Global Hydrodynamic Modelling of Large-scale Flooding in Continental Rivers

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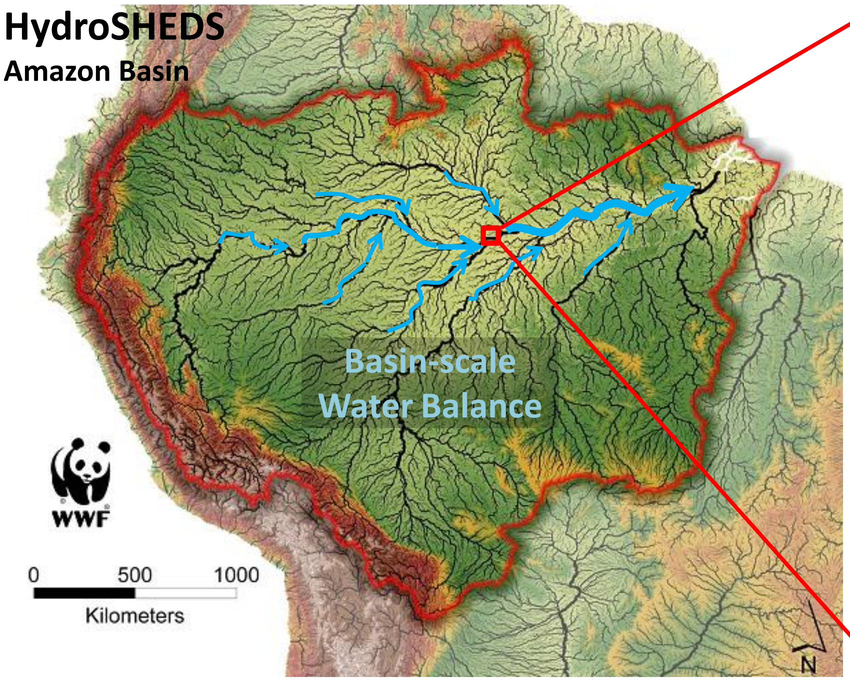
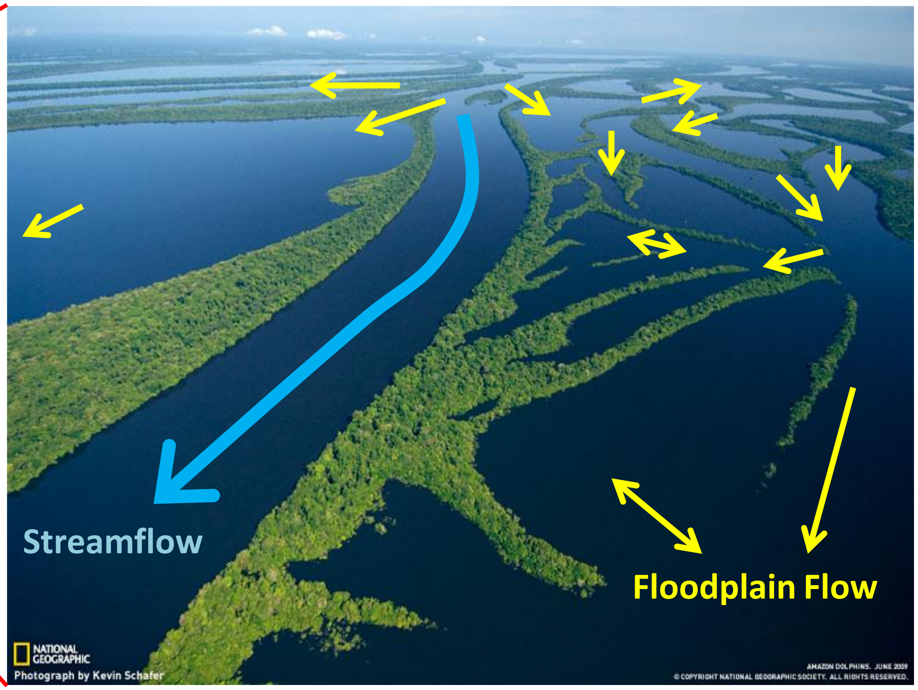
How can we model large-scale flooding?

Floodplain inundation dynamics plays an important role to control river and floodplain hydrodynamics (e.g. discharge, inundated area, water level).

- Floodplain inundation is regulated by smaller-scale topography than typical resolutions of global river models.
- It has been difficult to explicitly represent floodplain inundation.



The Amazon River

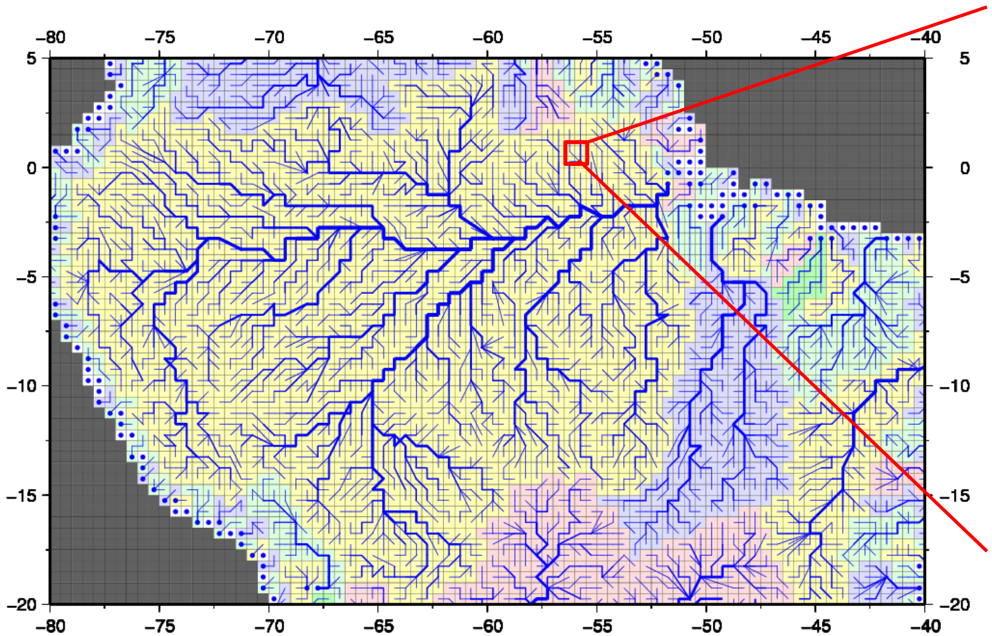


Amazonian Floodplains

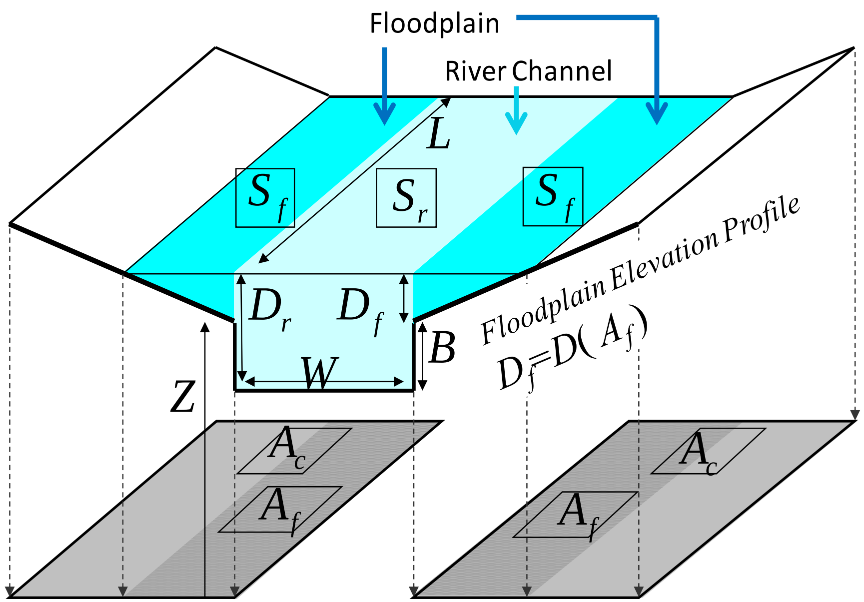
Floodplain inundation as sub-grid physics

CaMa-Flood (**Ca**tchment-based **Ma**cro-scale **Flood**plain model)

- Distributed river routing model using a prescribed river network map
- Input: LSM Runoff, Output : Water storage (Prognostic)
  River discharge, Water level, Inundated area (Diagnosed)
- River and floodplain storage with sub-grid topographic parameters.
  > Explicit representation of flood stage (diagnosed from storage)



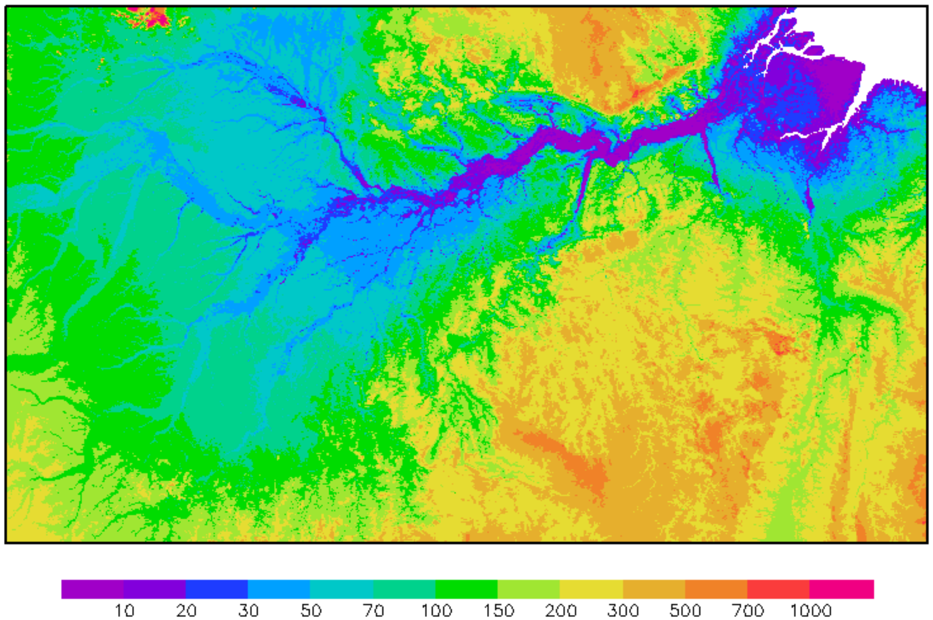
River Network Map



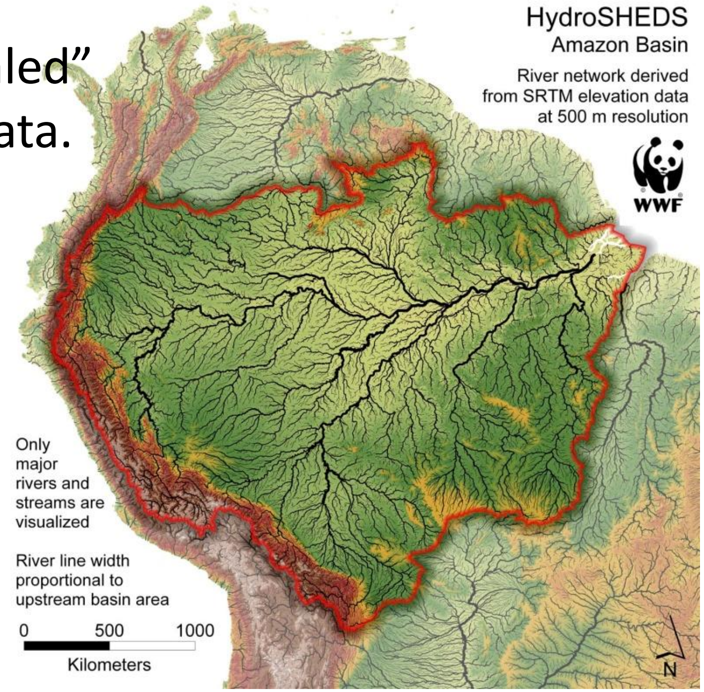
Sub-grid topography parameters

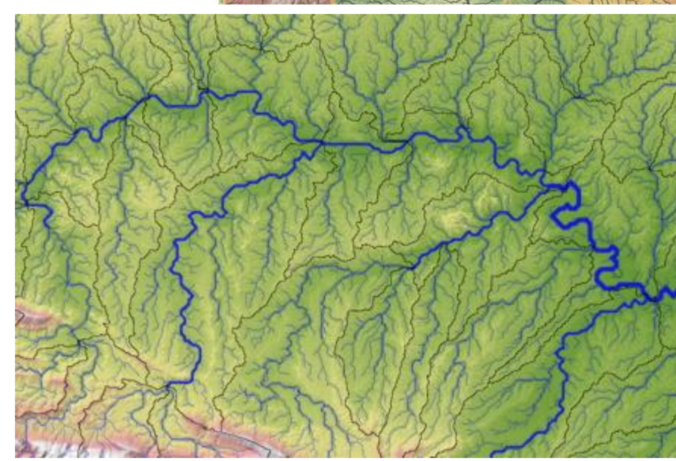
How to derive realistic sub-grid parameters?

The topographic parameters are automatically "upscaled" from satellite-based high-resolution topography data.



↑90 m elevation [SRTM3]





↑90 m Flow Direction Map [HydroSHEDS]

Algorithm: **FLOW**

(<u>F</u>lexible <u>L</u>ocation <u>o</u>f <u>W</u>aterways method)

Input: Fine-resolution (90 m) datasets

SRTM3 DEM

HydroSHEDS Flow Direction Map

Sub-grid Topographic Parameters

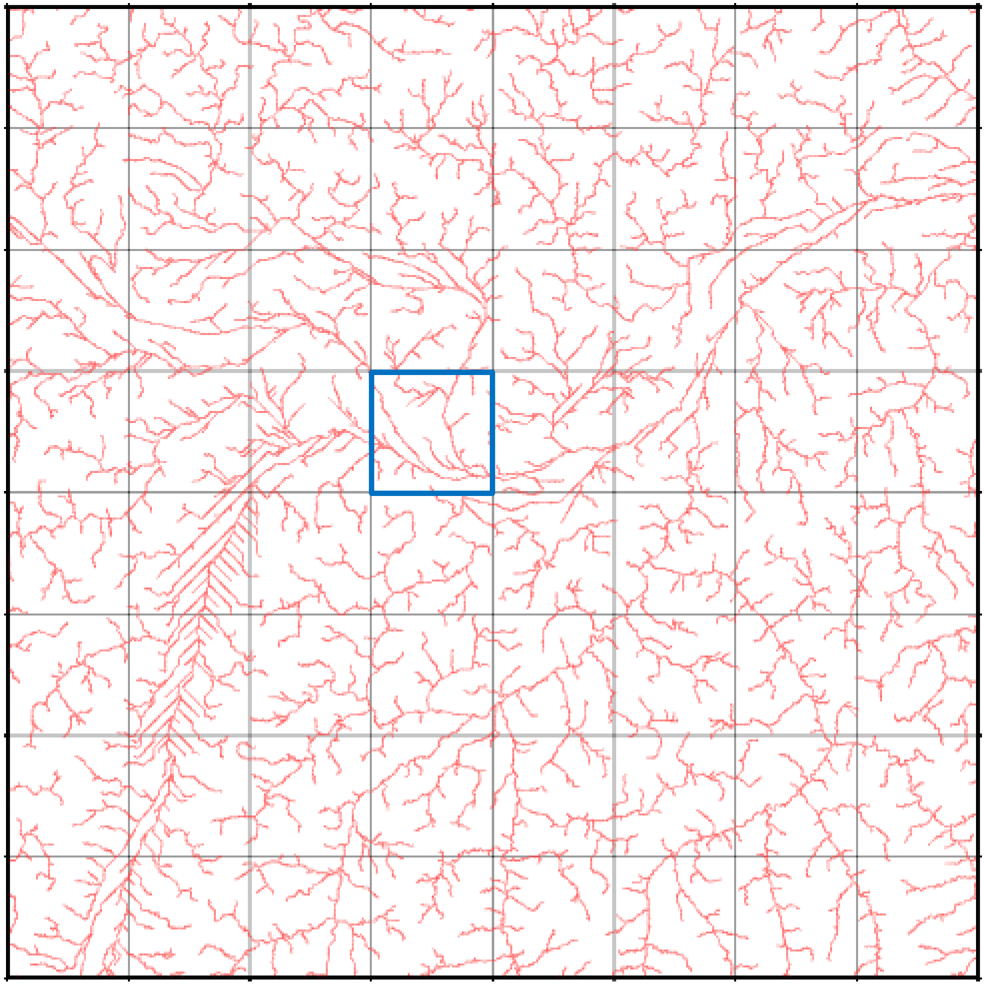
FLOW (**F**lexible **L**ocation **o**f **W**aterways method)

Blue (and grey) cells:

Grid-box of Large-Scale Model

Red pixels:

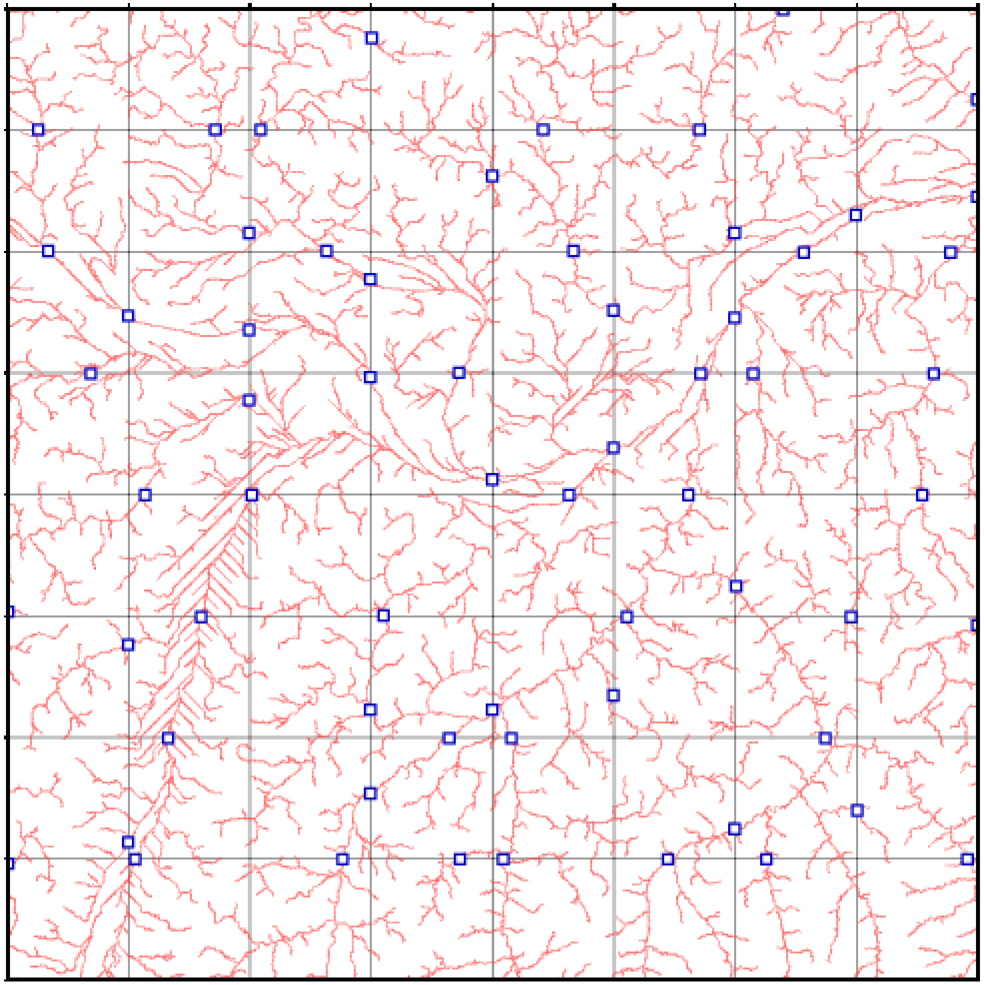
1-km flow direction map



Sub-grid Topographic Parameters

FLOW (Flexible Location of Waterways method)

1) Allocate one “outlet pixel” to one “grid-box”

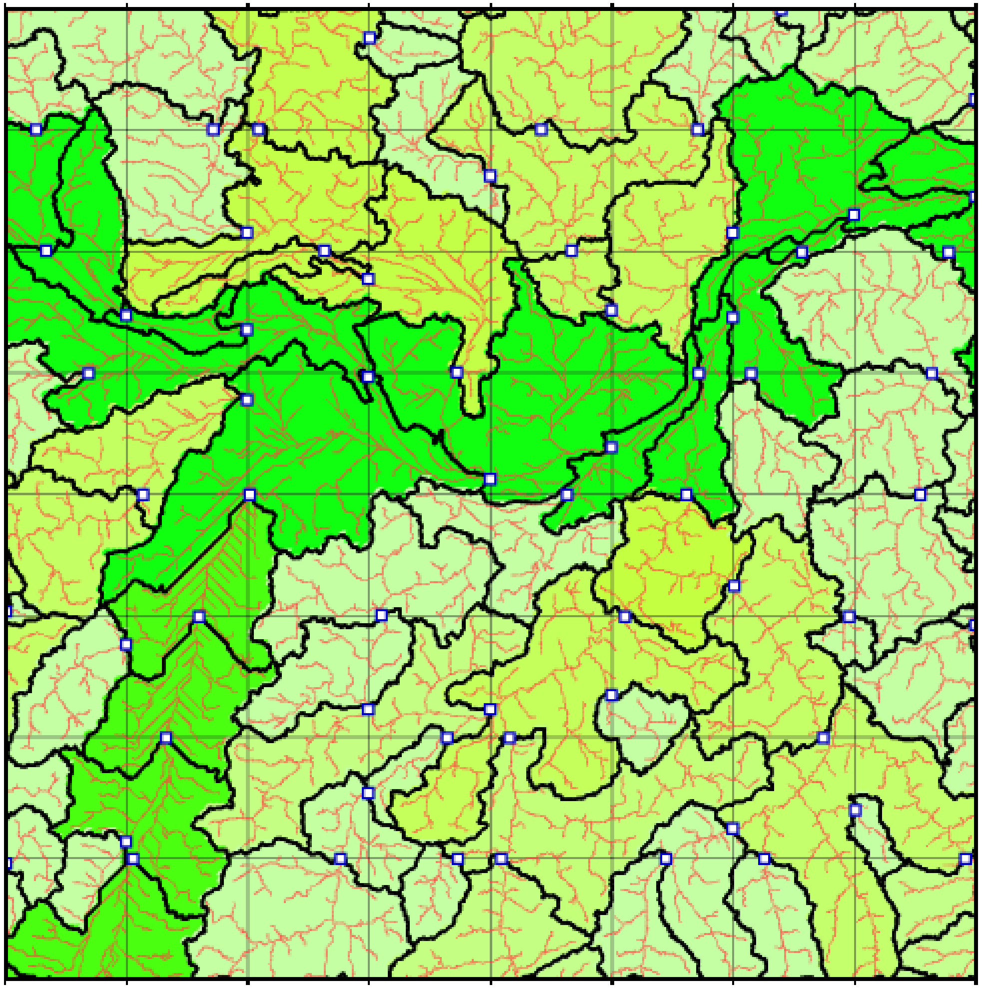


Sub-grid Topographic Parameters

FLOW (**F**lexible **L**ocation **o**f **W**aterways method)

1) Allocate one "outlet pixel" to one "grid-box"

2) Define "unit-catchment" for each "grid-box"



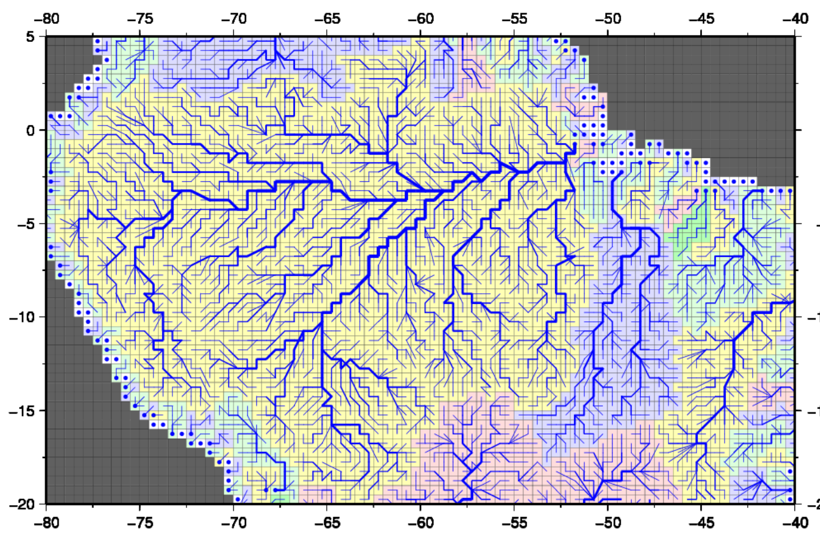
Sub-grid Topographic Parameters

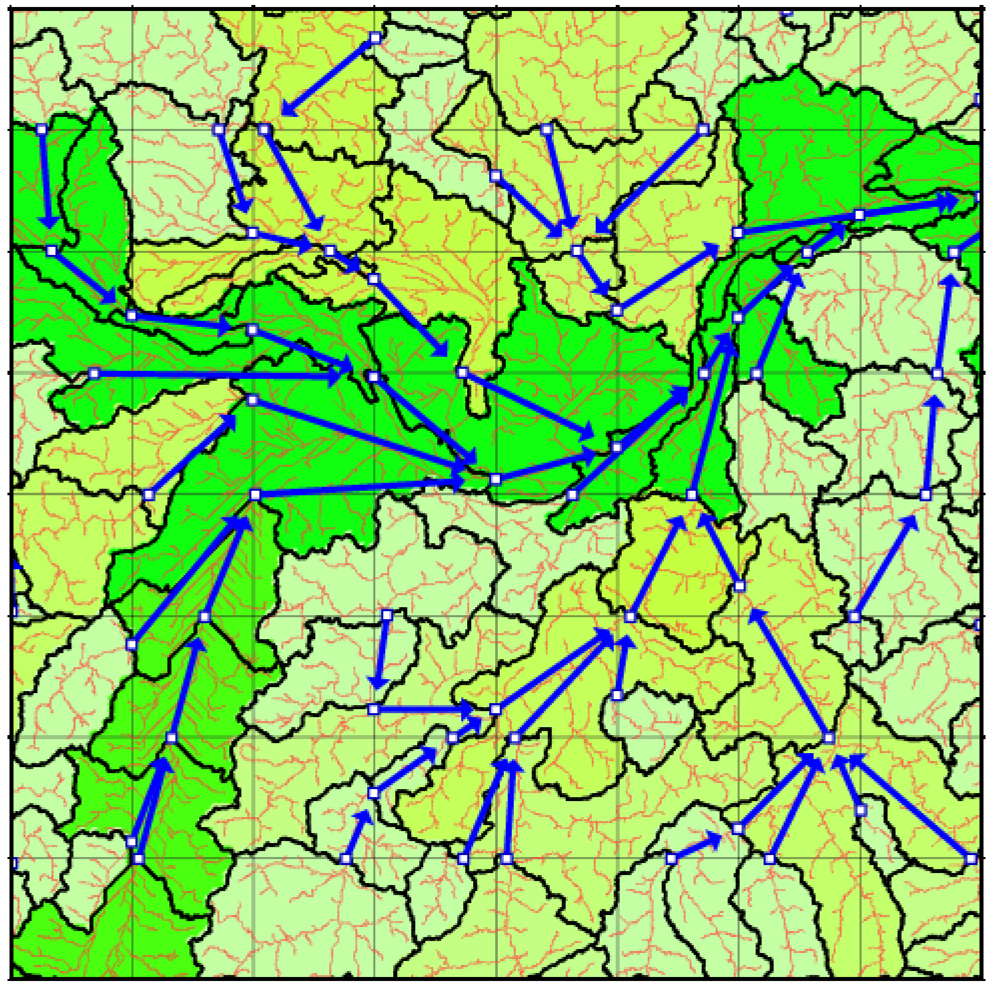
FLOW (**F**lexible **L**ocation **o**f **W**aterways method)

1) Allocate one "outlet pixel" to one "grid-box"

2) Define "unit-catchment" for each "grid-box"

3) Extract "river network map"
(Find downstream unit-catchment)





Sub-grid Topographic Parameters

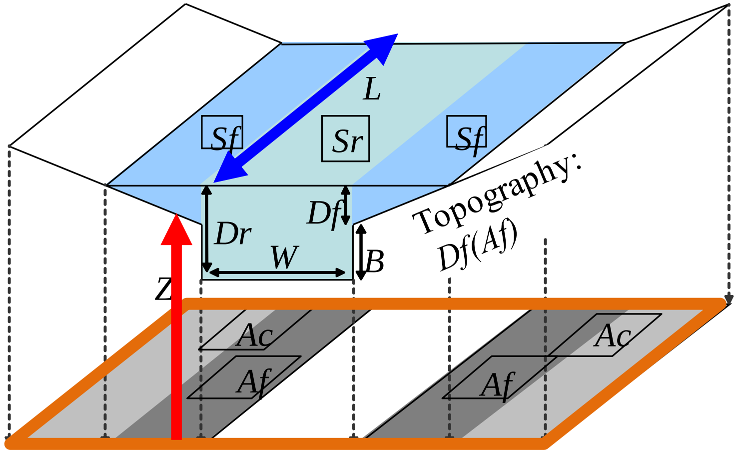
FLOW (**F**lexible **L**ocation **o**f **W**aterways method)

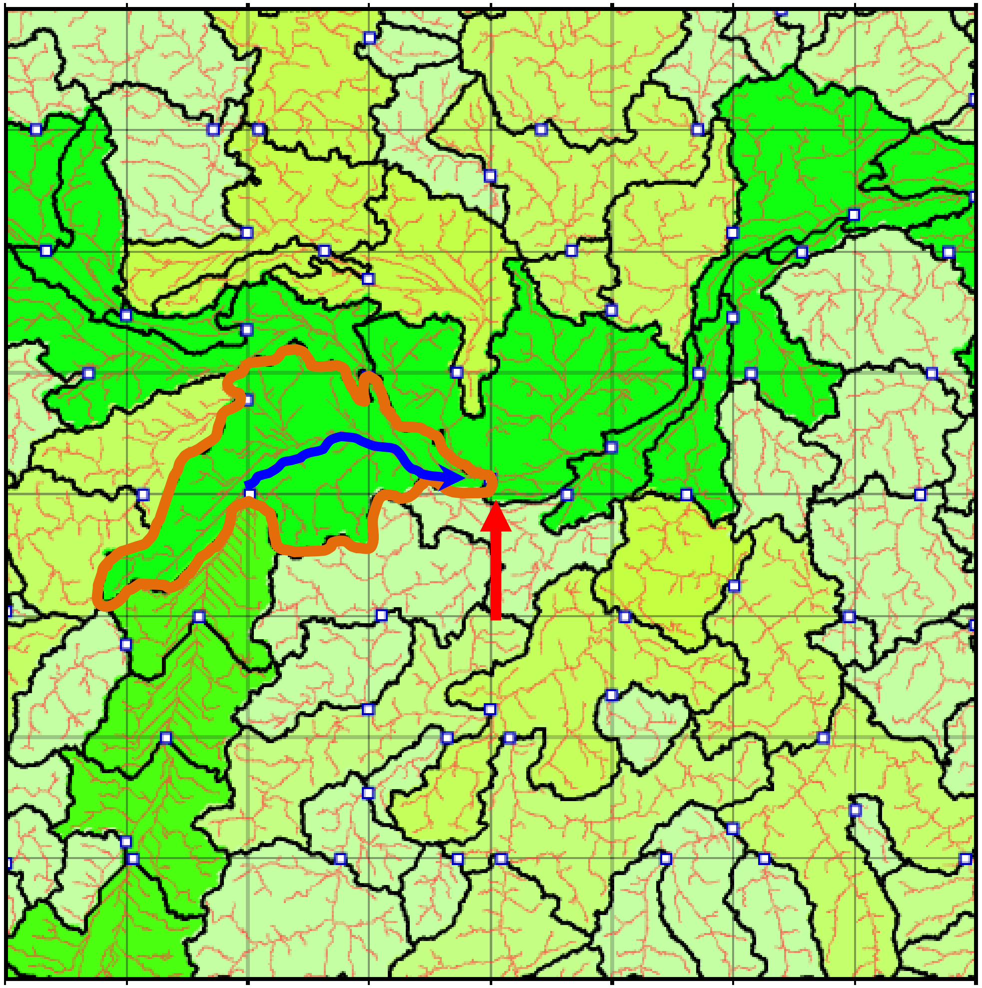
1) Allocate one "outlet pixel" to one "grid-box"

2) Define "unit-catchment" for each "grid-box"

3) Extract "river network map"
(Find downstream unit-catchment)

4) Set "unit-catchment area", "channel length",
and "ground elevation"





Sub-grid Topographic Parameters

FLOW (Flexible Location of Waterways method)

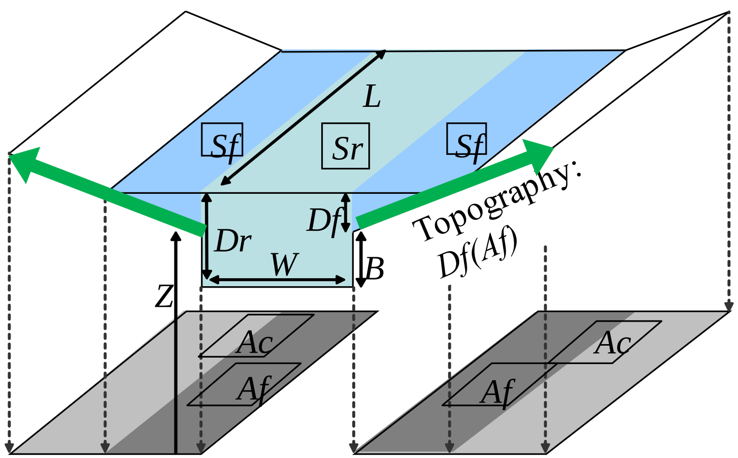
1) Allocate one "outlet pixel" to one "grid-box"

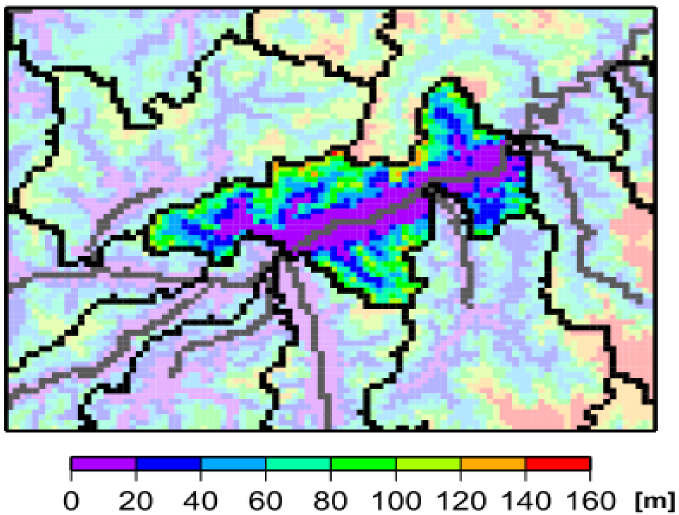
2) Define "unit-catchment" for each "grid-box"

3) Extract "river network map"
(Find downstream unit-catchment)

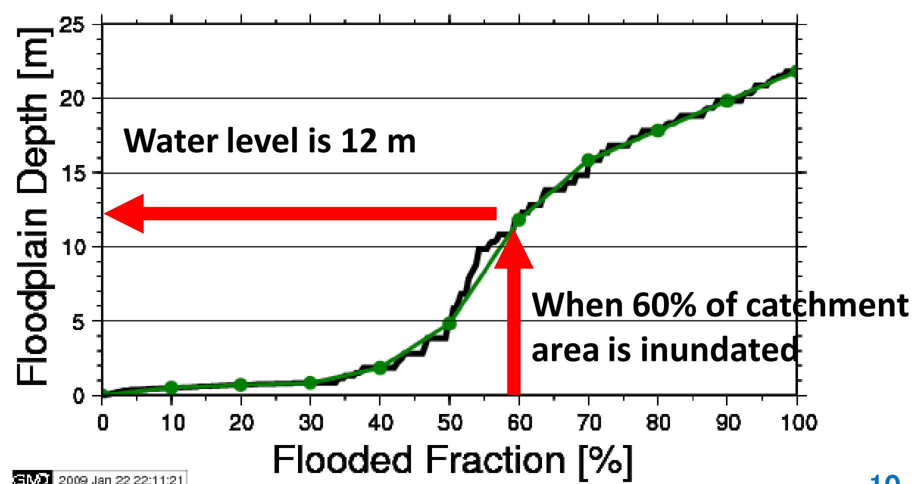
4) Set "unit-catchment area", "channel length",
and "ground elevation"

5) Calculate "floodplain elevation profile"





Generate CDF of
floodplain height above river channel.

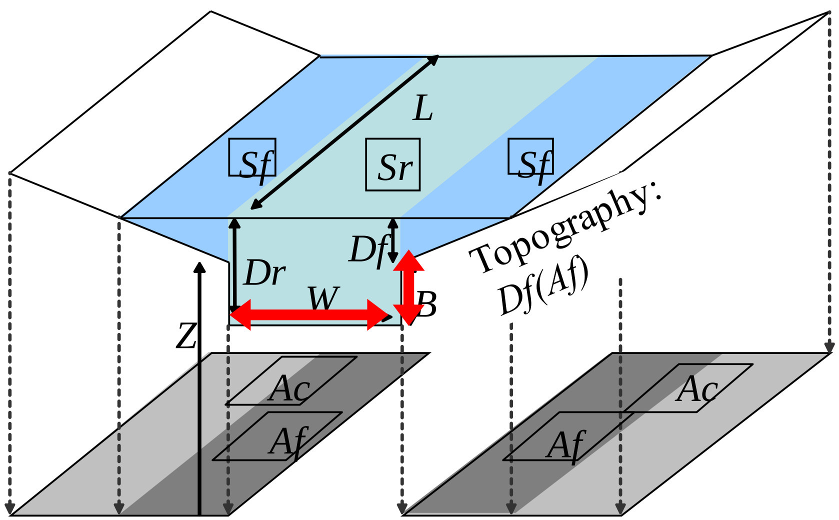


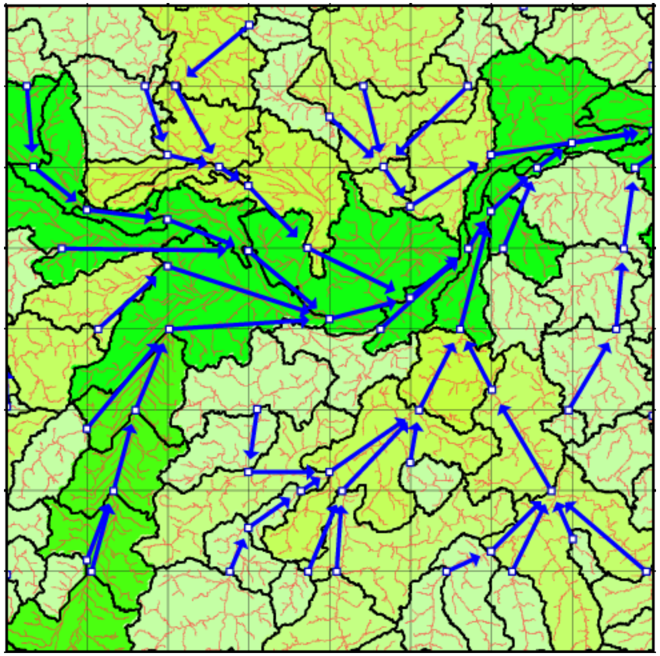
Sub-grid Topographic Parameters

FLOW (Flexible Location of Waterways method)

> Automatically derived from 1-km datasets

Ground elevation・Channel length・
Unit-catchment area・Floodplain elevation profile





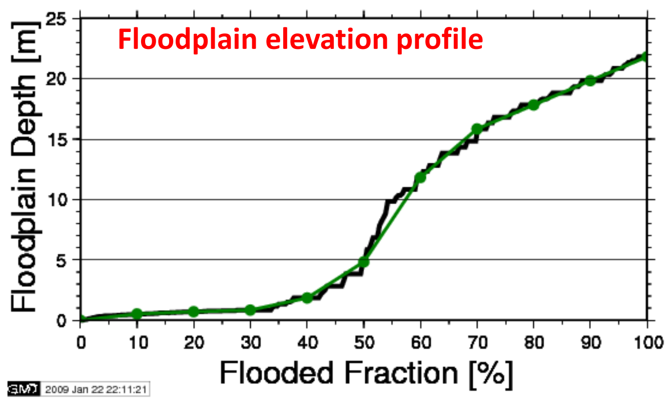
Ground elevation
Channel length
Unit-catchment area

> Empirically estimated by annual discharge

Channel width・Channel Depth

$$W = \max[1.00 \times R_{up}^{0.7}, 10.0]$$

$$B = \max[0.035 \times R_{up}^{0.5}, 1.0]$$



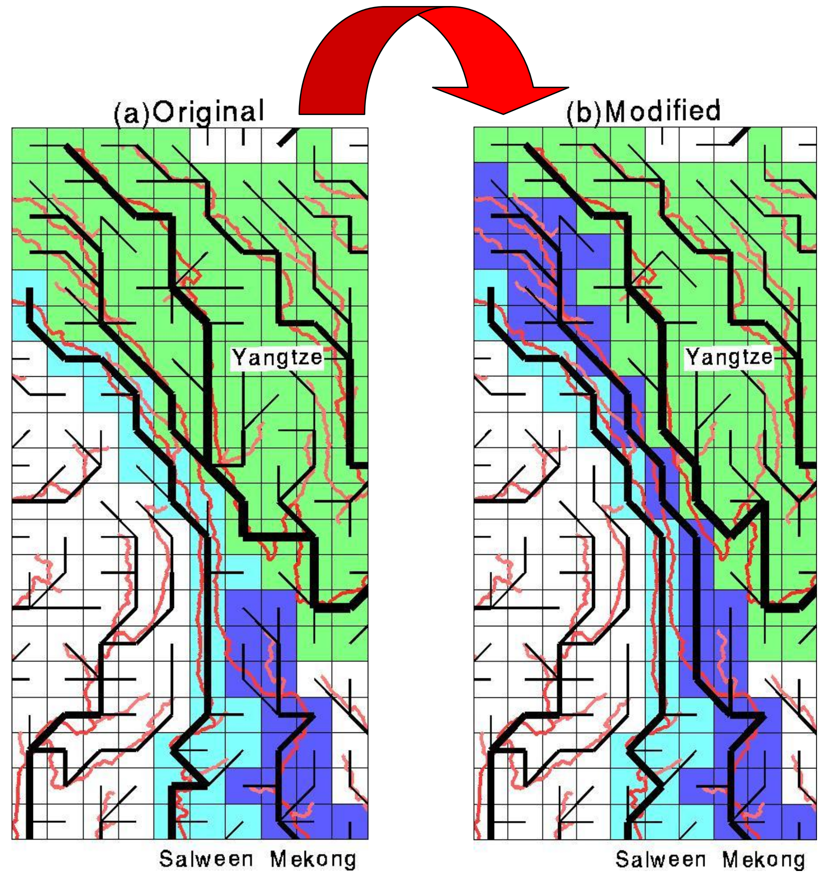
Key: **D8** .vs. **Flexible** River Network

FLOW (Flexible Location of Waterways method)

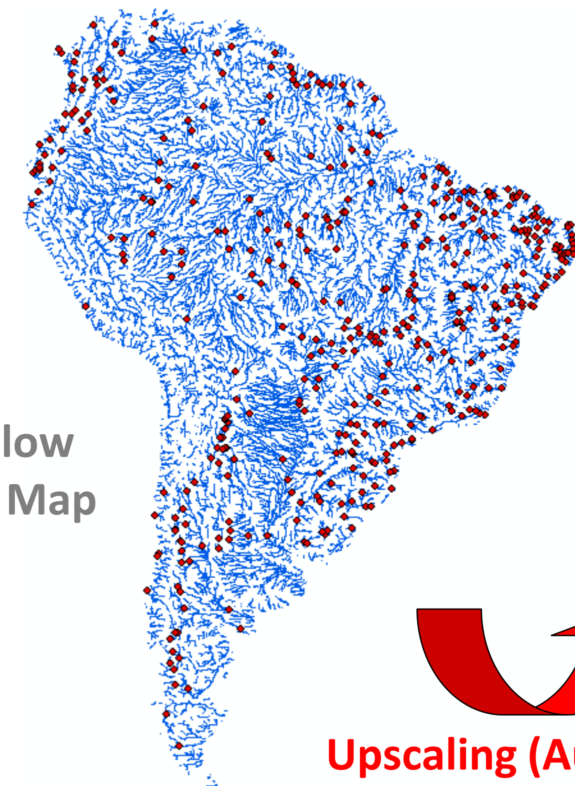
Traditionally, macro-scale river models use **D8 (neighboring cell) River Network**, but it requires **manual editing** of flow directions.

The relationship between upscaled grid-boxes and the original fine-resolution datasets is lost by the process of manual editing.

Manual Editing



Original Flow Direction Map



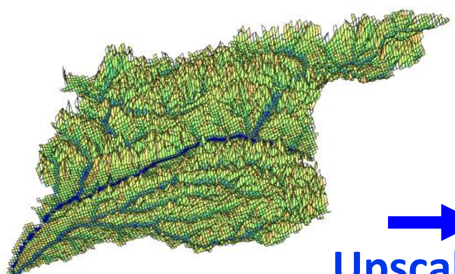
Upscaling (Automatic)

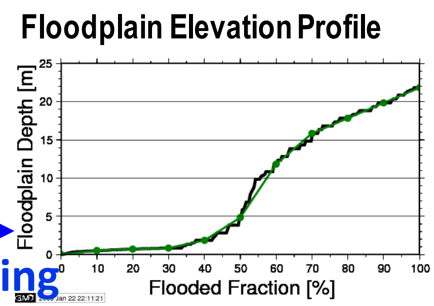
Key: **D8** .vs. **Flexible** River Network

FLOW (**F**lexible **L**ocation **o**f **W**aterways method)

The new model, CaMa-Flood, adopts **Flexible River Network.**
(i.e. The downstream grid does not have to be a neighboring cell)

- No manual editing, High resolution river networks are available
- Sub-grid topographic parameters can be objectively derived from the original datasets.

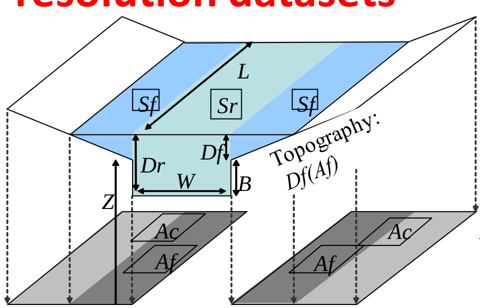


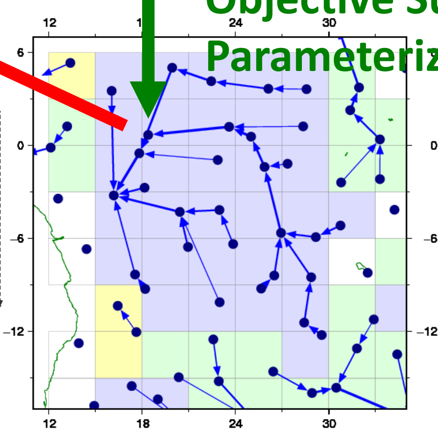


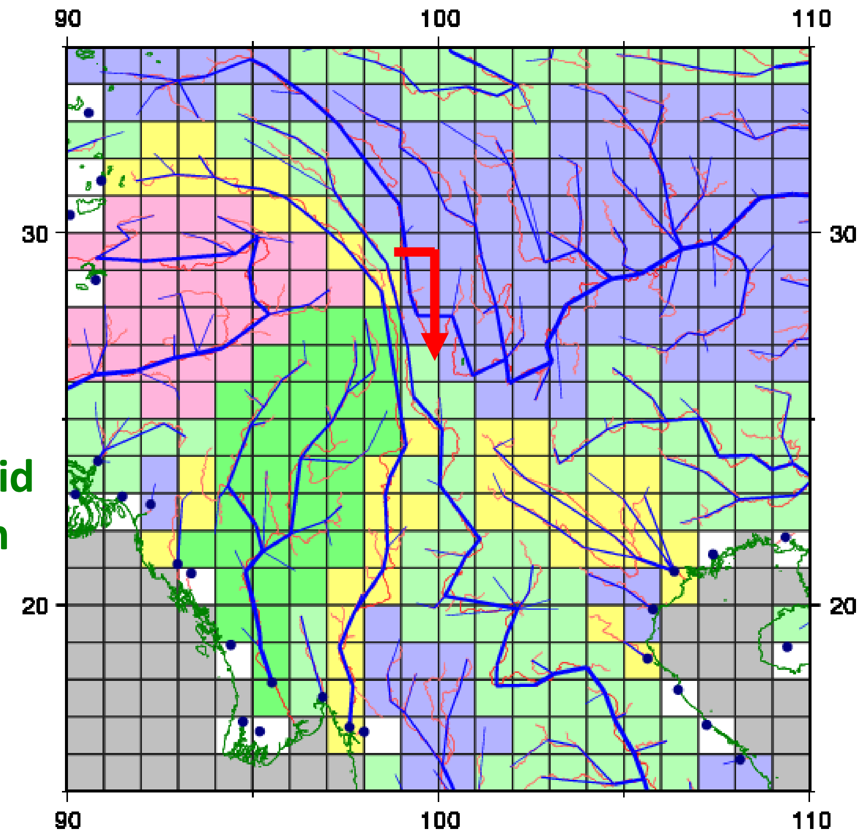
Upscaling

Objective Sub-grid Parameterization

Reference to fine-resolution datasets

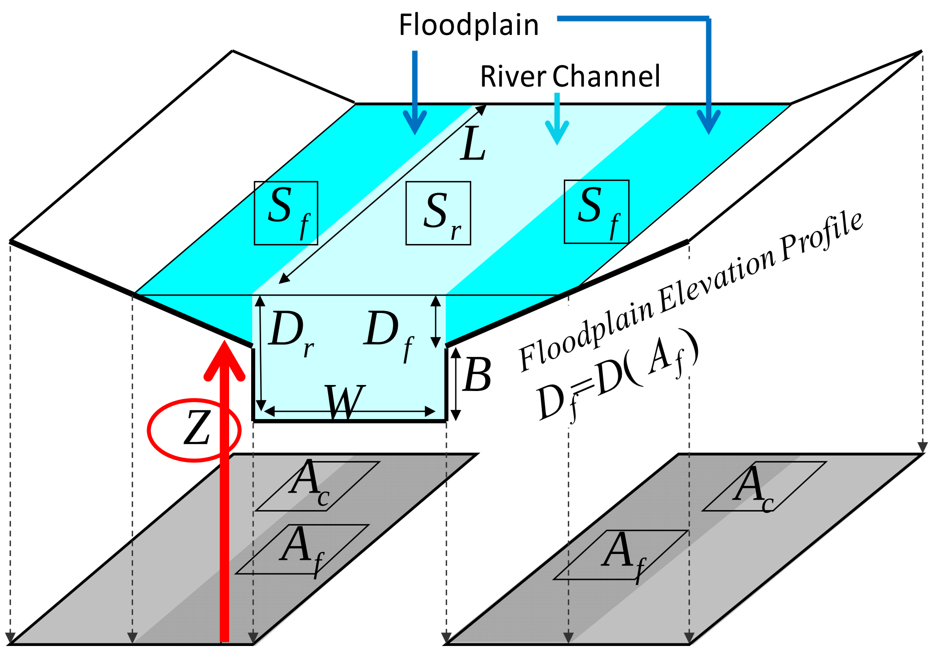




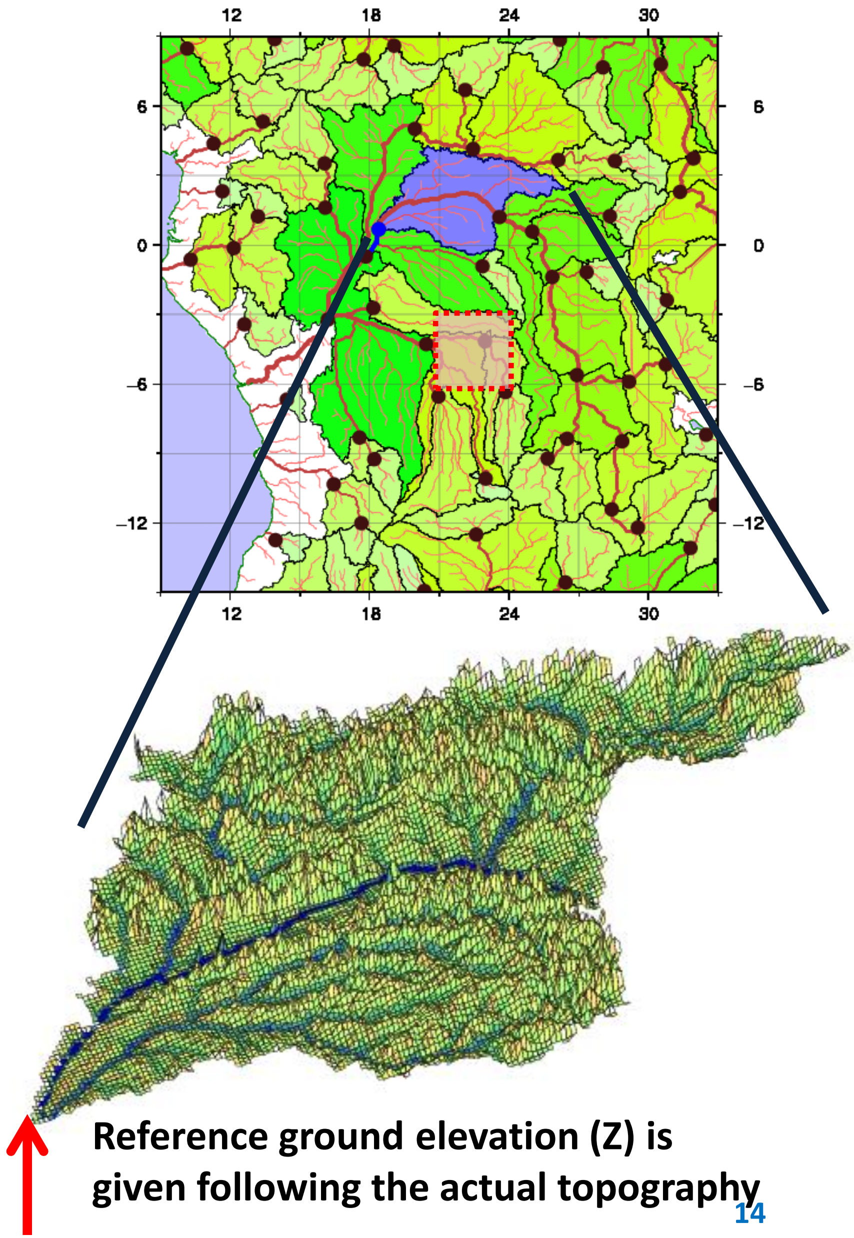


Key: **Absolute** water surface elevations

By **adopting a realistic unit-catchment** instead of rectangular grid-box, realistic **reference ground elevation** can be derived from high-resolution topography even though the simulation is done at the coarse-resolution.



Reference ground elevation (Z) is needed to convert water level into water surface elevation



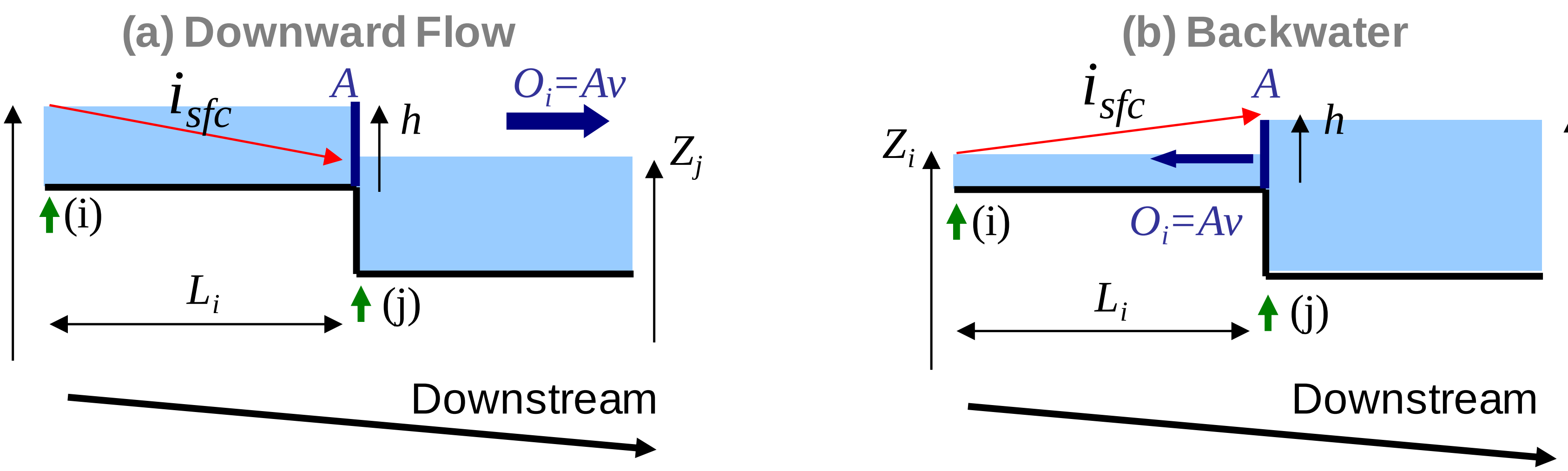
Reference ground elevation (Z) is given following the actual topography

Key: **Absolute** water surface elevations

By comparing "absolute" water surface elevation between upstream and downstream grids, "water surface slope" can be calculated.

Discharge calculation in previous models is based on "topographic slope".

Interactions between upstream and downstream grids, such as backwater efffect or backward flow from downstream to upstream, are firstly represented.



Governing Equation for River Flow

River flow is described by "**St. Venant momentum equation**"
(1-D derivation of Navier-Stokes Equation)

- Cannot numerically solve the full dynamic equation.
- Kinematic wave approximation in previous studies is not adequate.
- Diffusive wave approximation has numerical instability problem.

⇒ A Stable solution for Local Inertial Approximation is recently developed by Bates et al. in Univ. Bristol.


Paul Bates

Q: discharge **A**: cross-section area **h**: water depth
z: channel height **n**: roughness **R**: hydraulic radius
S: water surface slope

St. Venant momentum equation

$$\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)+\frac{\partial Q}{\partial t}+gA\frac{\partial h}{\partial x}+gA\frac{\partial z}{\partial x}+\frac{gn^2|Q|Q}{R^{4/3}A}=0$$

Kinematic Wave Equation
Used in previous models, but does not applicable for flow in flat regions (i.e. no backwater effect)

Diffusion Wave Equation
It has adequate physics to represent natural river flow.
Numerical instability problem cannot be avoided.

Local Inertial Equation
Recently developed in Univ. Bristol [Bates et al., 2010].
By adding "local inertial term" to the diffusive wave eq., more fast and stable flow calculation is achieved.

Calculation Flow

(1) Channel/floodplain topography parameters for sub-grid floodplain inundation dynamics.

->Diagnose water level and inundated area from water storage.

(2)Discharge calculation by the local inertial equation along a prescribed river network map.

Momentum Equation

$$\cancel{\frac{\partial q}{\partial x}} + \frac{\partial q}{\partial t} + gh\frac{\partial h}{\partial x} + gh\frac{\partial z}{\partial x} + ghi_f = 0$$

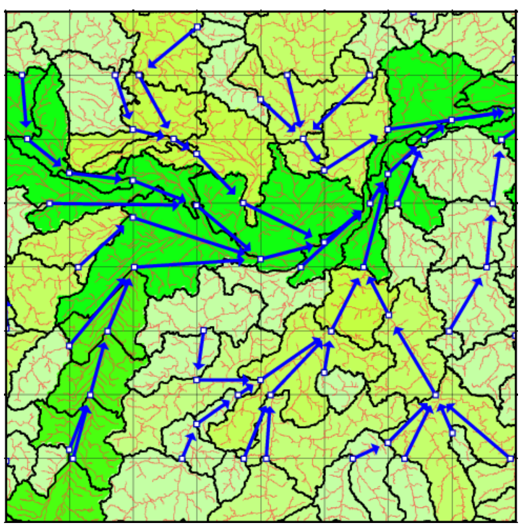
FTCS representation

$$q^{t+\Delta t} = \frac{q^t - ghi_{sfc}\Delta t}{(1 + gn^2|q^t|h^{-7/3}\Delta t)}$$

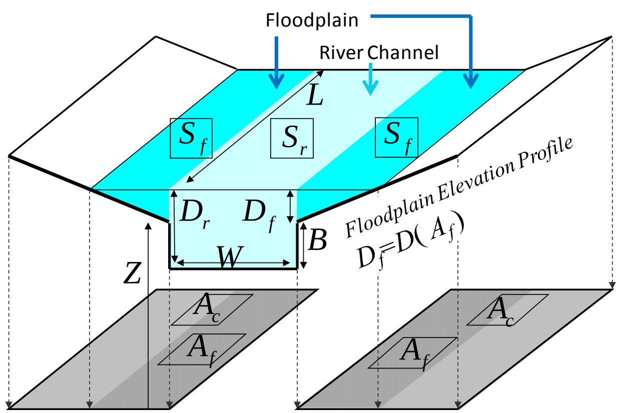
(3) Update water storage using mass balance equation.

Mass Conservation

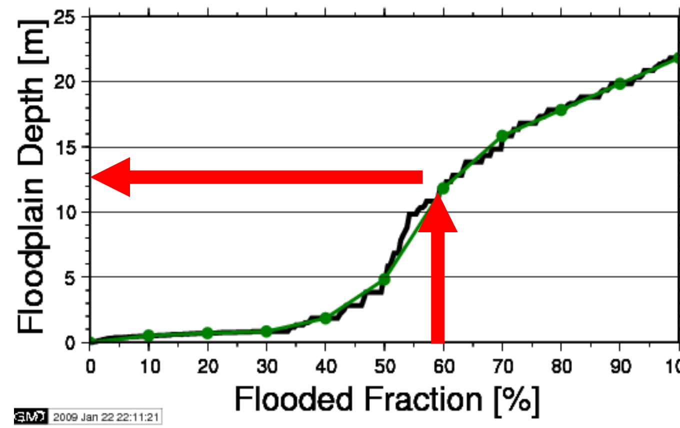
$$S_i^{t+\Delta t} = S_i^t + \sum_k^{Upstream} Q_k^t \Delta t - Q_i^t \Delta t + Ac_i R_i^t \Delta t$$



River network and unit-catchment



Sub-grid river / floodplain topography



Diagnose water level and inundated area from storage using floodplain topography.

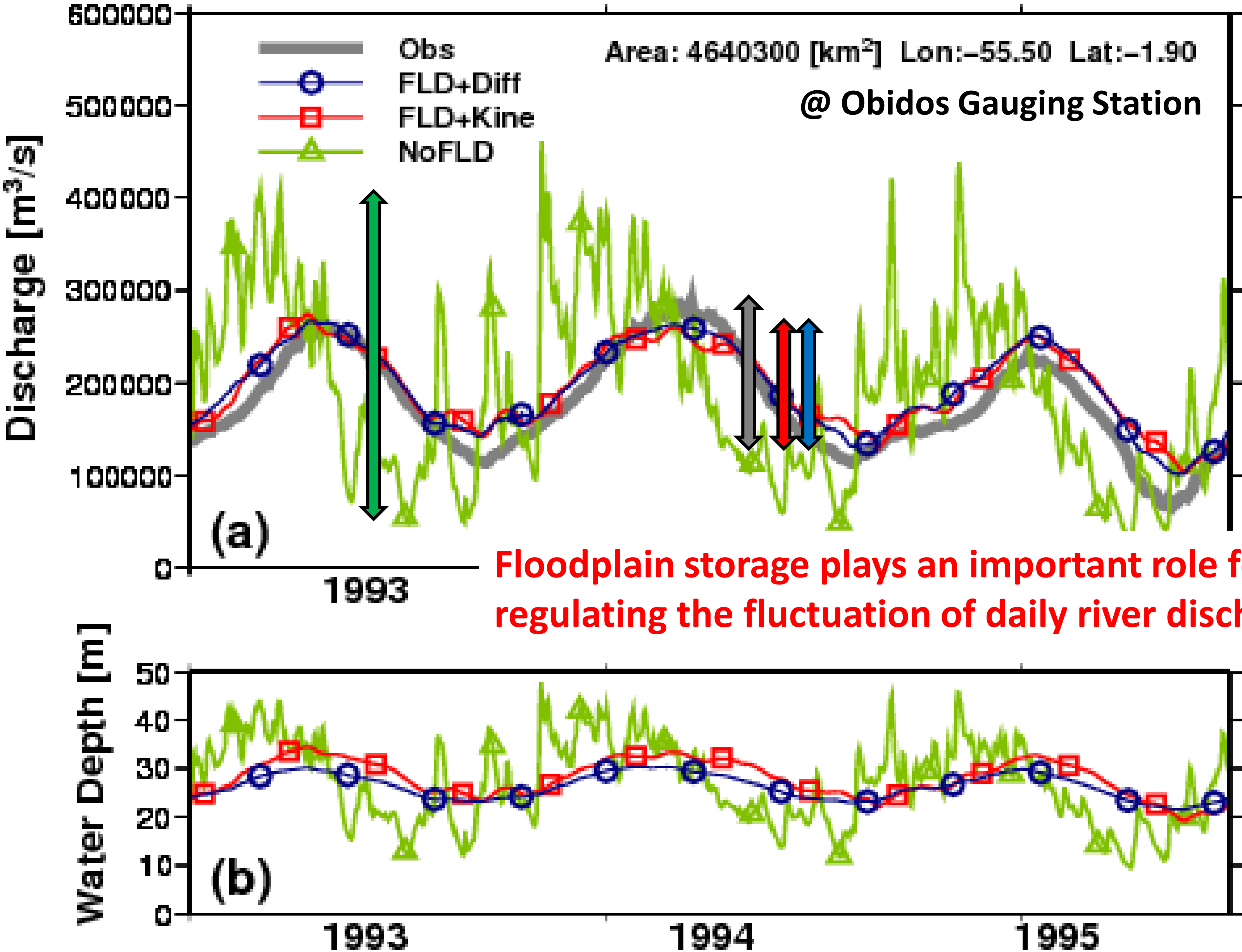
↑

Model Development

Model Validation

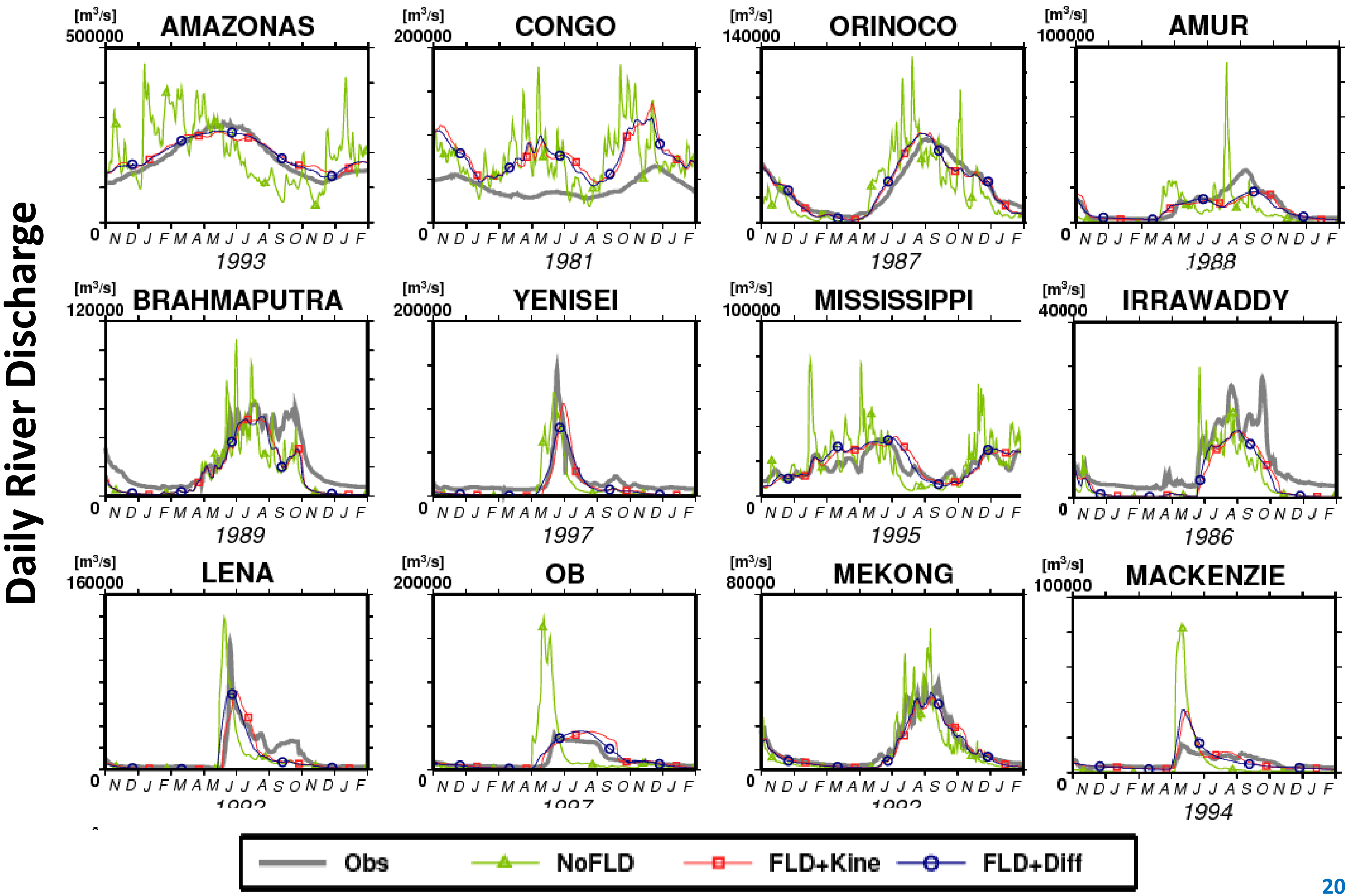
↓

Hydrodynamic Simulation (Amazon River)



Floodplain storage plays an important role for regulating the fluctuation of daily river discharge

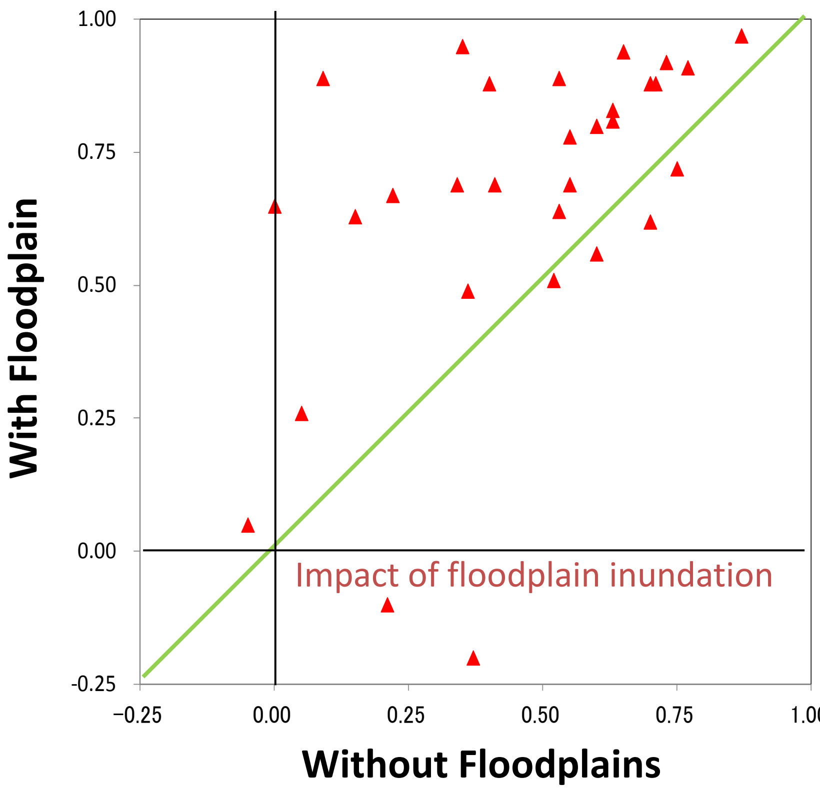
Hydrodynamic Simulation (Continental Rivers)

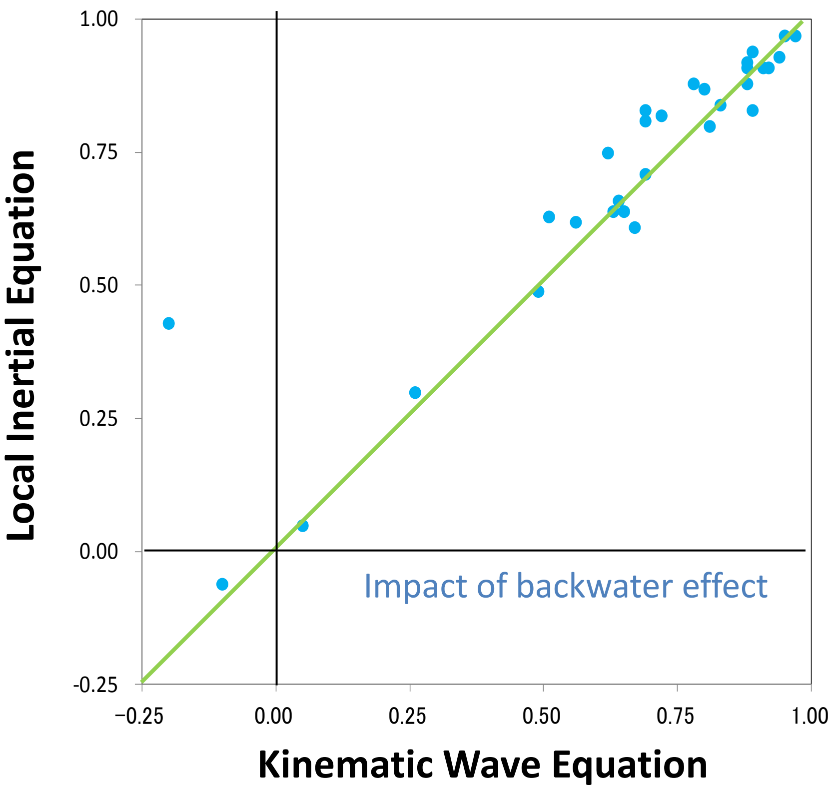


Hydrodynamic Simulation (Continental Rivers)

Daily discharge simulation is improved for most rivers in the world.

- Floodplain inundation controls daily-scale discharge fluctuation.
- Backwater effect is also important in some rivers.



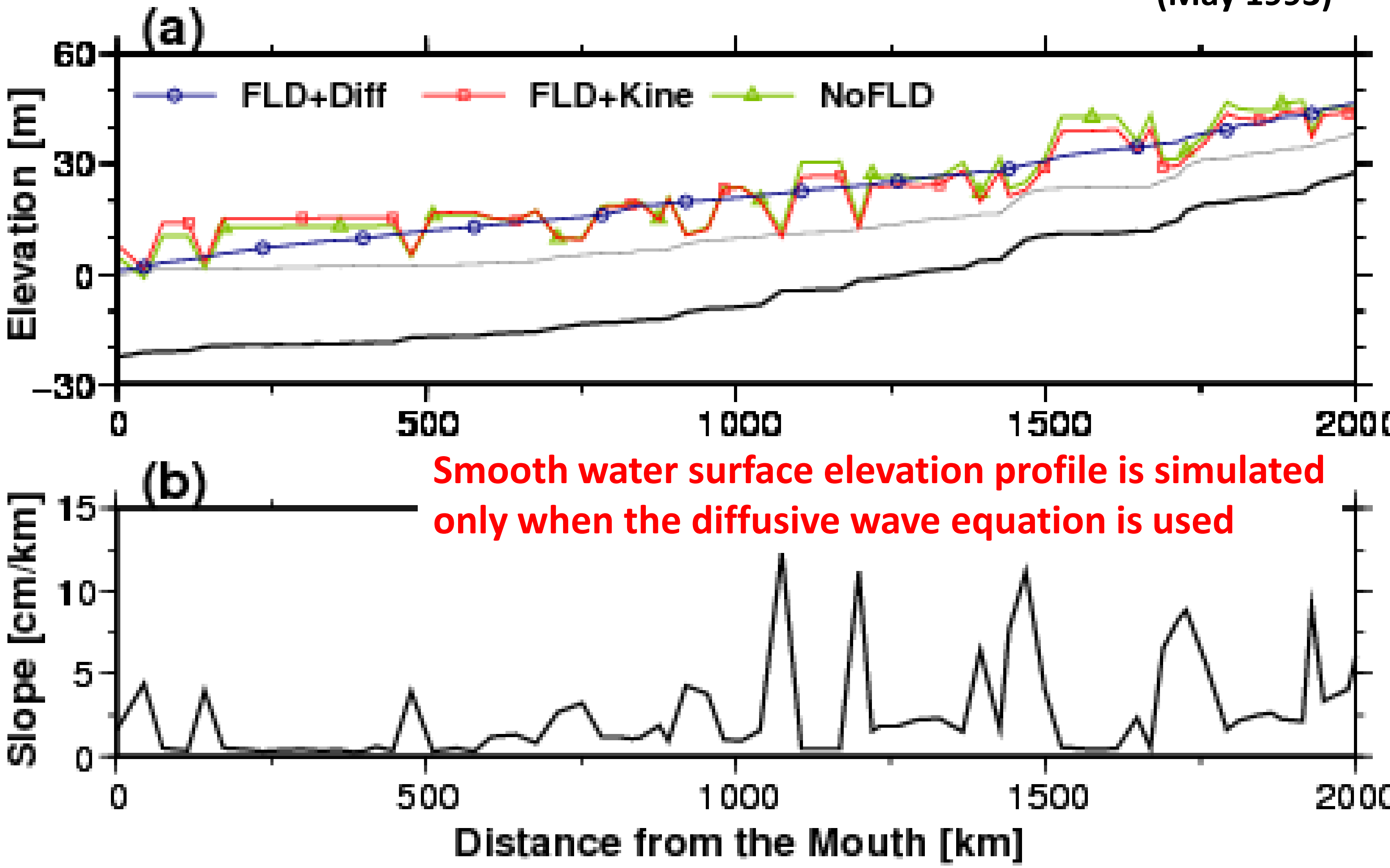


Daily discharge correlation to observations (30 continental rivers)

Hydrodynamic Simulation (Amazon River)

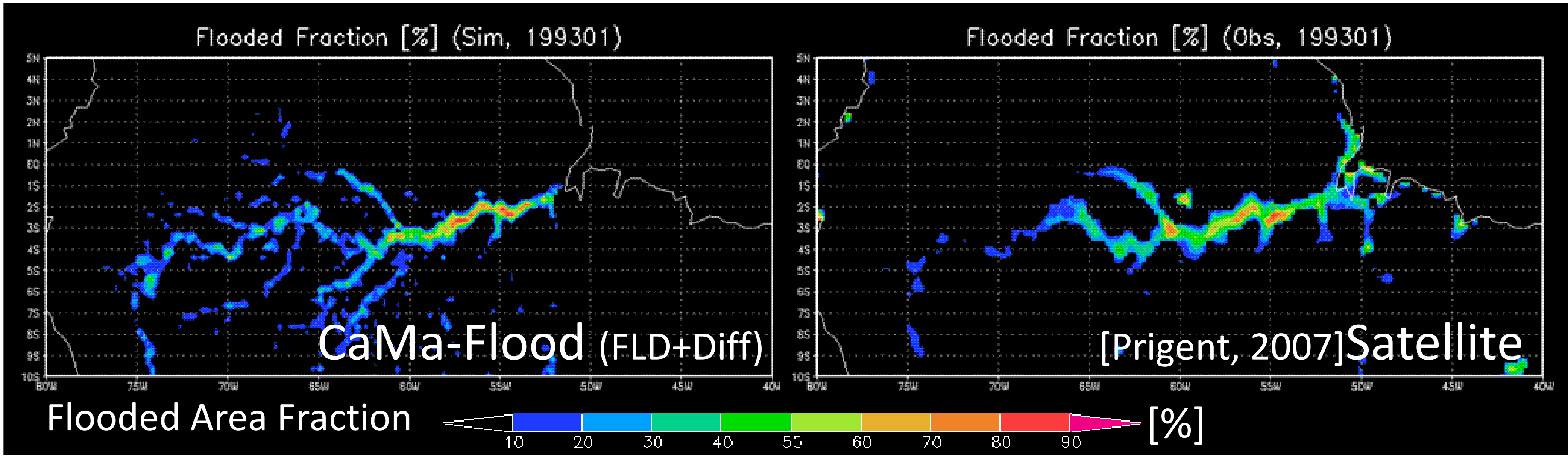
Monthly averaged water surface elevation along the mainstem

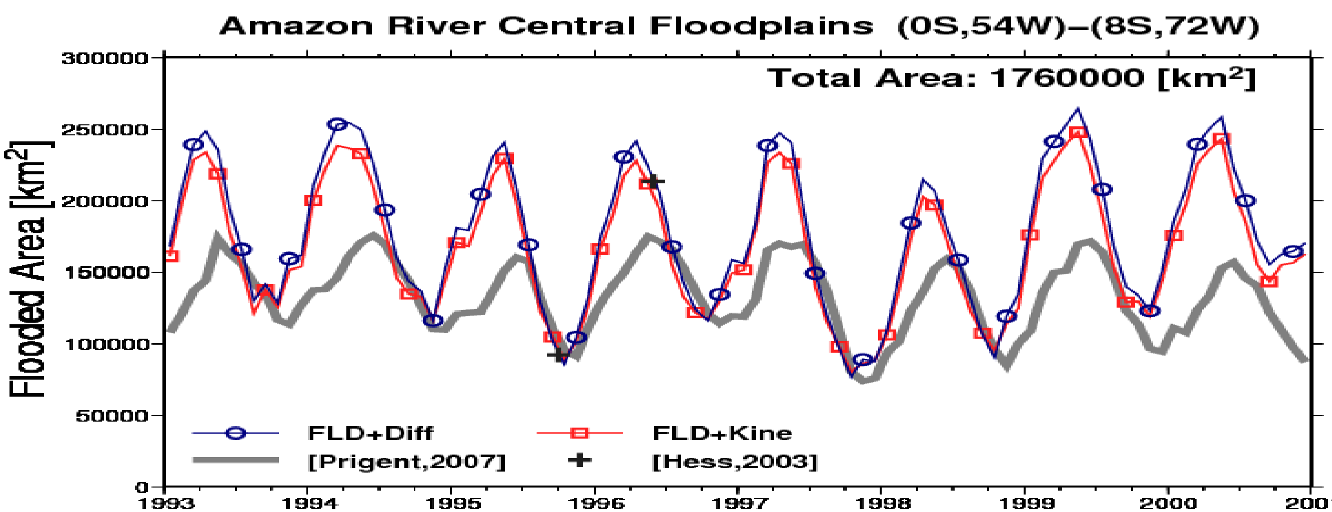
(May 1993)



Hydrodynamic Simulation (Amazon River)

Spatial-temporal distribution of flooded area

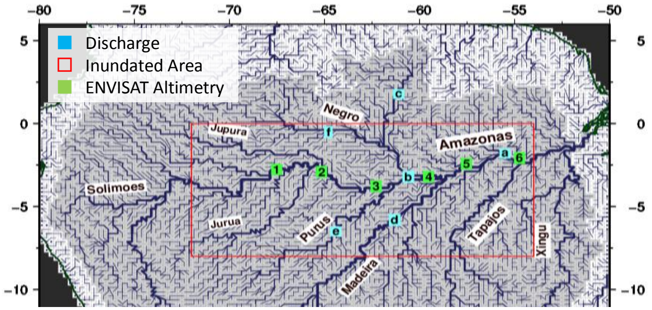


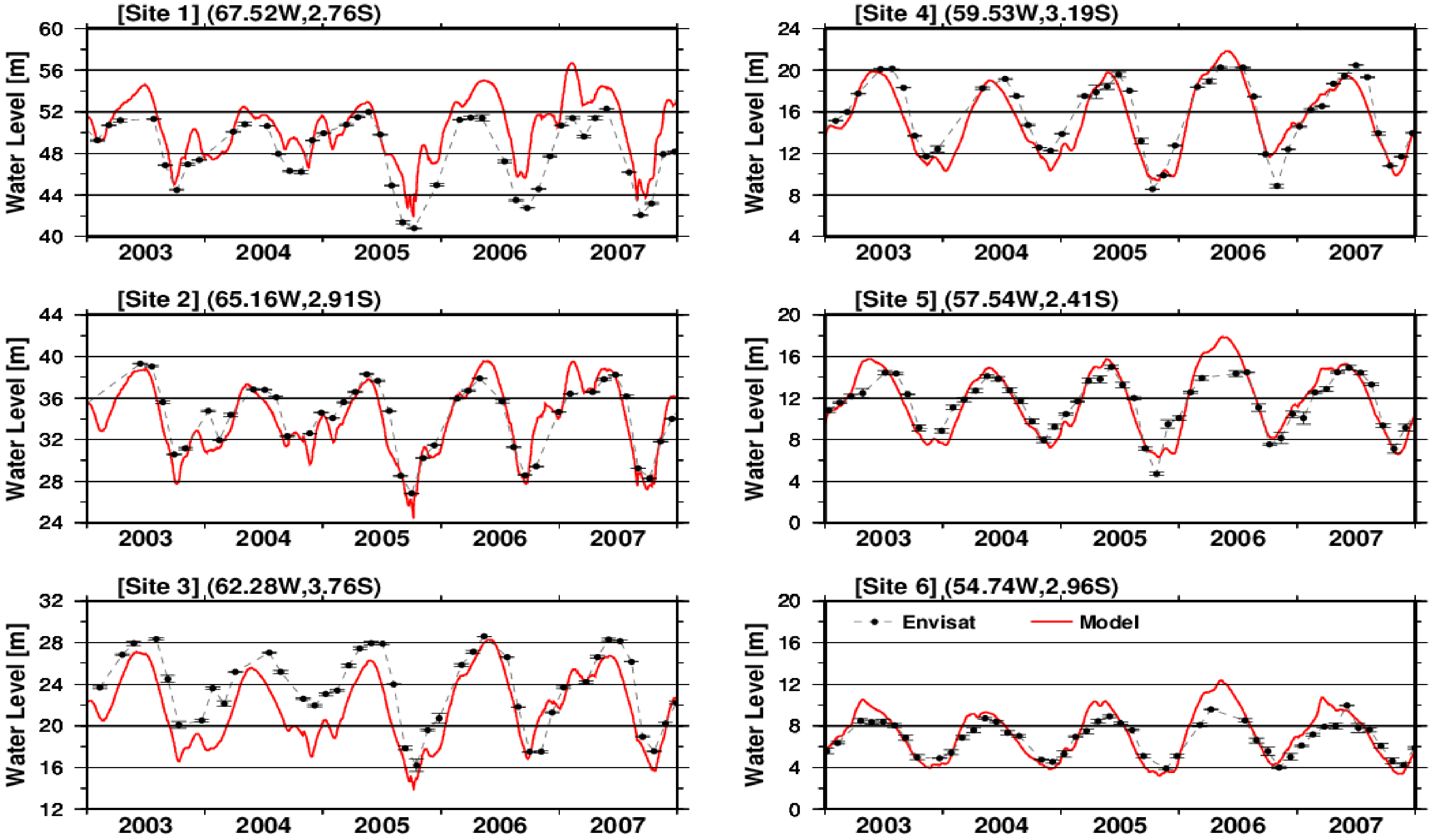


Many thanks to Dr. Prigent and Dr. Hess for providing the satellite datasets

Water Surface Elevation

Phase and amplitude are well simulated.
The average (absolute elevation) is also OK.





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Model Validation

Limitation / Uncertainty

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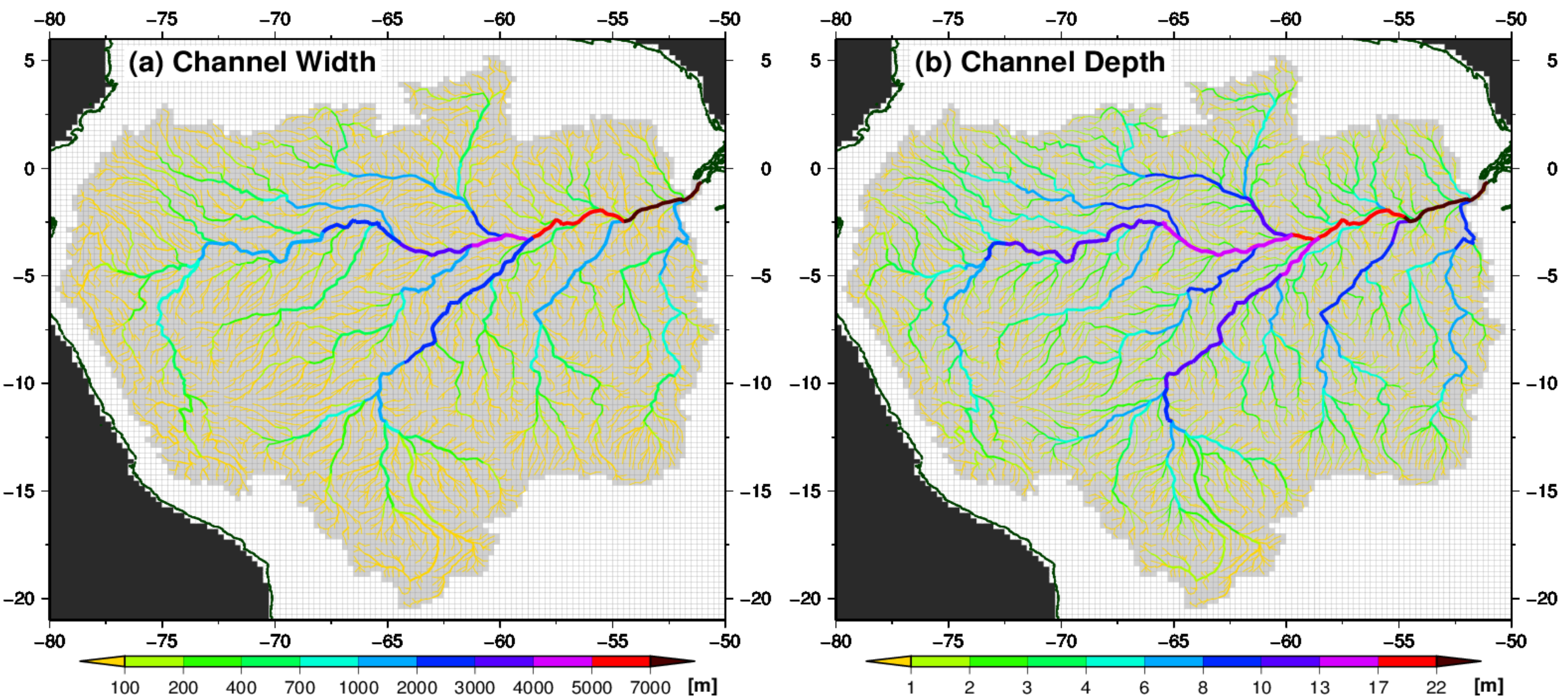
Uncertainty in Channel Parameters

The parameters for channel width and channel depth were estimated by a single empirical equation for all the basin. This assumption is not realistic because they changes following local topography.

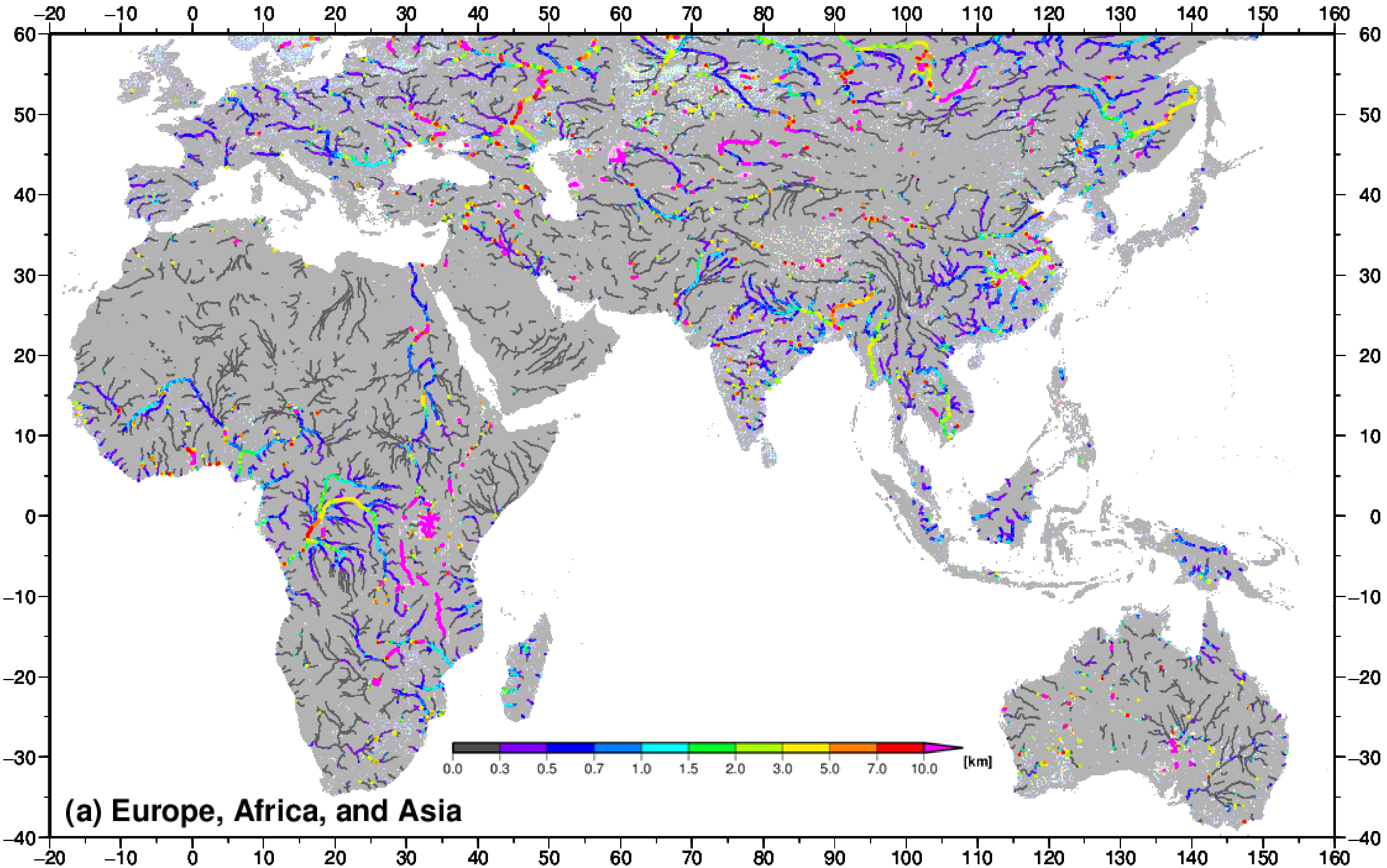
$$W = \max\left[0.53 \times R_{up}^{0.75}, 10.0\right] \qquad B = \max\left[0.14 \times R_{up}^{0.40}, 1.00\right]$$



Global River Width Database: GRWD

Fully-automated algorithm is recently developed.

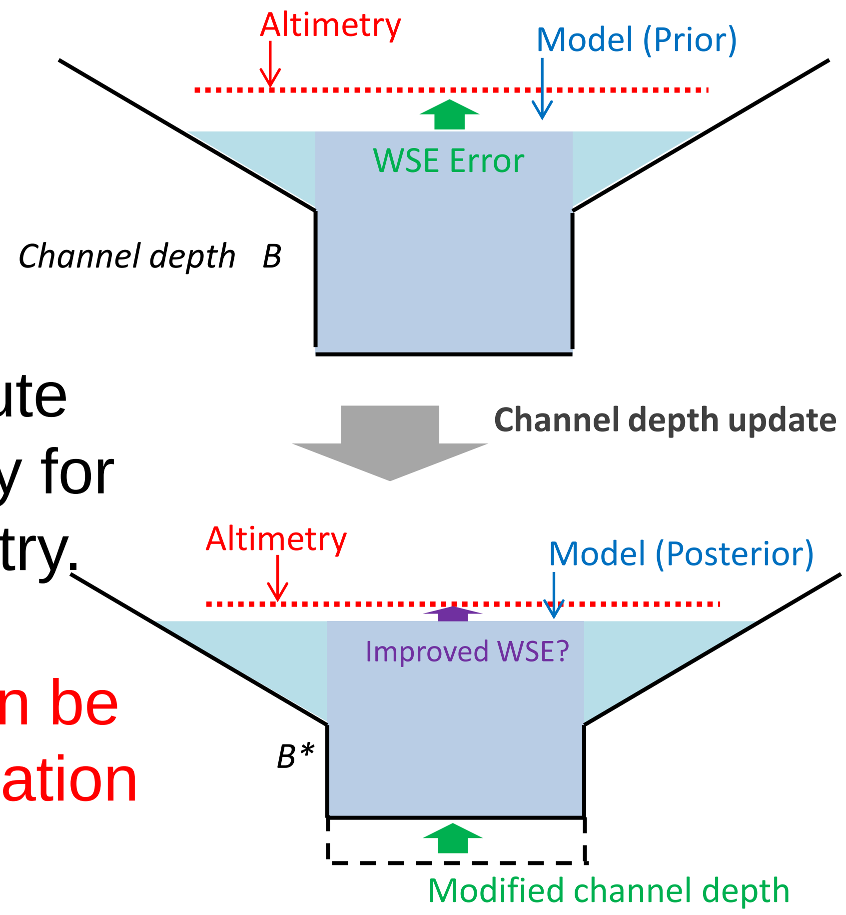
Input: SRTM Water Body and HydroSHEDS [Yamazaki et al., in review]



Chanel Depth Estimation

Channel depth is one of most important parameters to determine flood extend.

It has been estimated by
an empirical equation of annual flow,
being a large source of uncertainty.



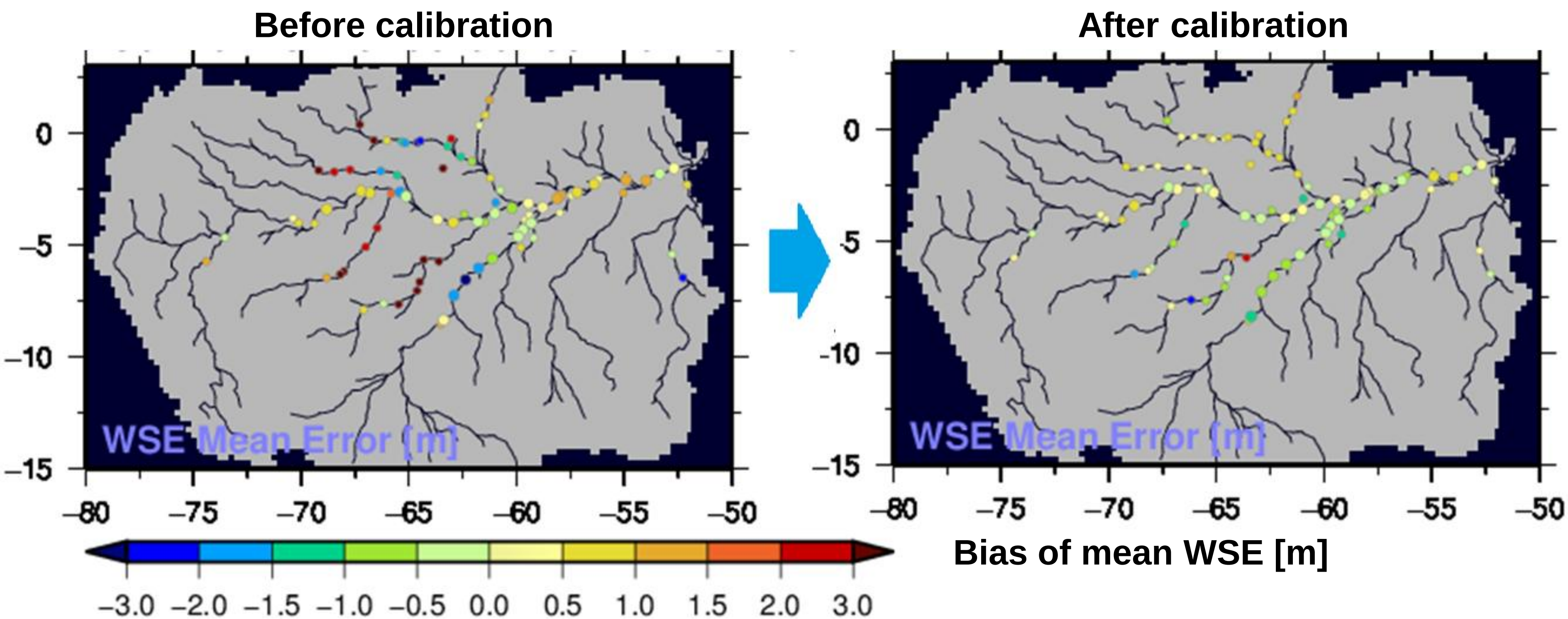
CaMa-Flood can simulate absolute WSE, with an adequate accuracy for direct comparison against altimetry.

⇒Information on WSE Error can be utilized for bathymetry estimation

Calibration of channel depth with altimetry

Primitive experiment with simple assumptions：

- “WSE Error” = “Channel depth adjustment”
- Liner spatial interpolation of errors between virtual gauges.



● WSE simulation can be improved.

● Data-assimilation-type method using error-covariance matrix may be better to get more feasible (or realistic) estimates of channel depth.

Global Hydrology to Global Hydrodynamics

Global river models have long been an “empirical” model.

- only calculate river discharge based by inadequate equations.

We developed the CaMa-Flood global hydrodynamic model.

- describes floodplain inundation as sub-grid physics
- explicitly represents absolute water surface elevation
- thus implement a “physically-based” flow equation

Explicit simulation of flood stage in addition to river discharge

- enables direct comparison between simulations and observation

Limitation:

Flood inundation is very sensitive to channel topography parameter.
Current version has not small uncertainty in channel parameters.

- Global calibration using satellite data is now under preparation.

CaMa-Flood: Global Hydrodynamics Model

Source code is freely available on request (written in Fortran 90).

Global river network and topography maps included in the package.

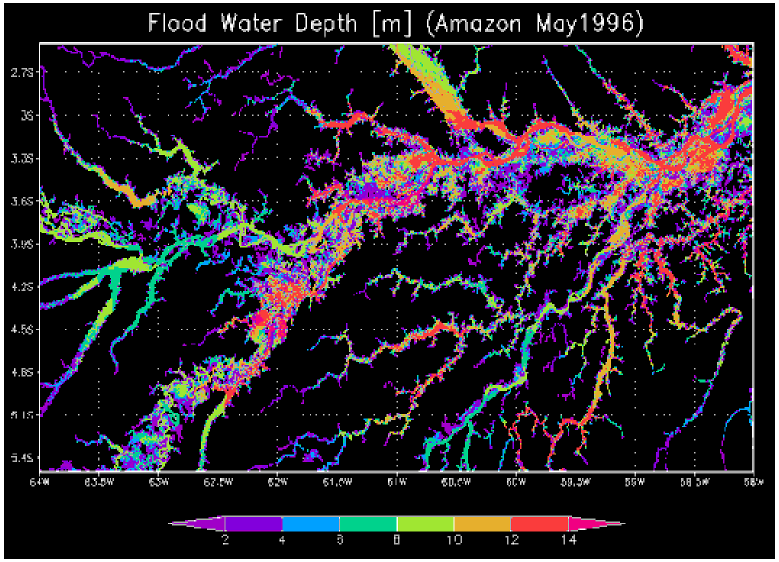
- Prepared at 5min & 15min resolutions, with regionalization tools.
- River maps at different resolutions can be generated by FLOW algorithm.

Runoff input (spatially distributed, daily) is needed to run CaMa-Flood.

- Suitable to couple with GCM, RCM, LSM, Hydrological models.
- Runoff interpolation sub-routing is included.

Output: discharge, inundated area, flood depth.

- Inundated area and flood depth can be downscaled onto high-resolution DEM.



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CaMa-Flood Description

Model Application

In Collaboration with:

Yukiko HIRABAYASHI, Hiroaki IKEUCHI @ Univ. Tokyo

Shinjiro KANAE, Tomoko SATO @ Tokyo Institute of Technology

Sujan KOIRALA @ Max Planck Institute

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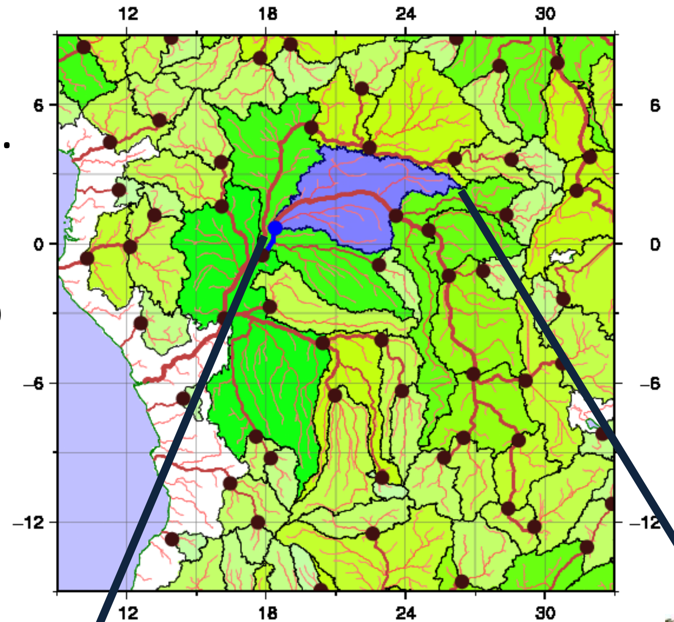
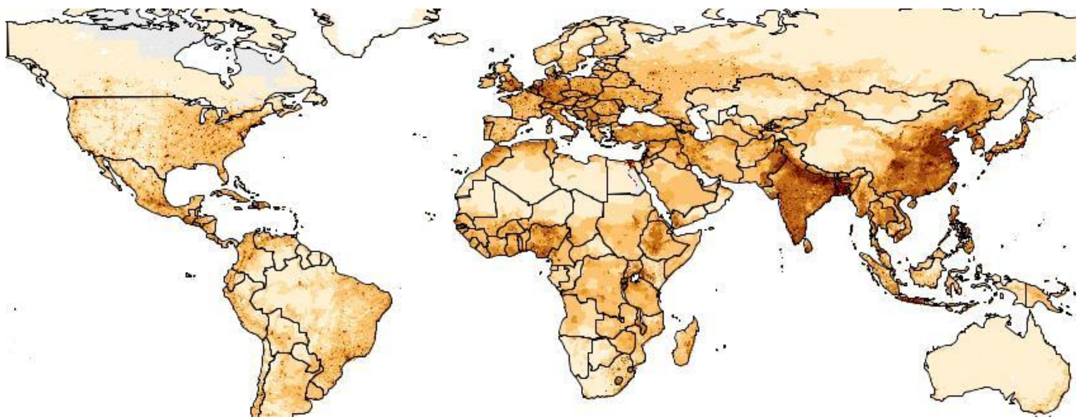
Flood Risk Assessment with CaMa-Flood

Simulated flood depth can be downscaled onto high-resolution DEM.

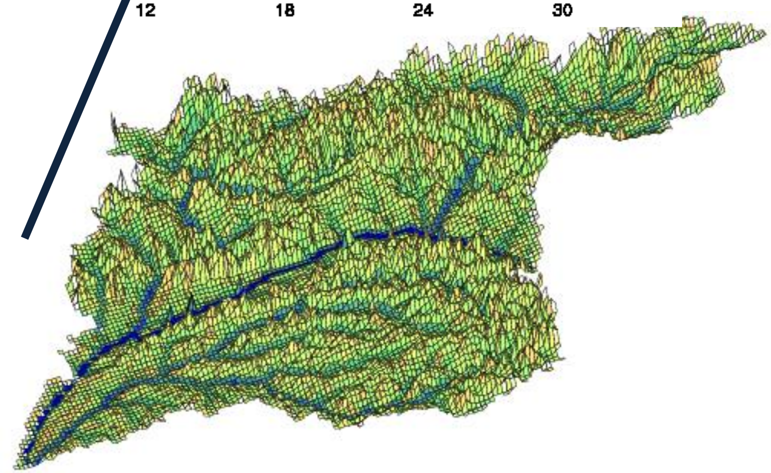
- Model output at 25km resolution can be downscaled to 500m resolution (in default setting).



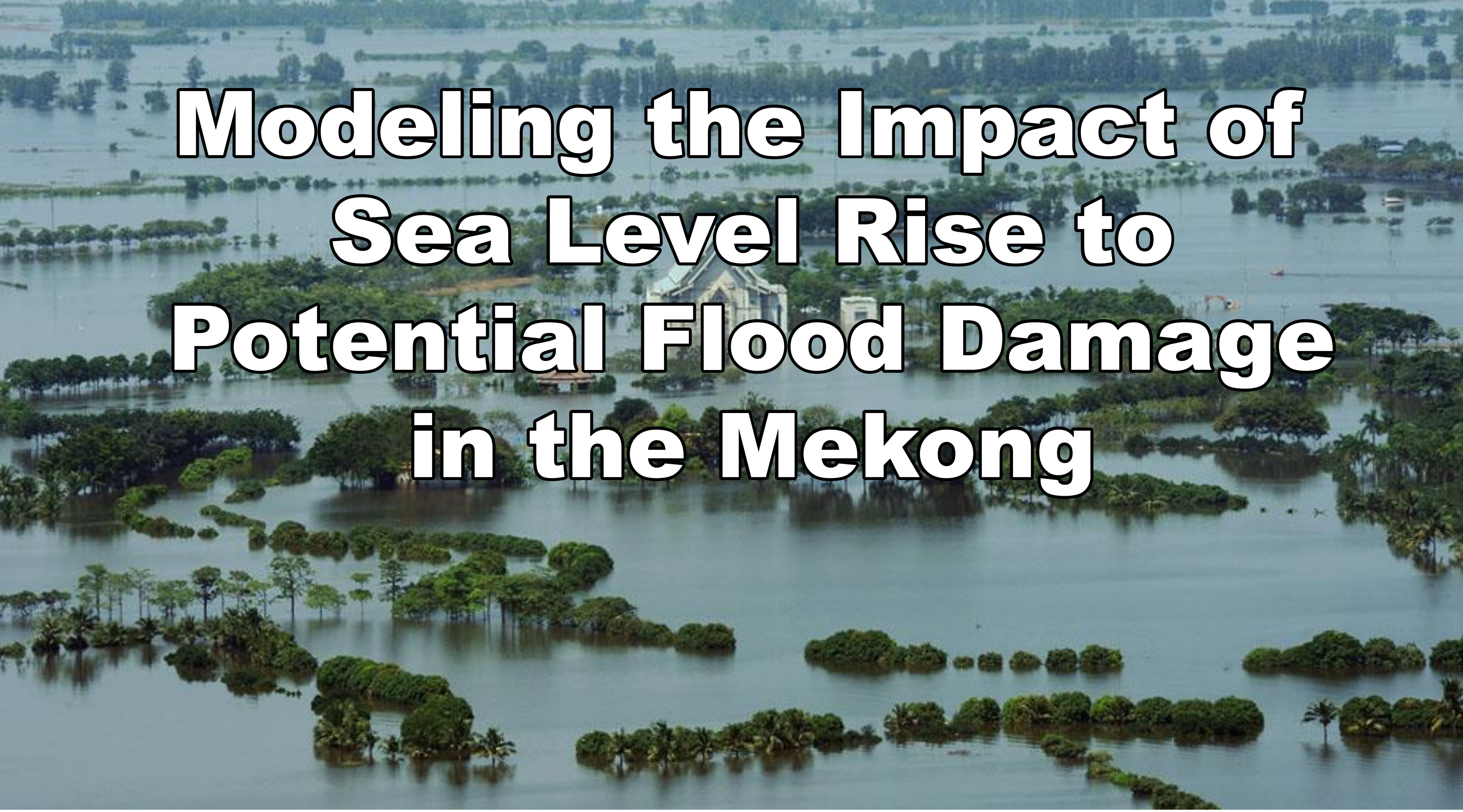
By overlaying downscaled flood depth onto gridded social data (Pop, GDP, Land Use), flood risk can be assessed.



<u>**Gridded Social Data (Pop, GDP, Land Use)**</u>



<u>**CaMa-Flood sub-grid topography**</u>



Modeling the Impact of Sea Level Rise to Potential Flood Damage in the Mekong

Tomoko SATO[1], Dai YAMAZAKI[2], Wee Ho LIM[2], Sujan KOIRALA[3], and Shinjiro KANAE[2]

[1]Tokyo Institute of Technology, [2]University of Bristol, [3]The University of Tokyo

Feb. 28th 2014 / The58th Conference on Hydraulic Engineering

Methodology

Climatologic Dataset

Runoff [2000] at 1 deg.
(Kim et al., 2009)

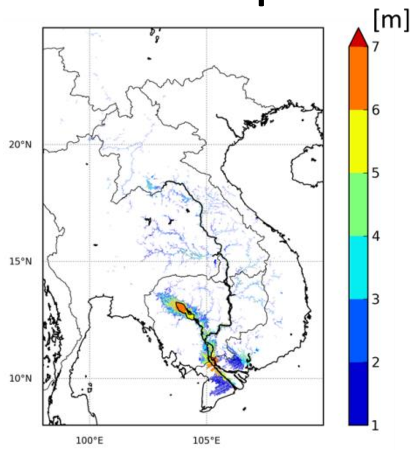
Economic Dataset

GDP [2000] for country, Population [2000] at 5 min,
Land use [2003] at 30 sec. (CIESIN, HYDE, GLCNMO V.1)

River Routing Model

1. HAZARD

Annual maximum inundation depth



Risk Assessment Approach

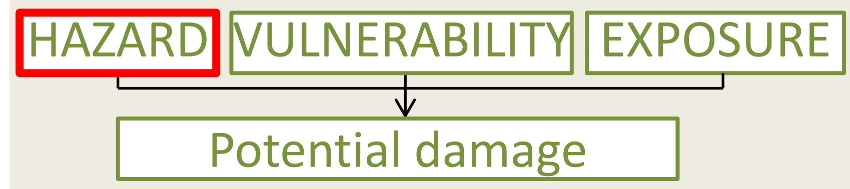
2. VULNERABILITY

Degree of resistance against floods

3. EXPOSURE

Potential affected number of assets

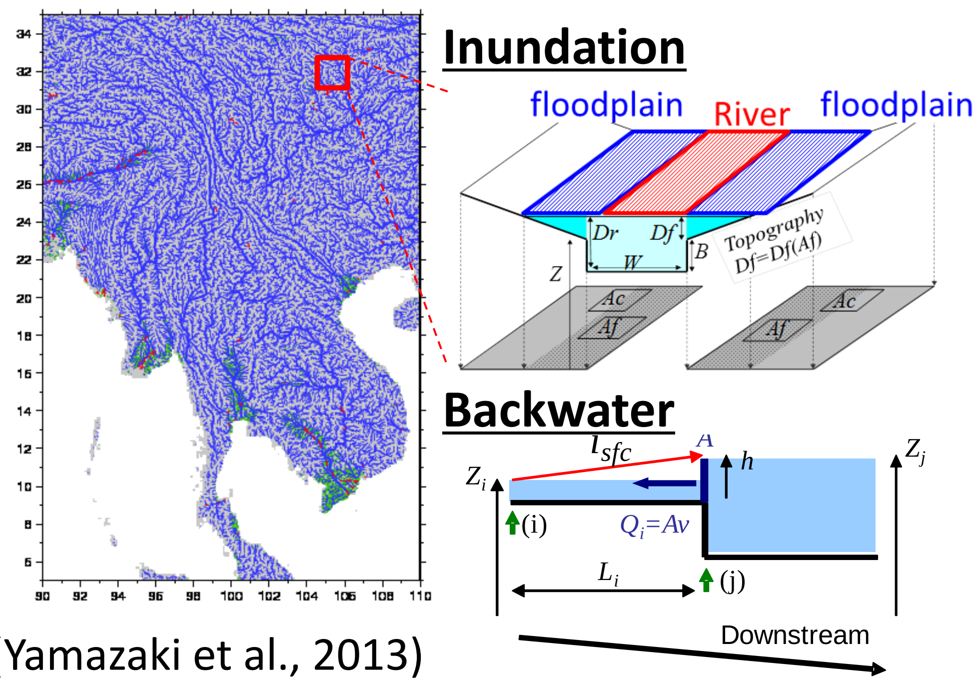
4. Potential Flood Damage



We calculated **maximum inundation depth in 2000** for each grid using the Catchment-based Macro-scale Floodplain Model (CaMa-Flood).

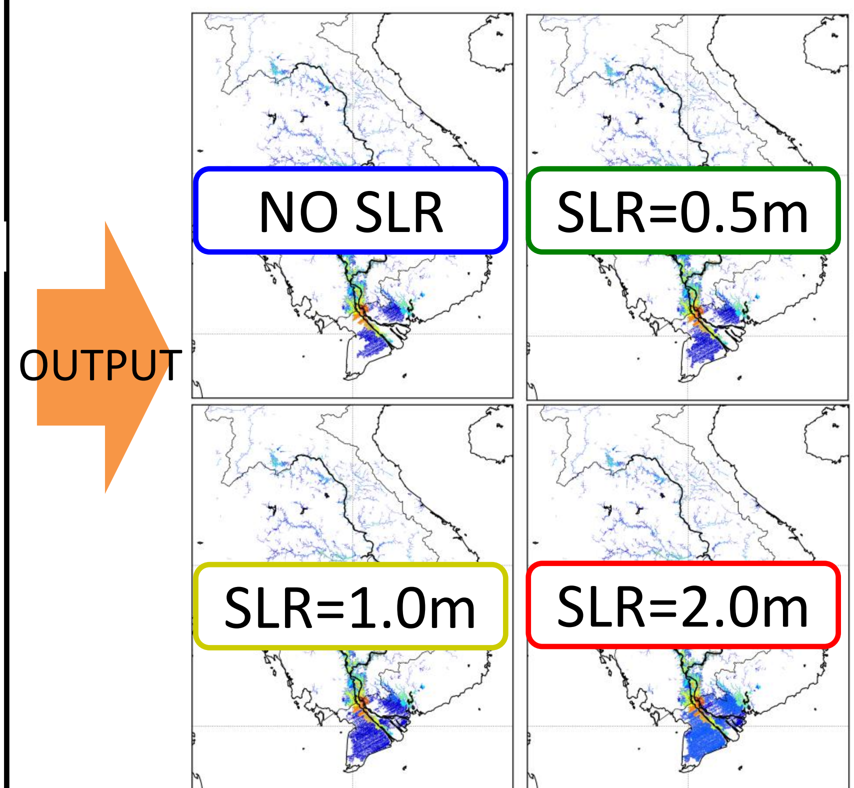
CaMa-Flood: River Model

Inundation in floodplain and backwater are considered.

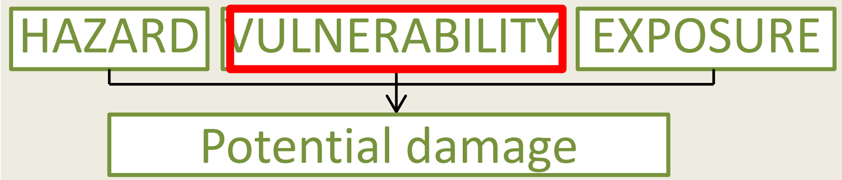


(Yamazaki et al., 2013)

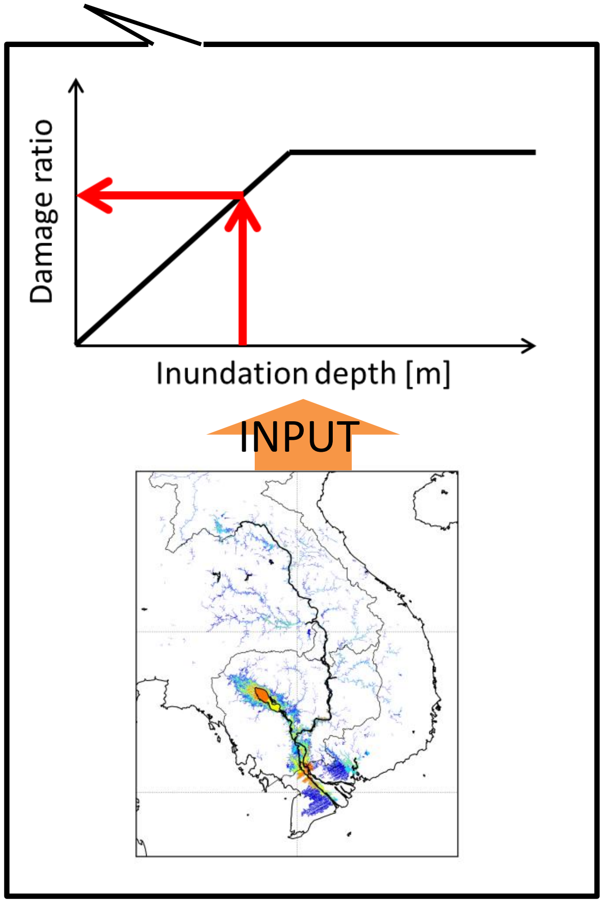
The maximum inundation depth in 2000



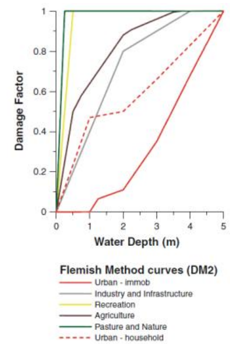
VULNERABILITY



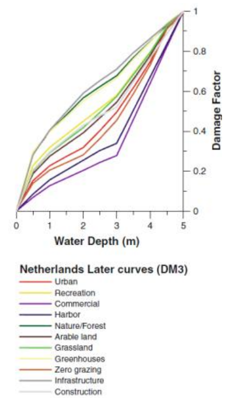
We calculated the degree of damage based on inundation depth using **Depth-Damage function.**



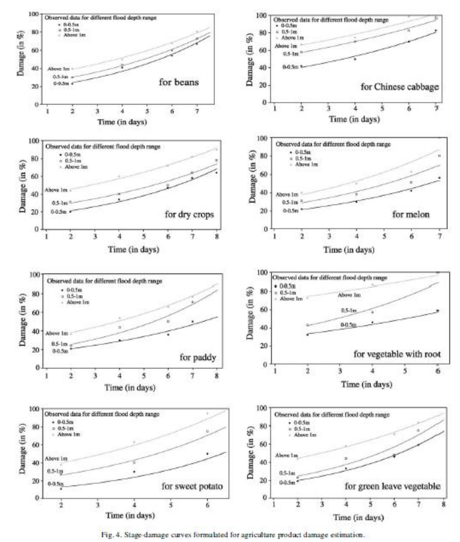
However, **validation of many previous functions is difficult** because of scarce observation. (Dutta et al., 2003)



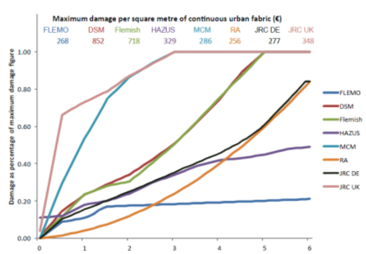
(Vanneuville et al., 2006)



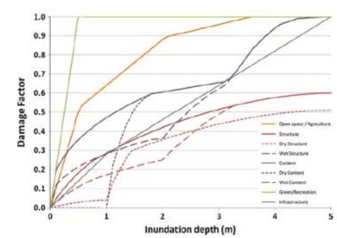
(Klijn et al., 2007)



(Dutta et al., 2003)

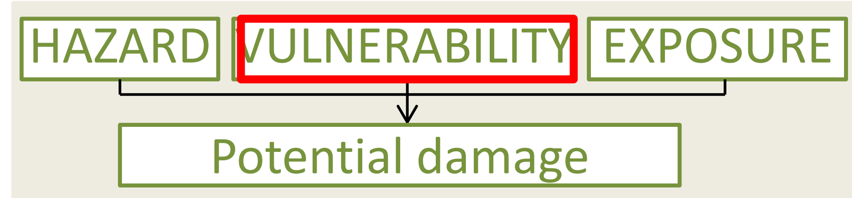


(Jongman et al.,2012)



(De Moel et al., 2013)

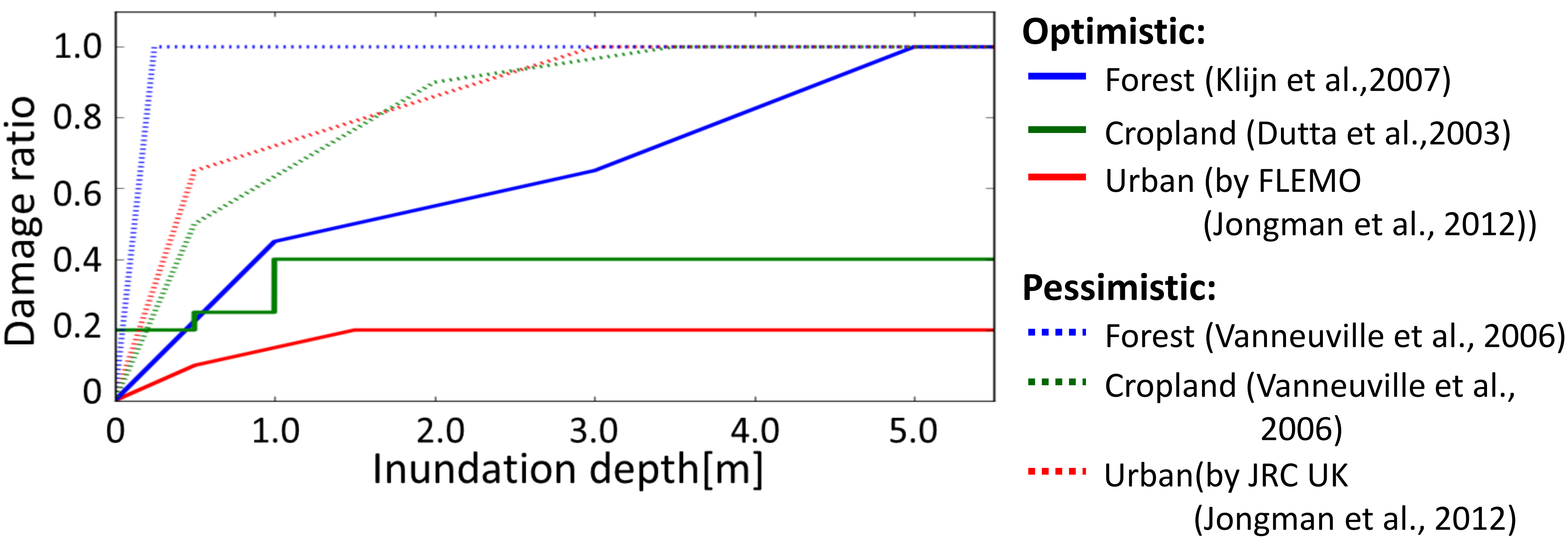
VULNERABILITY



We calculated the degree of damage based on inundation depth using **Depth-Damage function.**

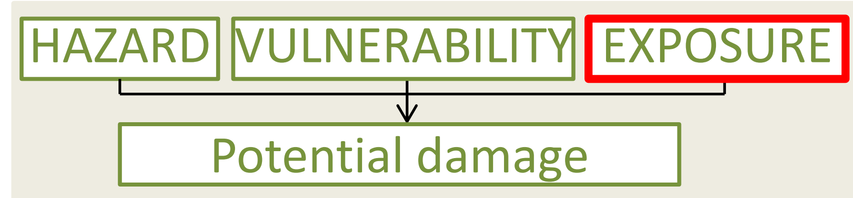
Problem: Validation of Depth-Damage functions is challenge.

We choose optimistic and pessimistic functions for each land use group to show the range of result.



EXPOSURE

Assets in each grid can be calculated as

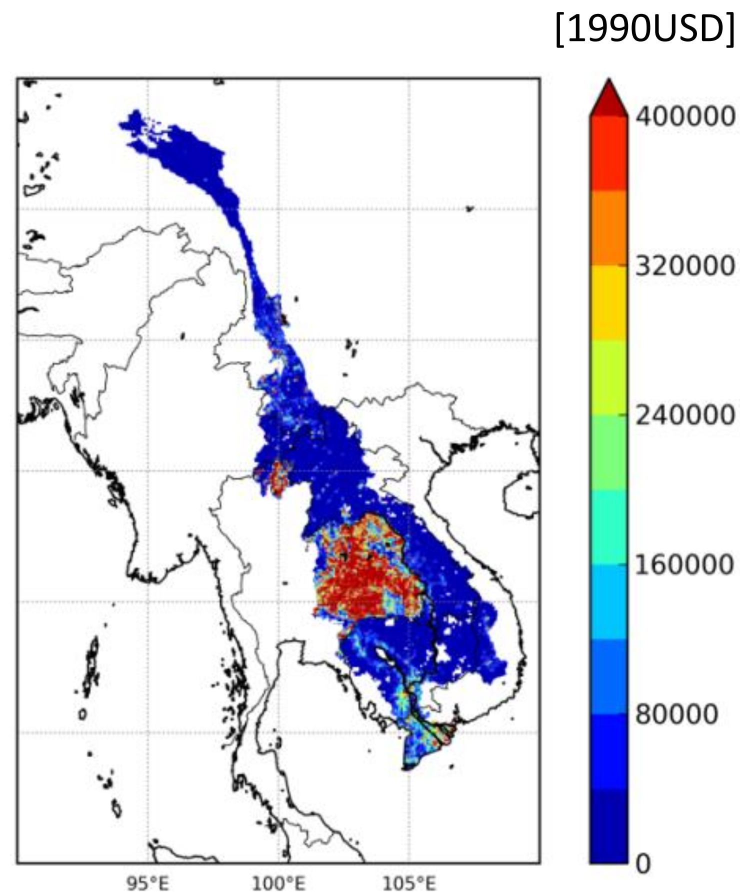


$$\textbf{Assets} = \textbf{K} \times \textbf{GDP per capita} \times \textbf{population}$$

(for country) (for each grid)

K is variable for each previous studies.

- K=1 (Ward et al., 2013, Winsemius et al., 2013)
- K=5 (Jongman et al., 2012)
- K=2.8 (Hallegatte et al., 2013)
- K is decided based on "Wealth". (Hallegatte et al., 2013)



Methodology

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3. EXPOSURE

Potential affected number of assets

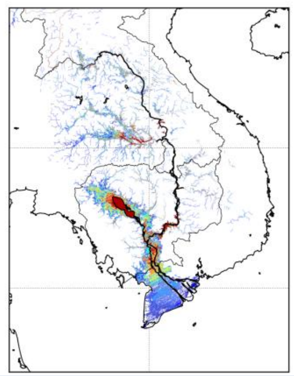
4. Potential Flood Damage

POTENTIAL DAMAGE

Damage Ratio × Assets = Potential Damage

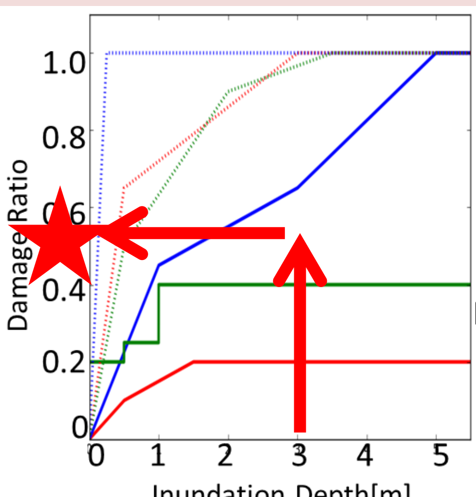
Damage Ratio

Maximum Inundation Depth in 2000 [m]



INPUT

Depth-Damage Function

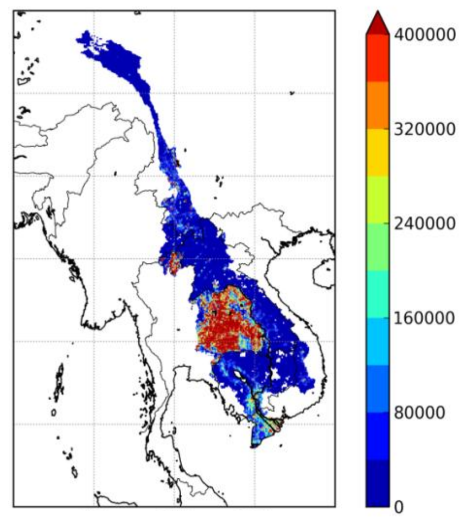


OUTPUT

Damage Ratio

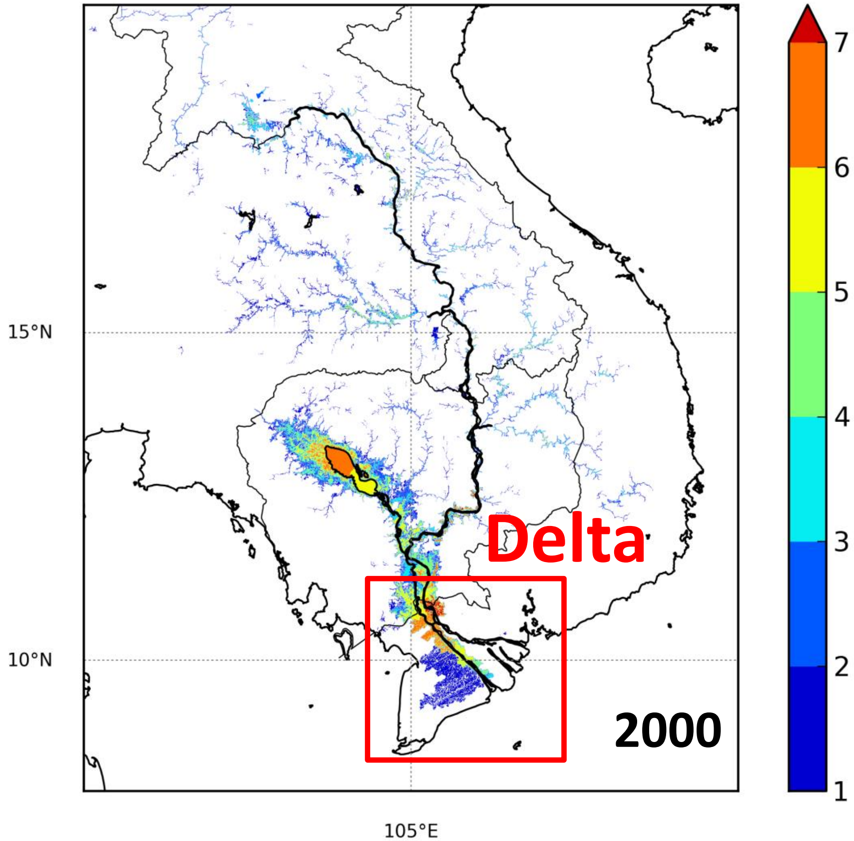
×

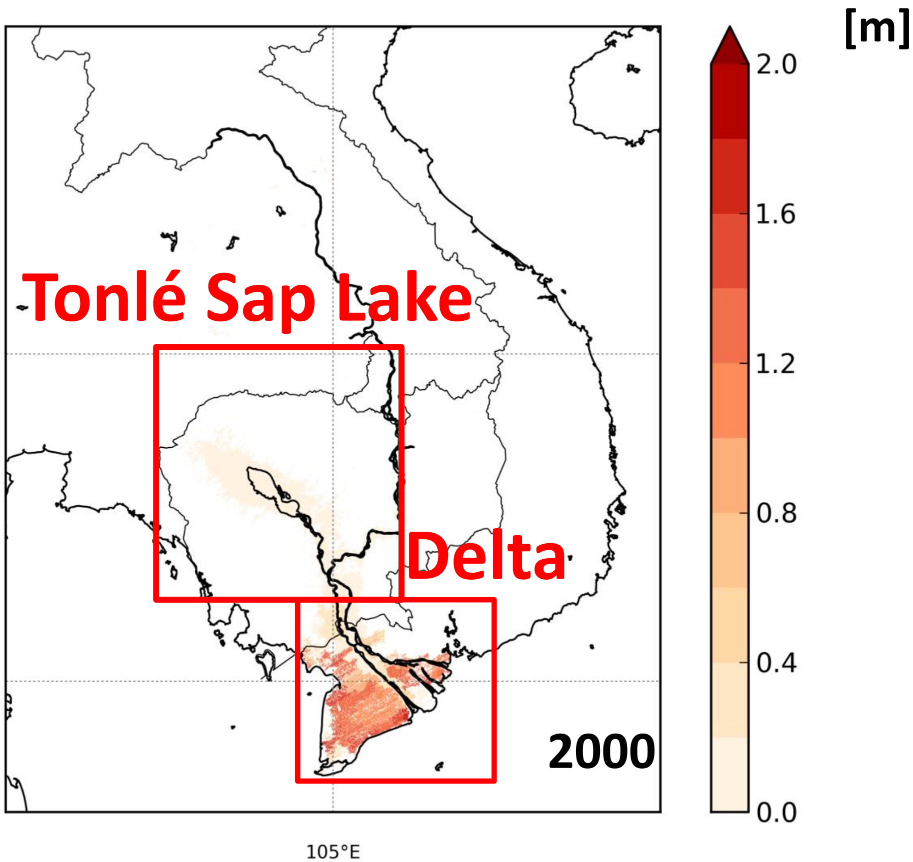
Assets [USD]



= **Flood Risk ?**

Impact to Inundation Depth



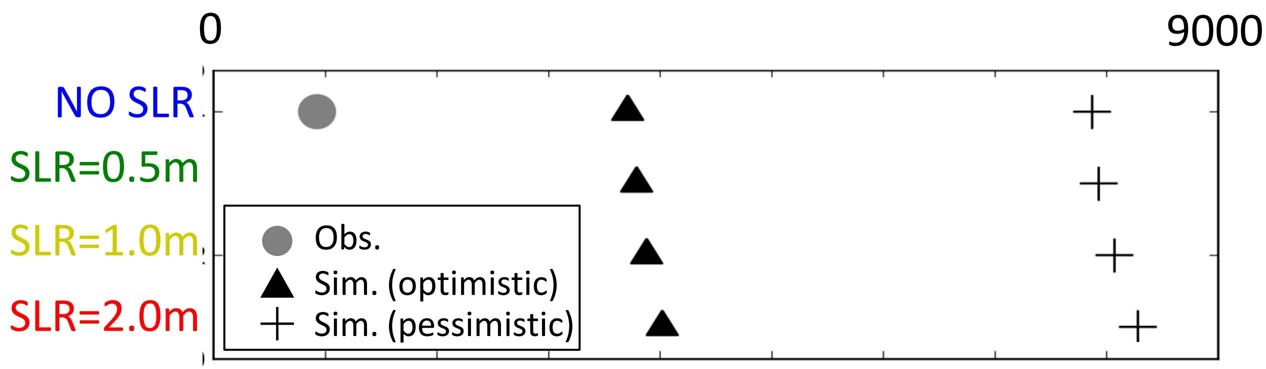


Inundation Depth
(NO SLR)

Difference of Inundation Depth
(SLR=2.0m—NO SLR)

- **The Mekong Delta** would be strongly impacted by sea level rise.
- The change of inundation depth in the Mekong Delta is more than **twice** in average in the case of SLR=2.0m.

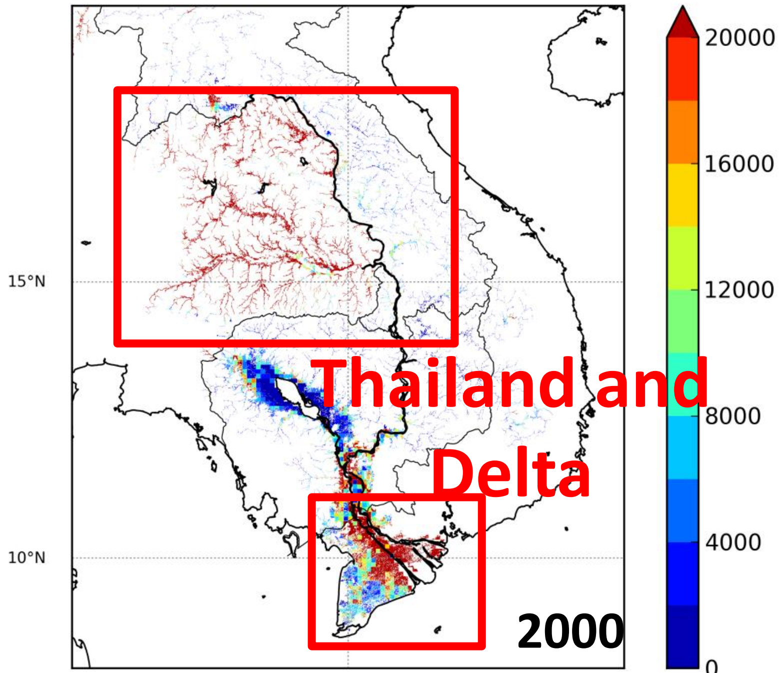
Impact to Potential Damage



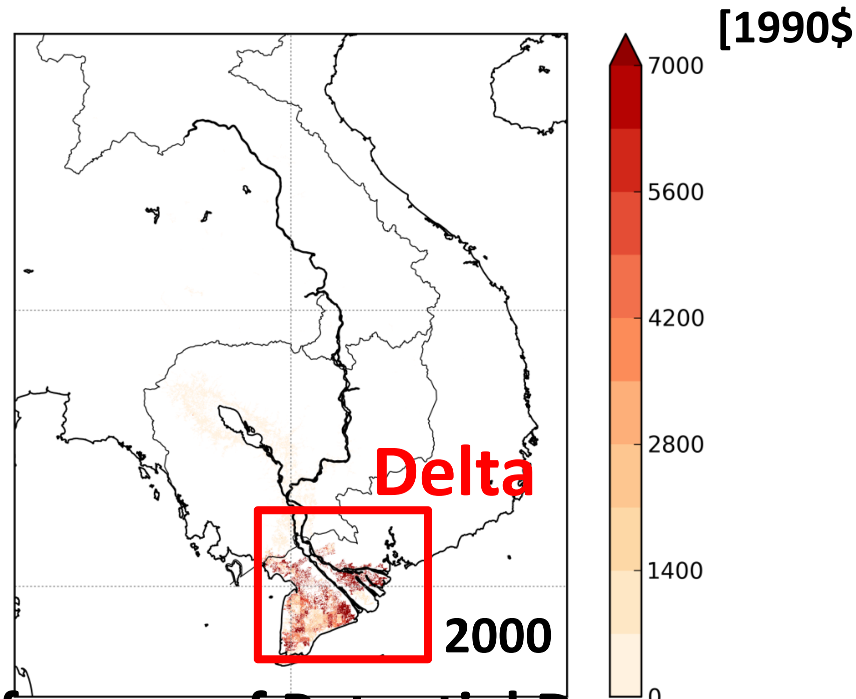
Sum of Potential Damage in the Mekong [mil 1990$]

Impact of SLR:

- 0.5m: 1-2%
- 1.0m: 2-5%
- 2.0m: 5-8%



Potential Damage
(NO SLR)

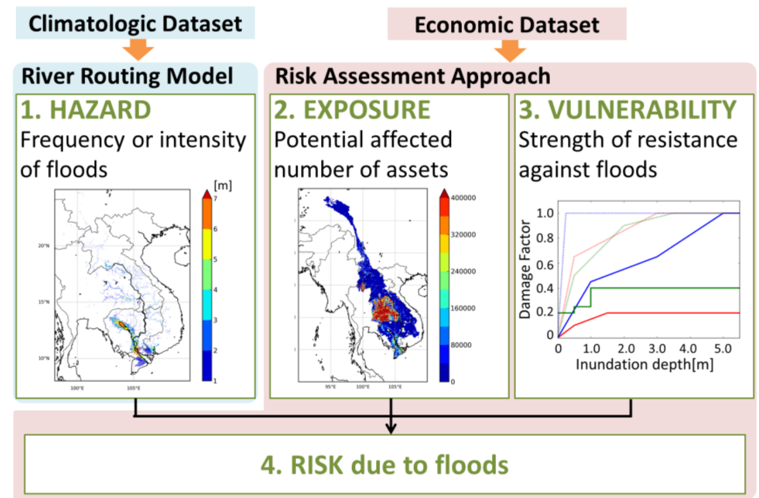


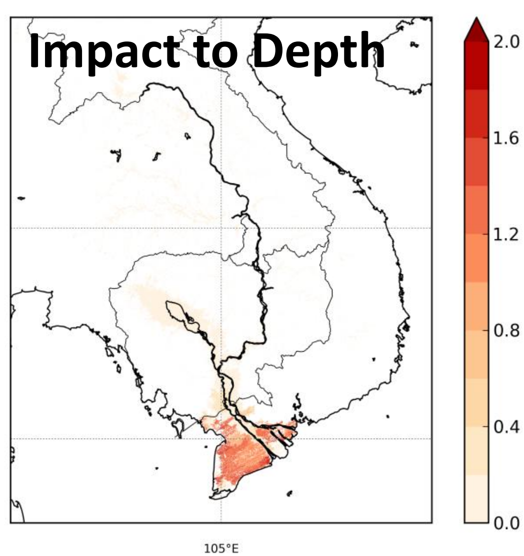
Difference of Potential Damage
(SLR=2.0m－NO SLR)

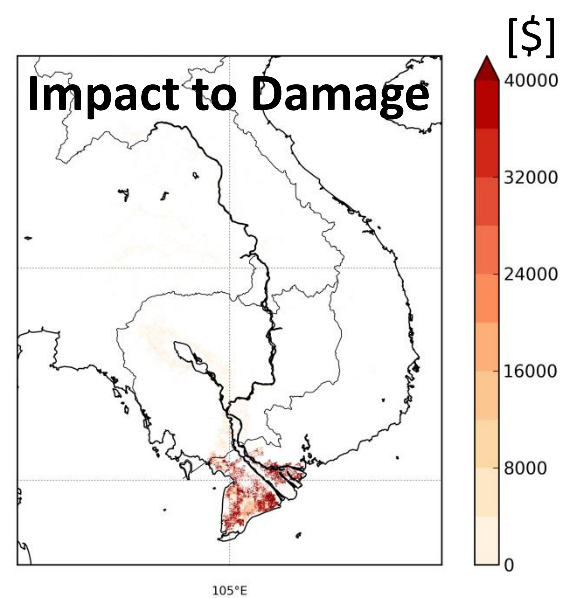
Summary

We assessed the **impact of sea level rise to extreme floods** in the Mekong Basin combining **river routing model** and **risk assessment approach**.

- The impact of sea level rise is highest in **the Mekong Delta** for both of inundation depth and potential damage.
- Inundation depth would be **more than twice** in the Mekong Delta with SLR=2.0m.







nature climate change

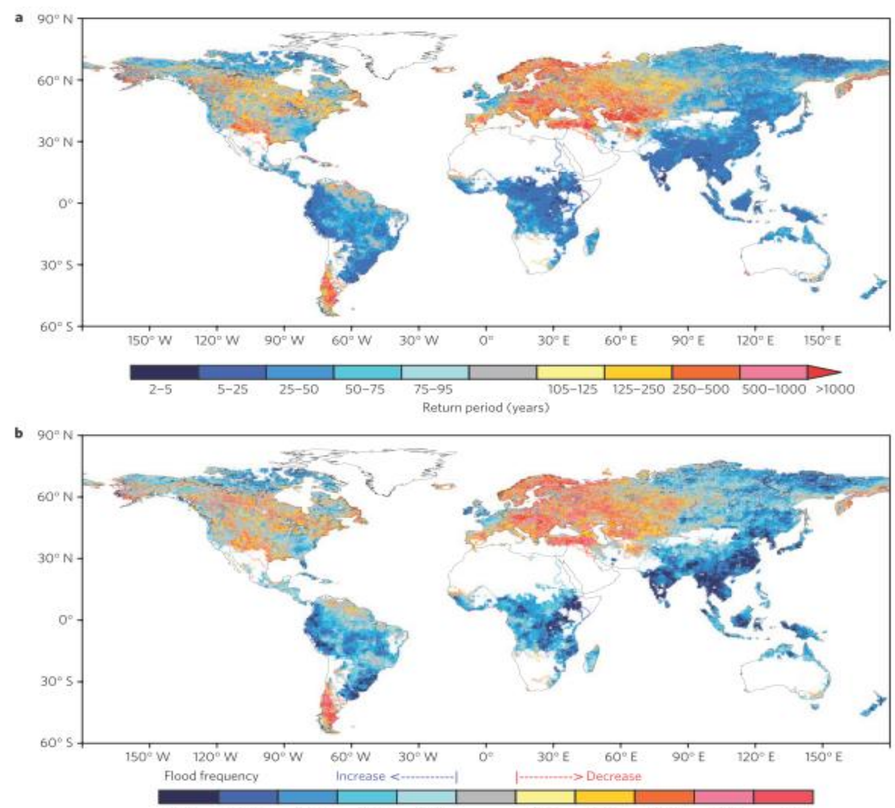
LETTERS

PUBLISHED ONLINE: 9 JUNE 2013 | DOI: 10.1038/NCLIMATE1911

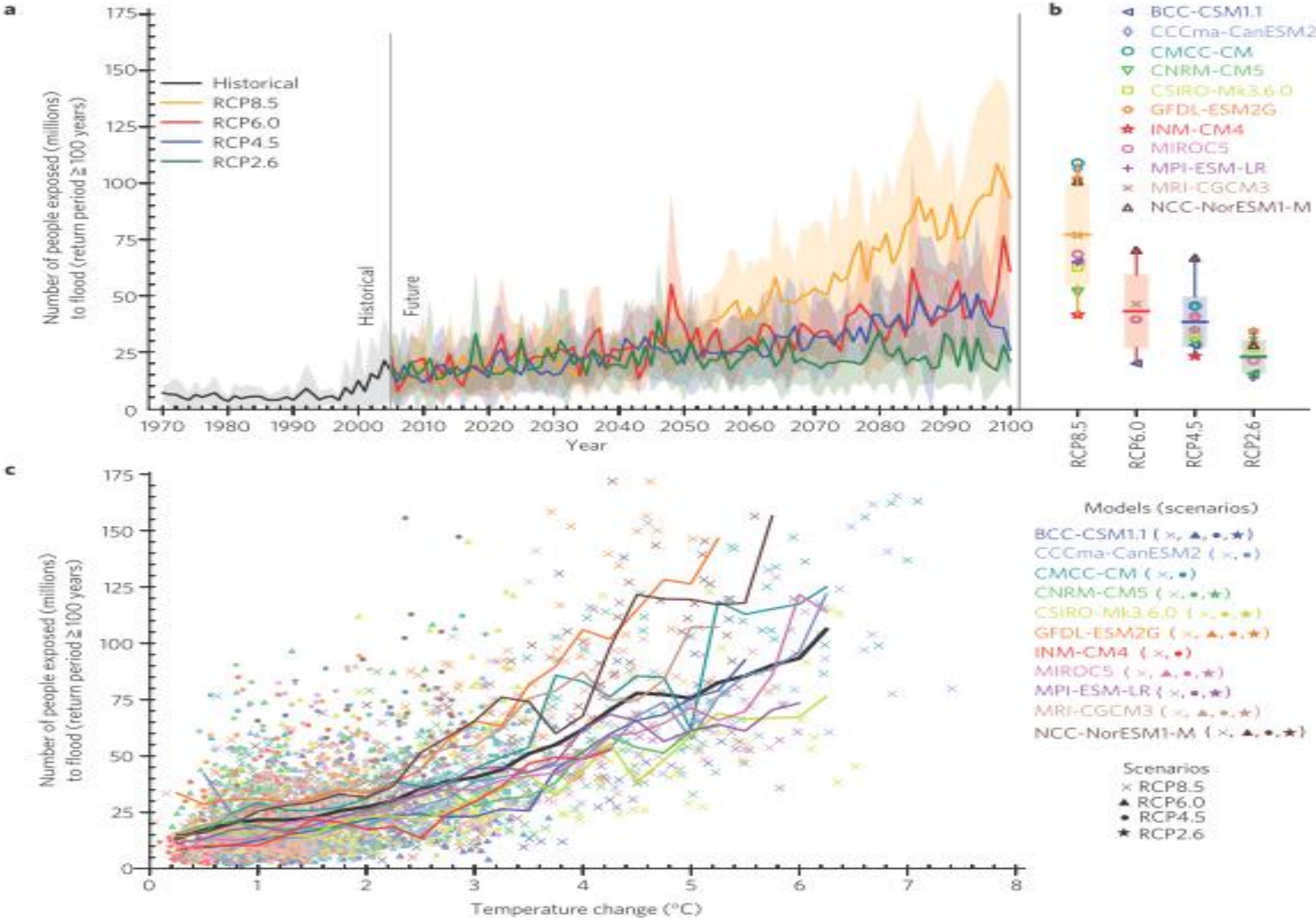
Global flood risk under climate change

Yukiko Hirabayashi[1]*, Roobavannan Mahendran[1], Sujan Koirala[1], Lisako Konoshima[1], Dai Yamazaki[2], Satoshi Watanabe[1], Hyungjun Kim[3] and Shinjiro Kanae[4]*

A warmer climate would increase the risk of floods[1]. So far, only a few studies[2,3] have projected changes in floods on a global scale. None of these studies relied on multiple climate models. A few global studies[4,5] have started to estimate the exposure to flooding (population in potential inundation areas) as a proxy of risk, but none of them has estimated it in a warmer future climate. Here we present global flood risk for the end of this century based on the outputs of 11 climate models. A state-of-the-art global river routing model with an inundation scheme[6] was employed to compute river discharge and inundation area. An ensemble of projections under a new high-concentration scenario[7] demonstrates a large increase in flood frequency in Southeast Asia, Peninsular India, eastern Africa and the northern half of the Andes, with small uncertainty in the direction of change. In certain areas of the world, however, flood frequency is projected to decrease. Another larger ensemble of projections under four new concentration scenarios[7] reveals that the global exposure to floods would increase depending on the degree of warming, but interannual variability of the exposure may imply the necessity of adaptation before significant warming.



Projected change in flood frequency. a, Multi-model median return period (years) in 21C for 20C 100-year discharge. b, Model consistency.



Global flood exposure for the 20C 100-year flood or above, in millions.

a, The ensemble means for each scenario. The shading denotes the ± 1 s.d.

b, The max, min, mean and individual values among AOGCMs averaged over 21C.

c, Global flood exposure and change in global mean surface air temperature.

Summary: CaMa-Flood applications

Explicit simulation of inundated area and flood depth is now possible by global/regional hydrodynamic model (CaMa-Flood).

-Simulated flood depth can be downscaled up to 500 m resolution.

-By overlaying simulated flood depth onto gridded social data,
(e.g. Population, GDB, Land Use), we can estimate flood risk.

-Limitation: Estimation of damage (in $, €) requires some assumptions.

CaMa-Flood is open source program. Any research collaborations are welcomed !

User's community of CaMa-Flood global hydrodynamic model