Research Paper

Scenario Simulation of Compound Flood Risk Based on Climate Resilience

——A Case Study of the Yangtze River Delta, China

Yuye ZHOU, Nanjing University, China
Yiwen WANG, Nanjing University, China
Jiangang XU, Nanjing University, China

Abstract

Under the influence of global climate change and urbanization, sea-level rise and frequent extreme weather caused by climate warming are gradually threatening the safety of coastal cities. The empirical area, the Yangtze River Delta, is located in the eastern coastal area of China, facing the compound risk of rainstorm and sea-level rise. However, there are few studies on regional flood risk simulation and adaptive planning to deal with the impact of global change. Moreover, the potential composite flood risk mechanism caused by rainstorm and sea-level rise is still unknown. This study mainly introduces the scenario matrix simulation method according to RCPs-SSPs(CMIP6) into simulating the compound flood risk scenario based on the coupling scenarios of different typical concentration paths and shared socio-economic paths. In response to the simulation results, a set of regional flood complex adaptive system is constructed to provide a framework for the realization of the goal of climate resilience in the Yangtze River Delta. Finally, this empirical study provides creative research ideas and strategic references for the adaptation and mitigation of climate change in the coastal delta region.

Keywords

Global climate change; scenario simulation based on RCPs-SSPs; Climate adaptative planning; Climate resilience; Yangtze river delta

1. Introduction

Since the beginning of the 21st century, the frequent occurrence of extreme weather, ocean warming, melting glaciers and ice sheets, rising sea levels and other issues have aroused the international community's attention to global climate change. According to the Sixth Assessment Report (AR6) of IPCC(IPCC, 2022), the global average land and sea surface temperature increased by 0.85℃ from 1880 to 2012, indicating that global climate change is an indisputable fact, and the warming trend of the climate system will continue. Global mean sea level rose by 0.19 m from 1901 to 2010 due to melting ice sheets and thermal expansion of seawater. Since the mid-19th century, sea levels have risen faster than the average for the past 2,000 years, seriously threatening many of the world's coastal areas and low-elevation islands.

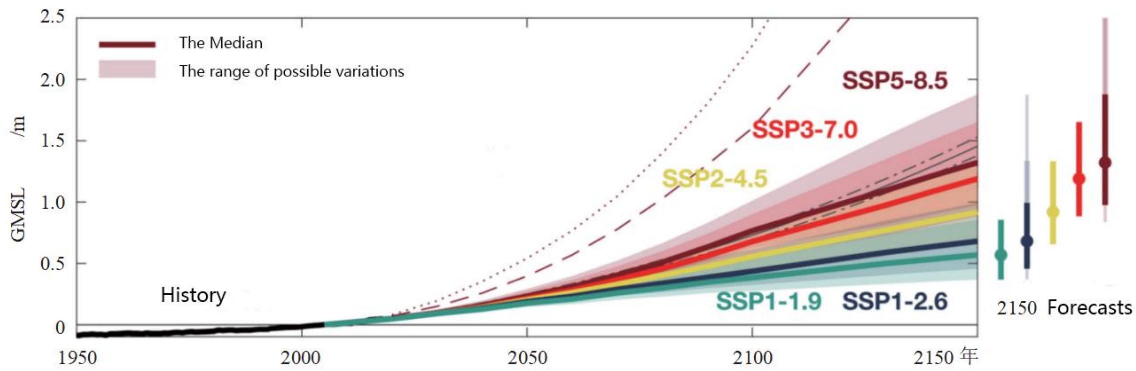

Figure 1. Projected increases in global mean sea level under different SSP scenarios. Source: NASA GISS.

At present, a large number of researches are focused on climate change scenario simulation(Arnell et al., 2016). Among them, Integrating climate science, Integrated Assessment Model (IAM) and Impacts, Adaptation, vulnerability, Scenario modeling of IAV research is an important method to reflect and assess climate change(O'Neill et al., 2016). Through scenario simulation, people can not only understand the impact of recent decisions on the long-term environment, but more importantly, they can find the potential uncertainties, so that they can take comprehensive strategies to cope with the possible changes(Riahi et al., 2017).

Since scenario simulation involves many variables and has great uncertainty, it is very important to establish a comprehensive simulation evaluation method(Harrison et al., 2016, Hammond et al., 2015, Kumar et al., 2021). Mossa et al. (van Vuuren et al., 2011) proposed the use of "parallel method" for scenario simulation. Representative Concentration Pathways (RCPs) that reflect changes in different Radiative forcing levels are developed and applied in the parallel approach. RCPs are composed of four representative emission paths, each of which contains the temporal dimension of GHG, aerosol and chemically active gas emissions. In the Fifth Coupled Model Comparison Programme (CMIP5), RCPs became the basis for climate model scenarios and an important part of the IPCC Fifth Assessment Report. Thereafter, Kriegler et al. (Kriegler et al., 2012)and Van Vuuren et al. (van Vuuren et al., 2012)proposed to increase the weight of human activities in scenario simulation, so as to build a scenario simulation framework closer to the reality. Based on this scenario, Shared socio-economic pathways (SSPs) were used to model changes in scenarios of mitigation and adaptation to different levels of challenges in the socio-economic environment facing future development(O'Neill et al., 2017). SSPs is used to reflect the changes of social and economic development through five different ways, which involve the qualitative description of scenario characteristics and the quantitative work of key drivers such as population change, economic growth and urbanization. Subsequently, a Matrix approach based on RCPs and SSPs to conduct Matrix simulations (Matrix Architecture) to assess climate change and impacts was established(Harrison et al., 2016, van Vuuren et al., 2012). In the latest studies, many future changes involving Land use/cover change (LUCC) (Fan, 2022)and stormwater inundation risk change have been simulated by the RCP-SSP framework, which is significant to the adaptation and mitigation of the climate change risk.

Sea-level rise and extreme weather caused by climate change are gradually threatening the safety of coastal cities(Wang et al., 2015). This study introduces the scenario matrix simulation method according to RCPs-SSPs(CMIP6) into simulating the compound flood risk scenario. In response to the simulation results, a set of regional flood complex adaptive system is constructed to enhance climate resilience. Finally, this empirical study provides creative research ideas and strategic references for the adaptation and mitigation of climate change in the coastal delta region.

2. Data and methods

2.1. Data

The Taihu Basin is located in the southern part of the Yangtze River Delta of China. It belongs to the subtropical monsoon climate zone along the coast, with four distinct seasons and abundant rain(Li et al., 2013). The average annual precipitation in the basin is 1177 mm. Taihu Lake basin is high in the southwest and low in the northeast. Plain is the main landform, accounting for 4/6 of the total area. The river network in this area is dense, and the seven districts in the basin are interconnected with each other. The lake and wetland resources are rich, and the water area accounts for 1/6 of the total area. The study area has high population density and rapid industrial development, and the flood disaster has become an important factor restricting the sustainable development of the city.

In this study, land use data are from GlobeLand30, multi-band remote sensing images are from Landsat 8 dataset, elevation data are from MERIT DEM released by Google Earth Engine, and climate data are mainly downloaded from the WorldClim website.

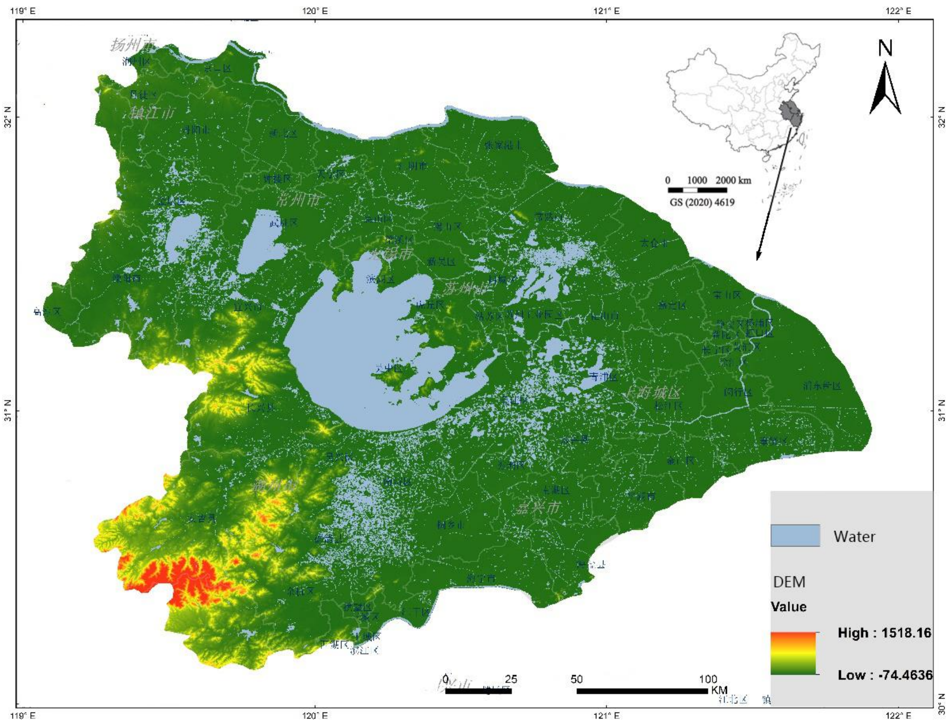

Figure 2. Study area. Source: MERIT DEM.

2.2. Methods

Due to the risk of failure of urban drainage system under extreme rainstorm conditions and the actual situation of imperfect and unbalanced drainage facilities in vast non-urban areas, this study takes the natural confluence area that does not consider the function of urban drainage facilities as a risk aversion factor to be considered when selecting the location of industry.

1. Watershed division

In order to simulate the natural catchment situation in each region, it is necessary to divide the study area into basins. In this study, Arc Hydro Tools was used to divide the basins, and then fill in the pits, calculate the flow direction, and calculate the cumulative flow. After the natural watershed division was completed, it was less than 0.025km^2 . The fine plots were merged into the neighboring watershed plots.

2. Rainstorm intensity model and watershed runoff construction

The Comprehensive Water Resources Planning of Wujiang City provides a rainstorm intensity model for Suzhou and its surrounding areas. This study adopted this model and extended it to the entire Taihu Lake basin. The model formula is as follows:

$$q = \frac{2887.43(1 + 0.7941\, log\, P)}{(t + 18.8)^{0.81}} \tag{1}$$

Where q is the intensity of the rainstorm, and the unit is L/(S *hm^2); P is rainfall return period, in years; t is rainfall duration, in minutes. Runoff coefficient refers to the ratio of runoff water volume and precipitation in the same period. According to the area of various land cover types in each watershed, the weighted sum of land runoff coefficient is calculated as the watershed runoff index, and then the total runoff is calculated according to the watershed runoff coefficient and rainfall. The calculation method is as follows:

$$Q = P \times \frac{\sum S_i * \varphi_i}{\sum S_i} \tag{2}$$

Where Q is the runoff volume; P is rainfall; And S_i is the area of the first i type of land cover type and φ_i is the corresponding runoff coefficient. The runoff coefficients of different land cover types are shown in Table 1:

Table 1. Corresponding table of runoff coefficients

Land use types	Road	Bare land	vegetation	Agricultural land	Rivers and lakes
Runoff coefficient	0.85	0.3	0.15	0.25	0

3. Inundation range and depth simulation

Based on the runoff and DEM data of each watershed, the flood inundation range and inundation depth were simulated by subdivision blocks. During the simulation process, the first preset submerged depth value, using cellular automata from spreading around the neighborhood, block the lowest place below submerged depth neighborhood unit from "not drown" state to a state of "overwhelm" switch, calculate each diffusion operation need filling water, and fill the water need to be deducted from the total runoff(Patro et al., 2009). Then, the newly added "submerged" unit is used as the starting point again, so that the cells continue to spread to the neighborhood until the total runoff is 0.If the diffusion process is finished but the runoff is still greater than 0, the inundation depth needs to be increased by one step to repeat the above simulation of flood and inundation process. In this study, the increase step of inundation depth was set as 0.1m.

3. Results and discussion

Based on the total amount of surface runoff in each sub-basin, cellular automata was used to simulate the risk area of flooding caused by natural rainwater confluence, as shown in Figure 3. Among them, meet suhu region of taihu lake watershed waterlogging disaster probability is bigger, this was partly due to Sue the opaque surface coverage of Shanghai area is larger, the west changzhou region of rainwater in low-lying areas, flooded risky areas include changzhou, wuxi, yixing, on the other hand, east of suzhou, Shanghai and other places flat, The relatively concentrated natural water bodies have limited capacity to relieve sudden rainstorms, and the areas with high inundation risk include Kunshan and Taicang in Suzhou and Baoshan, Qingpu and Songjiang districts in Shanghai.By contrast, the flood risk in Zhejiang is relatively small. On the one hand, Huzhou, Jiaxing and other cities in Zhejiang Province have small urban space and less natural water collected. On the other hand, the terrain conditions with high south and low north are conducive to channeling rainwater to Nanxun District of Huzhou, Wujiang District of Suzhou, Xiuzhou District of Jiaxing and Jiashan District. And the dense water network ponds and the historical polder system in these areas are conducive to the confluence of the sudden increase in rainwater accumulation.

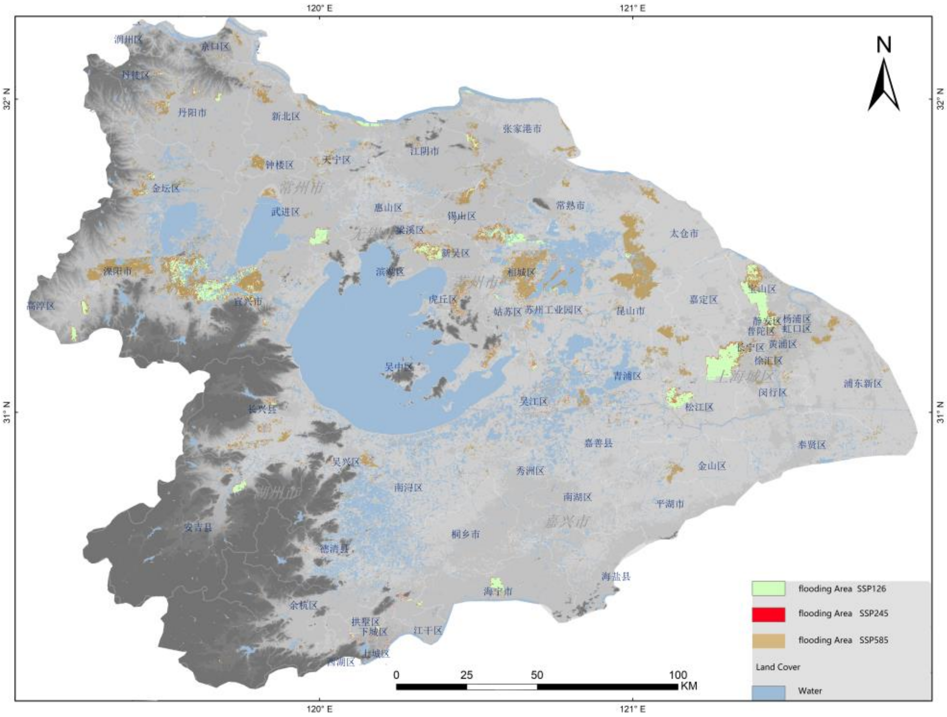

Figure 3. Simulation results of the inundation extent of a rainstorm in the Taihu Basin.

There is a mutually adaptive relationship between industrial economic system, natural system and social system. Comparing the inundation scope of the three periods, it can be found that the inundation scope of 2010 did not change significantly compared with that of 2000, but the inundation scope of 2020 increased significantly compared with that of 2010. This is mainly due to the significant expansion of industrial land and other impervious surface in Suhu area from 2010 to 2020. This directly led to the increase of the total catchment volume and the further expansion of the suspected inundation area. However, the impact of industrial land expansion on flood risk is not unidirectional. It can be found that most industrial land in Suhu area shows a certain avoidance to the areas with higher inundation risk during the spatial evolution, so as to reduce the economic cost of flood control and possible flood damage. For example, the junction of Yixing City in Wuxi, Taicang City in Suzhou and Kunshan City, as well as Qingpu, Minhang and Songjiang districts in Shanghai are shown in figure 4. By comparing the radar maps of the expansion direction of industrial land in different regions from 2000 to 2005 and from 2015 to 2020, it can be found that, except for parts of Changzhou City and the central urban area of Shanghai, all regions have more obvious avoidance of waterlogging prone areas in recent years. In the hard-to-avoid waterlogging areas, flood control and drainage facilities should be strengthened to ensure the safety of factories, workshops and residents, such as Baoshan District and Jing 'an District in Shanghai. These areas are densely populated, economically developed but low-lying, which are prone to urban waterlogging when subjected to short periods of heavy rainfall in summer. Therefore, it is necessary to reform the social system, implement flood control upgrading projects and drainage channel construction.

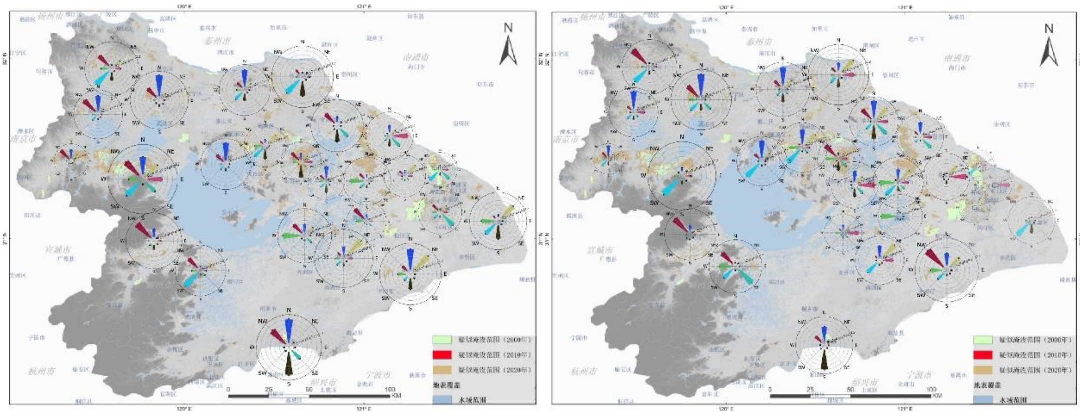

Figure 4. Radar map of land expansion direction.

4. Conclusion

The current storm-flood simulation models are generally generalized and not refined enough for socio-economic simulation, and the estimation of extreme weather events is not enough. Join scenario perspective, this paper use different social economic model driven new emissions scenario, which Shared economic path (SSPs) and path (RCPs) to simulate typical concentration prediction, while increasing focus on extreme events, integrate climate adaptation plans into the national spatial planning system, enhancing the accuracy and application value of research. The results showed that the risk of flood disaster in Jiangsu and Anhui was relatively high, while the risk of flood disaster in Shanghai and Zhejiang was relatively low. The direct economic losses of flood disasters per unit GDP of Anhui Province and Zhejiang Province and the area of crop damage in Anhui Province were significantly higher than those in Jiangsu Province and Shanghai, while the disaster losses in Shanghai were significantly lower than those in the other three provinces.

Future research on urban planning under climate change can focus more on climate resilience(Tourbier, 2012), mitigation and adaptation, climate equity and other areas. At the same time, we should pay attention to the scale and typicality of the research, increase the attention to extreme events, and introduce social and economic development data into future scenario simulation. In this way, local adaptive and resilient planning strategies with regional characteristics are proposed to enhance the practical application value of urban research in the context of global climate change.

This research was funded by the National Natural Science Foundation of China, grant number 52178043.

5. References

ARNELL, N. W., BROWN, S., GOSLING, S. N., GOTTSCHALK, P., HINKEL, J., HUNTINGFORD, C., LLOYD-HUGHES, B., LOWE, J. A., NICHOLLS, R. J., OSBORN, T. J., OSBORNE, T. M., ROSE, G. A., SMITH, P., WHEELER, T. R. & ZELAZOWSKI, P. (2016). The impacts of climate change across the globe: A multi-sectoral assessment. *Climatic Change,* 134**,** 457-474.

FAN, Z. (2022). Simulation of land cover change in Beijing-Tianjin-Hebei region under different SSP-RCP scenarios. *Acta Geographica Sinica,* 77**,** 228-244.

HAMMOND, M. J., CHEN, A. S., DJORDJEVIĆ, S., BUTLER, D. & MARK, O. (2015). Urban flood impact assessment: A state-of-the-art review. *Urban Water Journal,* 12**,** 14-29.

HARRISON, P. A., DUNFORD, R. W., HOLMAN, I. P. & ROUNSEVELL, M. D. A. (2016). Climate change impact modelling needs to include cross-sectoral interactions. *Nature Climate Change,* 6**,** 885-+.

IPCC (2022). Climate Change 2022: Impacts,Adaptation and Vulnerability. Working Group II contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. . Cambridge.

KRIEGLER, E., O'NEILL, B. C., HALLEGATTE, S., KRAM, T., LEMPERT, R. J., MOSS, R. H. & WILBANKS, T. (2012). The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. *Global Environmental Change-Human and Policy Dimensions,* 22**,** 807-822.

KUMAR, N., POONIA, V., GUPTA, B. B. & GOYAL, M. K. (2021). A novel framework for risk assessment and resilience of critical infrastructure towards climate change. *Technological Forecasting and Social Change,* 165**,** 120532.

LI, G. F., XIANG, X. Y., TONG, Y. Y. & WANG, H. M. (2013). Impact assessment of urbanization on flood risk in the Yangtze River Delta. *Stochastic Environmental Research and Risk Assessment,* 27**,** 1683-1693.

O'NEILL, B. C., TEBALDI, C., VAN VUUREN, D. P., EYRING, V., FRIEDLINGSTEIN, P., HURTT, G., KNUTTI, R., KRIEGLER, E., LAMARQUE, J.-F., LOWE, J., MEEHL, G. A., MOSS, R., RIAHI, K. & SANDERSON, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development,* 9**,** 3461-3482.

O’NEILL, B. C., KRIEGLER, E., EBI, K. L., KEMP-BENEDICT, E., RIAHI, K., ROTHMAN, D. S., VAN RUIJVEN, B. J., VAN VUUREN, D. P., BIRKMANN, J., KOK, K., LEVY, M. & SOLECKI, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change,* 42**,** 169-180.

PATRO, S., CHATTERJEE, C., MOHANTY, S., SINGH, R. & RAGHUWANSHI, N. S. (2009). Flood Inundation Modeling using MIKE FLOOD and Remote Sensing Data. *JOURNAL OF THE INDIAN SOCIETY OF REMOTE SENSING,* 37**,** 107-118.

RIAHI, K., VAN VUUREN, D. P., KRIEGLER, E., EDMONDS, J., O'NEILL, B. C., FUJIMORI, S., BAUER, N., CALVIN, K., DELLINK, R., FRICKO, O., LUTZ, W., POPP, A., CUARESMA, J. C., SAMIR, K. C., LEIMBACH, M., JIANG, L., KRAM, T., RAO, S., EMMERLING, J., EBI, K., HASEGAWA, T., HAVLIK, P., HUMPENOEDER, F., DA SILVA, L. A., SMITH, S., STEHFEST, E., BOSETTI, V., EOM, J., GERNAAT, D., MASUI, T., ROGELJ, J., STREFLER, J., DROUET, L., KREY, V., LUDERER, G., HARMSEN, M., TAKAHASHI, K., BAUMSTARK, L., DOELMAN, J. C., KAINUMA, M., KLIMONT, Z., MARANGONI, G., LOTZE-CAMPEN, H., OBERSTEINER, M., TABEAU, A. & TAVONI, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change-Human and Policy Dimensions,* 42**,** 153-168.

TOURBIER, J. A methodology to define flood resilience. EGU General Assembly Conference Abstracts, (2012). 13902.

VAN VUUREN, D. P., EDMONDS, J., KAINUMA, M., RIAHI, K., THOMSON, A., HIBBARD, K., HURTT, G. C., KRAM, T., KREY, V., LAMARQUE, J.-F., MASUI, T., MEINSHAUSEN, M., NAKICENOVIC, N., SMITH, S. J. & ROSE, S. K. (2011). The representative concentration pathways: an overview. *Climatic Change,* 109**,** 5-31.

VAN VUUREN, D. P., RIAHI, K., MOSS, R., EDMONDS, J., THOMSON, A., NAKICENOVIC, N., KRAM, T., BERKHOUT, F., SWART, R., JANETOS, A., ROSE, S. K. & ARNELL, N. (2012). A proposal for a new scenario framework to support research and assessment in different climate research communities. *Global Environmental Change-Human and Policy Dimensions,* 22**,** 21-35.

WANG, Z. L., LAI, C. G., CHEN, X. H., YANG, B., ZHAO, S. W. & BAI, X. Y. (2015). Flood hazard risk assessment model based on random forest. *Journal of Hydrology,* 527**,** 1130-1141.