Country-Wide Flood Hazard Mapping of China Using a Global Flood Model with ERA5-Land Runoff Forcing

Jayesh Parmar
PhD Student

Environmental Science and Engineering Department

Indian Institute of Technology Bombay (IIT Bombay)

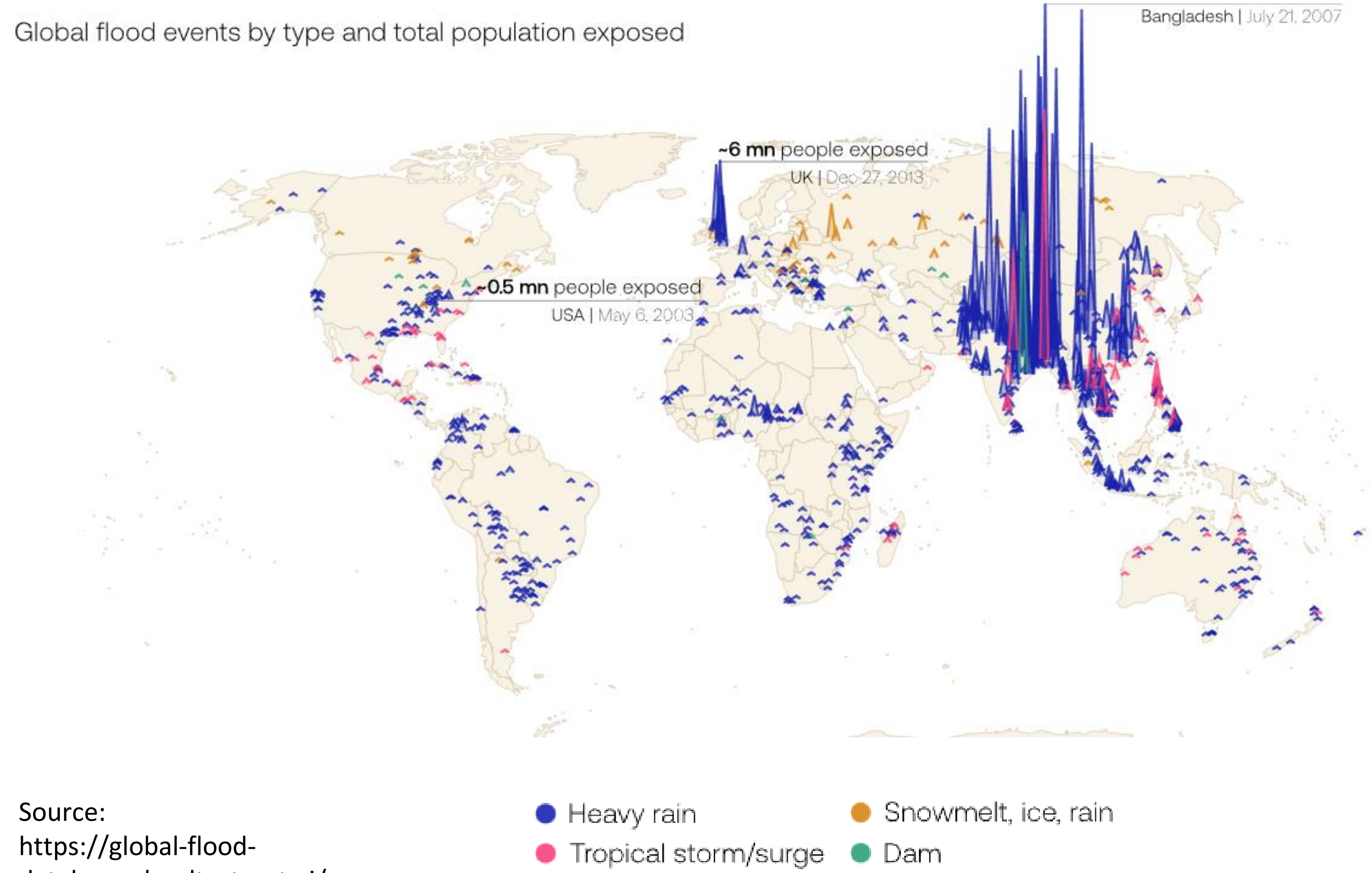
3rd ASIA INTERNATIONAL WATER WEEK
BEIJING, CHINA
SEP. 23-28, 2024

Contents

- Introduction
- Methodology- Flow Chart
- Runoff Inputs
- Hydrodynamic Models
- CaMa-Flood Model
- Results
    - Streamflow Validation
    - Flood Footprint Validation
- Hazard Mapping: 10-200 year flood depth return levels
- Province Wise Analysis and Observations
- Challenges and Way-forward

Introduction

Southeast Asia has high concentration of population exposed to floods



Source: https://global-flood-database.cloudtostreet.ai/

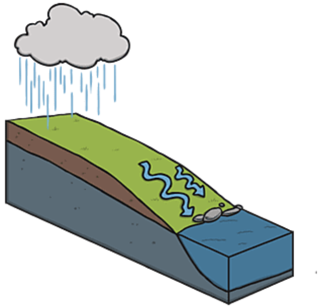
- The UN 2023 Water Conference underscores water's critical role in achieving the Sustainable Development Goals.
- Observing global impact of floods, UNISDR's global assessment emphasizes the urgent need for flood hazard and exposure evaluations.
- ICFM also enumerates the need to build resilience into future planning.
- Flood hazard and risk assessment are one of the critical aspects of building resilience using effective flood management

Introduction : Aim of the Study

- The aim of the present work is to use and apply open source flood model and input data to provide information to stakeholders and policymakers using flood hazard mapping.

- The current objective focusses on generating a national scale flood hazard map using the globally acclaimed flood model CaMa-flood model forced with the state of the art ERA 5 runoff forcing's.

Methodology: Flow Chart



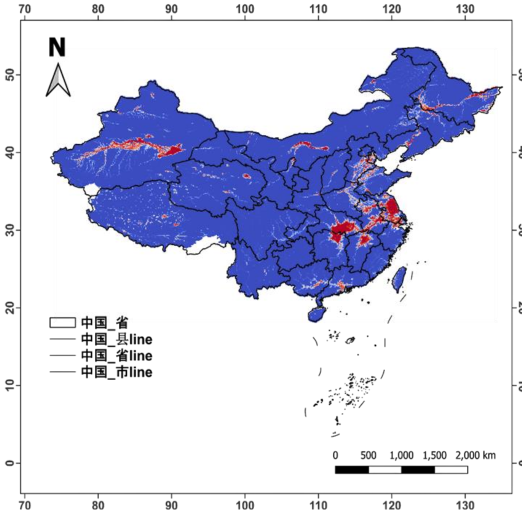
Step1

Daily Runoff as input obtained from ECMFW ERA products (1981 -2023)

Step2

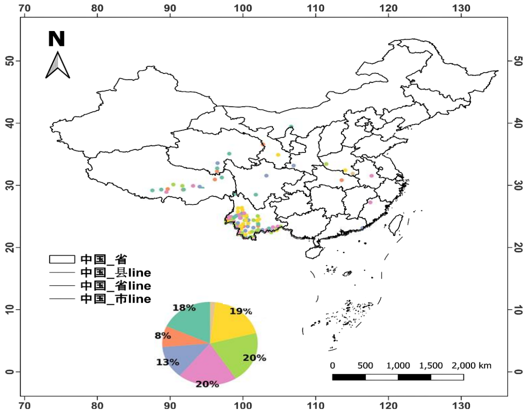
CaMa-Flood model set-up

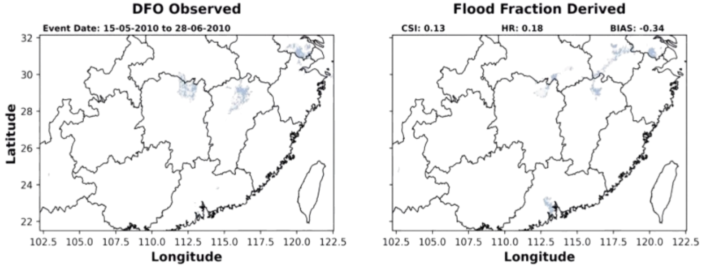
- **MERIT Hydro** [Global Hydrology Map]
- **Flow Direction Map** [Flexible Location of Waterways; FLOW method]
- **Global river width (GWD-LR)** [Global River width Algorithm; GRW algorithm on SRTM Waterbody data and HYDROSHEDS]
- **Global water map (G3WBM)**
- **Open street map water layer**



Step3

Obtain daily streamflow discharge, flooded area, flood discharge, flood fraction, flood depth





Step4

Validation of simulation either with streamflow or flood extent

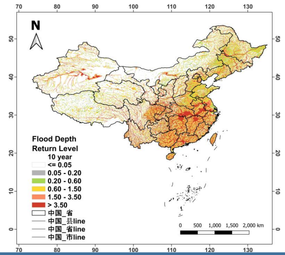
Step5

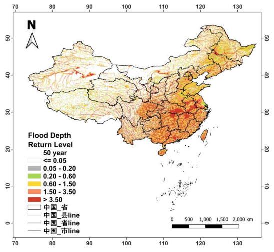
Fitting Kernel Density Estimator (KDE) to the extreme timeseries of daily flood depth during for 1981-2023 at grid cell level

$very\ high, \quad d \geq 3.5$
$high, \quad 1.5 \leq d \leq 3.5$
$moderate, \quad 0.6 \leq d \leq 1.5$
$low, \quad 0.2 \leq d \leq 0.6$
$very\ low, \quad 0 \leq d \leq 0.2$

Step6

Obtaining and classifying the obtained various return level flood depths

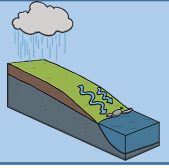




Technical flood risk management guideline: Flood hazard (Australian Disaster Resilience Handbook Collection)
https://docslib.org/doc/3722929/technical-flood-risk-management-guideline-flood-hazard

Methodology
Section 1

Run-off Inputs



- ***ECMFW*** *provides* global reanalysis and modeled dataset ***in public domain and openly available to everyone with product such as ERA5 and ERA Land***. (Source 1 and 2)

- ***ERA5 Reanalysis (0.25°, hourly scale) combines model data with observations*** from across the world using ***data assimilation techniques***. (Source 1)

- The ***temporal and spatial resolutions*** of these dataset very useful for land surface applications such as **flood or drought modelling**.

- ***ERA5-Land*** provides hourly ***high resolution (0.1°)*** information of ***surface variables***. The data is a ***replay*** of the ***land component*** of the ***ERA5 Reanalysis*** with a finer spatial resolution.

- ***Runoff obtained from ERA 5 Reanalysis and ERA5 Land is fed into CaMa-Flood flood model for generation of river and flood prognostic variables at daily scale during 1980-2023***

Hydro-dynamic model – Saint Venant Eqs.

1D Conservation of Mass
$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \ldots\ldots\ldots \quad (1)$$

Conservation of Momentum
$$\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{A}\frac{\partial(\frac{Q^2}{A})}{\partial x} + g\frac{\partial h}{\partial x} - g(S_0 - S_f) = 0 \ldots\ldots \quad (2)$$

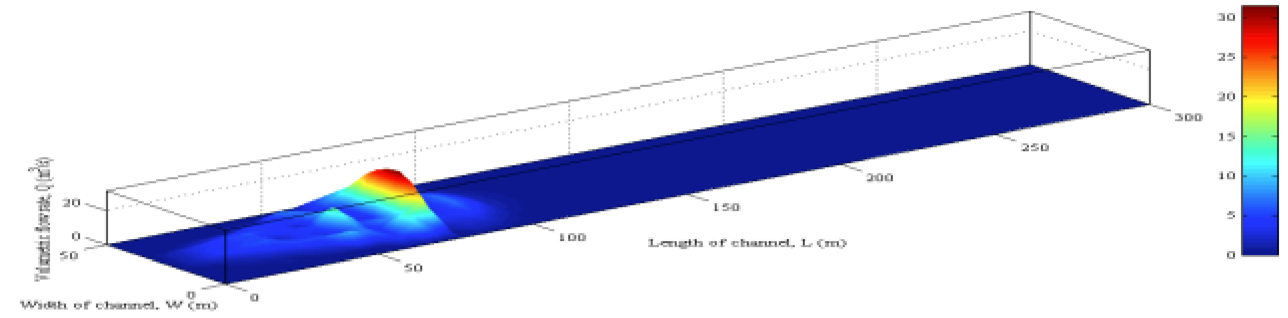
Local acceleration | Advective acceleration | Pressure force | Gravity force | Friction force

Inertial force (local acceleration + advective acceleration)

Kinematic Wave Approximation (gravity force + friction force)

Diffusive Wave Approximation (pressure force + gravity force + friction force)

Q is the flow discharge,
A is the flow cross-section area
t is the time
h represents water depth
g is the gravitational acceleration
Sf is the friction slope
So is the channel bed slope.



Time Steps N=50

- **Solution of equations estimates horizontal velocity and depth of the flow.**
- **The number of terms used in equation defines the speed and accuracy of computation.**

Hydro-dynamic model – Saint Venant Eqs.

Conservation of Mass $\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \ldots\ldots\ldots$ (1)

Conservation of Momentum $\frac{1}{A} \quad \frac{\partial Q}{\partial t} \qquad + g\frac{\partial h}{\partial x} - g(S_0 - S_f) = 0 \ldots\ldots$ (2)

Local acceleration

Diffusive Wave Approximation

- The local inertial approximation is a relatively new formulation for fast and stable flood modelling, that was developed at the University of Bristol, in which only the advective inertial term is neglected.
- The hydrodynamic and routing models known to be performing best at fine resolutions (in meters) with detailed inputs, which the global flood models lacks.
- Before CaMa-Flood development, work on the refinement of topography and generation of river characteristics was ongoing for global flood models.

Bates, P. D., Horritt, M. S., & Fewtrell, T. J. (2010). A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. Journal of Hydrology, 387(1), 33–45. https://doi.org/10.1016/j.jhydrol.2010.03.027

CaMa-Flood model

CaMa-Flood model set-up

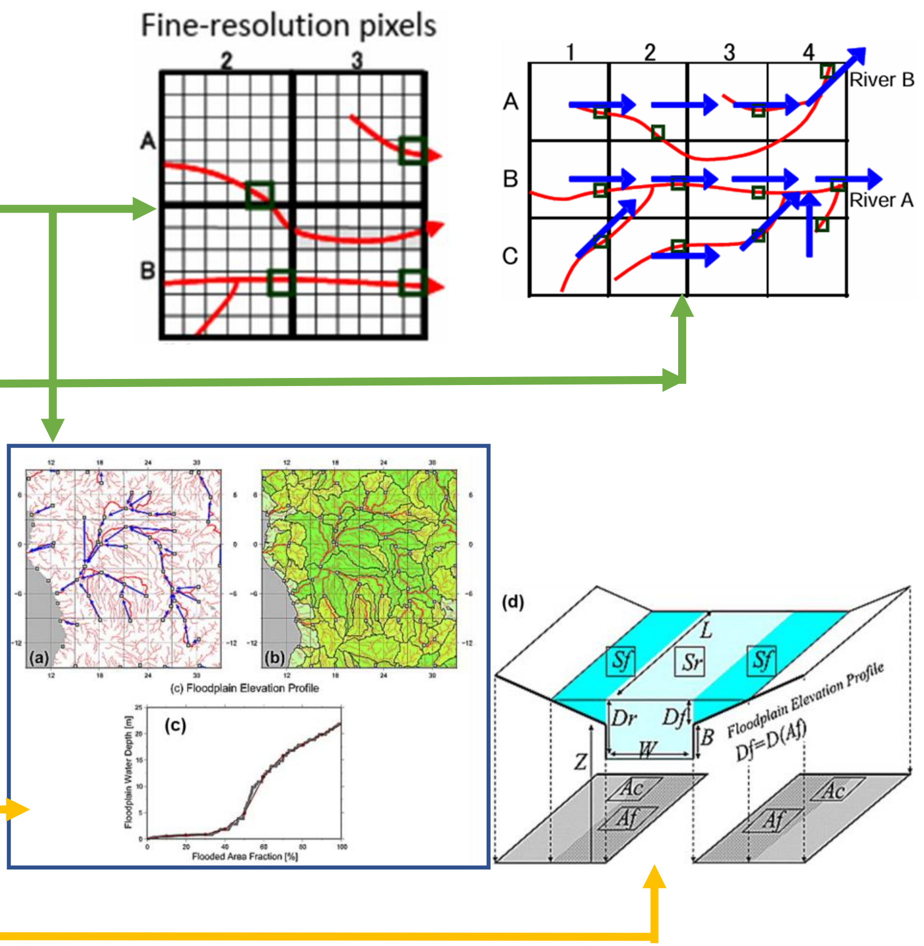
MERIT Hydro
[Global Hydrology Map]

Flow Direction Map
[Flexible Location of Waterways; FLOW method]

Global river width (GWD-LR)
[Global River width Algorithm; GRW algorithm on SRTM Waterbody data and HYDROSHEDS]

Global water map (G3WBM)

Open street map water layer



Yamazaki et al., 2009, 2011;

Yamazaki, O'Loughlin, et al., 2014;

Yamazaki, Sato, et al., 2014

Parametrization data is available in public domain

Thus the only varying input to the model is Runoff

The model was used to simulate flood characteristics for the time period of 1981-2023.

Yamazaki, D., Kanae, S., Kim, H., & Oki, T. (2011). A physically based description of floodplain inundation dynamics in a global river routing model. Water Resources Research, 47(4). https://doi.org/10.1029/2010WR009726
Yamazaki, D., Oki, T., & Kanae, S. (2009). Deriving a global river network map and its sub-grid topographic characteristics from a fine-resolution flow direction map. Hydrology and Earth System Sciences, 13(11), 2241–2251. https://doi.org/10.5194/hess-13-2241-2009
Yamazaki, D., O'Loughlin, F., Trigg, M. A., Miller, Z. F., Pavelsky, T. M., & Bates, P. D. (2014). Development of the Global Width Database for Large Rivers. Water Resources Research, 50(4), 3467–3480. https://doi.org/10.1002/2013WR014664
Yamazaki, D., Sato, T., Kanae, S., Hirabayashi, Y., & Bates, P. D. (2014). Regional flood dynamics in a bifurcating mega delta simulated in a global river model. Geophysical Research Letters, 41(9), 3127–3135. https://doi.org/10.1002/2014GL059744

Inclusion of Reservoir Operation

- Shen et. al. (2023) developed the first database of reservoir-catchment characteristics for 3254 reservoirs with storage capacity totaling 682595 km^3 (73.2% of reservoir water storage capacity in China)
- Such dataset is crucial for water resource management and hydrologic/hydrodynamic modeling
- Helping in modelling reservoir dynamics to more realistically estimate different reservoir parameters, such as flood storage capacity
- Reservoir operational rules are implemented in the CaMa-Flood to produce realistic flood modelling (Hanazaki et. al. 2022)
- Compared to the previous studies, the newly estimated flood storage capacity reduced the peak discharge error at 47% of the gauges downstream

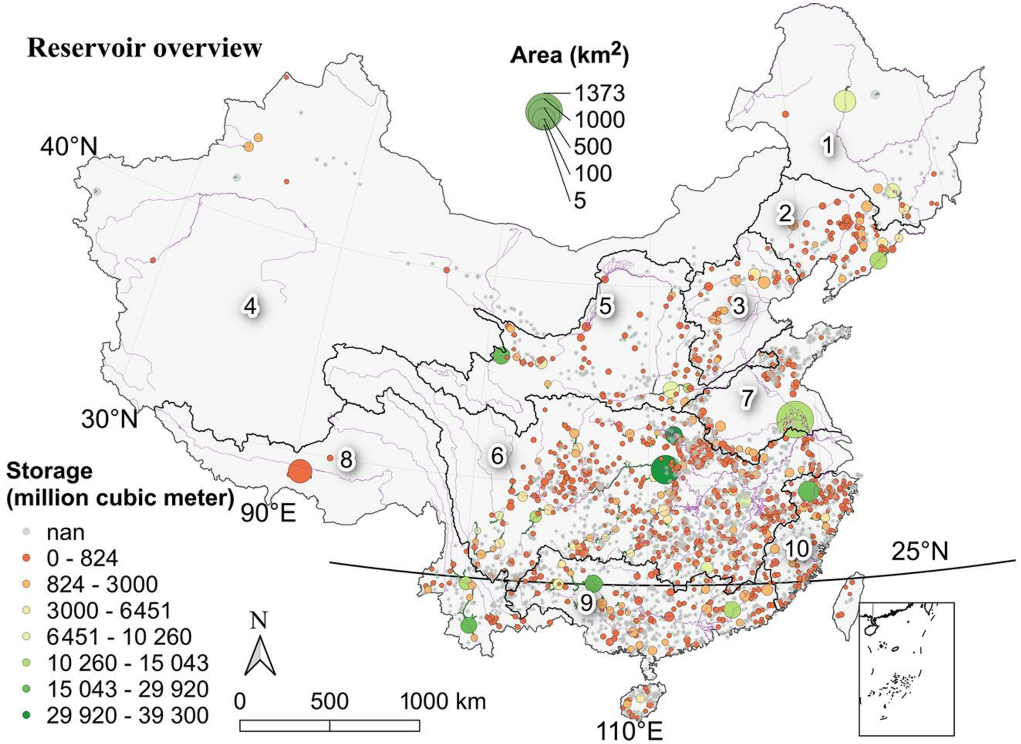
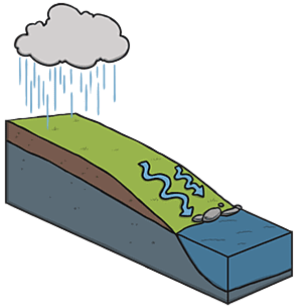


Figure 1. Overview of the reservoirs contained in Res-CN and the dams with storage capacity (circle color; nan means not available) and water surface area of reservoirs (circle size). The black lines indicate the boundaries of the 10 river regions within Res-CN. Numbers (1–10): 1 – Songhua River; 2 – Liao River; 3 – Hai River; 4 – Northwest River; 5 – Yellow River; 6 – Yangtze River; 7 – Huai River; 8 – Southwest River; 9 – Pearl River; 10 – Southeast River regions.

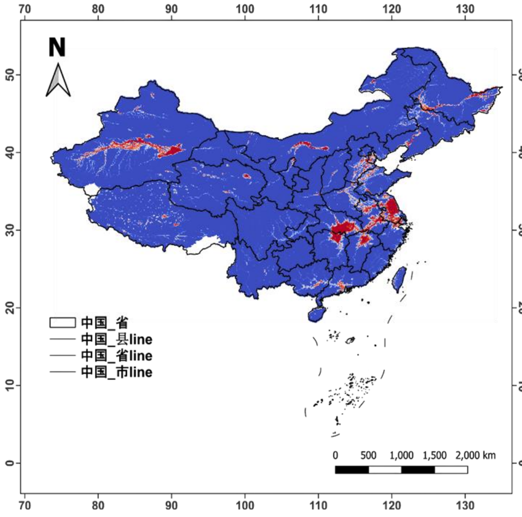
Shen, Y., Nielsen, et. al. (2023). Res-CN (Reservoir dataset in China): hydrometeorological time series and landscape attributes across 3254 Chinese reservoirs. Earth System Science Data, 15(7), 2781-2808.
Hanazaki, R., Yamazaki, D., &Yoshimura, K. (2022). Development of a reservoir flood control scheme for global flood models. Journal of Advances in Modelling Earth Systems,14, e2021MS002944.

Methodology: Flow Chart



Step1

Daily Runoff as input obtained from ECMFW ERA products (1981 -2023)



Step2

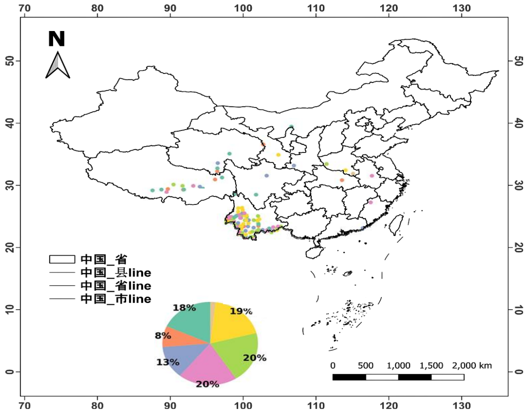
CaMa-Flood model set-up

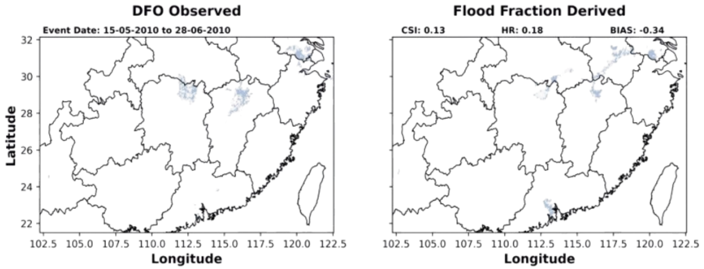
- **MERIT Hydro** [Global Hydrology Map]
- **Flow Direction Map** [Flexible Location of Waterways; FLOW method]
- **Global river width (GWD-LR)** [Global River width Algorithm; GRW algorithm on SRTM Waterbody data and HYDROSHEDS]
- **Global water map (G3WBM)**
- **Open street map water layer**

Step3

Obtain daily streamflow discharge, flooded area, flood discharge, flood fraction, flood depth

Step4





Validation of simulation either with streamflow or flood extent

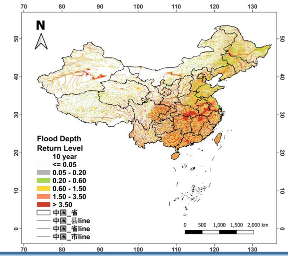
Step5

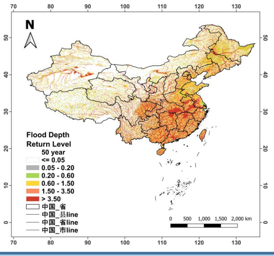
Fitting Kernel Density Estimator (KDE) to the extreme timeseries of daily flood depth during for 1981-2023 at grid cell level

very high,	$d \geq 3.5$
high,	$1.5 \leq d \leq 3.5$
moderate,	$0.6 \leq d \leq 1.5$
low,	$0.2 \leq d \leq 0.6$
very low,	$0 \leq d \leq 0.2$

Step6

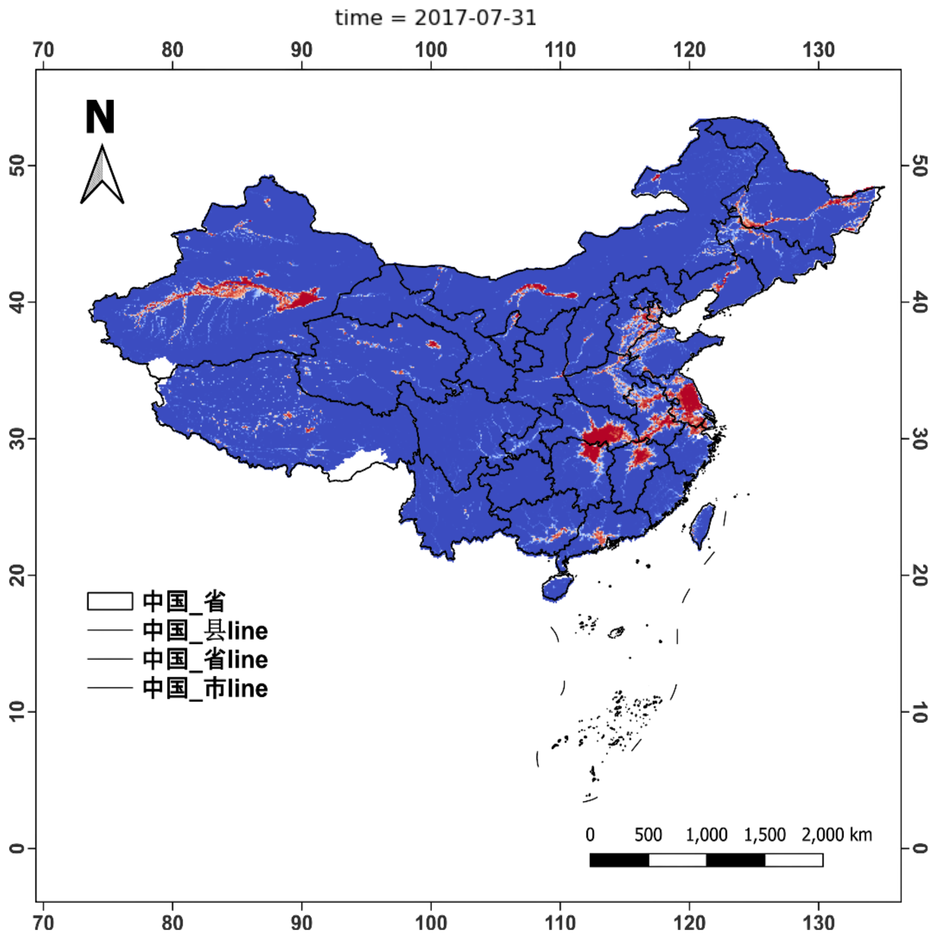
Obtaining and classifying the obtained various return level flood depths





Technical flood risk management guideline: Flood hazard (Australian Disaster Resilience Handbook Collection)
https://docslib.org/doc/3722929/technical-flood-risk-management-guideline-flood-hazard

Obtained Simulation Results: Output Variables

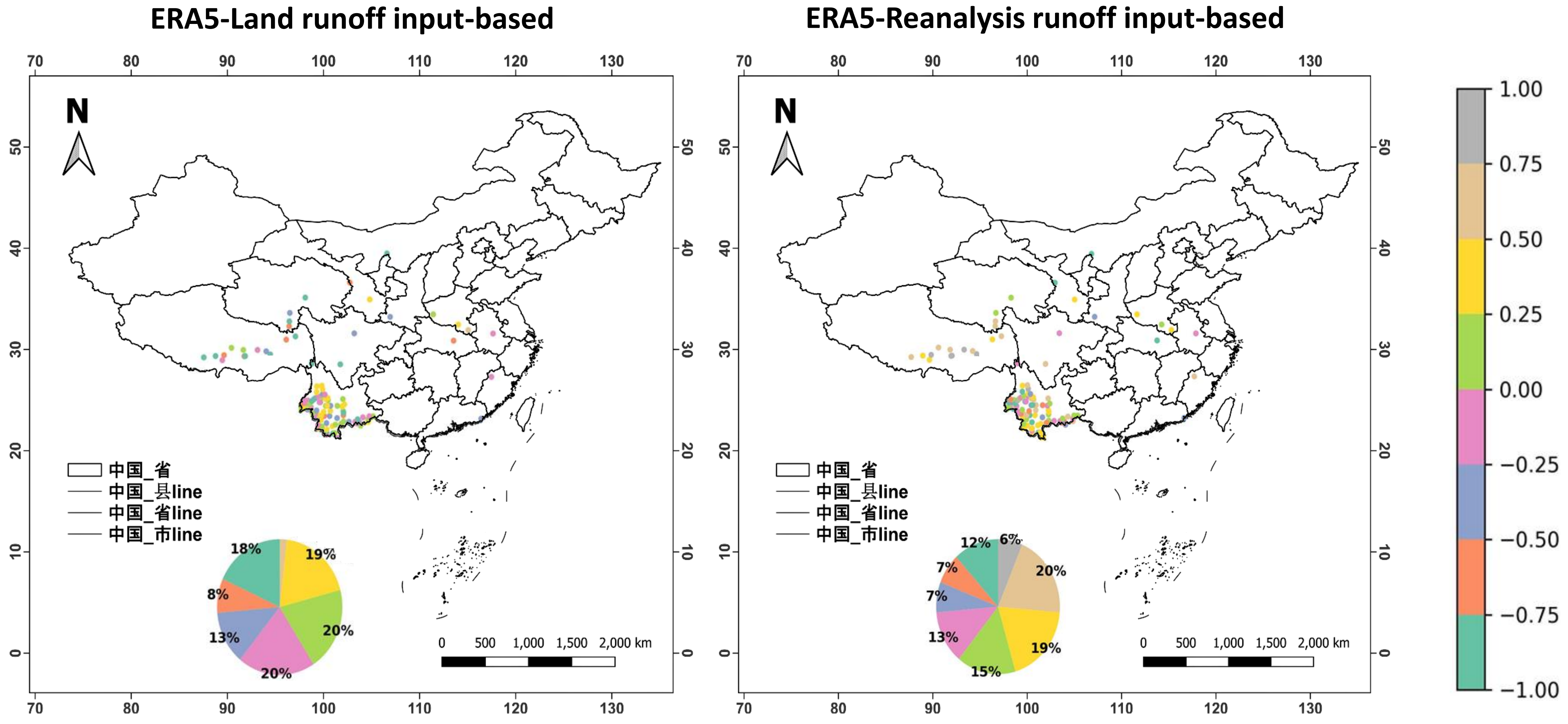


Variable	Symbol	Description	Unit
rivout	Qr	River Discharge	[m3/s]
rivsto	Sr	River Wter Storage	[m3]
rivdph	Dr	River Water Depth	[m]
rivvel	V	River Flow Velocity	[m/s]
flddph	Qf	Floodplain Flow	[m3/s]
flddph	Df	Floodplain Water Deoth	[m]
fldare	Af	Flood Area	[m2]
fldfrc	Ff	Flood Fraction	[m2/m2]
fldsto	Sf	Floodplain Water Storage	[m3]
storge	Sall	Total Storage (Sr + Sf)	[m3]
fldare	Af	Flood Area	[m2]

Results obtained at 0.05 degree approximately 5 km resolution

Validation: Streamflow comparison

using Nash-Sutcliffe Efficiency (NSE)



Significant increase in positive NSE values with the use of ERA5 reanalysis data as runoff input

Do, H. X., Gudmundsson, L., Leonard, M., and Westra, S.: The Global Streamflow Indices and Metadata Archive (GSIM) – Part 1: The production of a daily streamflow archive and metadata, Earth Syst. Sci. Data, 10, 765–785, https://doi.org/10.5194/essd-10-765-2018, 2018.

Validation: Flood Footprint comparison

ERA5 Reanalysis runoff data based outputs analysis

Fig 1

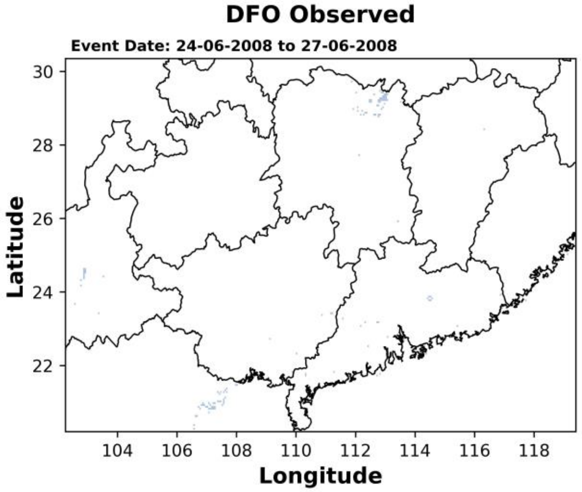


Fig 2

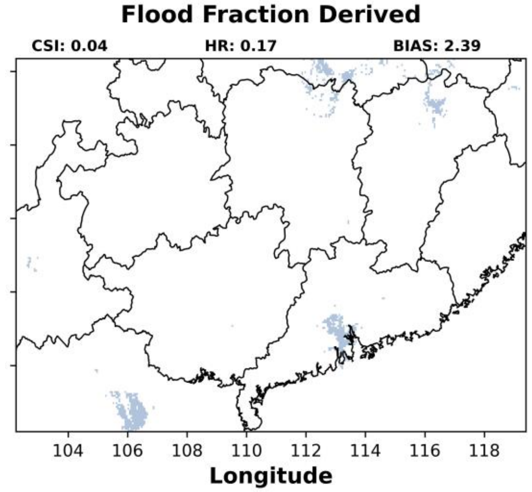


Fig 3

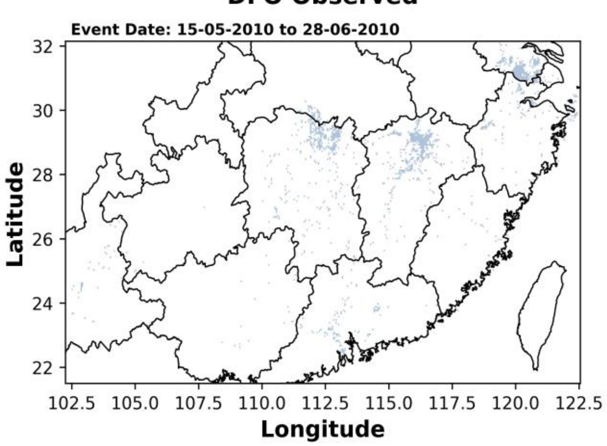


Fig 4

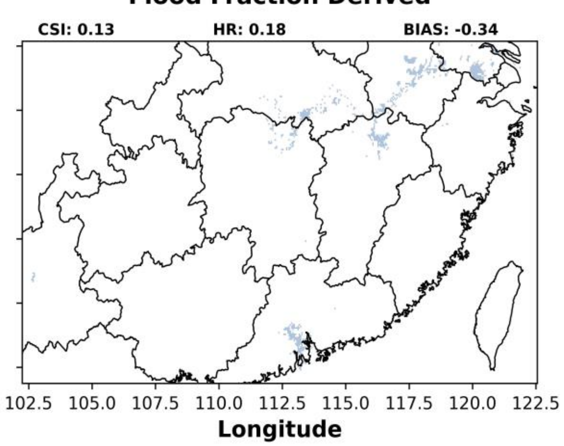


Fig 5

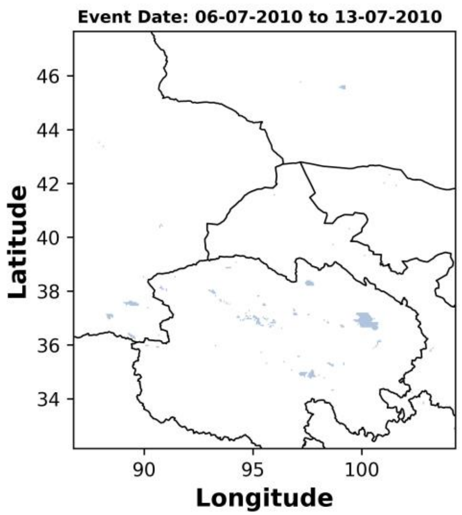


Fig 6

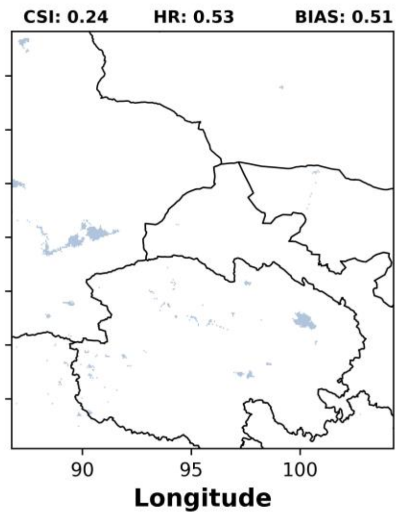


Fig 7

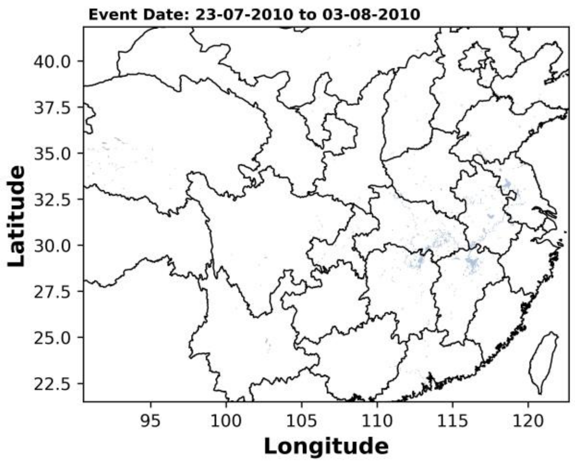
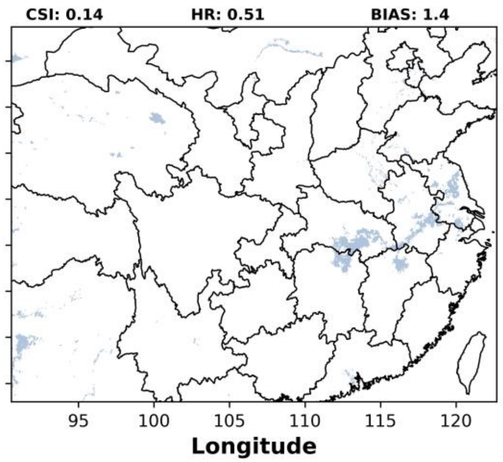


Fig 8



Methodology: Frequency Analysis

- Frequency Analysis: Frequency analyses are used to predict design values for flood characteristics.

- **Daily flood depth** obtained from CaMa-Flood simulations for time period of 1981-2023 is **utilized in flood frequency analysis after extreme value extraction**.

- The Frequency Analysis involves
  - Using **extracted series of flood depth** to calculate statistical information **such as mean values, and recurrence intervals**.
  - The **extreme values** from the timeseries were extracted using **peak over threshold method (POT)**.
  - After testing multiple disributions and finding the best fit distribution. (Karmakar et. al. (2008),Vittal et. al. (2015))
  - Non-parametric: Kernel density Estimator (KDE) were fitted to the extracted time series,
  - **Cumulative distribution function** obtained from the **fitted distributions** is used to calculate the **return level.**

Karmakar, S., and S. P. Simonovic. "Bivariate flood frequency analysis: Part 1. Determination of marginals by parametric and nonparametric techniques." Journal of Flood Risk Management 1.4 (2008): 190-200.
Vittal, H., Singh, J., Kumar, P., & Karmakar, S. (2015). A framework for multivariate data-based at-site flood frequency analysis: Essentiality of the conjugal application of parametric and nonparametric approaches. Journal of Hydrology, 525, 658-675.

Hazard to human safety: Flood Depth Classification

- The ranges flood depth values for safety of human and building are defined in European Commission reports (Huizinga et al., 2017),
- Technical flood risk management guideline: Flood hazard report by Australian Emergency Management Institute (Australian Institute for Disaster Resilience, 2012; McLuckie, 2015).
- Utilizing the similar principles of human and infrastructure safety the hazard classification using the flood depth is adopted in literature (Mohanty et al., 2020; Tingsanchali & Karim, 2005).

- Australian Institute for Disaster Resilience. (2012). *Technical flood risk management guideline: Flood hazard Australian Disaster Resilience Handbook Collection*. https://knowledge.aidr.org.au/media/1891/guideline-7-3-technical-flood-risk-management.pdf
- Huizinga, J., De Moel, H., & Szewczyk, W. (2017). *Global flood depth-damage functions: Methodology and the database with guidelines*. Joint Research Centre (Seville site). DOI: doi/10.2760/16510
- McLuckie, D. (2015). *Improving National best practice in flood risk management*.
- Mohanty, M. P., H, V., Yadav, V., Ghosh, S., Rao, G. S., & Karmakar, S. (2020). A new bivariate risk classifier for flood management considering hazard and socio-economic dimensions. *Journal of Environmental Management*, *255*, 109733. https://doi.org/10.1016/j.jenvman.2019.109733
- Tingsanchali, T., & Karim, M. F. (2005). Flood hazard and risk analysis in the southwest region of Bangladesh. *Hydrological Processes*, *19*(10), 2055–2069. https://doi.org/10.1002/hyp.5666

Table 1 Combined hazard curves – vulnerability thresholds

Hazard Vulnerability Classification	Description
H1	Generally safe for vehicles, people and buildings.
H2	Unsafe for small vehicles.
H3	Unsafe for vehicles, children and the elderly.
H4	Unsafe for vehicles and people.

Table 2 Combined hazard curves – vulne

Hazard Vulnerability Classification	Limiting still water depth (D) m
H1	0.3
H2	0.5
H3	1.2
H4	2.0

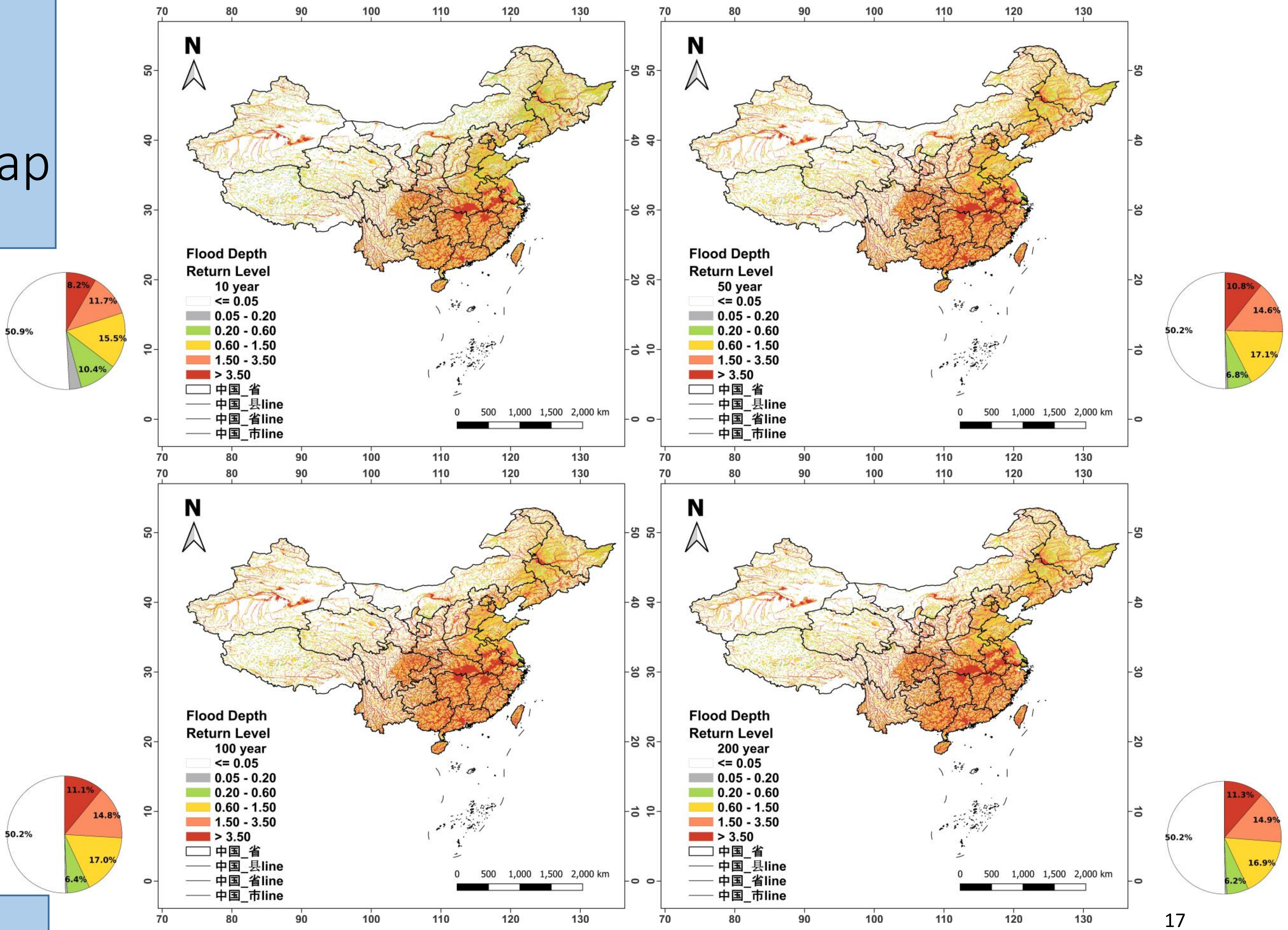
Throughout the present work the flood depth classification According to these conventions are followed

$$hazard = \begin{cases} very\ low, & 0 \le f_d \le 0.2 \\ low\ , & 0.2 < f_d \le 0.6 \\ medium\ , & 0.6 < f_d \le 1.5 \\ high\ , & 1.5 < f_d \le 3.5 \\ very\ high\ , & f_d > 3.5 \end{cases}$$

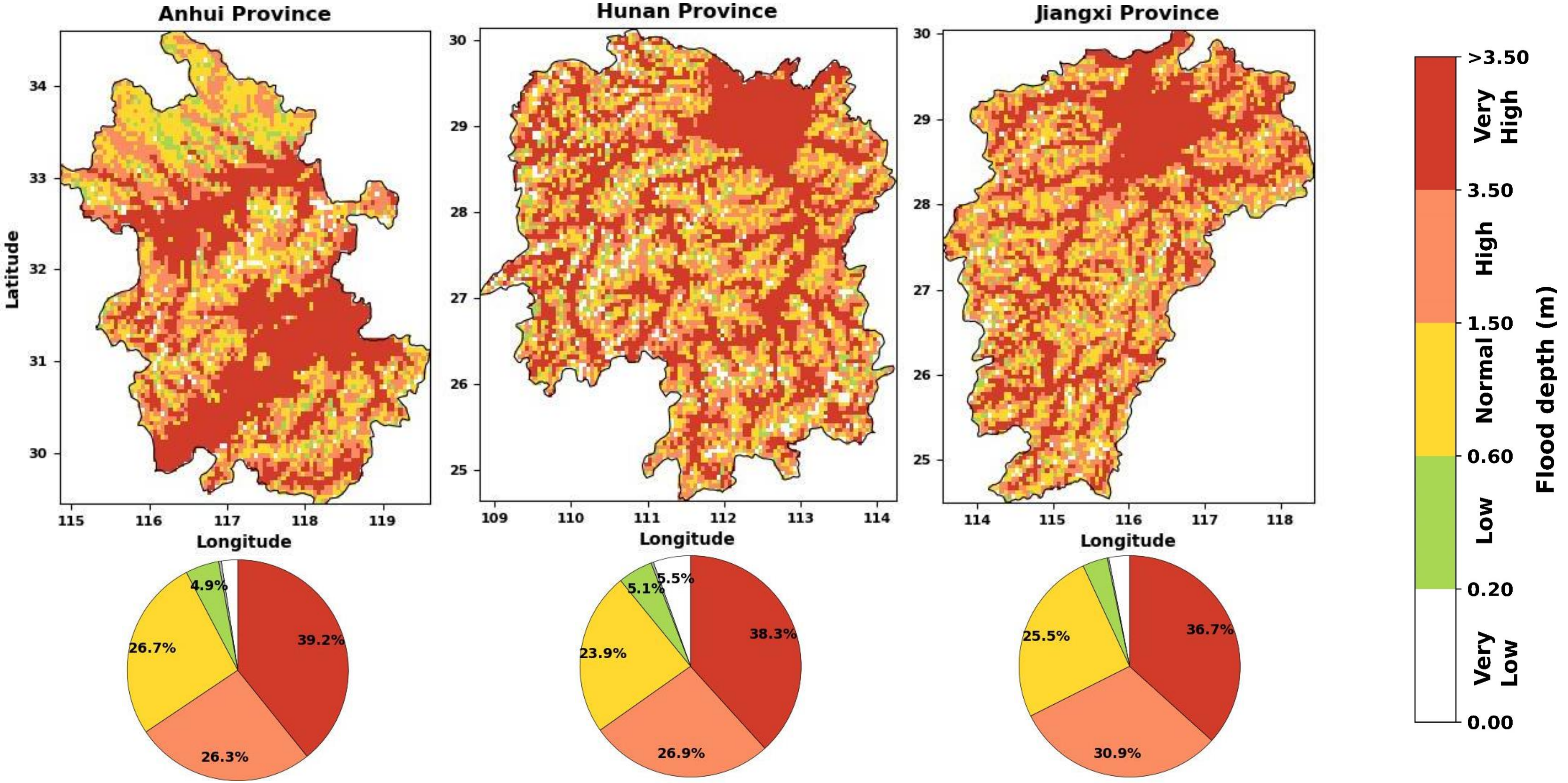
Results
Flood Hazard Map

Return level of flood depth for 10, 50,100, 200 Year with KDE fit

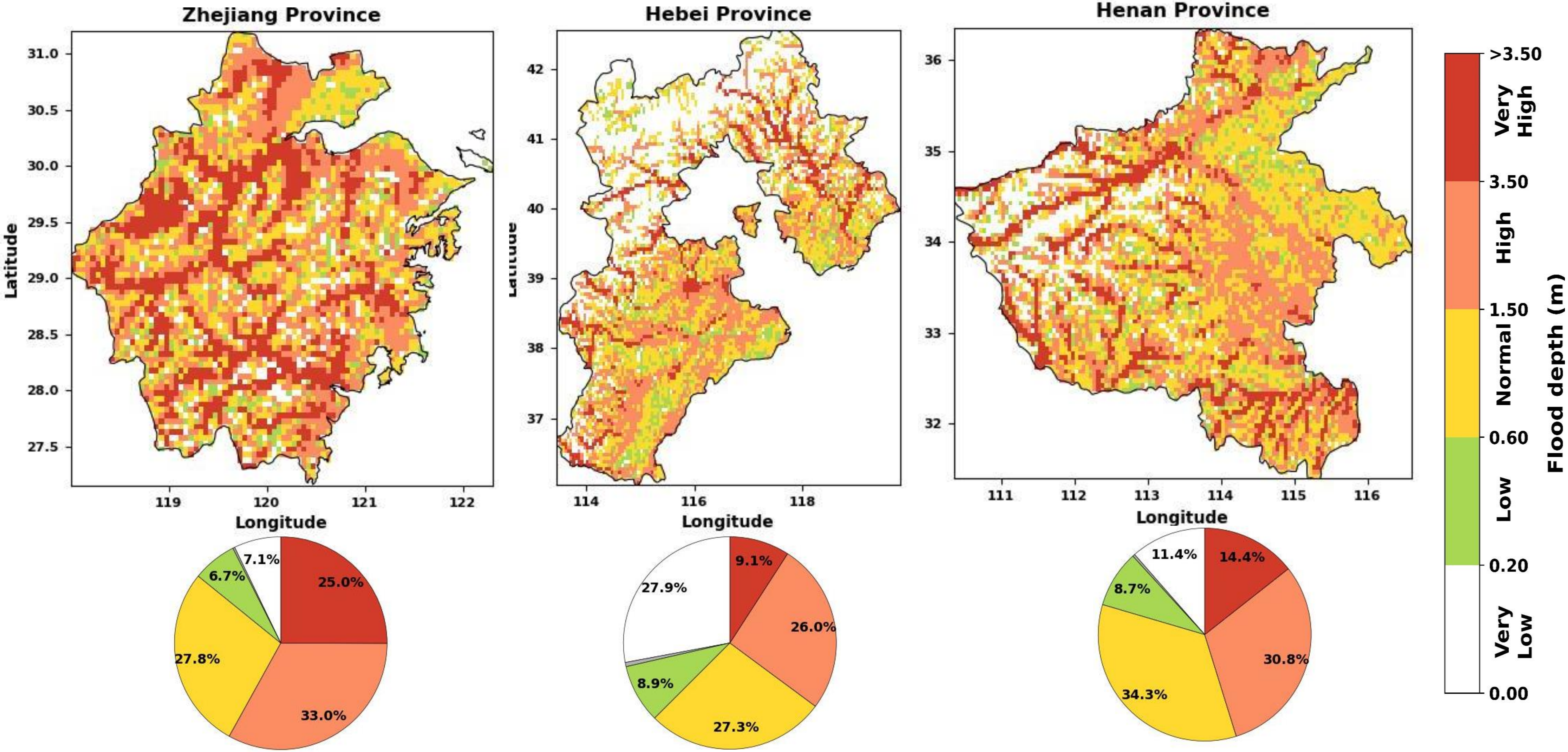
Obtained at 0.05 degree resolution



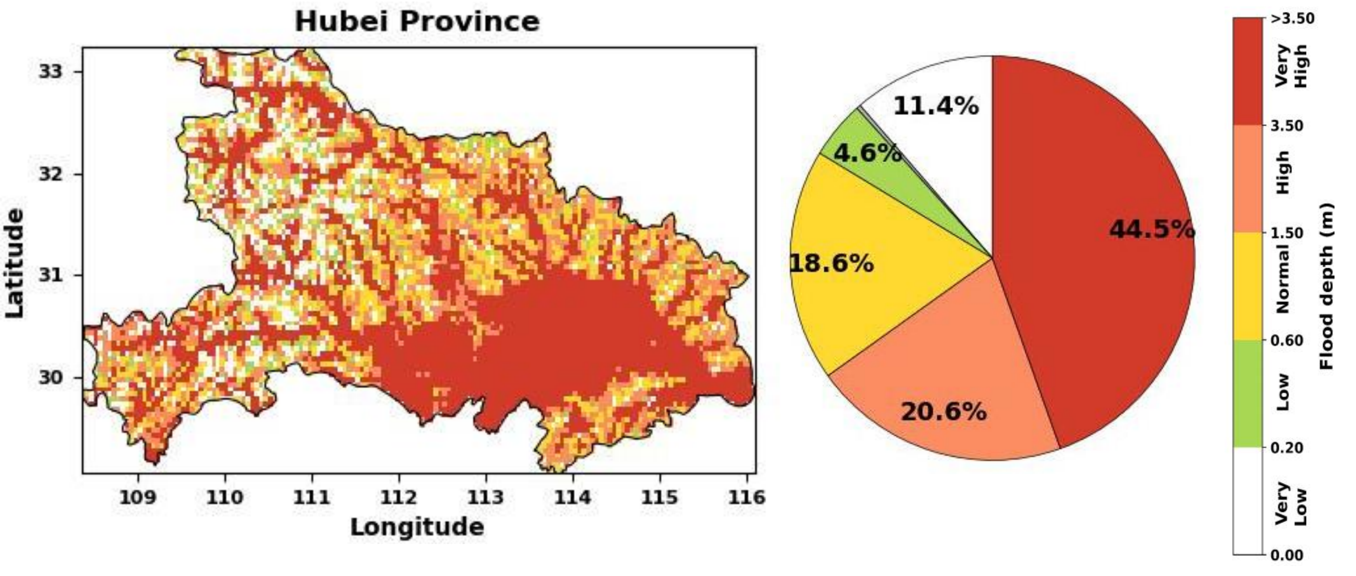
Results Province Wise Flood Hazard



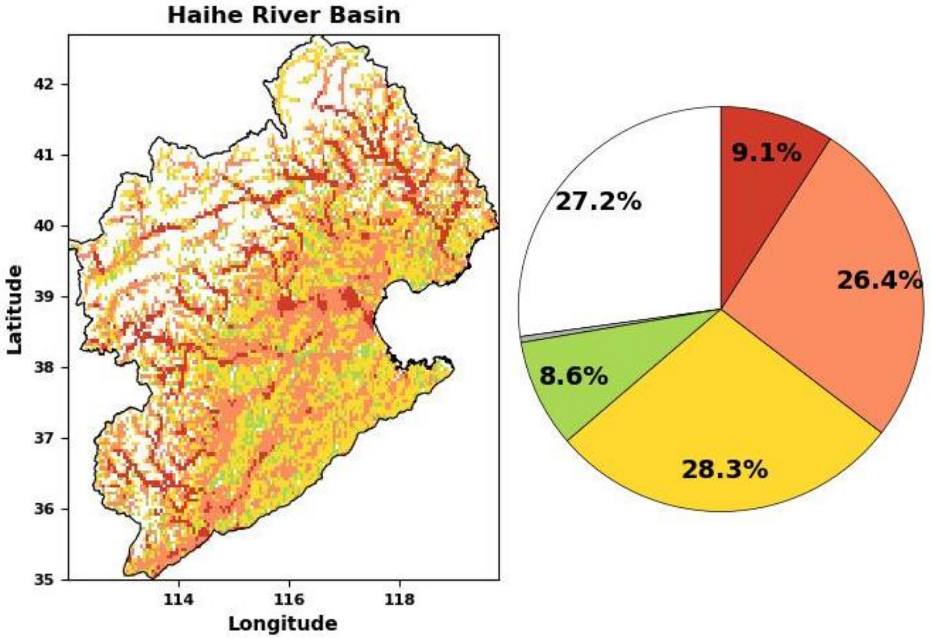
Results Province Wise Flood Hazard

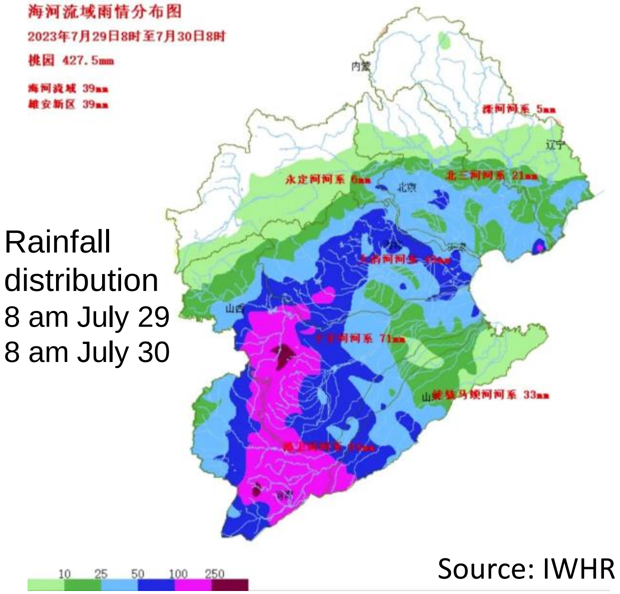


Results Province Wise Flood Hazard



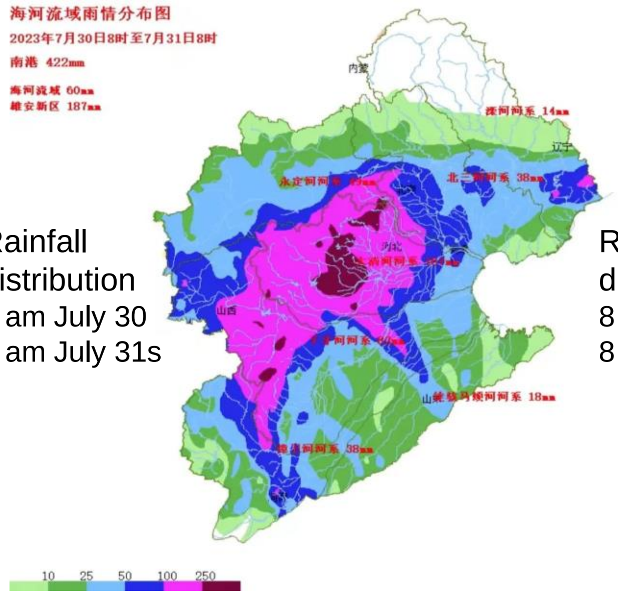
Haihe River Basin within the Hebei province



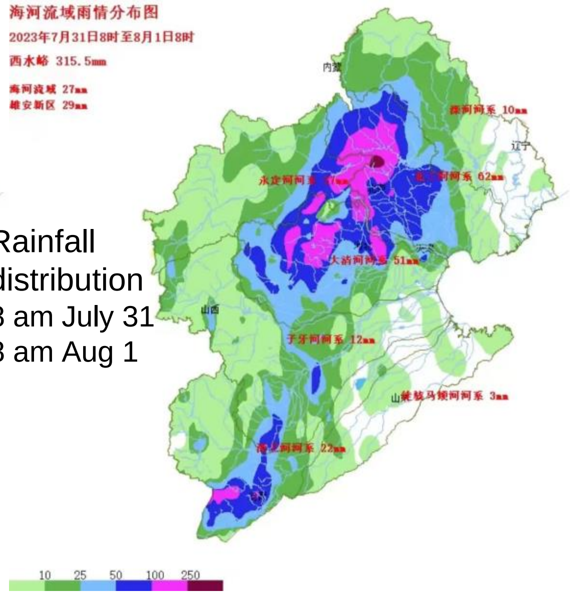


Rainfall distribution
8 am July 29
8 am July 30

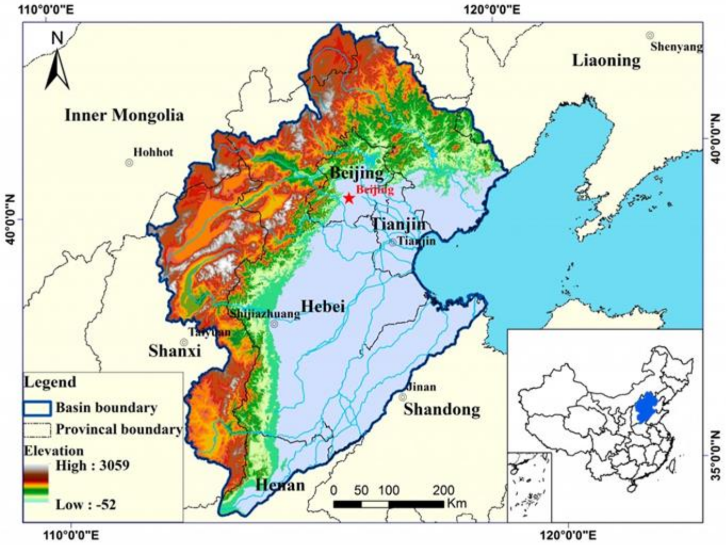
Source: IWHR



Rainfall distribution
8 am July 30
8 am July 31s



Rainfall distribution
8 am July 31
8 am Aug 1

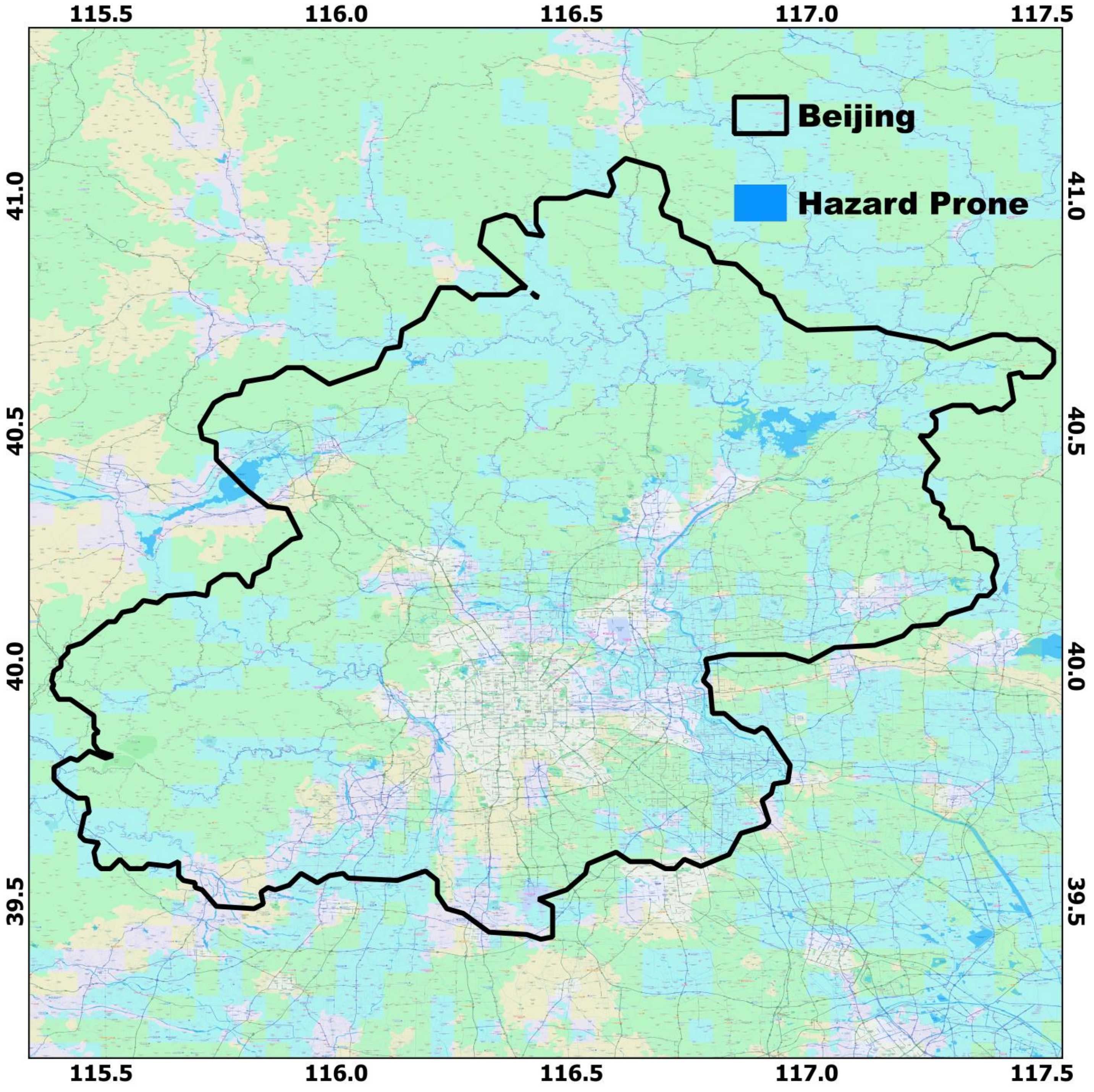


Source: Yang, et. al. (2017)

Yang, M.; Xiao, W.; Zhao, Y.; Li, X.; Lu, F.; Lu, C.; Chen, Y. Assessing Agricultural Drought in the Anthropocene: A Modified Palmer Drought Severity Index. Water 2017, 9, 725. https://doi.org/10.3390/w9100725 (IWHR Study)

Possible implications

Moreover
finer resolution runs
can be utilized for the
hazard exposure within
regions by overlaying the
flood hazard over
infrastructural maps



Summary, challenges and way forward

- A **open source flood hazard produc**t in the form of **methodology** and **flood hazard** maps is presented.

- The **physical representation** of the **flood depth** with the hazard levels and **utilization of the flood prognostic variable** in the flood **hazard assessment brings reliability** and natural variability in the assessment.

- The **physical process inclusion** with the modelling technologies and the **inclusion of reservoir operation** further adds reliability to the flood hazard map generation.

- One of the **challenging task** is the **validation of outputs**.

- Moreover if regionally produced runoff dataset prepared and validated for at the nationals scale for the China, could be utilized for future flood assessments.

Thank you

- 3rd Asia International Water Week (AIWW)
- China Institute of Water Resources and Hydropower Research (IWHR)
- Indian Institute of Technology Bombay (IITB)
- Prof. Karmakar and Prof. Simonovic
- Prof. Cheng and Dr. Liu