Rainfall-Runoff-Inundation Prediction at the River Basin Scale

Development of RRI Model and Its Application to Climate Change Impact Assessment and Real-time Flood Inundation Predictions

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2) International Centre for Water Hazard and Risk Management (ICHARM)

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Summary of Rainfall-Runoff-Inundation (RRI) Model

- Since 2010 at ICHARM, Public Works Research Institute, Japan

- Concept: rainfall-runoff and inundation simulation at the river basin scale

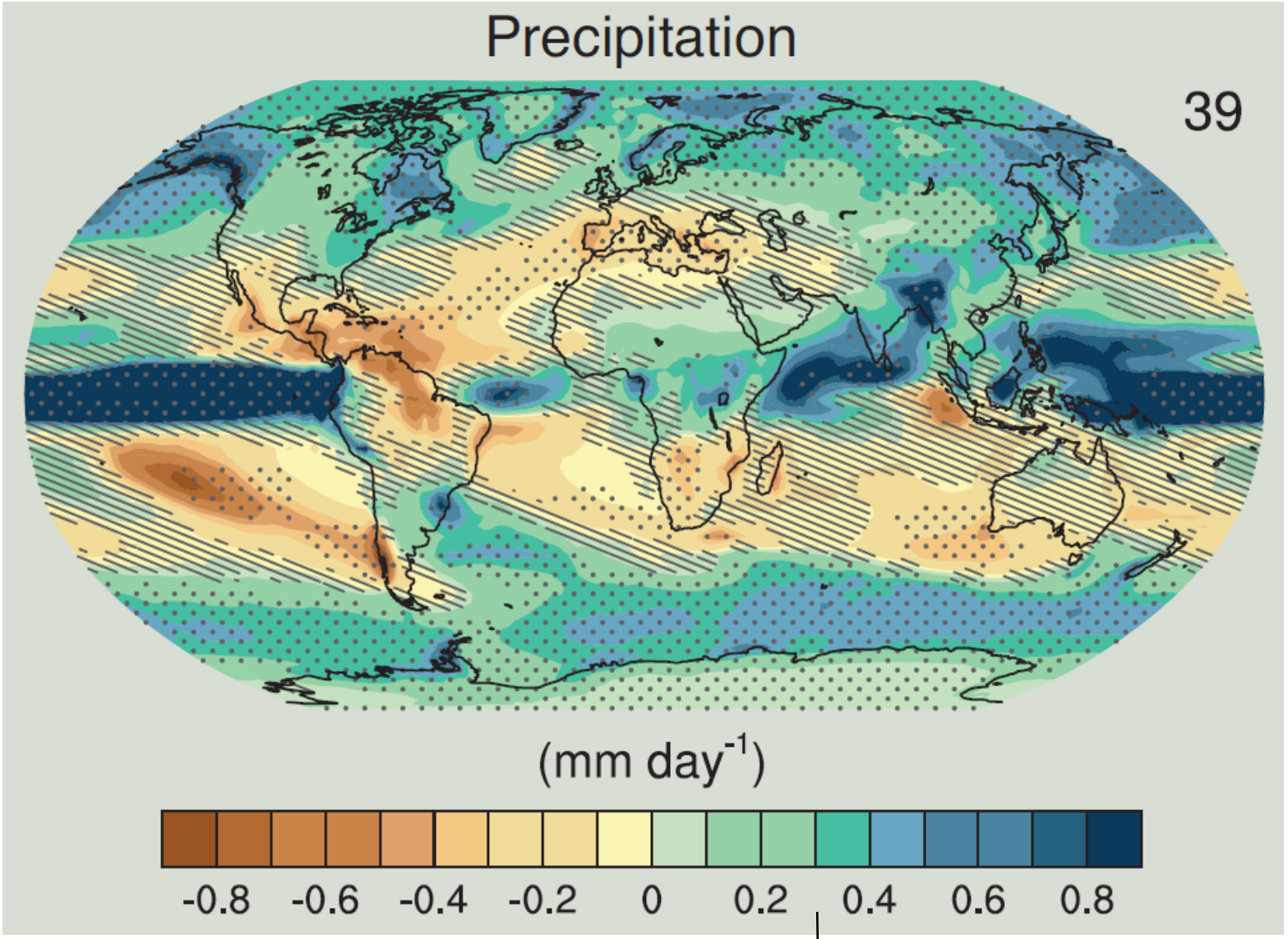
- Target: real time inundation predictions and risk assessment

- As of 2016, the package including Fortran source codes, English manual, GUI (Model builder + Viewer) are available through ICHARM webpage (http://www.icharm.pwri.go.jp/research/rri/rri_top.html)

- Recent advancement: GW, detail cross section, time and space accounting, coupling with WEB-DHM (mainly SiB2 component) and RRI.

- Practical applications at ICHARM: UNESCO Pakistan Project (Indus), JICA Thai Project (Chao Phraya), ADB Myanmar Project for hazard mapping (Irrawaddy)

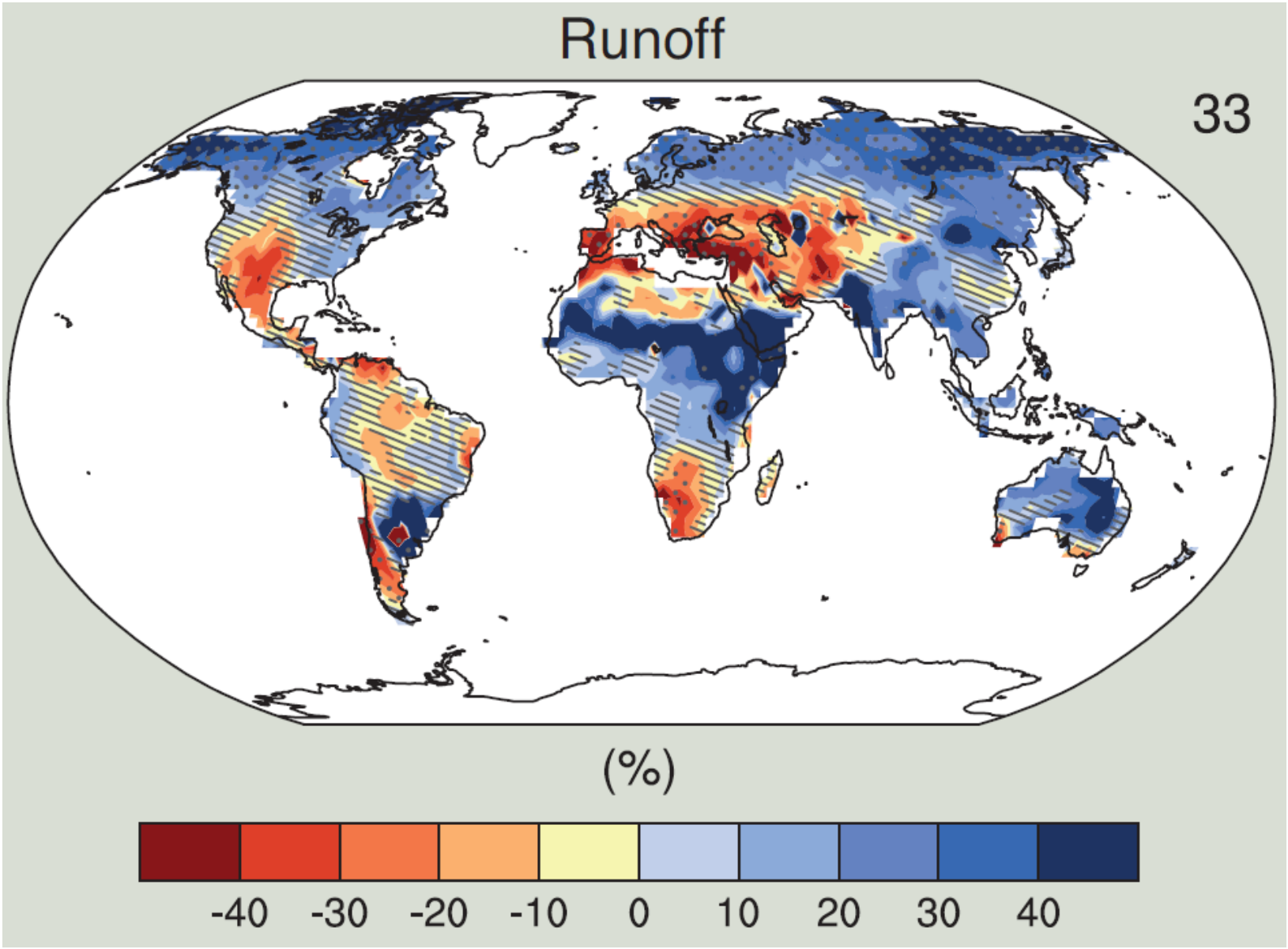
- Application for scientific studies: hydrologic sensitivity, climate change impact, effects of GW etc.



Annual Mean Change (CMIP5 : RCP8.5)
(2081-2100) – (1986-2005)

+ 100 mm/year

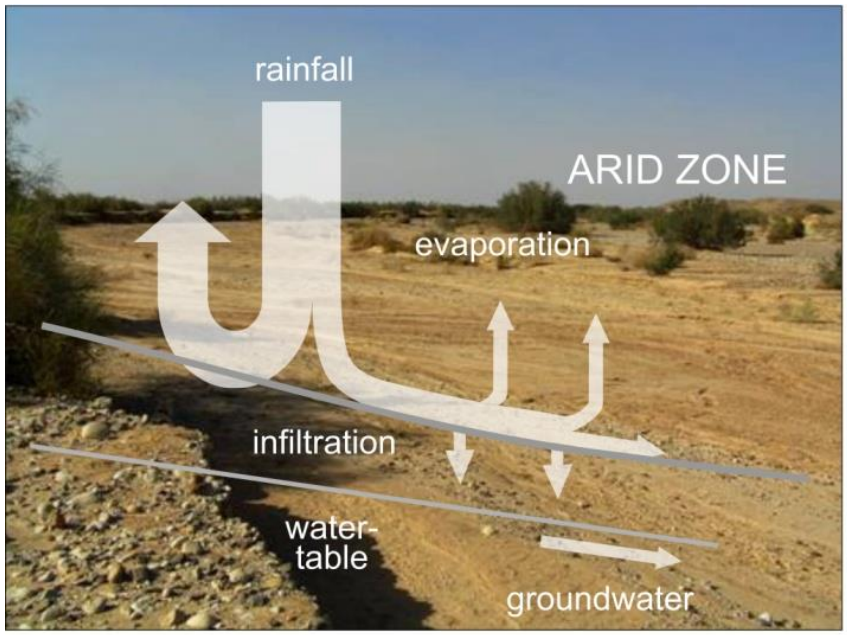
IPCC AR5 (WG1)

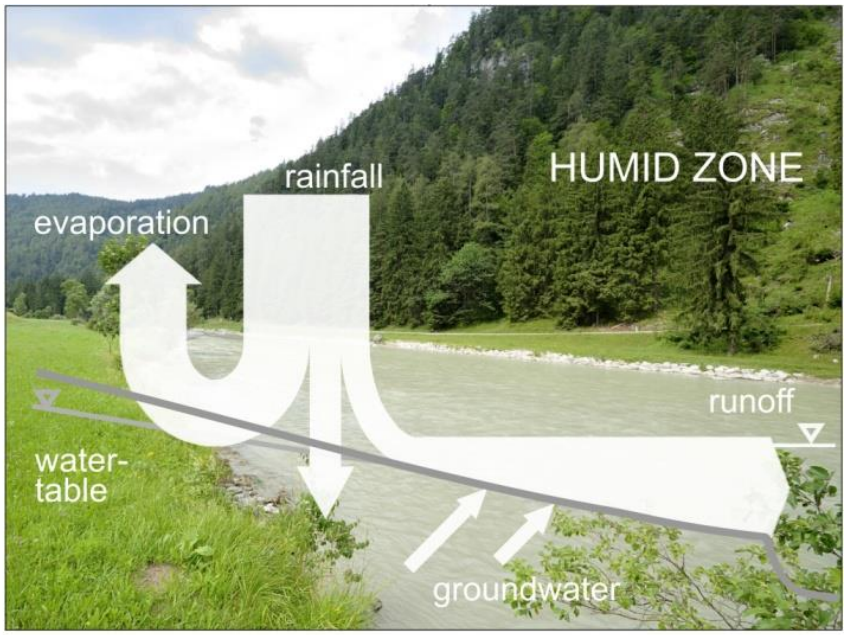


Annual Mean Change (CMIP5 : RCP8.5)
(2081-2100) – (1986-2005)

IPCC AR5 (WG1)

Hydrologic Sensitivity





How much runoff (*Q*) is expected to increase, in percentage term, with a 1% increase in rainfall (*P*)

$$\varepsilon_Q = \frac{dQ/Q}{dP/P}$$

(Schaake, 1990)

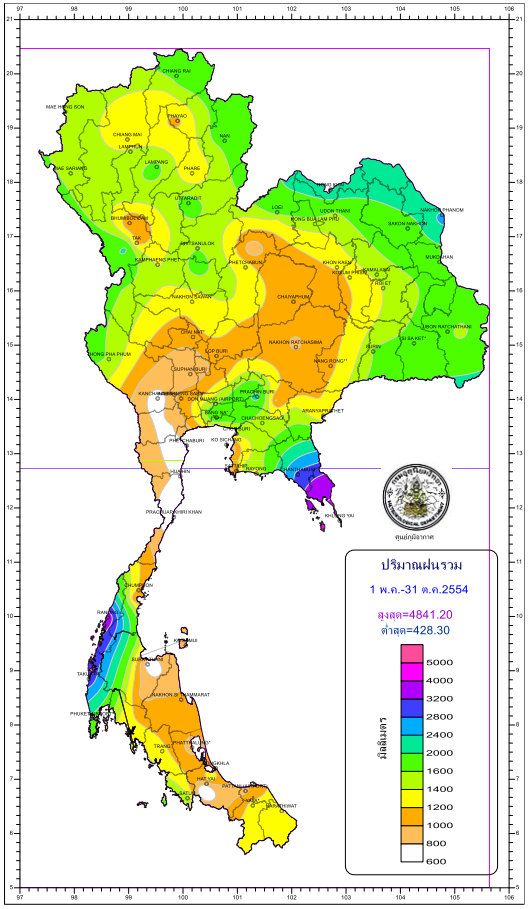
Elasticity of Flood Runoff and Inundation

How much runoff (*Q*) and inundation (ΔF) volumes are expected to increase, in percentage term, with a 1% increase in rainfall (*P*)

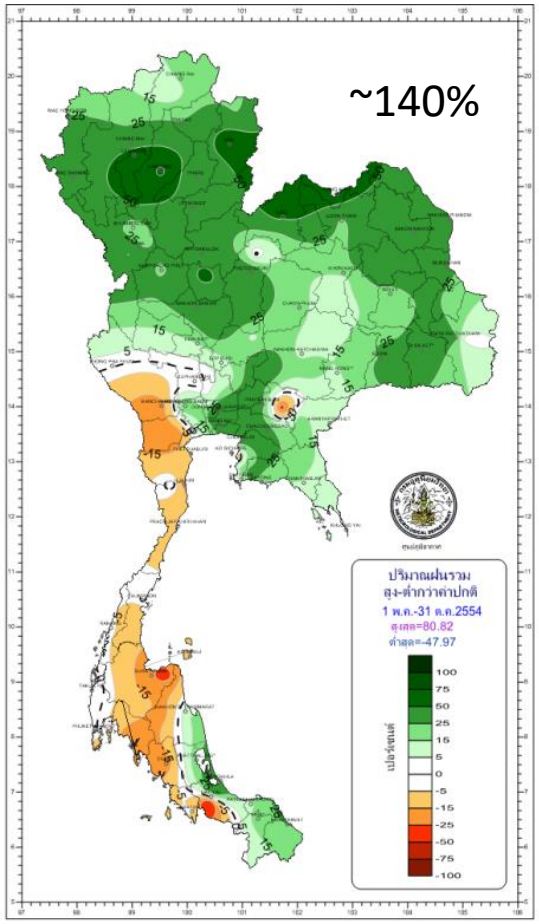
$$\varepsilon_Q = \frac{dQ/Q}{dP/P}$$ (Schaake, 1990)

$$\varepsilon_F = \frac{d\Delta F/\Delta F}{dP/P}$$ (Sayama, NHESS, 2015)

Cumulative rainfall in millimeter (May to October)



Departure of accumulative rainfall(%) (May to October)



TMD

<u>Six months rainfall in the basin</u>

in 2011 : 1400 mm

in past severe events (1995, 2006) : 1200 mm

in average years : 1000 mm

Approach

STEP1 : Rainfall-Runoff-Inundation simulation with observed rainfall

2 km resolution, 52 years : 1960-2011

⇒ Estimate rainfall and flood inundation volumes

⇒ Estimate elastisity of flood runoff and inundation to rainfall

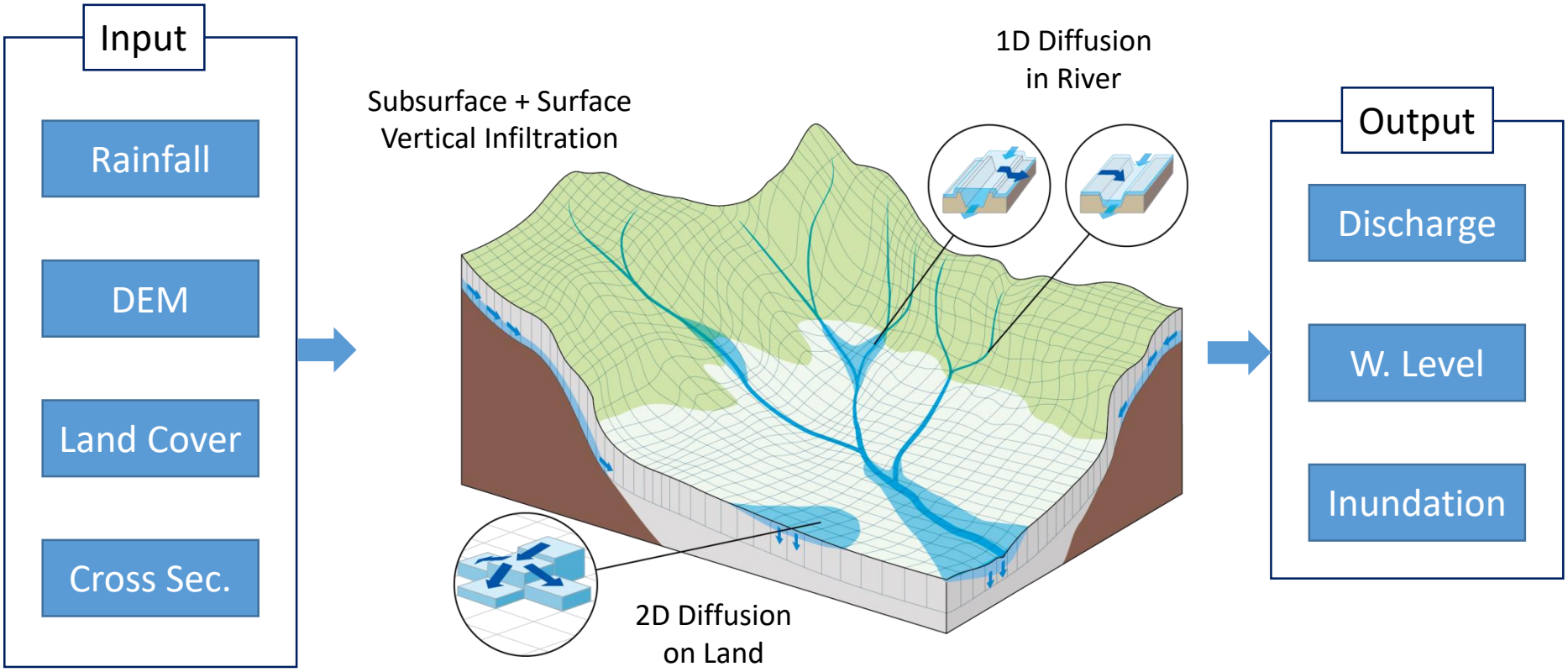
STEP2: RRI simulation with MRI-AGCM projection

AGCM3.2S (20 km), AGCM3.2H (60 km) – RCP 8.5 scenario

⇒ Present climate (1979-2003) : 1 cases (3.2S)

⇒ Future climate (2075-2099) : 4 cases (3.2S, 3.2H: 3 cases)

Rainfall-Runoff-Inundation Model

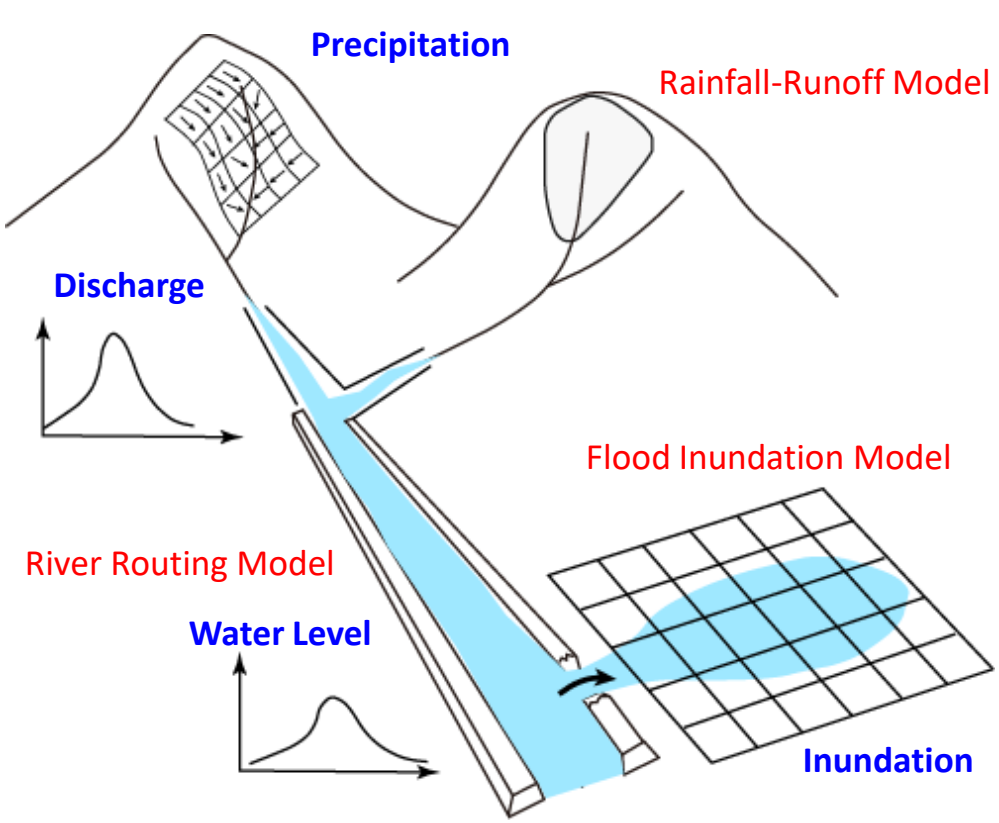


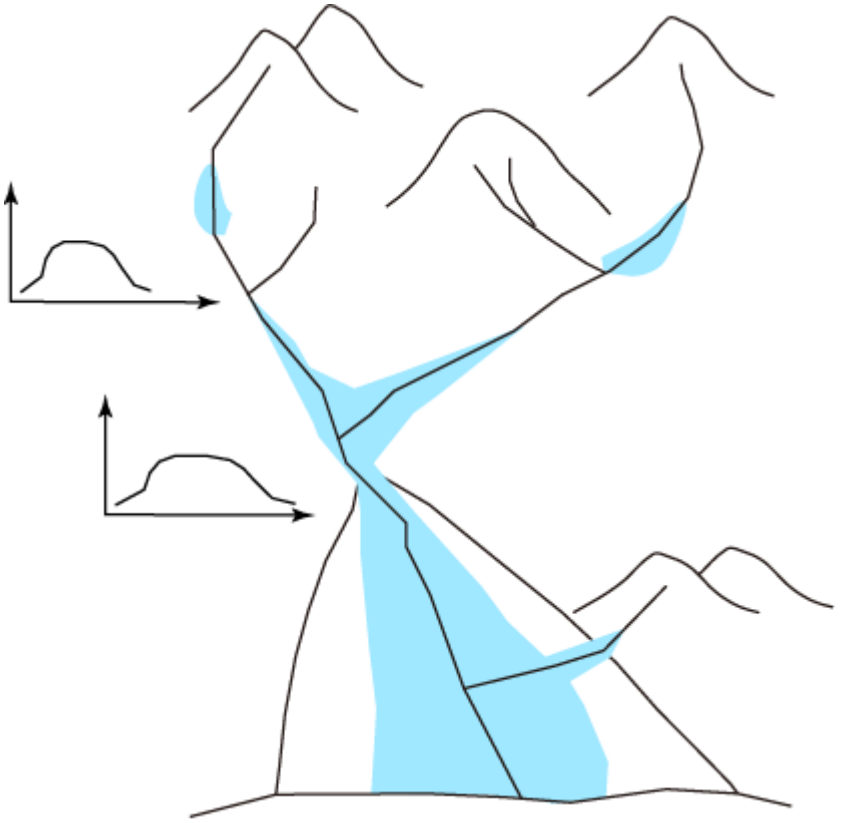
- Two-dimensional model capable of simulating rainfall-runoff and flood inundation simultaneously
- The model deals with slopes and river channels separately
- At a grid cell in which a river channel is located, the model assumes that both slope and river are positioned within the same grid cell

Sayama, T. et al.: Rainfall-Runoff-Inundation Analysis of Pakistan Flood 2010 at the Kabul River Basin, *Hydrological Sciences Journal*, 57(2), pp. 298-312, 2012.

Three kinds of models for flood predictions

Rainfall-Runoff-Inundation

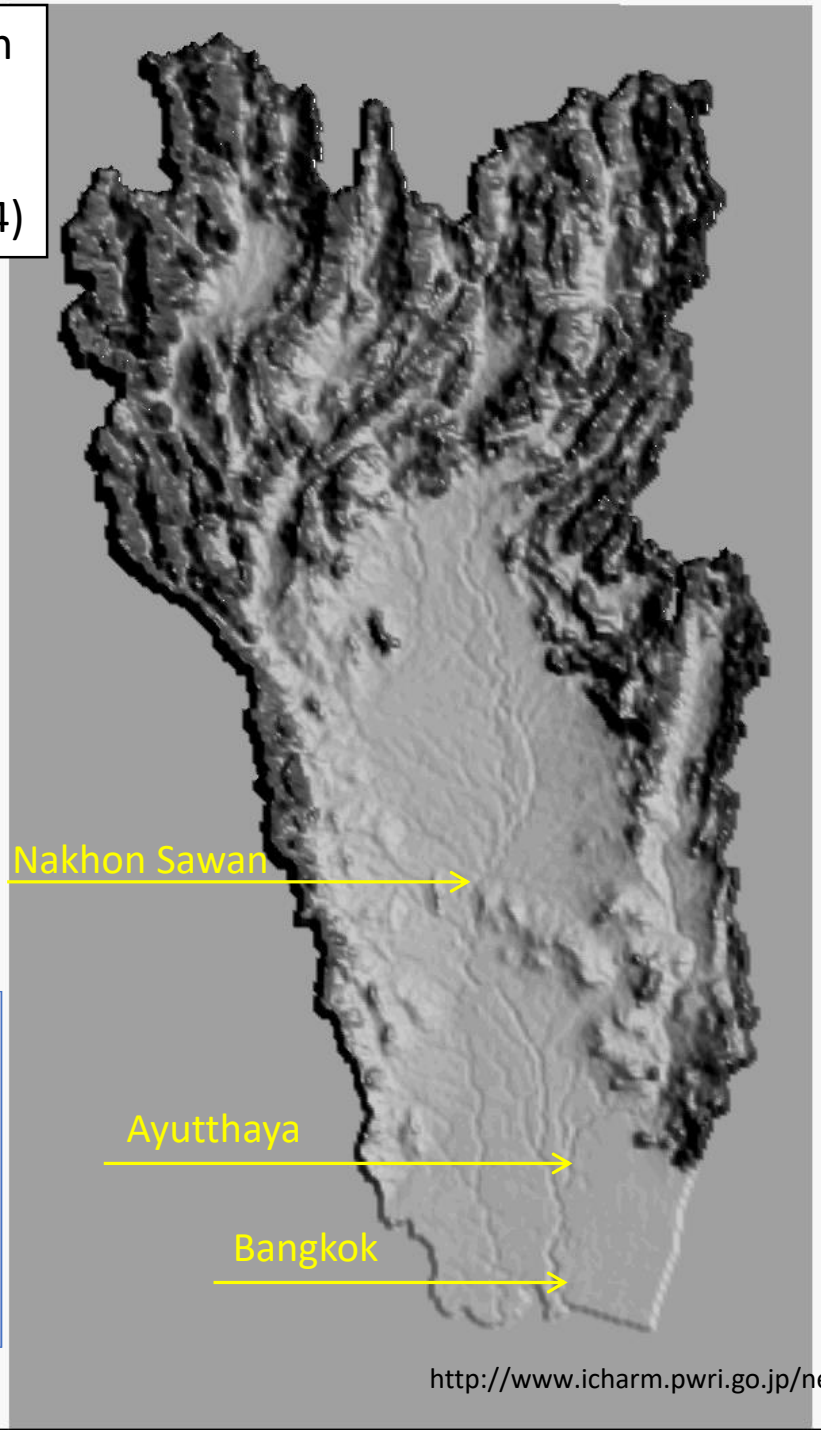




Motivations of using Rainfall-Runoff-Inundation Model

1. Rainfall-runoff and inundation cannot be separated with large inundation
2. Kinematic wave is not suitable for flat topography
3. Important for representing inundation process for better river predictions
4. Inundation itself may be of interest in flood forecasting or risk assessment

Rainfall-Runoff-Inundation Prediction of Thailand Flood 2011 (conducted on 2011/10/14)



W. Depth
5
4.5
4
3.5
3
2.5
2
1.5
1

$T = 1$

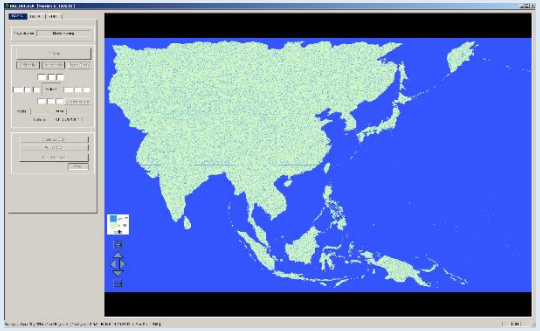
1 : July 1
31 : Aug 1
62 : Sep 1
92 : Oct 1
123 : Nov 1
152 : Nov 30

Simulation Domain : 163,293 km^2
Grid Size : 60sec (1776 x 1884 m)
Simulation Period :
2011/07/01 – 2011/11/30
Input Rainfall:
✓2011/07/01 – 2011/10/14
3B42RT (Satellite Based Rainfall)
(Every 3hours, Spatial Resolution: 0.25 deg)
✓2011/10/14 – 2011/10/21
JMA- GSM Weekly Weather Forecasting
（Forecasting Lead Time: 8 days, Update every 12 hours）
✓2011/11/15 – 2011/11/30
(Previous year's 3B42RT rainfall in the same period)

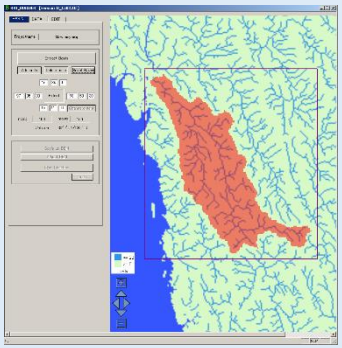
http://www.icharm.pwri.go.jp/news/news_j/111024_thai_flood_j.html

Model Building with RRI-GUI

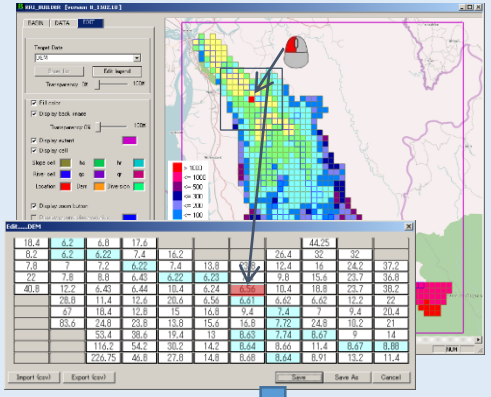
STEP1: HydroSHEDS data



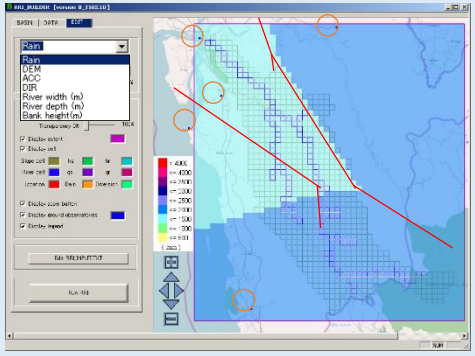
STEP2: Catchment delineation



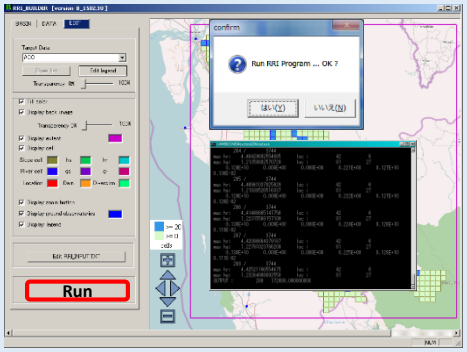
STEP3: Modifying topographic data (optional)



STEP4: Reading rainfall data (gauged / satellite)

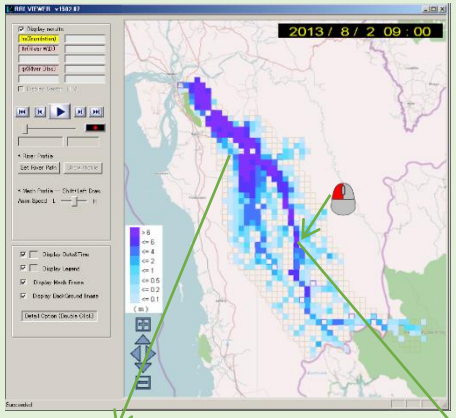


STEP5: Running RRI Model

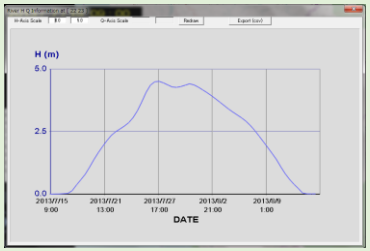


STEP6: Visualizing simulation results

Animation of flood inundation depths

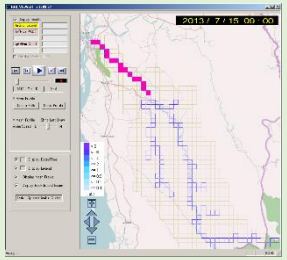


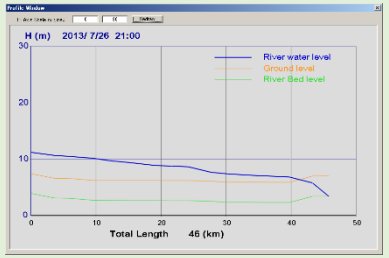
Time-series of flood inundation depths



Hydrograph of river discharge and water level

Longitudinal flood water level





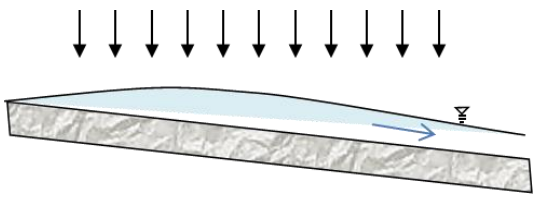
Three Conditions of Surface / Subsurface Flow

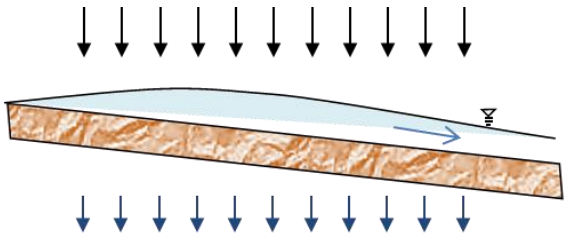
Surface / subsurface flow conditions

(A) Only overland flow (no infiltration loss, no subsurface flow)

(B) Vertical infiltration + Infiltration excess overland flow

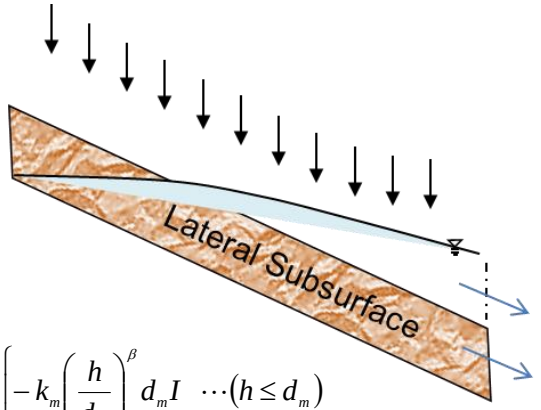
(C) Saturated subsurface + Saturation excess overland flow





Infiltration : Green Ampt Model

$$f = k_v \left[1 + \frac{(\phi - \theta_i) S_f}{F} \right]$$

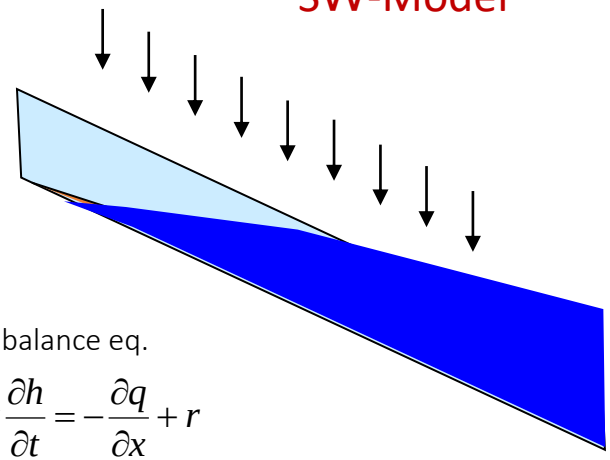


$$q = \begin{cases} -k_m \left(\dfrac{h}{d_m} \right)^{\beta} d_m I & \cdots (h \le d_m) \\ -\left[k_m d_m + k_a (h - d_m) \right] I & \cdots (d_m < h \le d_a) \\ -\left[k_m d_m + k_a (h - d_m) \right] I + \dfrac{\sqrt{I}}{n} (h - d_a)^{\frac{5}{3}} & \cdots (d_a < h) \end{cases}$$

(Tachikawa et al., JSCE, 2004)

Groundwater Modeling in the RRI

SW-Model



Mass balance eq.

$$\gamma \frac{\partial h}{\partial t} = -\frac{\partial q}{\partial x} + r$$

Darcy's low

$$q = -kh\left(\frac{\partial h}{\partial x}\cos i + \sin i\right)$$

Boussinesq eq.

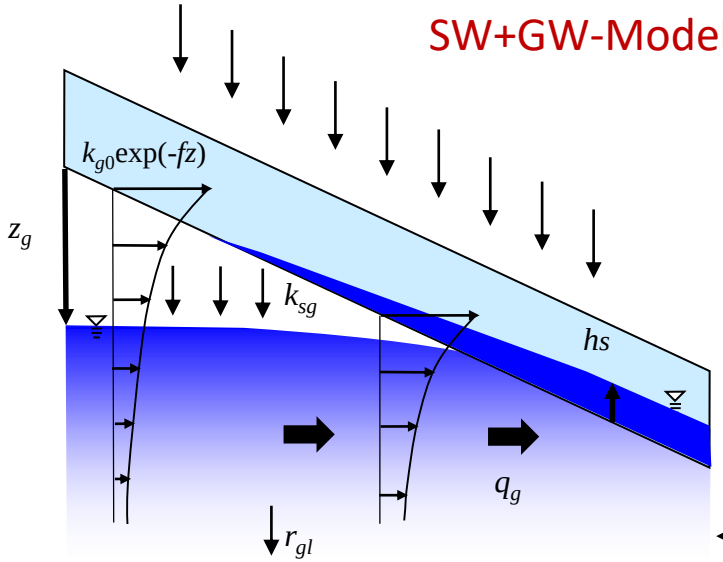
$$\frac{\partial h}{\partial t} = \frac{k}{\gamma}\left[\cos i \frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right) + \sin i \frac{\partial h}{\partial x}\right] + \frac{r}{\gamma}$$

Stage-discharge relationship for unsat., sat. subsurface and surface

$$q = \begin{cases} -k_m\left(\dfrac{h}{d_m}\right)^{\beta} d_m I & \cdots (h \le d_m) \\ -\left[k_m d_m + k_a(h - d_m)\right] I & \cdots (d_m < h \le d_a) \\ -\left[k_m d_m + k_a(h - d_m)\right] I + \dfrac{\sqrt{I}}{n}(h - d_a)^{\frac{5}{3}} & \cdots (d_a < h) \end{cases}$$

(Tachikawa et al., JSCE, 2004, Sayama and McDonnell, 2009)

SW+GW-Model



Cannot define the bottom…

Assumption:
Dupuit-Forchheimer
Vertically integrated,
Exponentially declined
Transmissivity (*T*)

Four parameter model

Mass balance eq. for GW

$$-\gamma_g \frac{\partial z_g}{\partial t} = -\frac{\partial q_g}{\partial x} + q_{sg}$$

Darcy's low with exp. decay T

$$q_g = -\frac{k_{g0}}{f_g} I_g \exp\left(-f_g z_g\right)$$

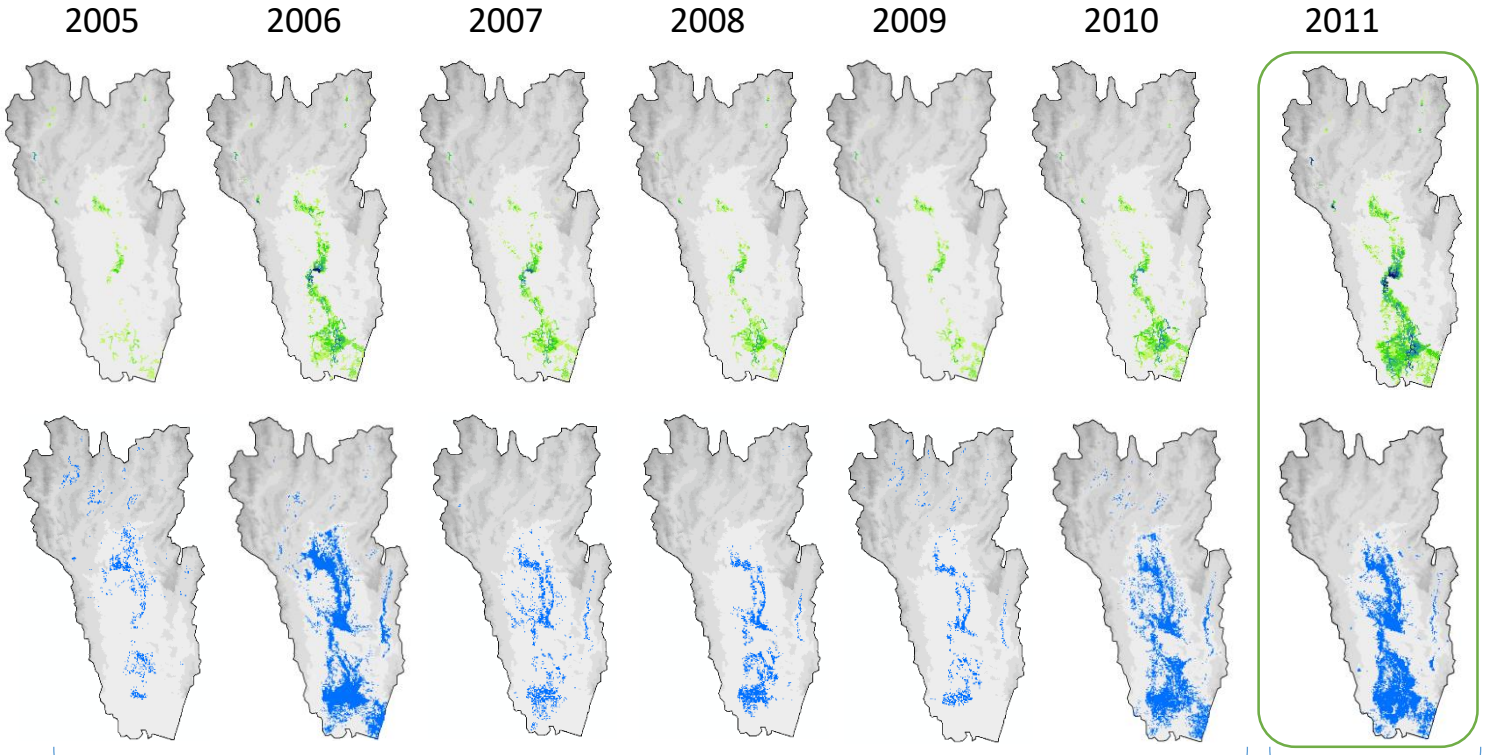
SW – GW flux interaction

$$q_{sg} = \begin{cases} k_{sg} & \cdots (z_g > 0) \\ 0 & \cdots (z_g \le 0) \end{cases}$$

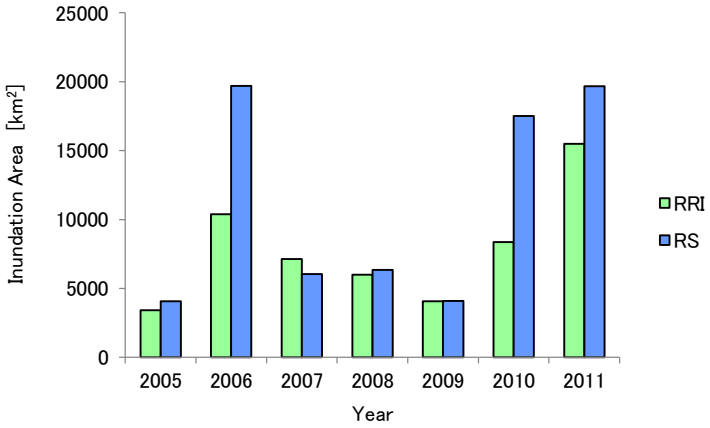
(Sayama et al., in prep.)

(Coupled to a distributed RRI model: Sayama et al., HSJ2012, NHESS2015)

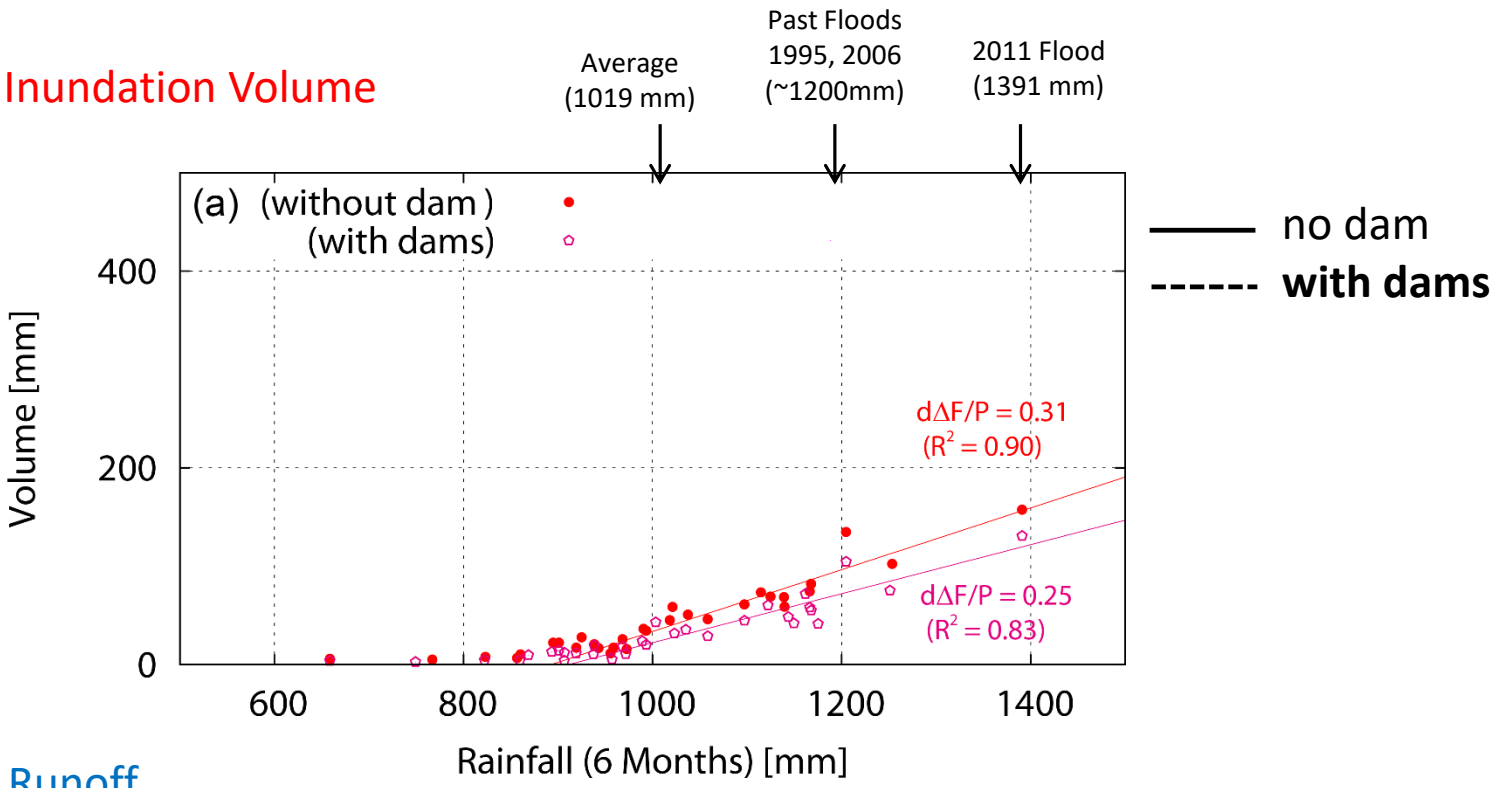
Annual Maximum Inundation Extent



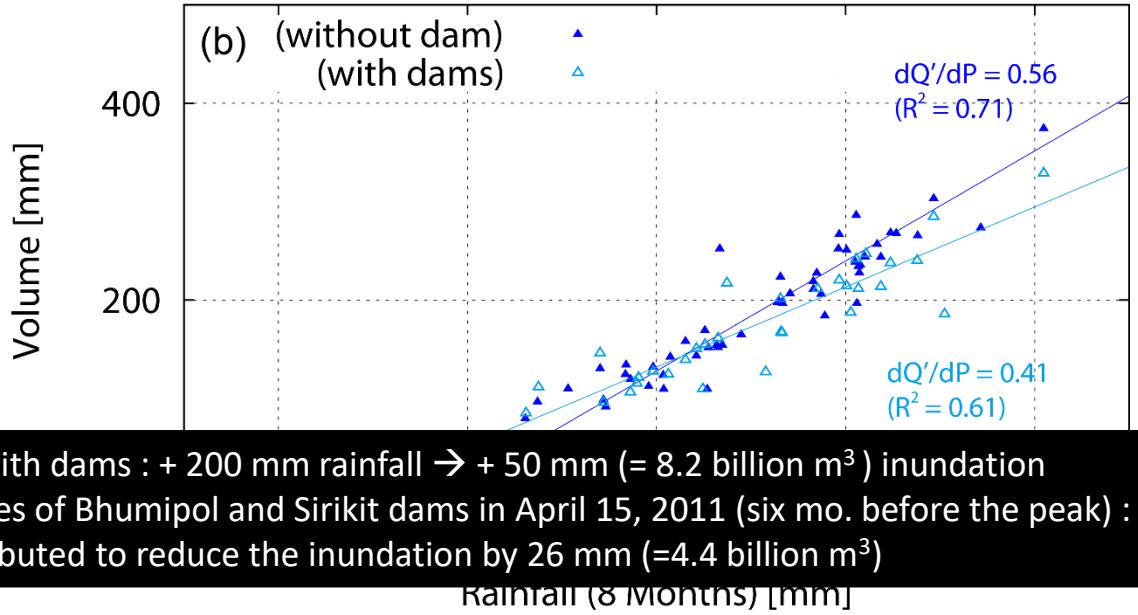
	Relative Error	FIT
2005	0.16	0.08
2006	0.47	0.31
2007	0.18	0.14
2008	0.05	0.15
2009	0.01	0.12
2010	0.52	0.25
2011	0.21	0.46
Avg.	0.23	0.21



Flood Inundation Volume



Flood Runoff



- ✓ $d\Delta F/dP$ = 0.25 with dams : + 200 mm rainfall → + 50 mm (= 8.2 billion m^3) inundation
- ✓ Available storages of Bhumipol and Sirikit dams in April 15, 2011 (six mo. before the peak) : 46 mm (=7.5 billion m^3)
- ✓ The dams contributed to reduce the inundation by 26 mm (=4.4 billion m^3)

Elasticity of Flood Runoff and Inundation

$$\varepsilon_Q = \frac{dQ/Q}{dP/P} \qquad \varepsilon_F = \frac{d\Delta F/\Delta F}{dP/P}$$

By taking 6 month rainfall = 1200 mm as the basis,

Elasticity of peak discharge at C2: ε_{pQ} = 1.5

Elasticity of total runoff : ε_Q = 2.3

Elasticity of flood inundation volume: ε_F = 4.2

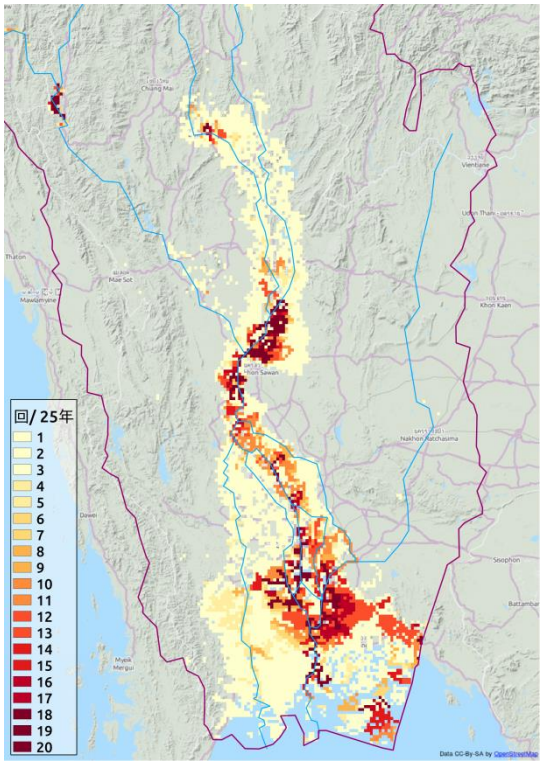
Flood inundation volume increases by 4.2 %

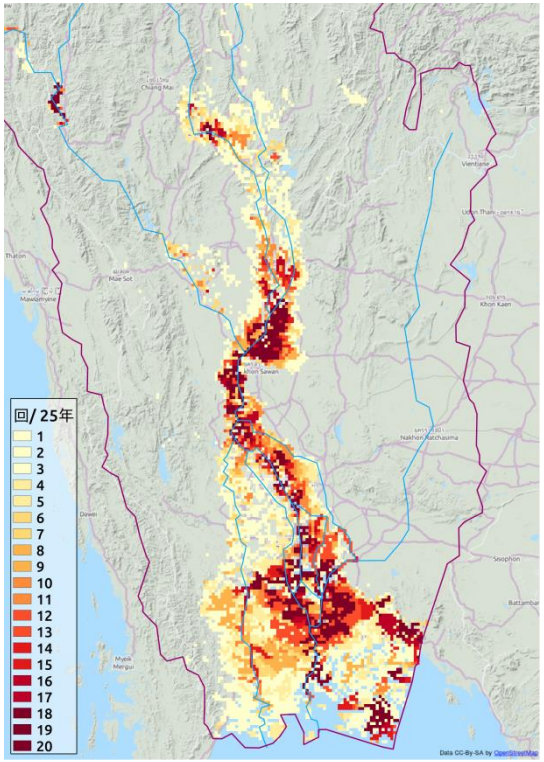
if the monsoon rainfall increases by 1%

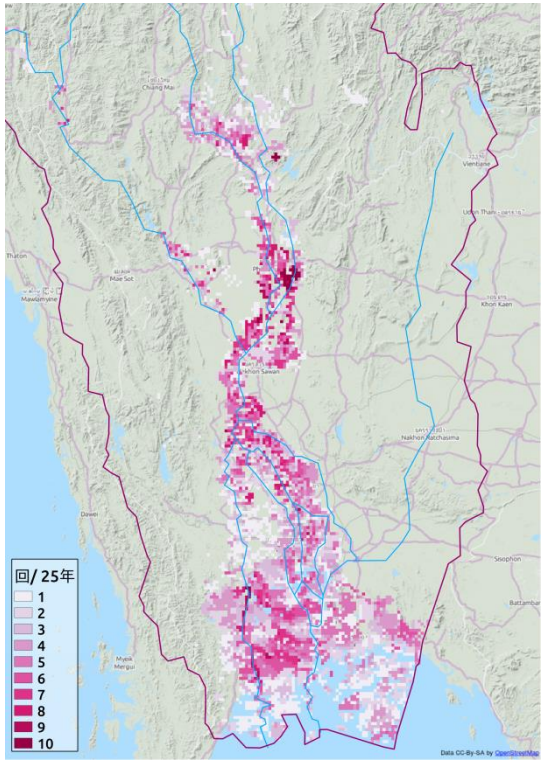
Sayama et al., Hydrologic sensitivity of flood runoff and inundation: 2011 Thailand floods in the Chao Phraya River basin, Nat. Hazard Earth Syst. Sci., 15, pp. 1 – 14, doi:10.5194/nhess-15-1-2015, 2015

Impact Assessment based on AGCM : Inundation Extent and Frequency

Present (1979-2003) **Future (2075-2099)** **Future - Present**





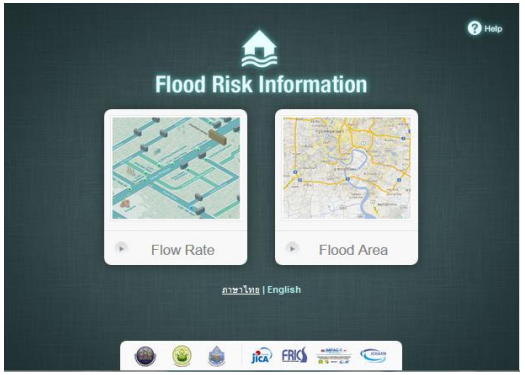


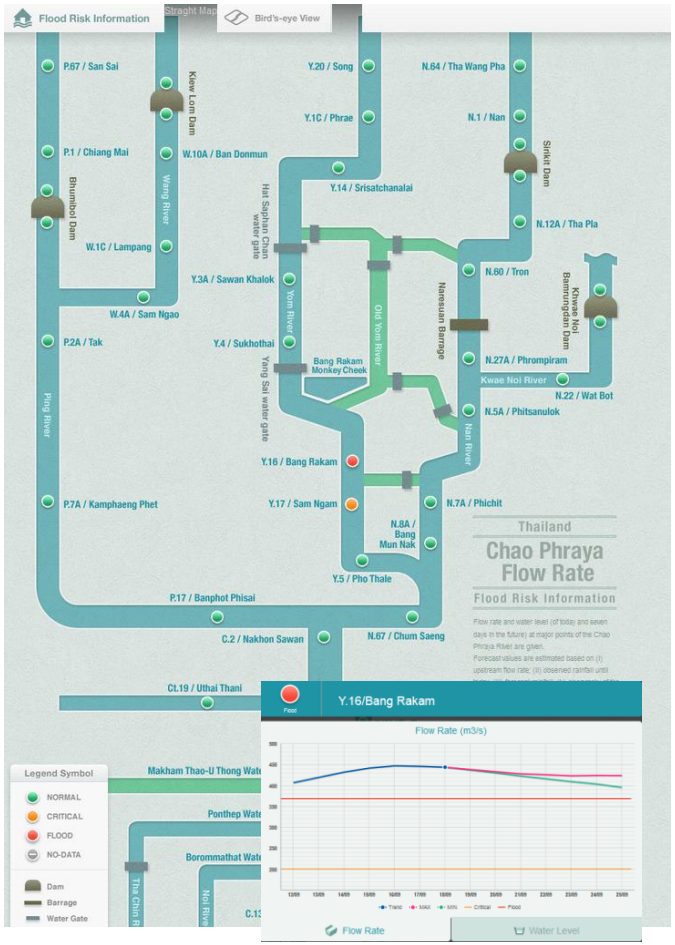
Inundation extent and frequency (times / 25 years)

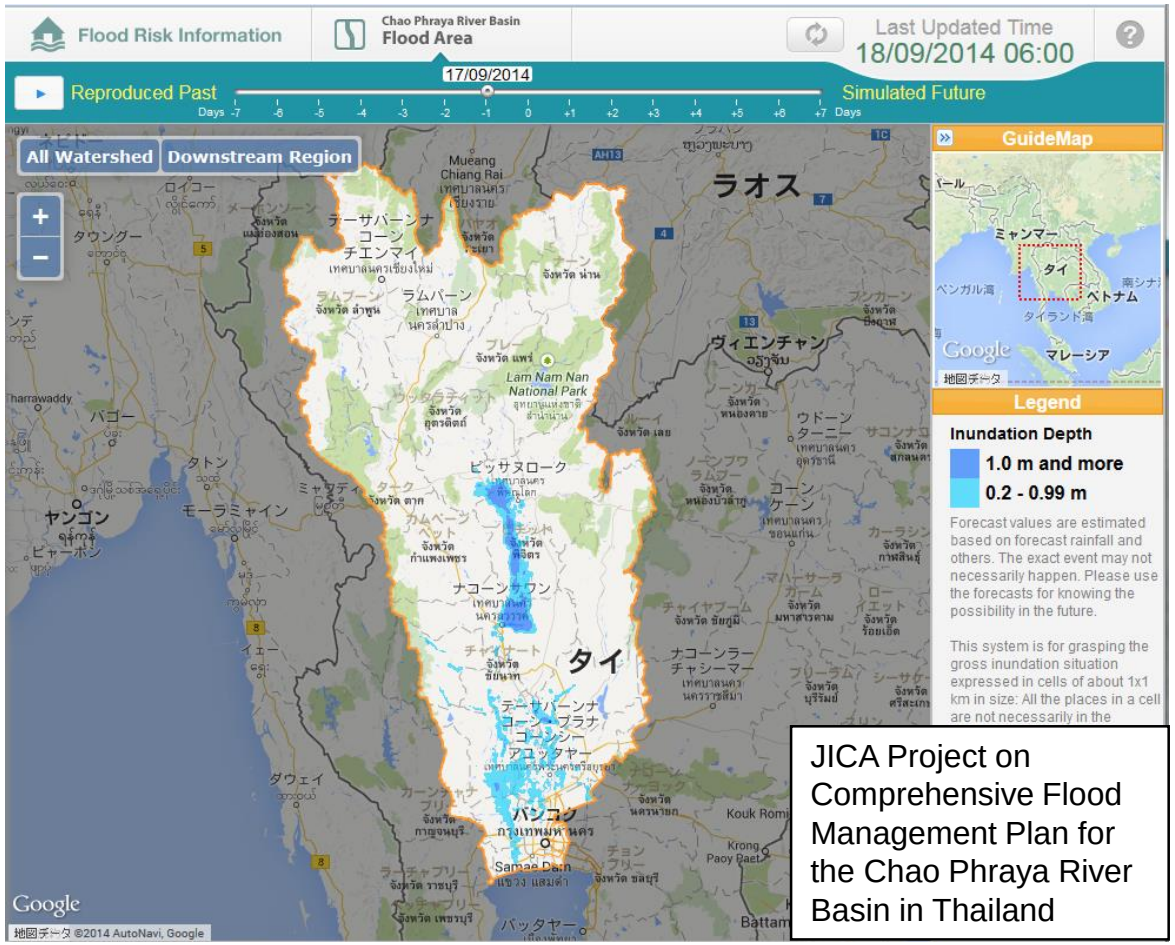
Increase in inundation frequency
(e.g. : +3 ~ 5 times / 25 years in NE Bangkok)
Inundation areas will not change significantly

Real-time flood runoff and inundation forecasting system
for the Chao Phraya River Basin based on RRI Model
(developed by JICA/FRICS and operated under RID, Thailand)

http://floodinfo.rid.go.th/index_en.html

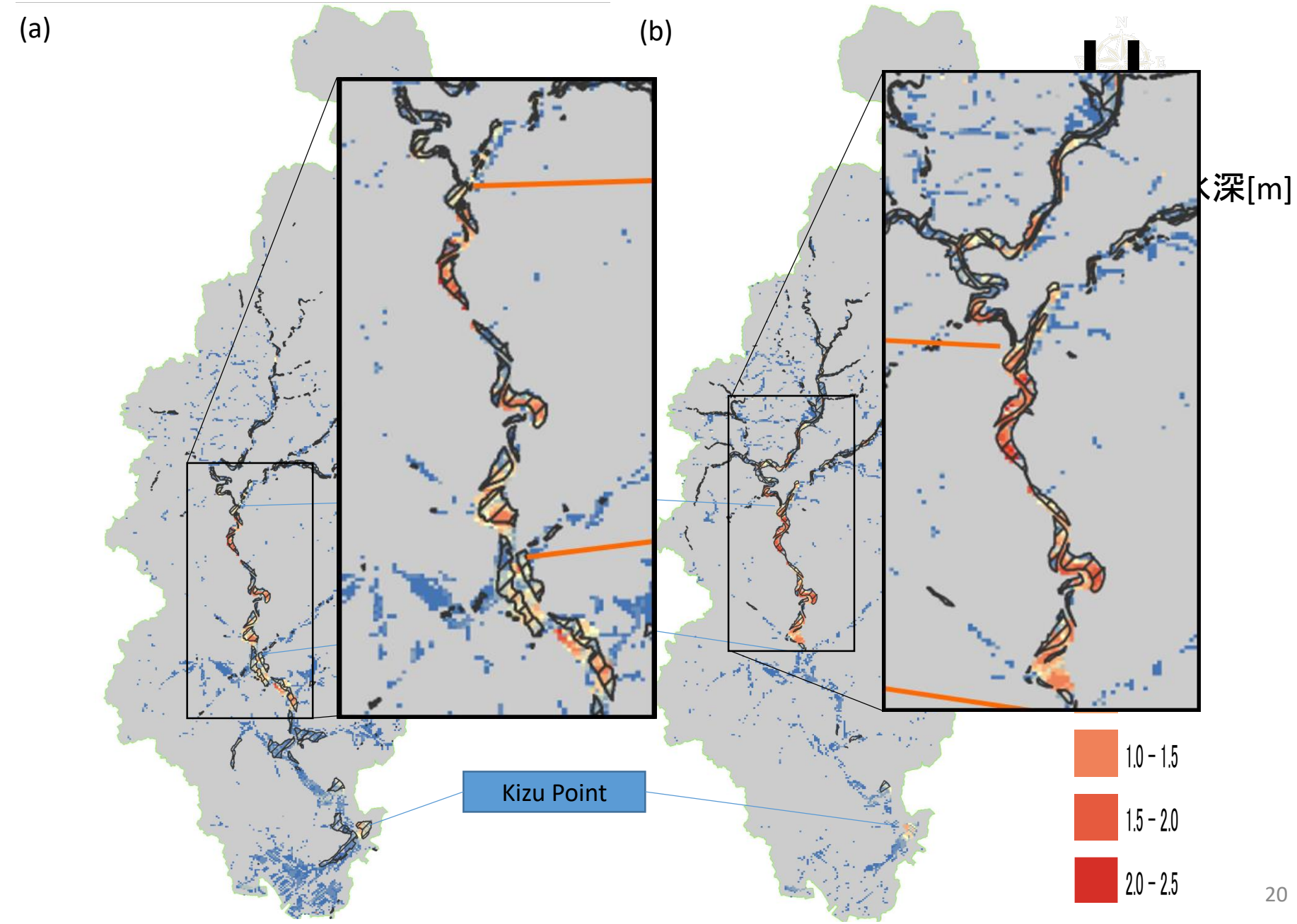






JICA Project on Comprehensive Flood Management Plan for the Chao Phraya River Basin in Thailand

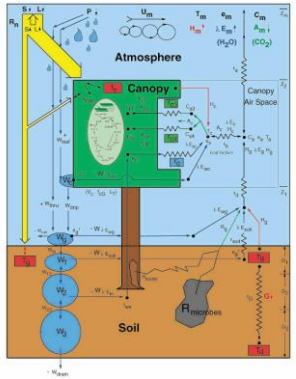
Application to a Japanese River basin (Chikusa River: 777.6 km^2)



(a) 2004 Flood Event

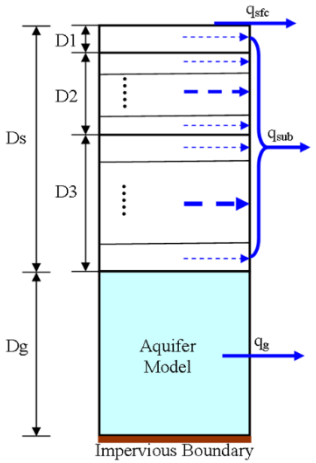
(b) 2009 Flood Event

Coupling Hydro-Sib-RRI with RRI Model

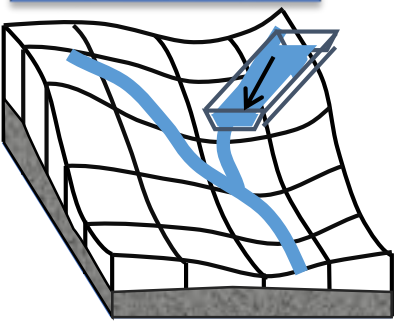


Energy and Water flux Balance (SiB2)

Vertical Soil moisture Profile



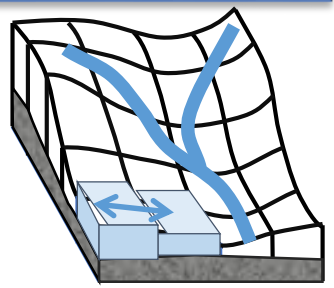
River Routing



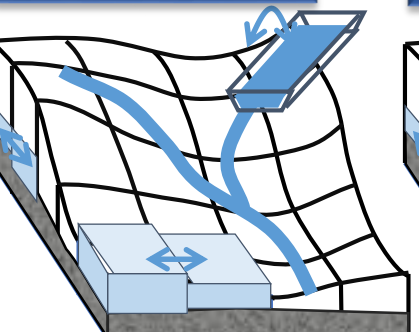
River flow - 1D Diffusion wave

Lateral flow-2D Diffusion wave

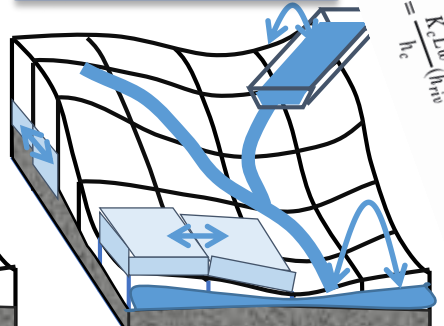
Surface flow



Slope-River Interaction

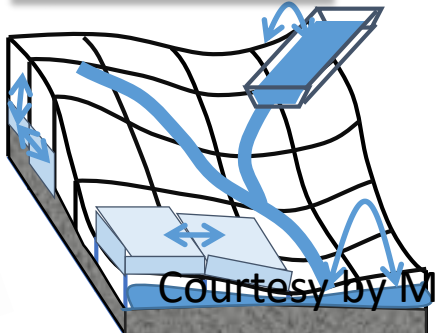


GW-River Interaction

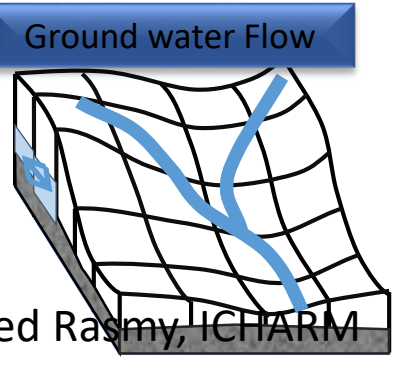


$$Q_{MF} = \frac{K_c L w}{h_c}(h_{riv} - h) = c_{riv}(h_{riv} - h) \quad (1)$$

GW-Soil Moisture Interaction



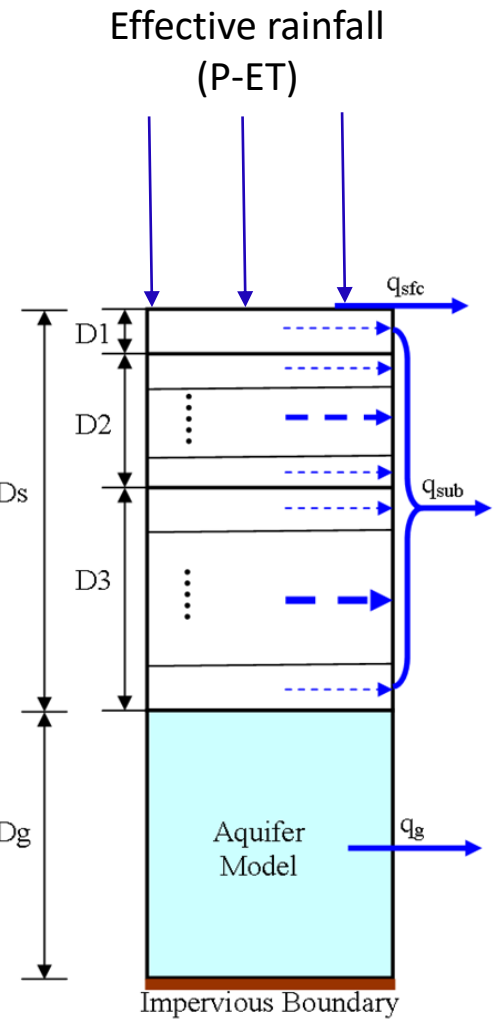
Ground water Flow

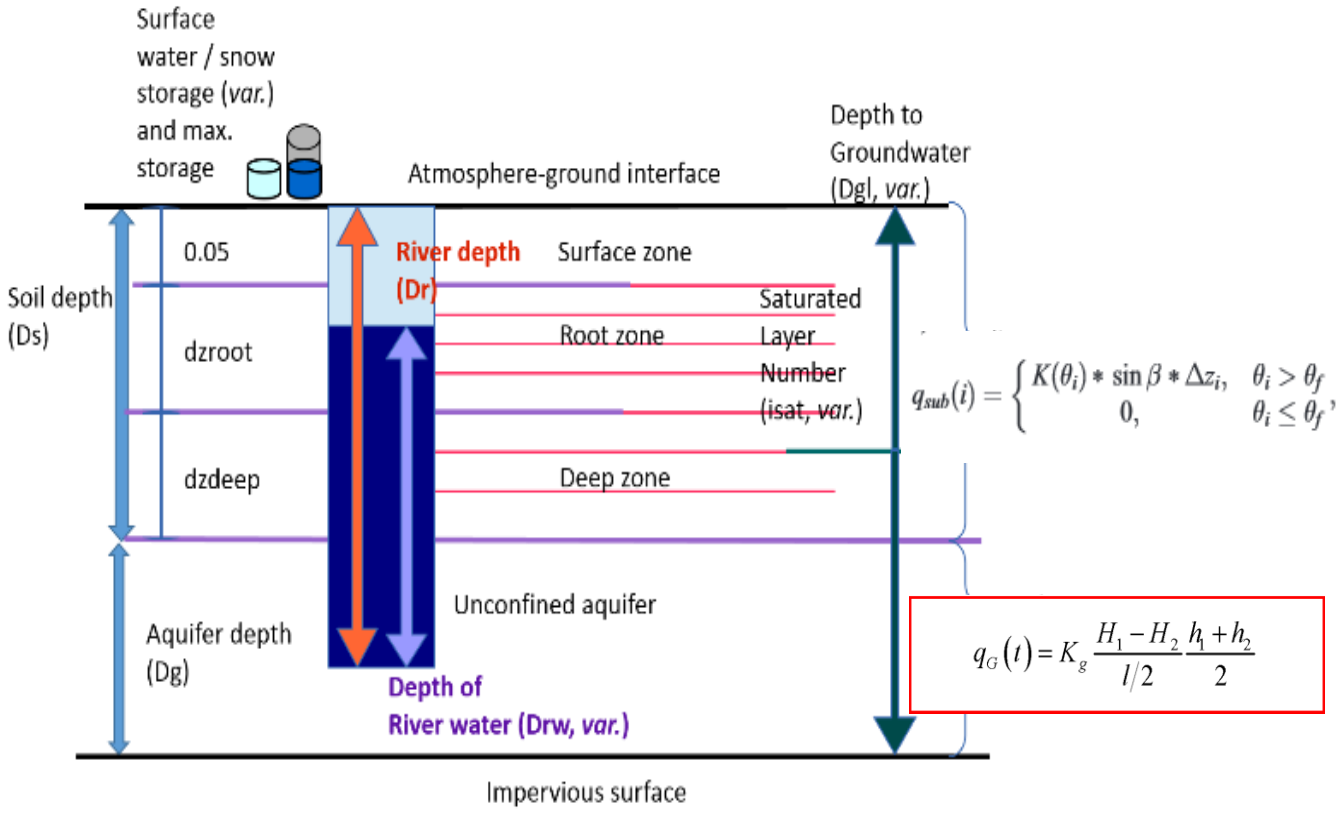


Courtesy by Mohamed Rasmy, ICHARM

Vertical_profile.f → SubroutineRun2

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K + D\frac{\partial \theta}{\partial z}\right]$$





Courtesy by Mohamed Rasmy, ICHARM

Water Balance Analysis

Simulations for 52 years (1960-2011)

↓

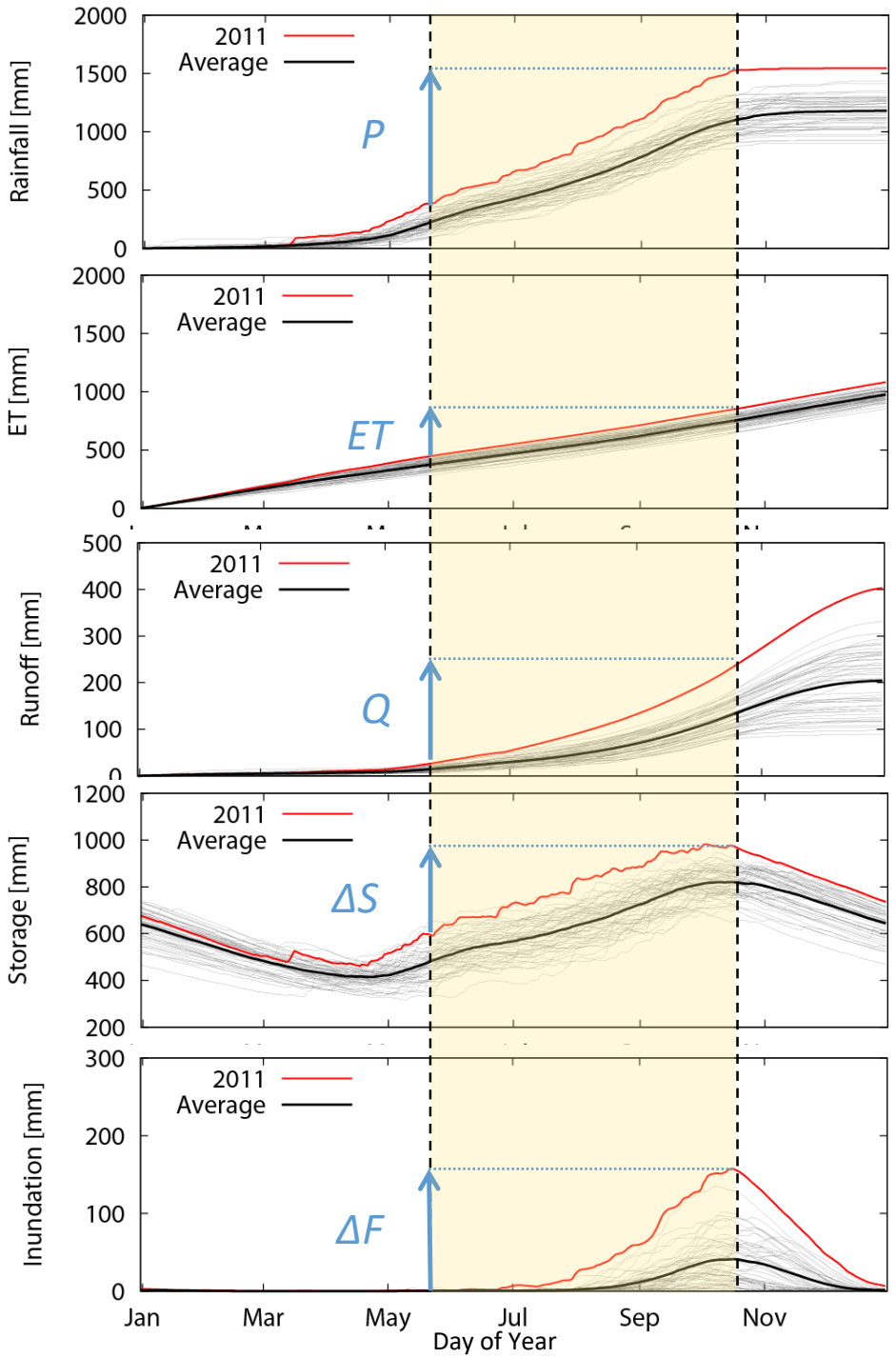
Calculate *P*, *ET*, *Q*, Δ*S*, Δ *F* for each year

↓

Highest correlation between 6 month *R* and *F*

↓

$$P = ET + Q + \Delta S + \Delta F$$



Cumulative Rainfall

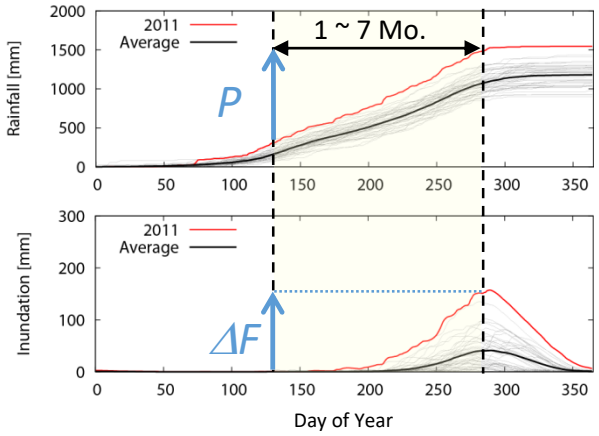
Cumulative ET

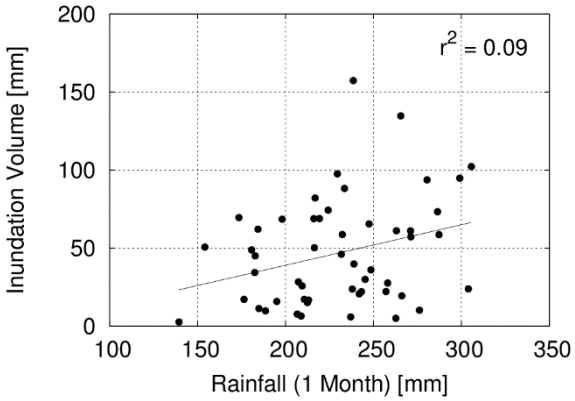
Cumulative Streamflow (at the outlet of the catchment)

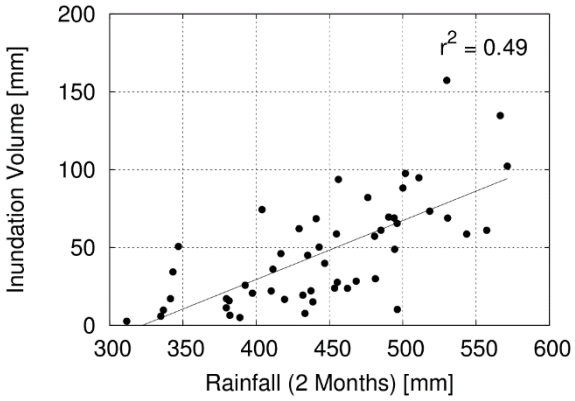
Soil Storage

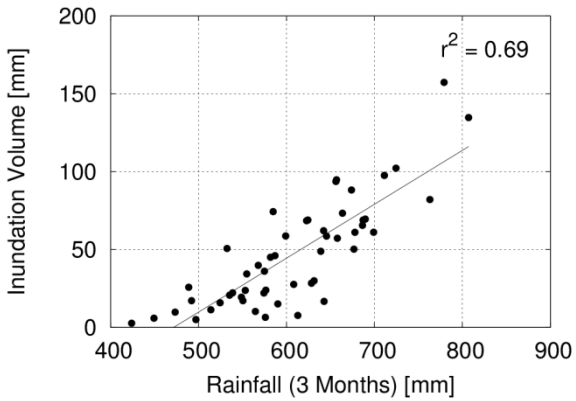
Flood Inundation

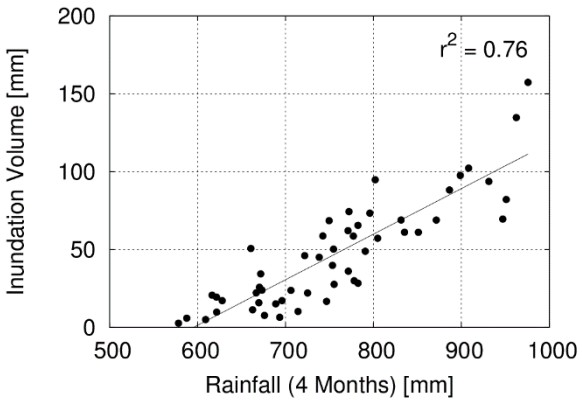
Period of Rainfall Contributing to Flood Inundation

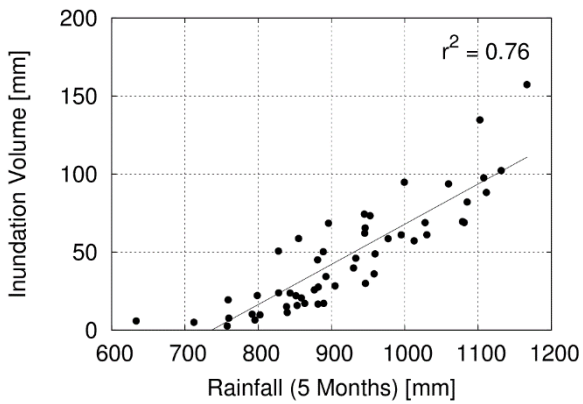


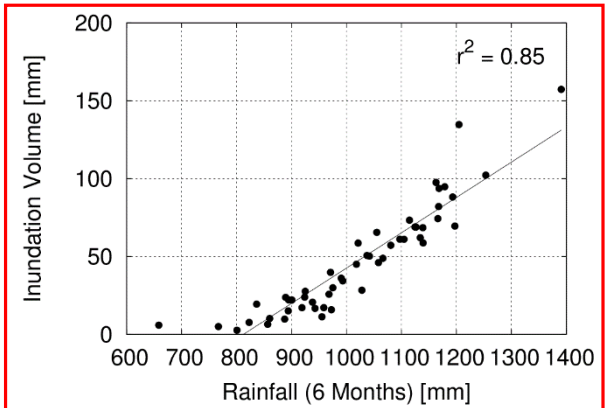


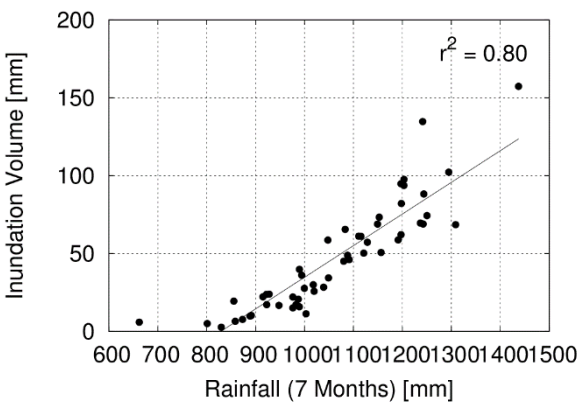






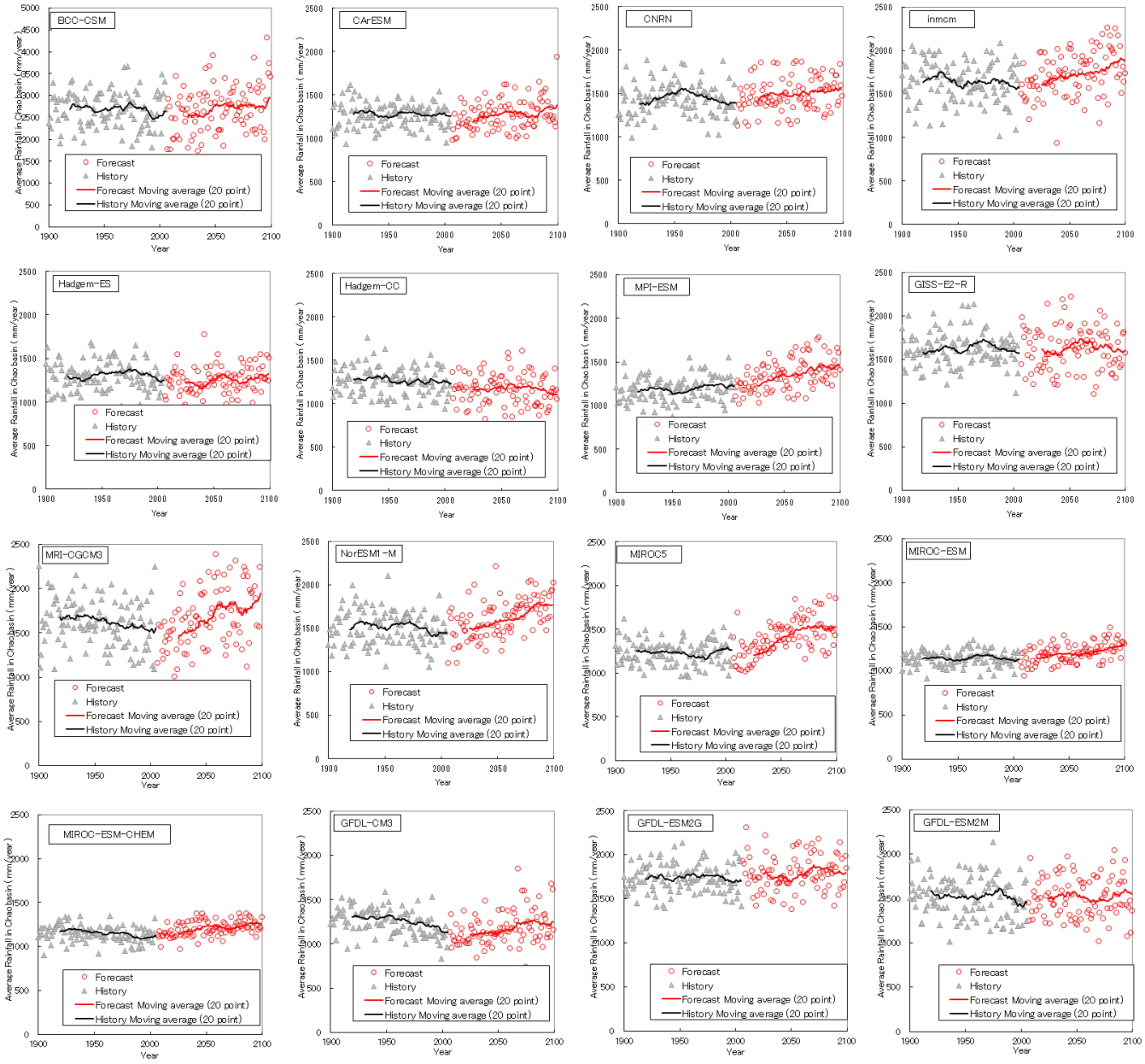






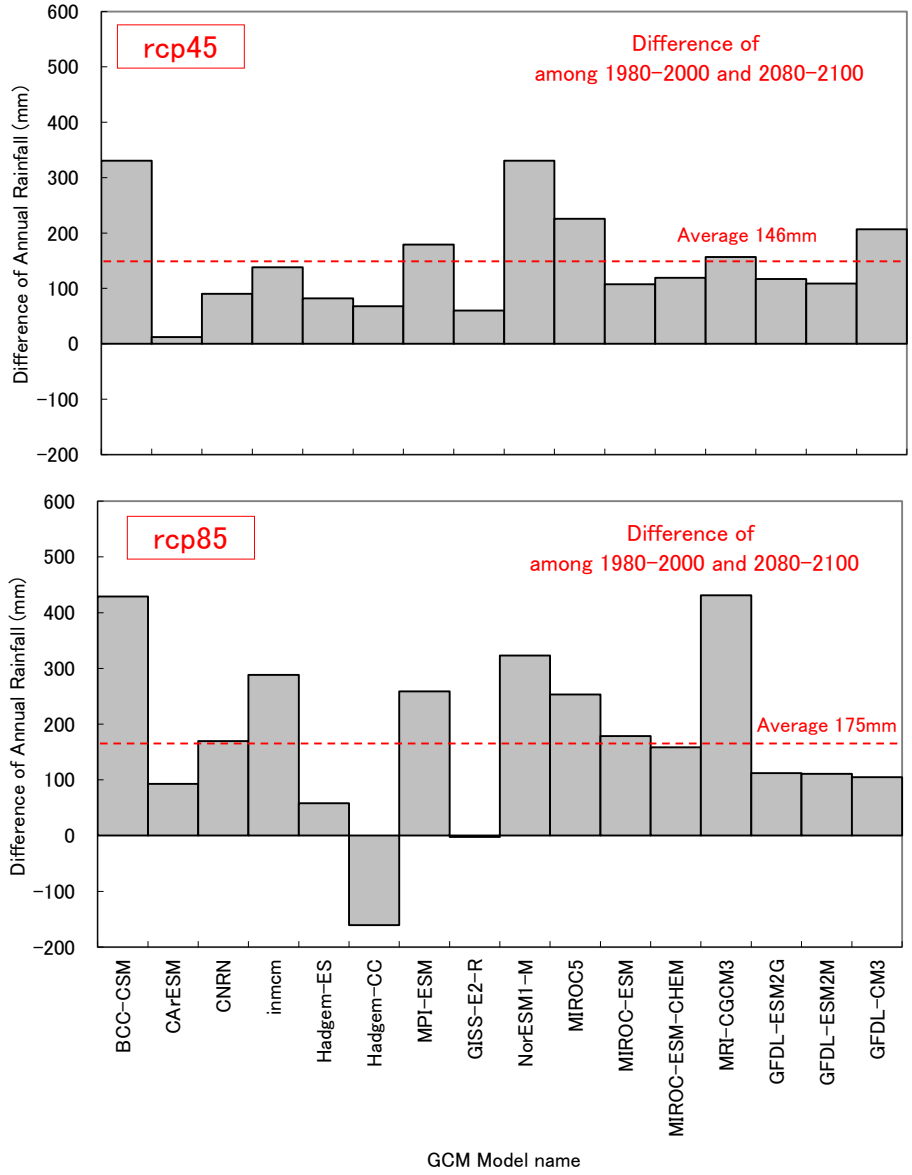
✓ Six month rainfall has the highest correlation with peak inundation volume.

Projected Rainfall in the Chao Phraya River Basin by 16 GCMs in CMIP5



(RCP 8.5)

Projected Rainfall in the Chao Phraya River Basin by 16 GCMs in CMIP5



(mm/year)

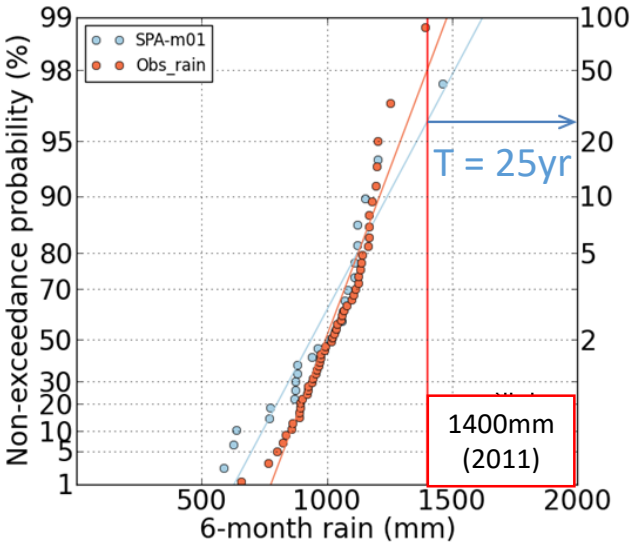
GCMs in CMIP5	Present 1980-2000	Future (rcp4.5) 2080-2100	Future (rcp8.5) 2080-2100	Future-Present (rcp4.5) 2100-2000	Future-Present (rcp8.5) 2100-2000
BCC-CSM	2537	2868	2966	331	429
CArESM	1290	1302	1383	12	93
CNRN	1379	1470	1549	90	169
Inmcm	1590	1728	1878	138	288
Hadgem-ES	1267	1349	1326	82	58
Hadgem-CC	1267	1335	1106	68	-161
MPI-ESM	1198	1377	1457	179	259
GISS-E2-R	1601	1661	1599	60	-2
NorESM1-M	1447	1777	1770	331	323
MIROC5	1274	1500	1528	226	253
MIROC-ESM	1123	1231	1301	108	179
MIR-ESM-CHEM	1100	1219	1259	119	159
MRI-CGCM3	1516	1673	1947	157	431
GFDL-ESM2G	1689	1806	1801	117	112
GFDL-ESM2M	1440	1549	1551	109	111
GFDL-CM3	1143	1350	1248	207	105
All	1429	1575	1604	146	175

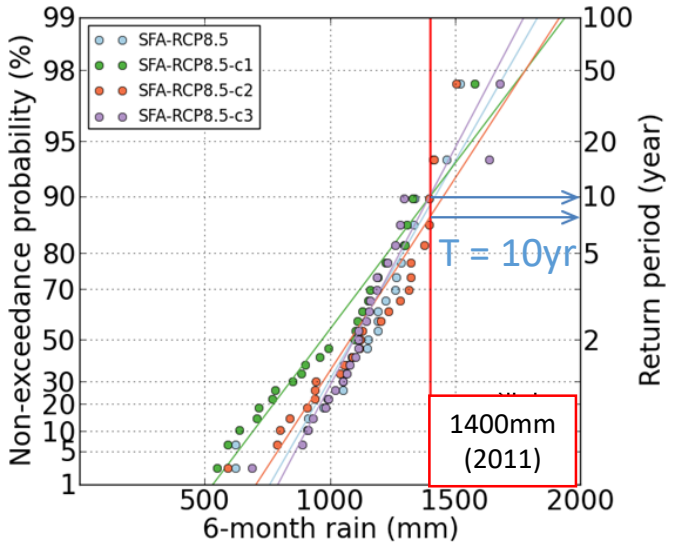
Reference:
Observed Rainfall (ave. 1964-2011)
Annual : 1191 mm
Six Months: 1062 mm (89%)

Impact Assessment by RRI Model with MRI-AGCM (RCP8.5)

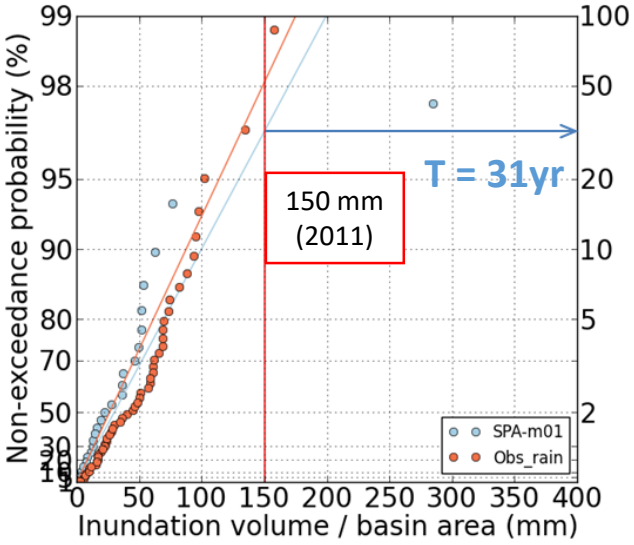
Present | **Future**

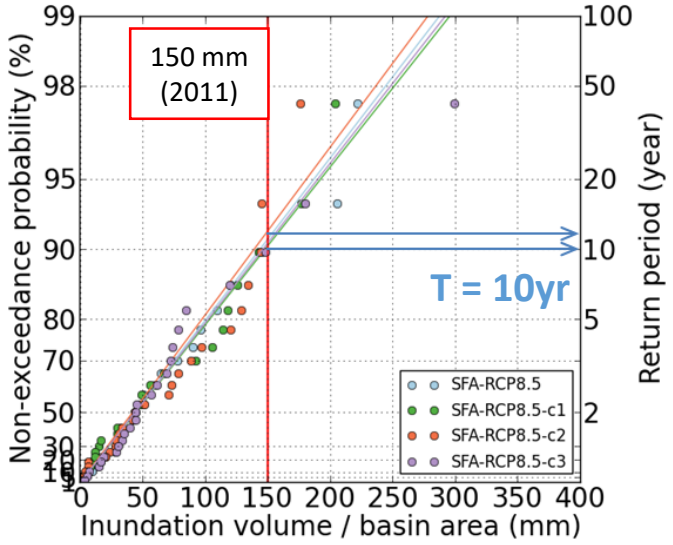
6 month Rainfall





Inundation Volume





MRI-AGCM3.2S (20 km),
MRI-AGCM3.2H (60 km)
RCP8.5 Scenario(Sousei)
Present (1979-2003)
Future (2075-2099) : 3.2S : 1 case + 3.2H : 3 cases

Return period of 150mm inundation (equivalent to 2011 flooding):

Present: 31 years → Future : 10 years

Conclusions

- Peak of flood inundation volume has the highest correlation (r^2 = 0.85) with six month rainfall.

- Elasticity of flood inundation volume is estimated to be 4.2%, higher than peak discharge (1.5%) and total runoff (2.3%).

- Ensemble mean of GCM projections in CMIP5 suggested the increase of annual rainfall by 175 mm in the Chao Phraya River basin.

- RRI model with MRI-AGCM projected that the return period of flood inundation volume equivalent to 2011 flooding will decrease from 31 years to 10 years.

Development of Rainfall-Runoff-Inundation Model

- Since 2010 at ICHARM, PWRI
- Original concept: simple and fast rainfall-runoff and inundation simulation at the river basin scale
- Target: real time inundation predictions, risk assessment, etc.
- As of 2015, the package including Fortran source codes, English manual, GUI (Model builder + Viewer) are freely available based upon personal requests.
- Recent advancement: ground water, detailed cross sections, etc.
- Practical application projects (ICHARM): UNESCO Pakistan Project (Indus), JICA Thai Project (Chao Phraya), ADB Myanmar Project (Irrawaddy).
- Application to scientific study: hydrologic sensitivity and climate change focusing on flood inundation at the river basin scale