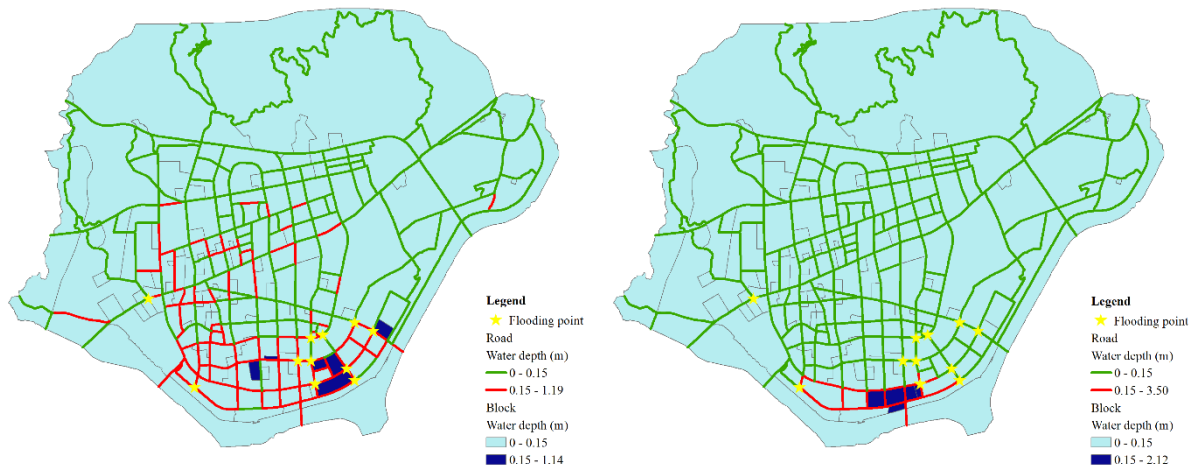
Figure 10. Changes in the surface water depths (dep) and velocity (vel)ies for eight severely flooded areas. The "dep" indicates water depth, and "vel" indicates water velocity.

(a) Pluvial flood   **(b) Fluvial flood**

Figure 11. Map of the flooded area indicating the flooding simulation and real flood in 2014. Data for the flooded area were provided by Lishui City Housing and Urban-Rural Construction Bureau.

(a) Block   **(b) Road**

Figure 1~~2~~1. Population changes in blocks and roads for the six scenarios.

(a) Daily, weekday (T = 09:00)

(b) Daily, weekend (T = 09:00)

(c) Bad weather, weekday (T = 09:00)

(d) Bad weather, weekend (T = 09:00)

(e) Warning, weekday (T = 09:00)

(f) Warning, weekend (T = 09:00)

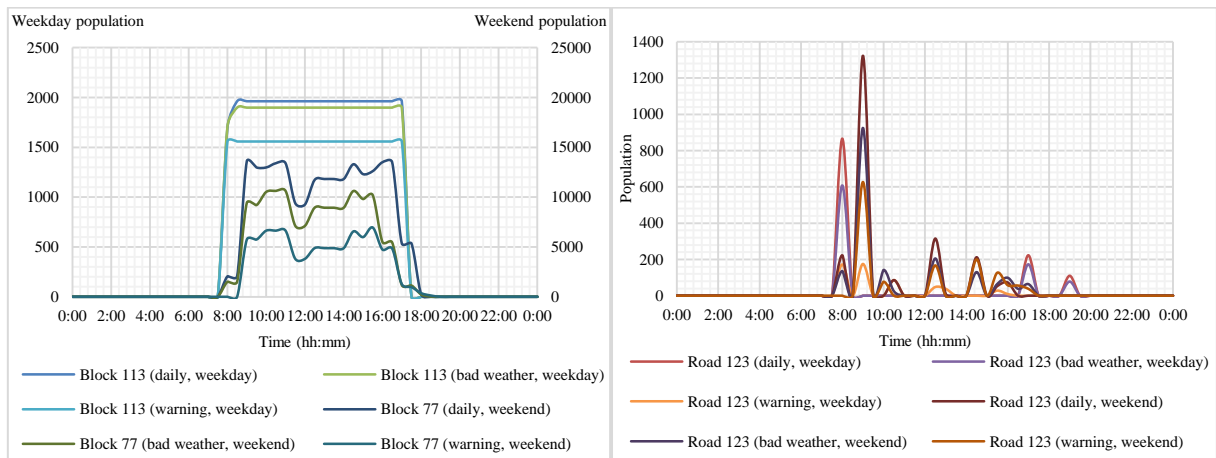



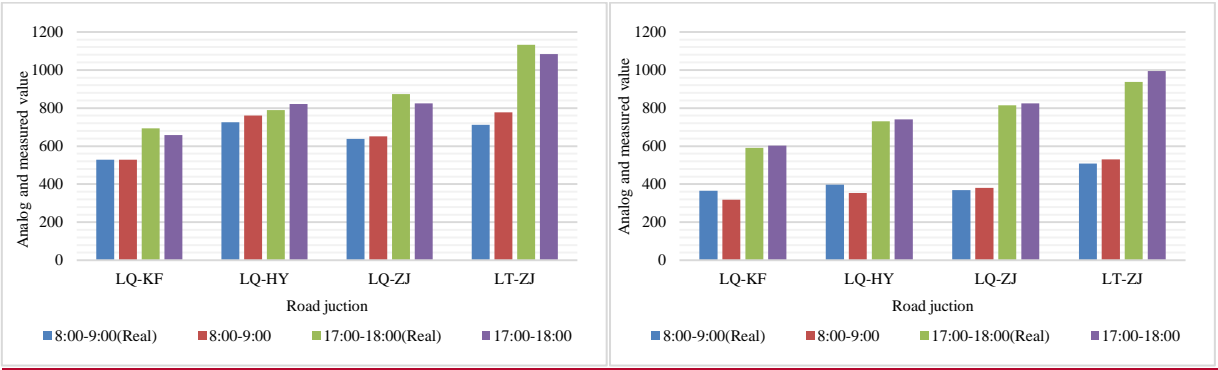
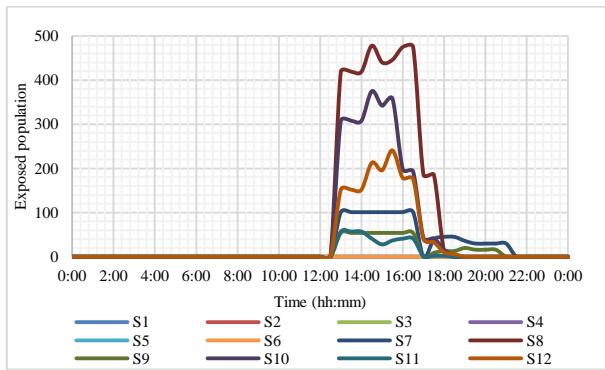
Figure ~~12~~13. Population distribution for the six scenarios. "T" ~~mean~~indicates time ~~here~~.

(a) Weekday   **(b) Weekend**

Figure 14. Traffic flow and population simulation results during peak hours on weekdays and weekends. Traffic flow data were provided by the Lishui City Traffic Bureau. Real means measured value. LQ is Liqing Road, KF is Kaifa Road, HY is Huayuan Road, ZJ is Zijin Road, and LT is Lutang Street.

(a) Population exposure (Block 168)   **(b) Population exposure (Block 6)**

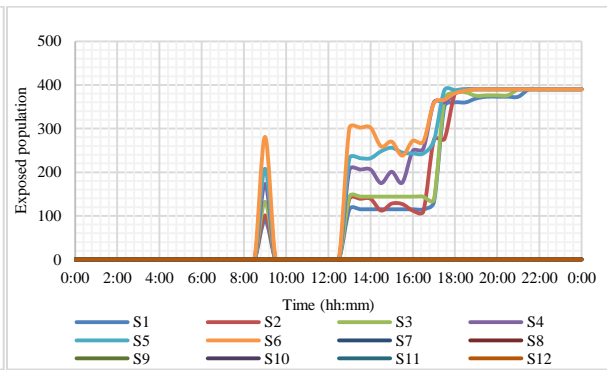
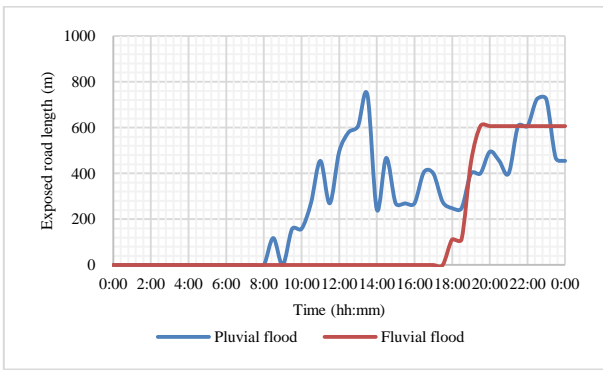



Figure 1~~3~~5. Changes in ~~the~~ population exposure of two blocks for the 12 scenarios. Block 168 was a recreational area, and Block 6 was a residential area.

(a) Exposed road length (Block 6) **(b) Exposed building area (Block 168)**

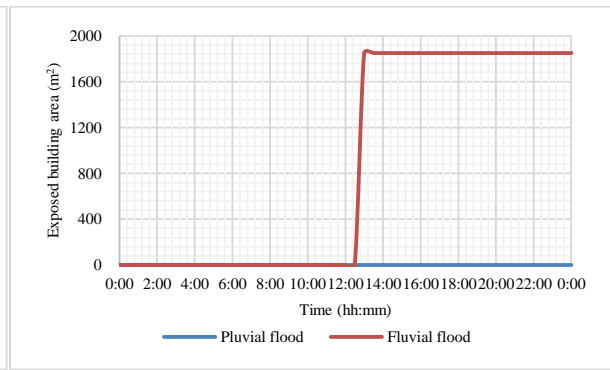



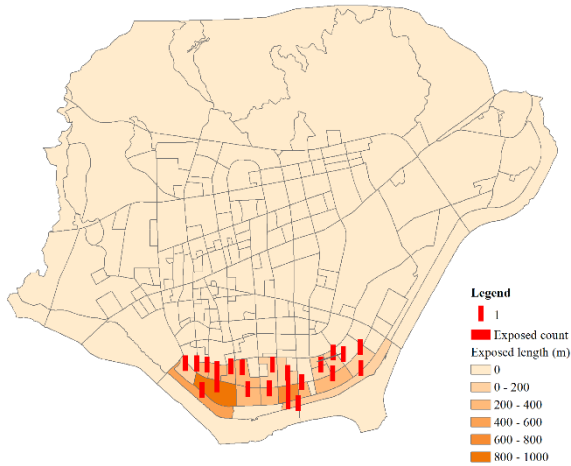
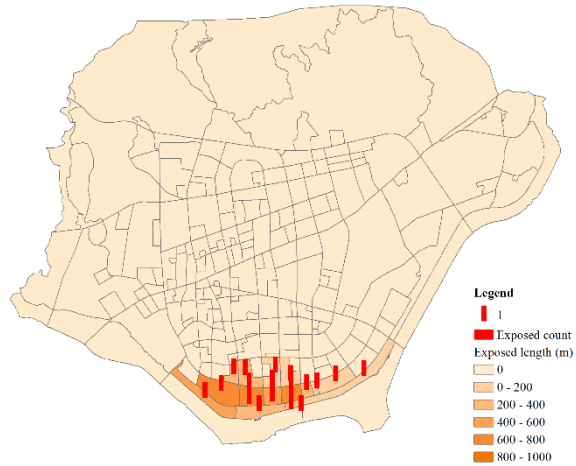
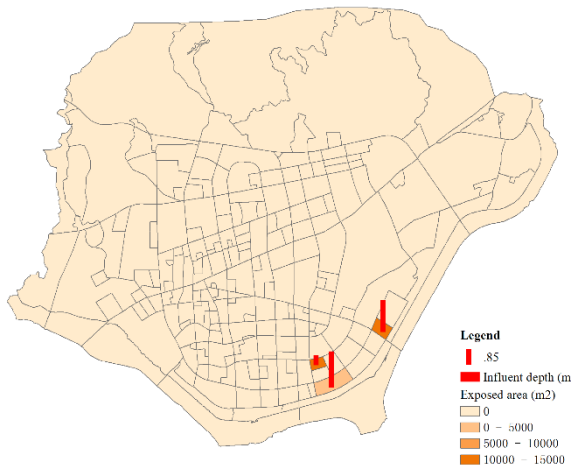
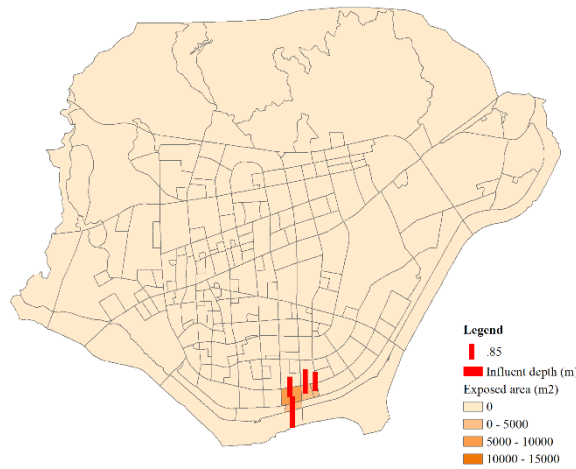
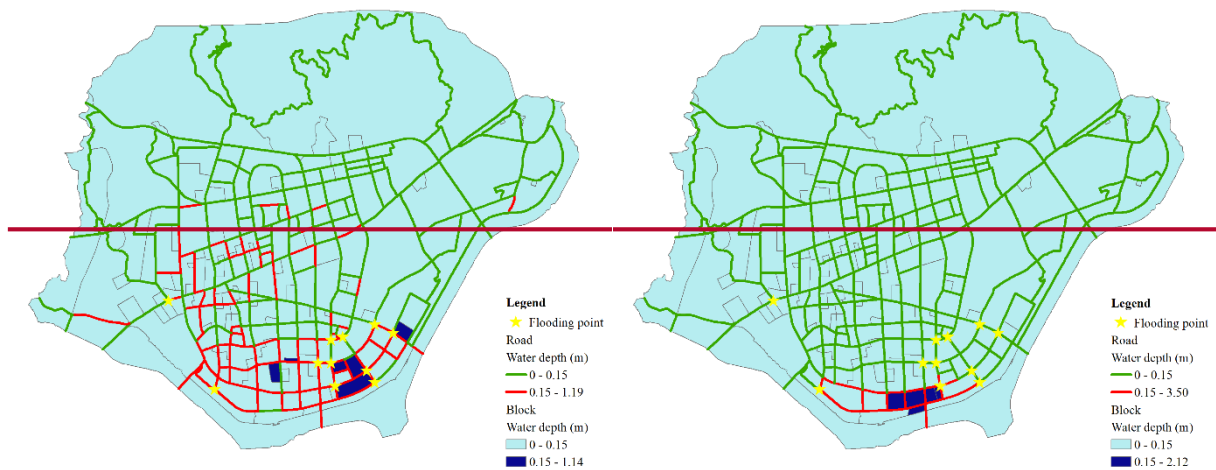
Figure 1~~6~~4. Changes in road and building exposures in severely flooded blocks. ~~The e~~Exposed road length and building area represent road and building exposures, respectively.

(a) Road exposure (pluvial flood, T = 18:30)   (b) Road exposure (fluvial flood, T = 18:30)

(c) Building exposure (pluvial flood, T = 18:30) (d) Building exposure (fluvial flood, T = 18:30)

5   Figure 1517. Map of road and building exposures. "T" indicatesmeans time here.

(a) Pluvial flood   (b) Fluvial flood

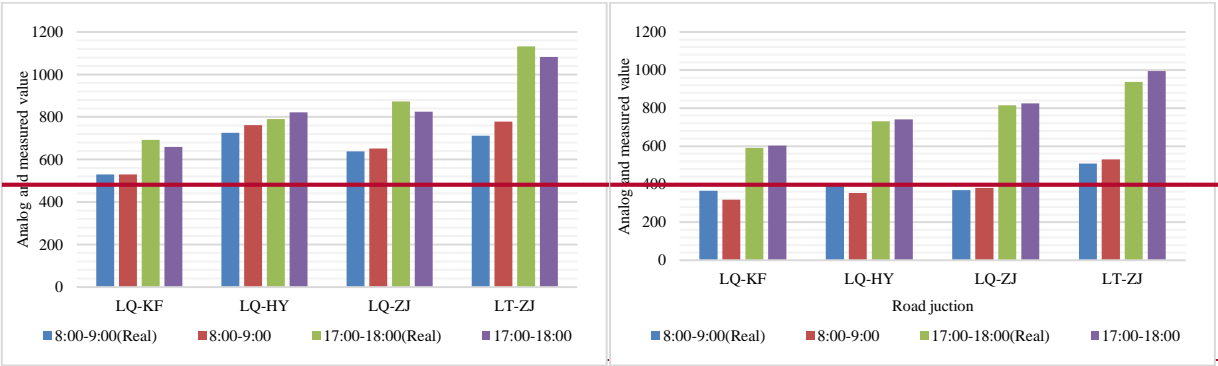
Figure 16. Map of the flooded area indicating the flooding simulation and the real flood in 2014. The information for the flooded area was provided by Lishui City Housing and Urban-Rural Construction Bureau.

(a) Weekday   (b) Weekend

Figure 17. Traffic flow and population simulation results during peak hours on weekdays and weekends. The traffic flow data were provided by the Lishui City Traffic Bureau. Real means measured value here. LQ is Liqing Road, KF is Kaifa Road, HY is Huayuan Road, ZJ is Zijin Road, and LT is Lutang Street.

Tables

Table 1 Data used in this study.

Table 2. Parameter values for the rainstorm intensity formula.

Table 3. Parameter variations used in the simulation scenarios.

5 **Table 4. Sociodemographic characteristics of the population in the case study area.**

Table 5. ~~The heights of Bb~~uilding step~~s heights~~ for different block types.

Table 1. Data used in this study.

Data	Source	Time	Use
Digital elevation model	Local government	2013	Topography (regular square grids with a 5 m resolution)
Basic geographic data	Local government	2015	Location of river, road and building
Hydrological data	Local government	20 Aug 2014	River discharge Flow and water level
1km grid population data	National Earth System Science Data Sharing Infrastructure, National Science & Technology Infrastructure of China (http://www.geodata.cn)	2010	Number of residents in grid of the study area.
Population profile	Lishui Statistical Yearbook and Liandu Yearbook (http://tjj.lishui.gov.cn/sjjw/tjnj/201511/t20151105_448284.htm)	2014	Gender profile, age profile, education level profile, employment profile and travel mode profile were used to classify agent groups.
Travel survey data	Field investigation	2018	The social characteristics and daily activities of 500 residents in random survey
Traffic flow data	Local government	24 June 2017 to 7 July 2017	The number of vehicles passing through a node within one hour at four intersections from 24 June 2017 to 7 July 2017 in this area,
Water accumulation points	Local government (http://www.zjjs.com.cn/n17/n26/n44/n47/c339697/content.html)	20 Aug 2014	Location

Table 2. Parameter values for the rainstorm intensity formula.

Parameter	Value
A	1265.3
b	5.919
c	0.587
n	0.611

Table 3. Parameter variations used in the simulation scenarios.

Scenarios	Flooding Type	Human behavior	Weekdays or Weekends
S1	Pluvial flood	Daily	Weekdays
S2	Pluvial flood	Daily	Weekends
S3	Pluvial flood	Bad weather	Weekdays
S4	Pluvial flood	Bad weather	Weekends
S5	Pluvial flood	Warning	Weekdays
S6	Pluvial flood	Warning	Weekends
S7	Fluvial flood	Daily	Weekdays
S8	Fluvial flood	Daily	Weekends
S9	Fluvial flood	Bad weather	Weekdays
S10	Fluvial flood	Bad weather	Weekends
S11	Fluvial flood	Warning	Weekdays
S12	Fluvial flood	Warning	Weekends

Table 4. Sociodemographic characteristics of the population in the case study area.

Variables	Groups	Percentage (%)
Gender	Male	50.43
	Female	49.57
Age	0-17	18.73
	18-60	63.34
	>60	17.93
Professional status	Employed	55.77
	Unemployed	44.23
Education Level (Highest diploma)	University, school-college, bachelor	14.46
	No diploma	85.54
Travel mode	Walk	25.24
	Bus	43.06
	Car	31.70

Note: The data are from the 2015 Lishui Statistical Yearbook and 2015 Liandu Yearbook.

Table 5. The heights of Bbuilding steps heights for different block types.

No	Block type	Building type	Building steps height
1	Residential area I	Garden house, villa	0.35 m(floors>9, 0.60 m)
2	Residential area II	High-rise apartments and new village houses before and after liberation (before 1988); new residential quarters and commercial houses (after 1988)	0.35 m(floors>9, 0.60 m)
3	Residential area III	New and old Lane homes, three types of staff housing	0.10 m
4	Residential area IV	Shed house	0.05 m
5	School	Educational building	0.35 m(floors>9, 0.60 m)
6	Company	Office building	0.35 m(floors>9, 0.60 m)
7	Recreational area	Public buildings for business, culture, sports and other use	0.35 m(floors>9, 0.60 m)