CAHMDA-DAFOH Joint Workshop, 8-12 Sep. 2014, Austin, Texas, USA

Session 7: Advancing Data Assimilation Science for Operational Hydrology (11 Sep. 2014)

Particle Filtering for Hydraulic Models:
Probabilistic Urban Inundation Modeling and Assimilation-based H-Q Relationships

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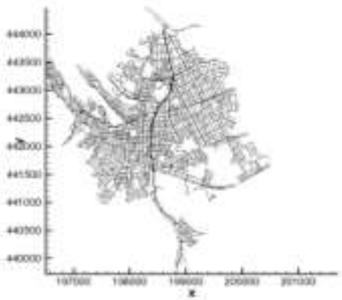
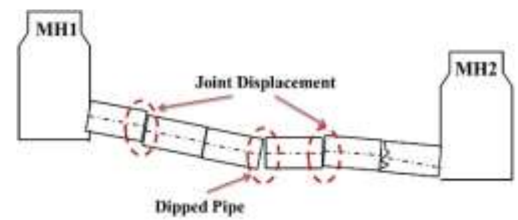
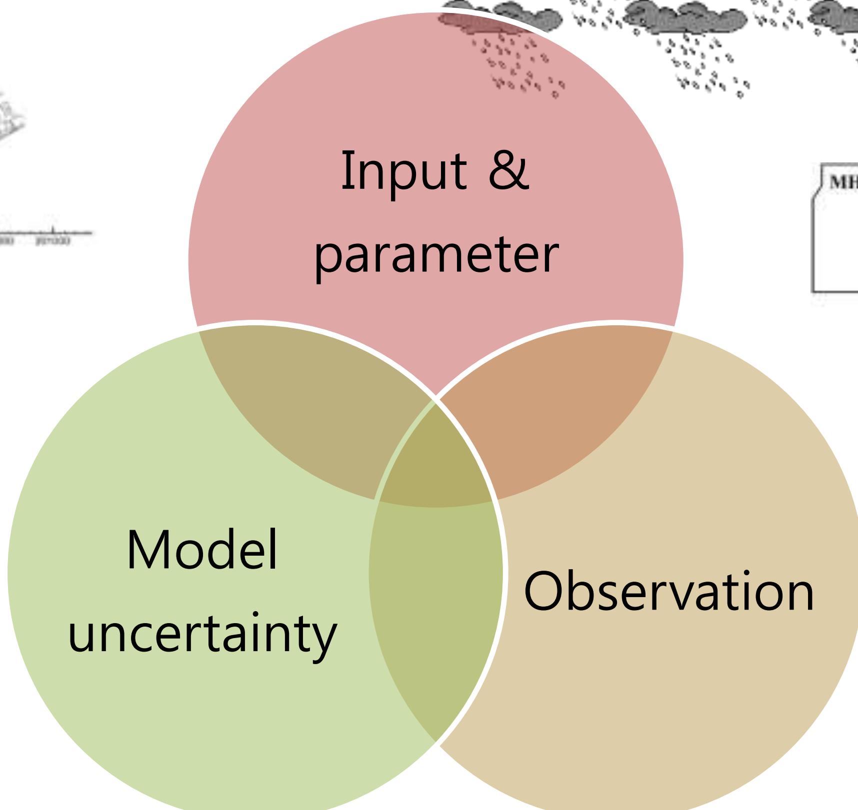
Probabilistic Inundation Modeling using Urban Flood Model and PF

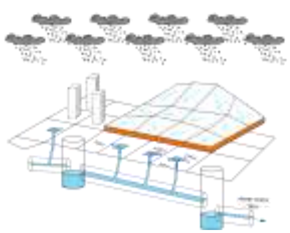
Introduction – Probabilistic urban flood model

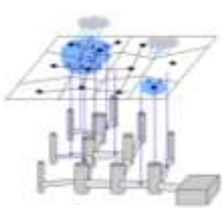
Model ensembles + Data assimilation

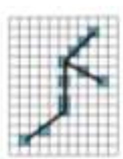


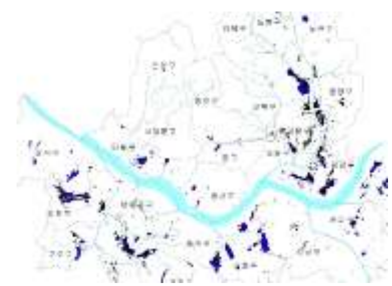








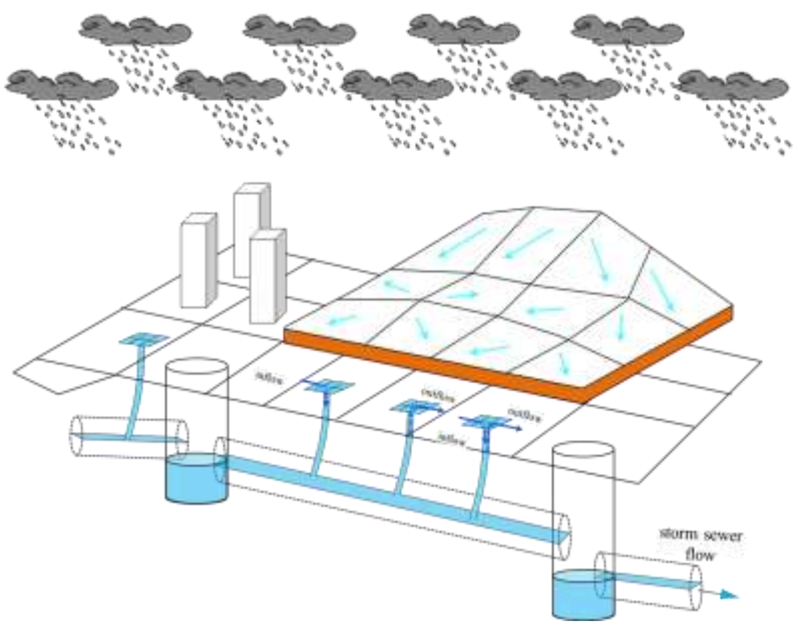


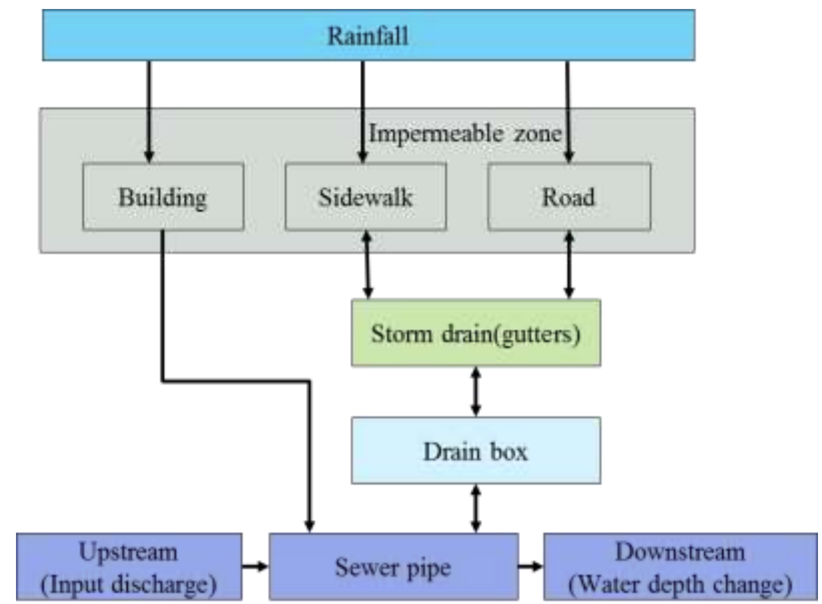


Methodology – Integrated urban flood model

Integrated urban flood model (DPRI, Kyoto Univ.)

- 2-D inundation model on the ground surface
- 1-D network model of sewer pipes
- Combined by a sub-model to exchange storm water between the ground surface and the sewerage system





Methodology – Integrated urban flood model

Governing equations

Ground surface

$$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=r_e-q_{drain}-q_{sew}$$

$$\frac{\partial M}{\partial t}+\frac{\partial (uM)}{\partial x}+\frac{\partial (vM)}{\partial y}=-gh\frac{\partial H}{\partial x}-\frac{gn^2M\sqrt{u^2+v^2}}{h^{4/3}}$$

$$\frac{\partial N}{\partial t}+\frac{\partial (uN)}{\partial x}+\frac{\partial (vN)}{\partial y}=-gh\frac{\partial H}{\partial y}-\frac{gn^2N\sqrt{u^2+v^2}}{h^{4/3}}$$

drain box

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q_{drain}$$

※ FDM & leap-frog methods are adopted

- h : water depth
- H : water elevation
- u : x-direction water velocity
- v : y-direction water velocity
- M : uh(x-direction flux)
- N : vh(y-direction flux)
- r_e : effective rainfall
- q_{drain} : unit area drainage discharge between ground and drain box
- q_{sew} : unit area drainage discharge between ground and sewer pipe
- g : acceleration of gravity
- n : Manning's roughness coefficient
- A : box bottom area
- Q : discharge
- q_{drain} : unit area drainage discharge between ground and drain box

Governing equations (sewer pipe)

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_{sew} + q_{drain}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (uQ)}{\partial x} = -gA\frac{\partial H_p}{\partial x} - gn^2\frac{|Q|Q}{R^{4/3}A}$$

$$h = \begin{cases} f(A) & : A \le A_0 \\ D + \dfrac{(A - A_0)}{b_s} & : A > A_0 \end{cases}$$

$$\phi = 2\cos^{-1}(1 - 2\frac{h}{d})$$

$$\frac{A}{A_0} = \frac{\phi - \sin\phi}{2\pi}$$

$$\frac{R}{R_0} = 1 - \frac{\sin\phi}{\phi}$$

$$B_s = \frac{gA_0}{a^2}$$

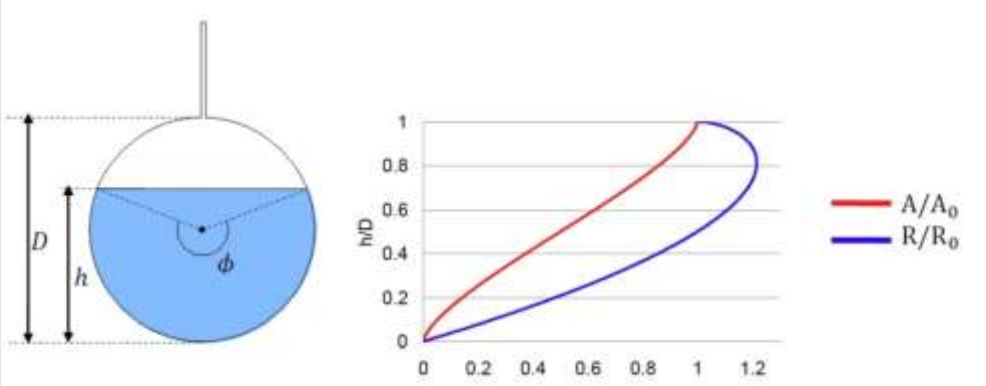


Fig. Hydraulic characteristic curves of the circular sewer pipe

The a is decided as 5.0*m/s* in this study

- R : hydraulic radius
- q_{sew} : unit area drainage discharge between ground and sewer pipe
- q_{drain} : unit area drainage discharge between sew pipe and drain box
- g : acceleration of gravity
- n : Manning's roughness coefficient
- A : stream cross-section
- Q : discharge
- u : water velocity
- H_p : piezometric head
- h : water depth
- H_L : head losses

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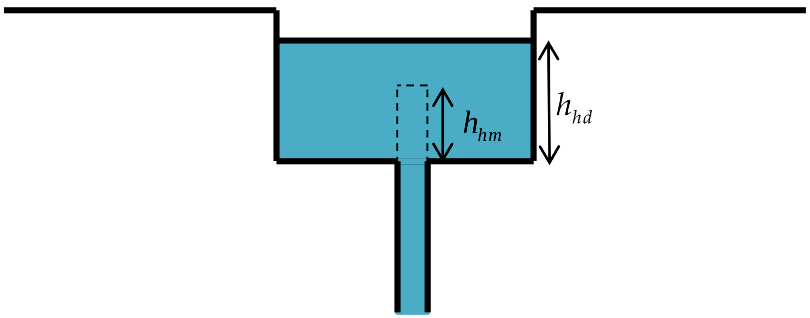
❑ Interaction model (surface water - sewer pipe)

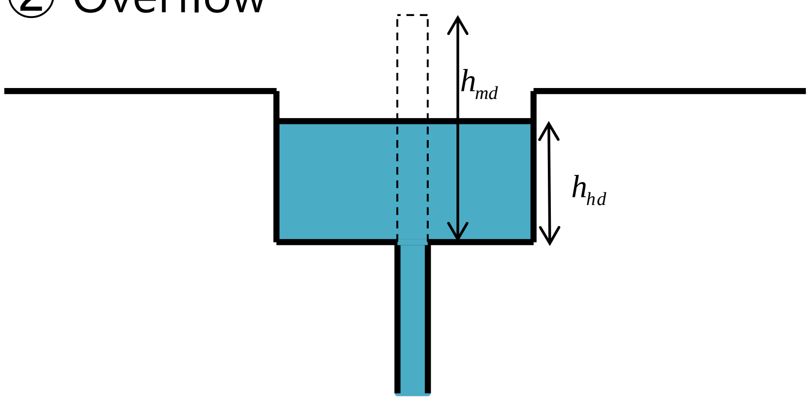
① Inlet



if, $\dfrac{h_{hd}-h_{md}}{b_o} \ge 0.5$ $\quad Q = C_{do} \times A \times \sqrt{2g(h_{hd}-h_{hm})}$

if, $\dfrac{h_{hd}-h_{md}}{b_o} < 0.5$ $\quad Q = C_{dw} \times L \times \dfrac{2}{3}\sqrt{2g}\,(h_{hd}-h_{hm})^{\frac{3}{2}}$

② Overflow



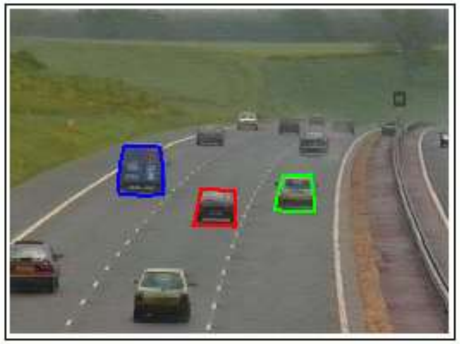
if, $\dfrac{h_{md}-h_{hd}}{b_o} \ge 0.5$ $\quad Q = -C_{do} \times A \times \sqrt{2g(h_{md}-h_{hd})}$

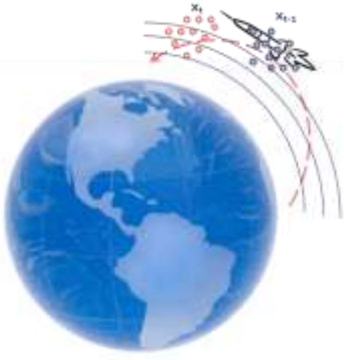
if, $\dfrac{h_{md}-h_{hd}}{b_o} < 0.5$ $\quad Q = -C_{dw} \times L \times \dfrac{2}{3}\sqrt{2g}\,(h_{hm}-h_{hd})^{\frac{3}{2}}$

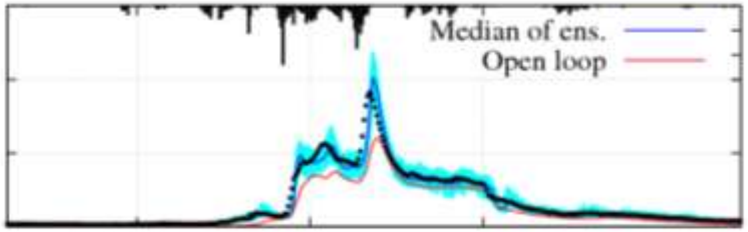
C_{do}: orifice coefficient (0.57)
C_{dw} : weir coefficient (0.48)
Q: discharge
h_{hd}: piezometric head of drain channel
h_{md}: piezometric head of sewer pipe
A: area of bottom hole

Particle filtering

- Also known as sequential Monte Carlo (SMC)
- Applicable for non-linear, non-Gaussian state-space models (most of hydraulic and hydrologic models)
- Point mass (“particle”) representations of probability densities with associated weights
- Expensive computation but easy for parallelization
- Wide-spread applications including image processing, target tracking, and flood forecasting
- Noh, S. J., Rakovec, O., Weerts, A. H., and Tachikawa, Y.: On noise specification in data assimilation schemes for improved flood forecasting using distributed hydrological models. J. Hydrol. in press, 2014.

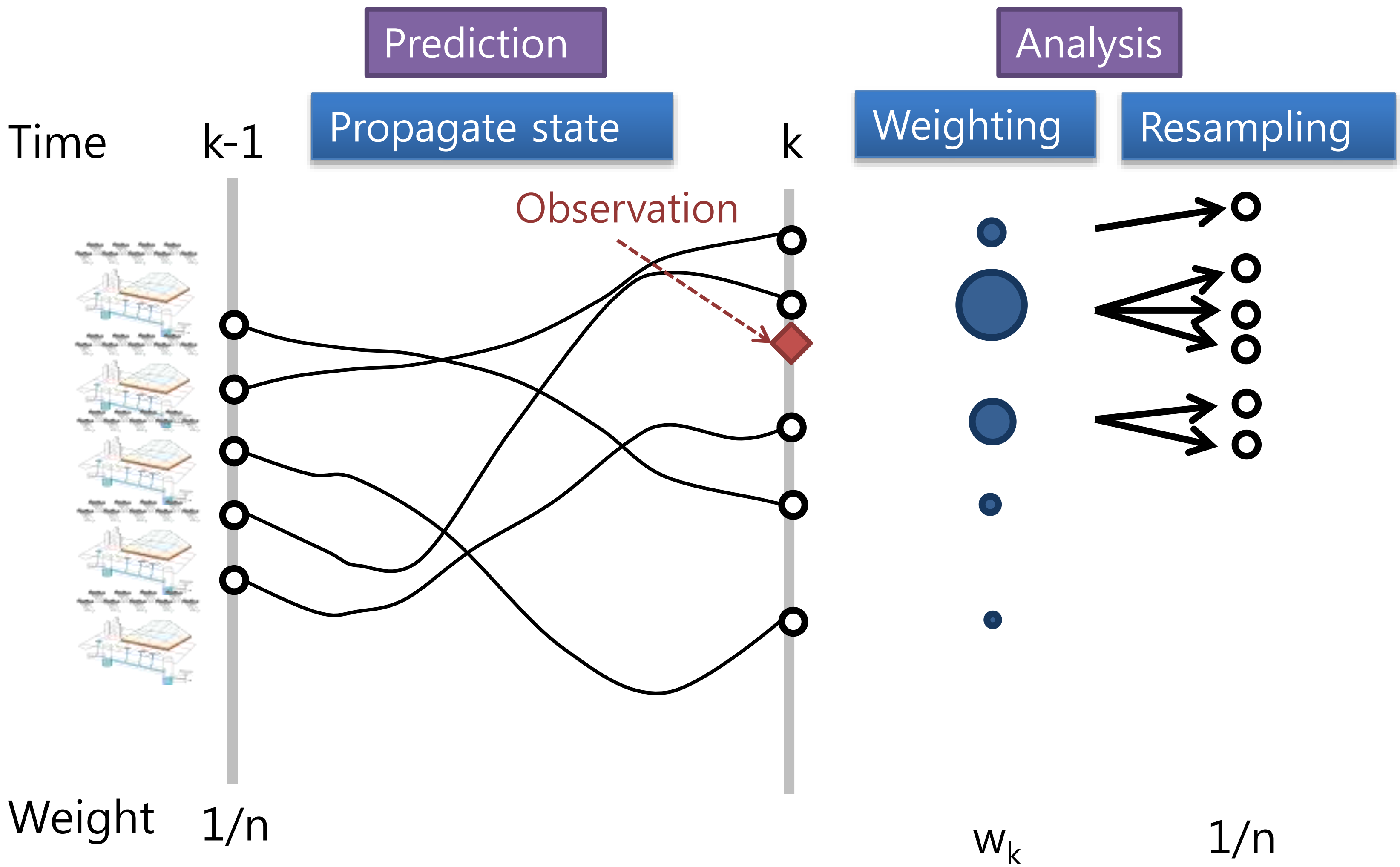






Methodology – Particle filtering

SIR particle filter



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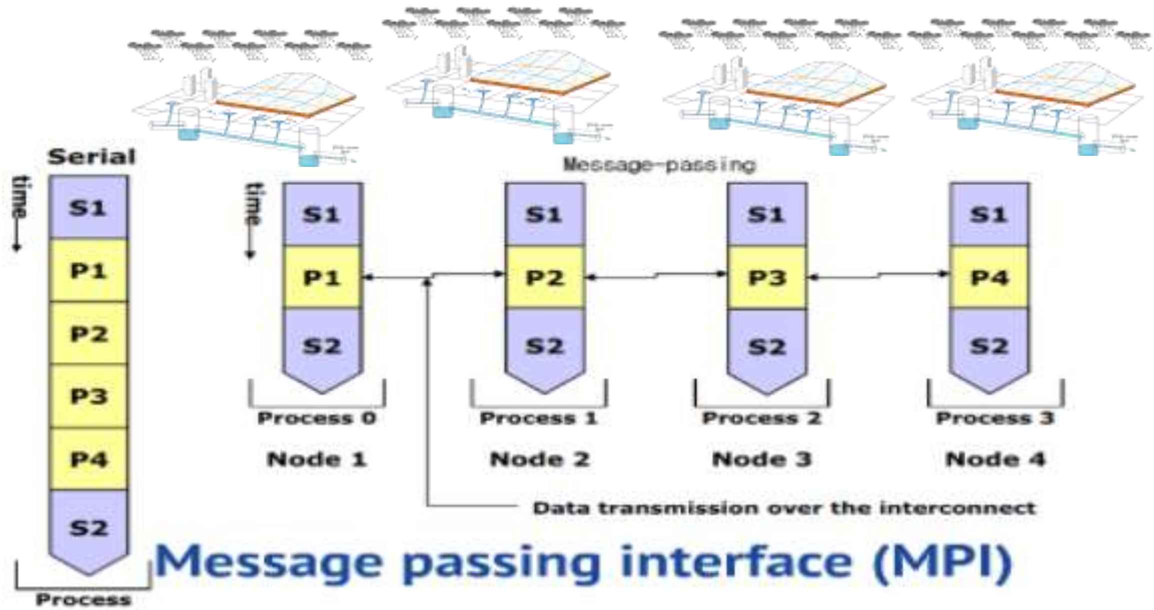
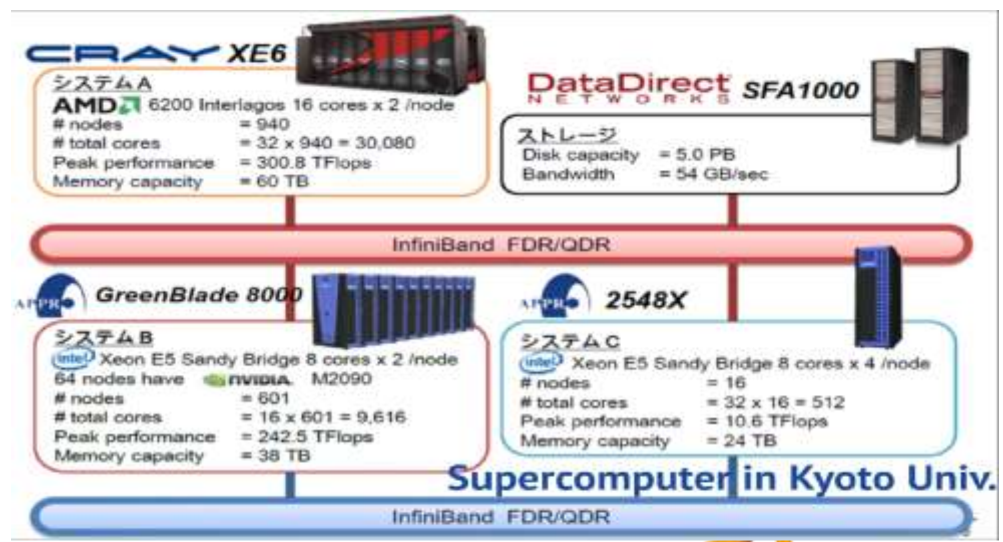
Methodology – Parallel computing



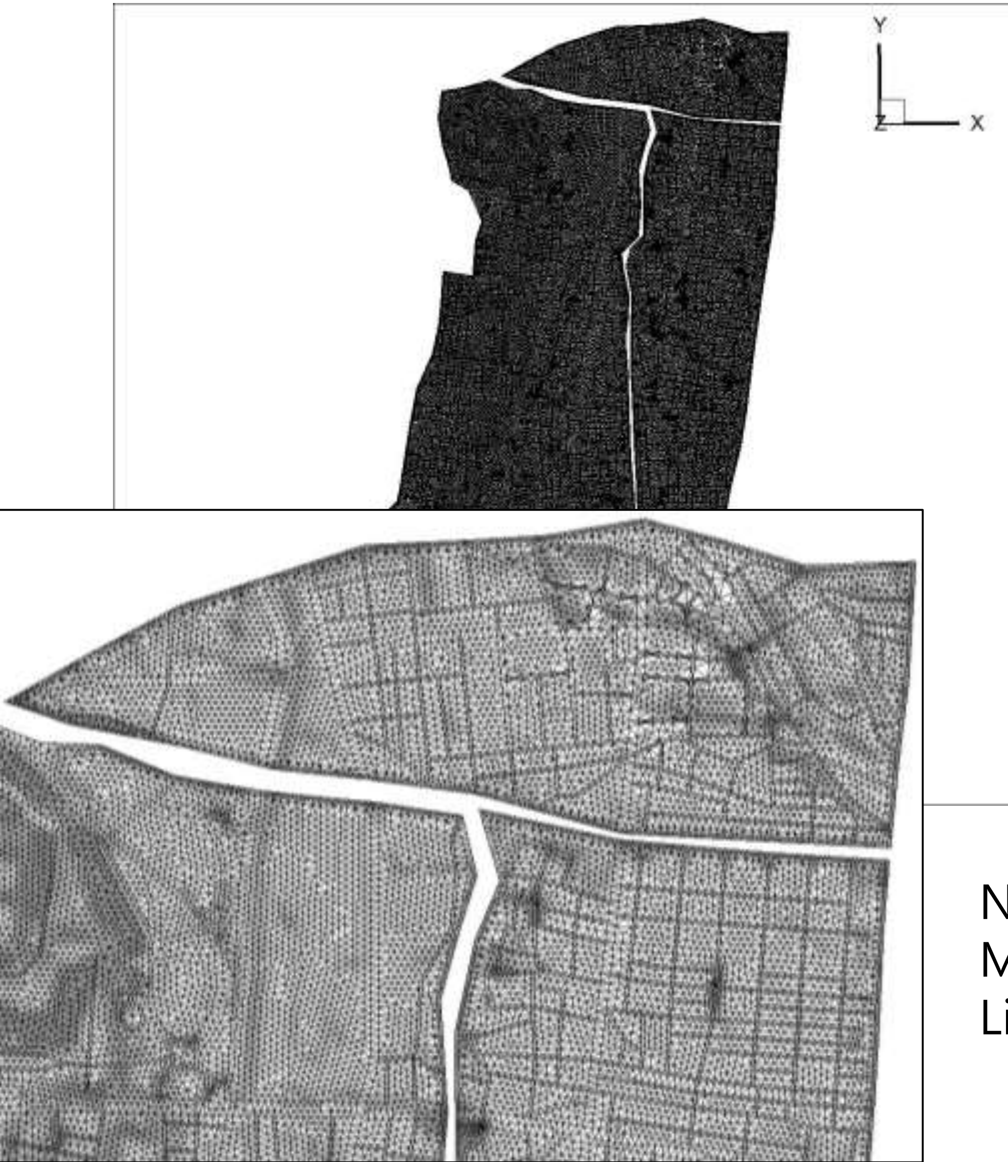
Message passing interface (MPI)



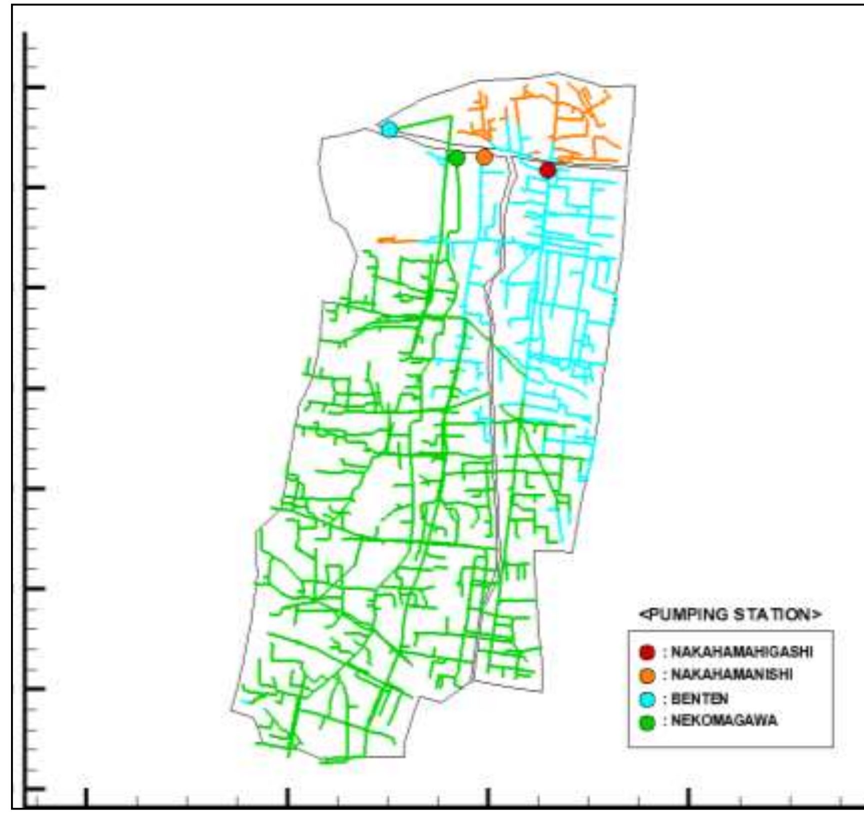
Supercomputer in Kyoto Univ.

Application – Study area

Urban surface



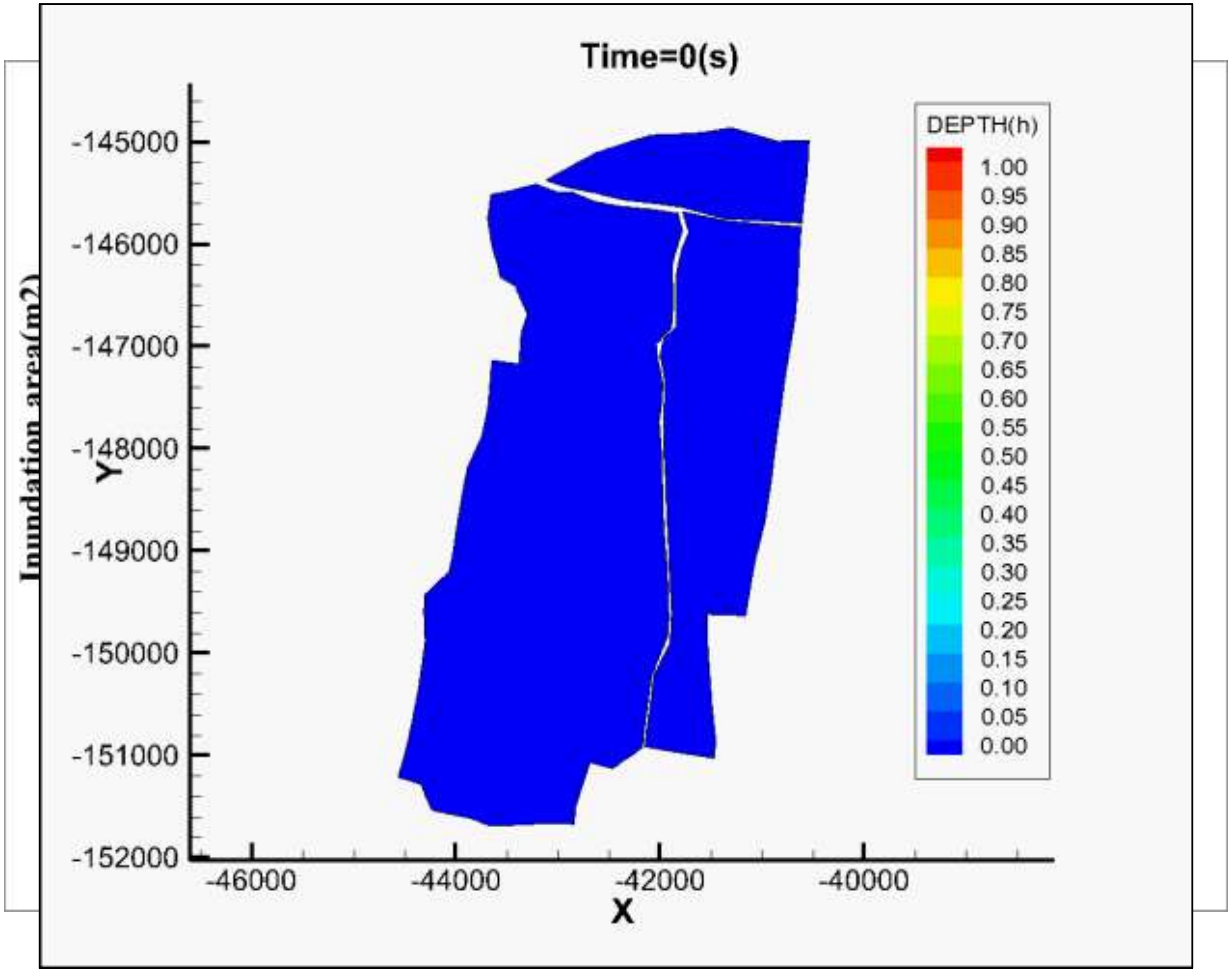
Sewer pipe network



Node : 60,411
Mesh : 117,435
Link : 177,843

Application – Deterministic simulation result

Deterministic modeling case



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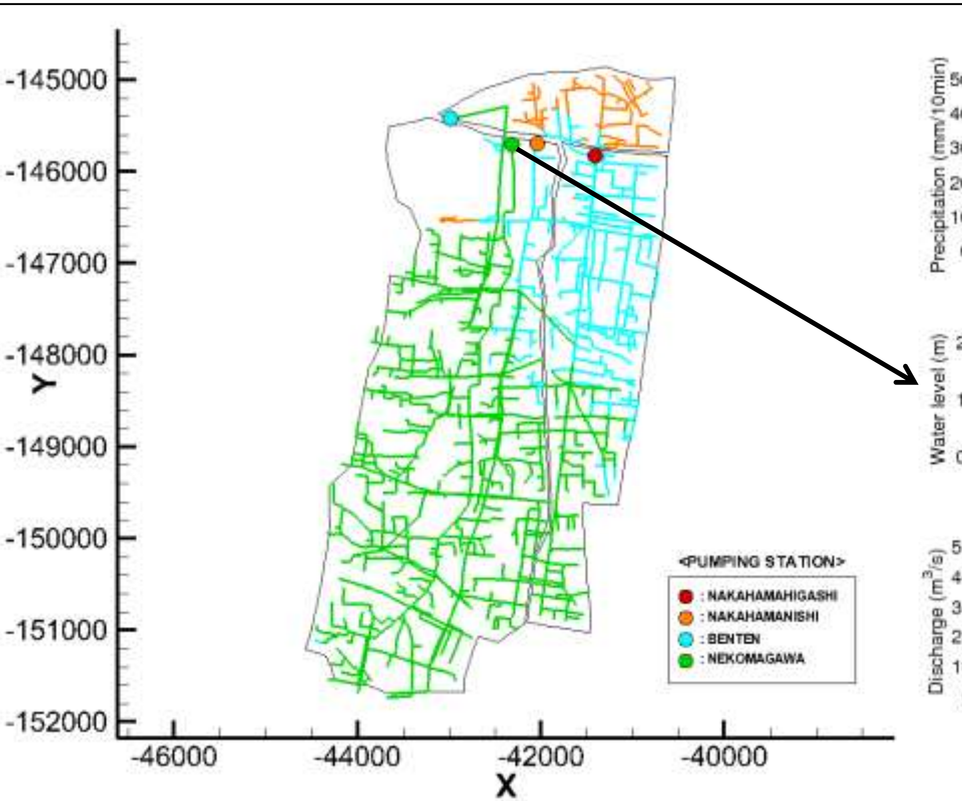
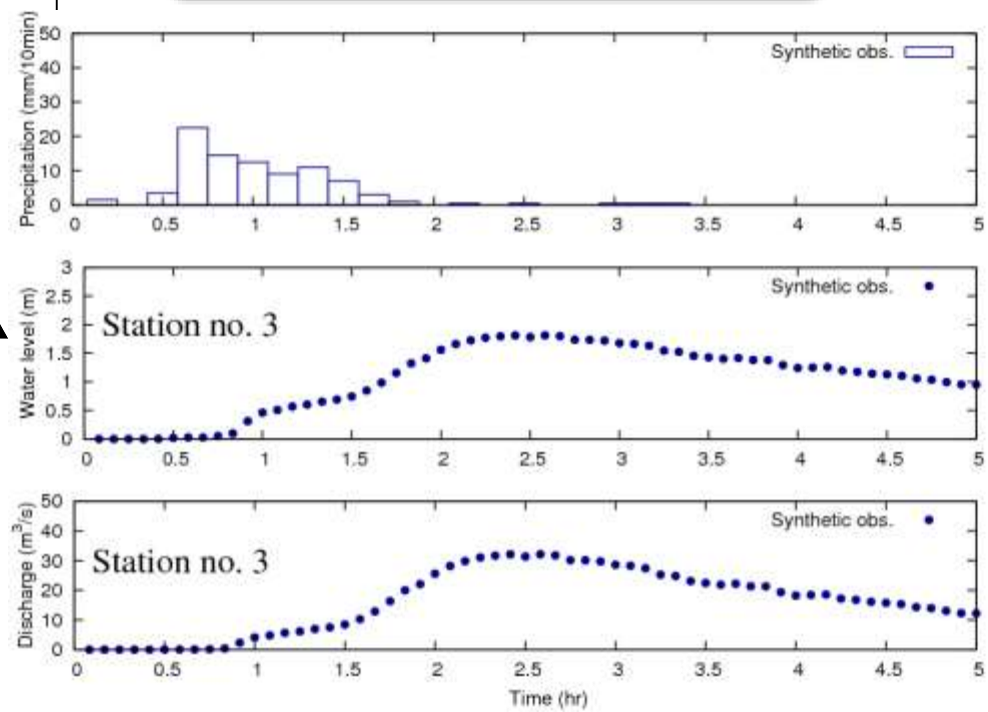
Application – Setup of synthetic experiment



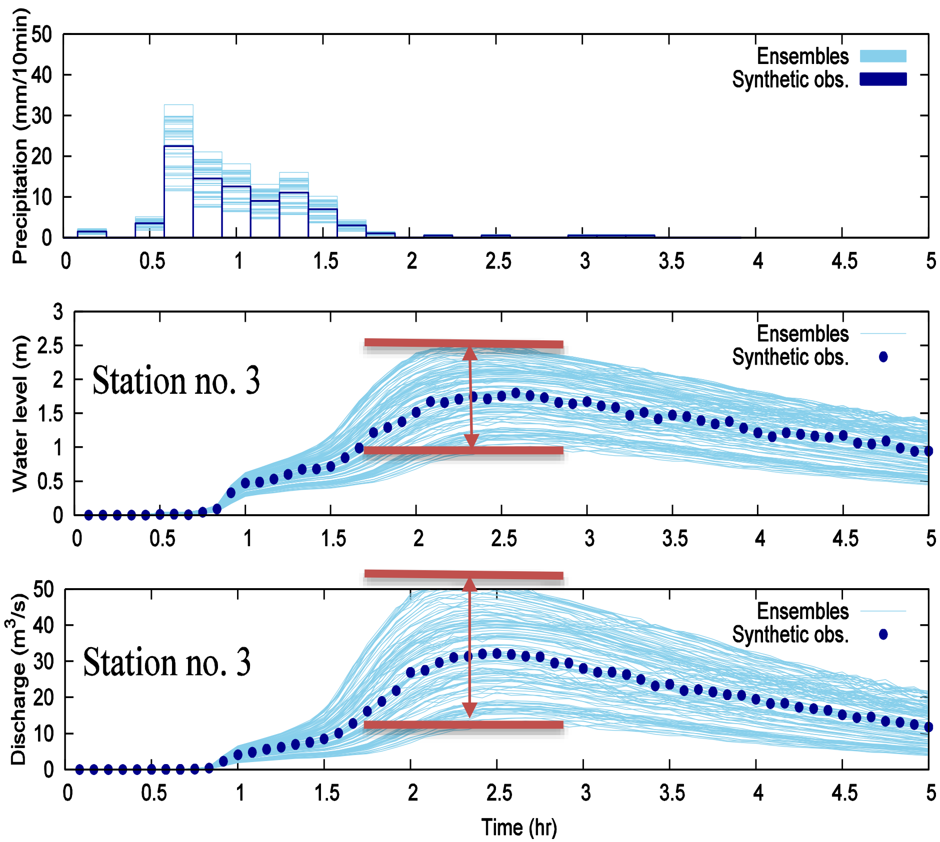
Synthetic observation



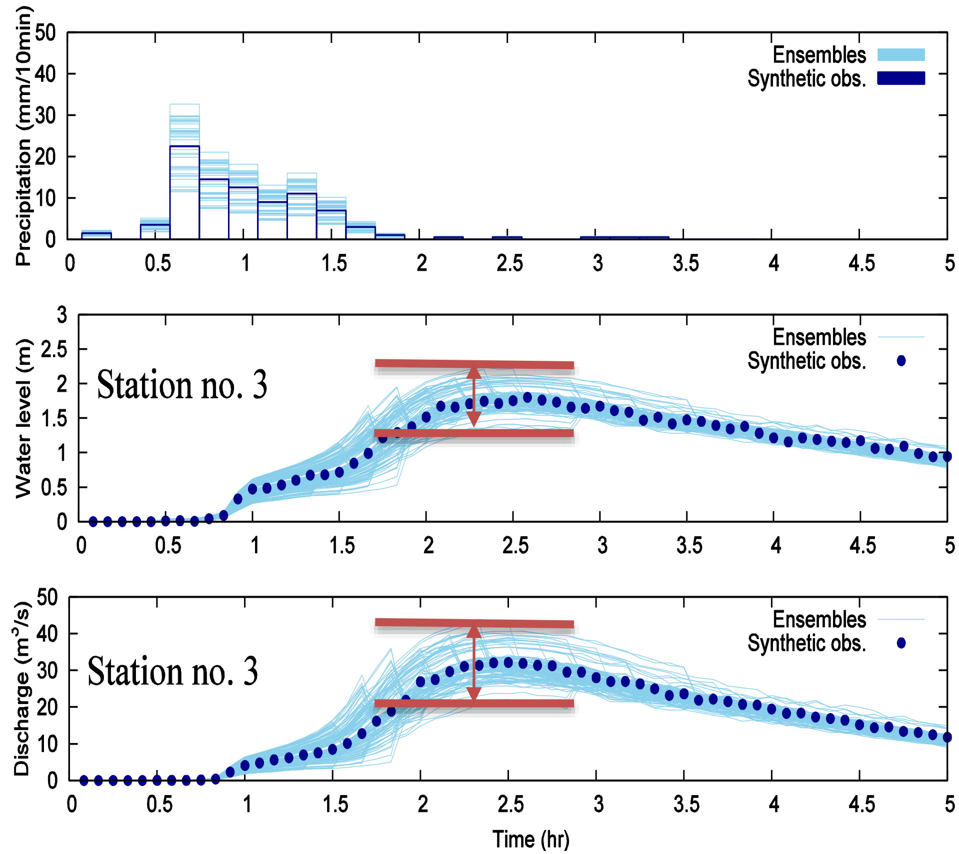
- Water level and discharge at pumping station no. 3 were used as synthetic observation
- Spatial distribution of rainfall was not considered

Application – Comparison on H & Q

Without particle filtering



With particle filtering



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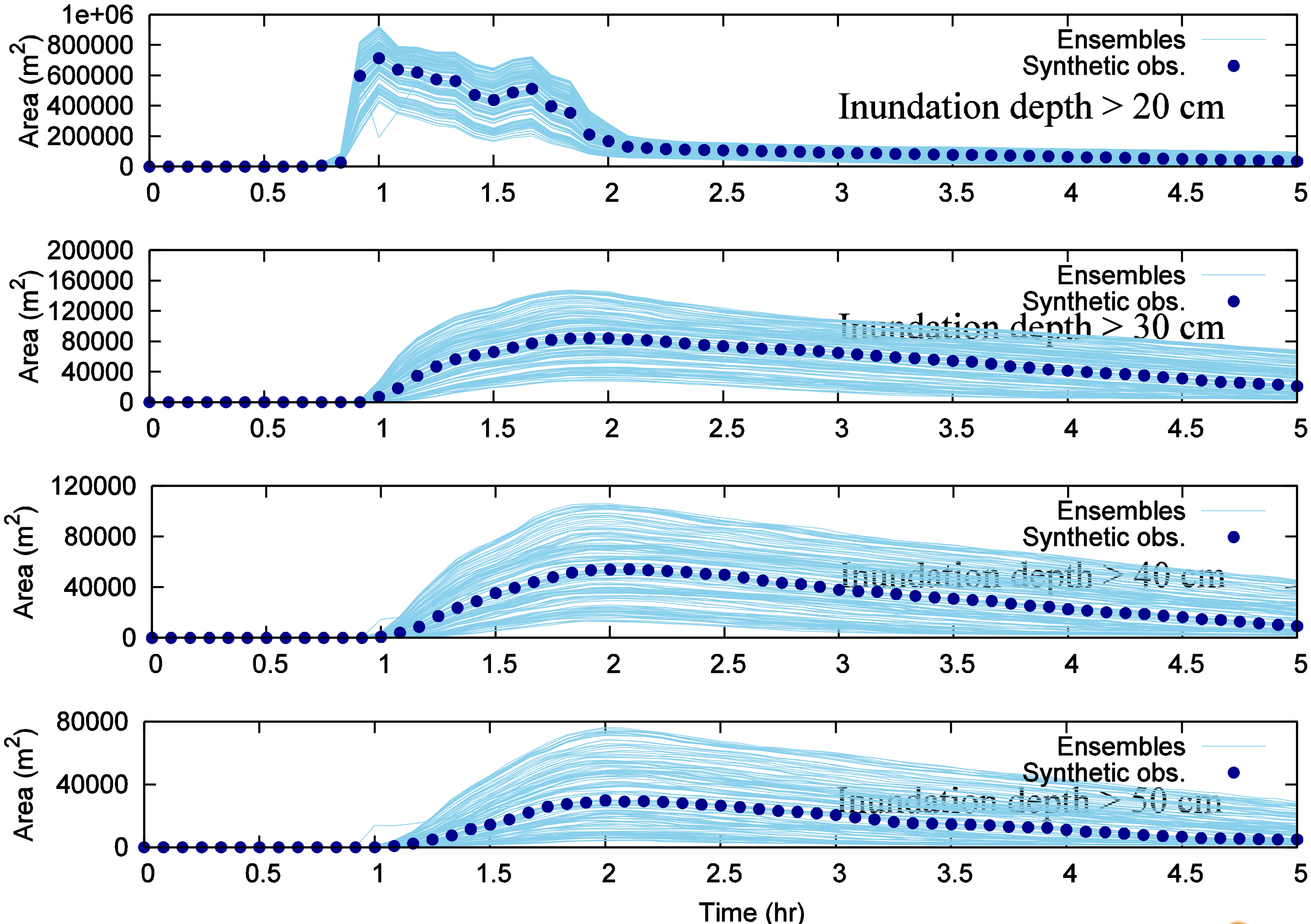
Application – Comparison on inundation area

Inundation area – without particle filtering



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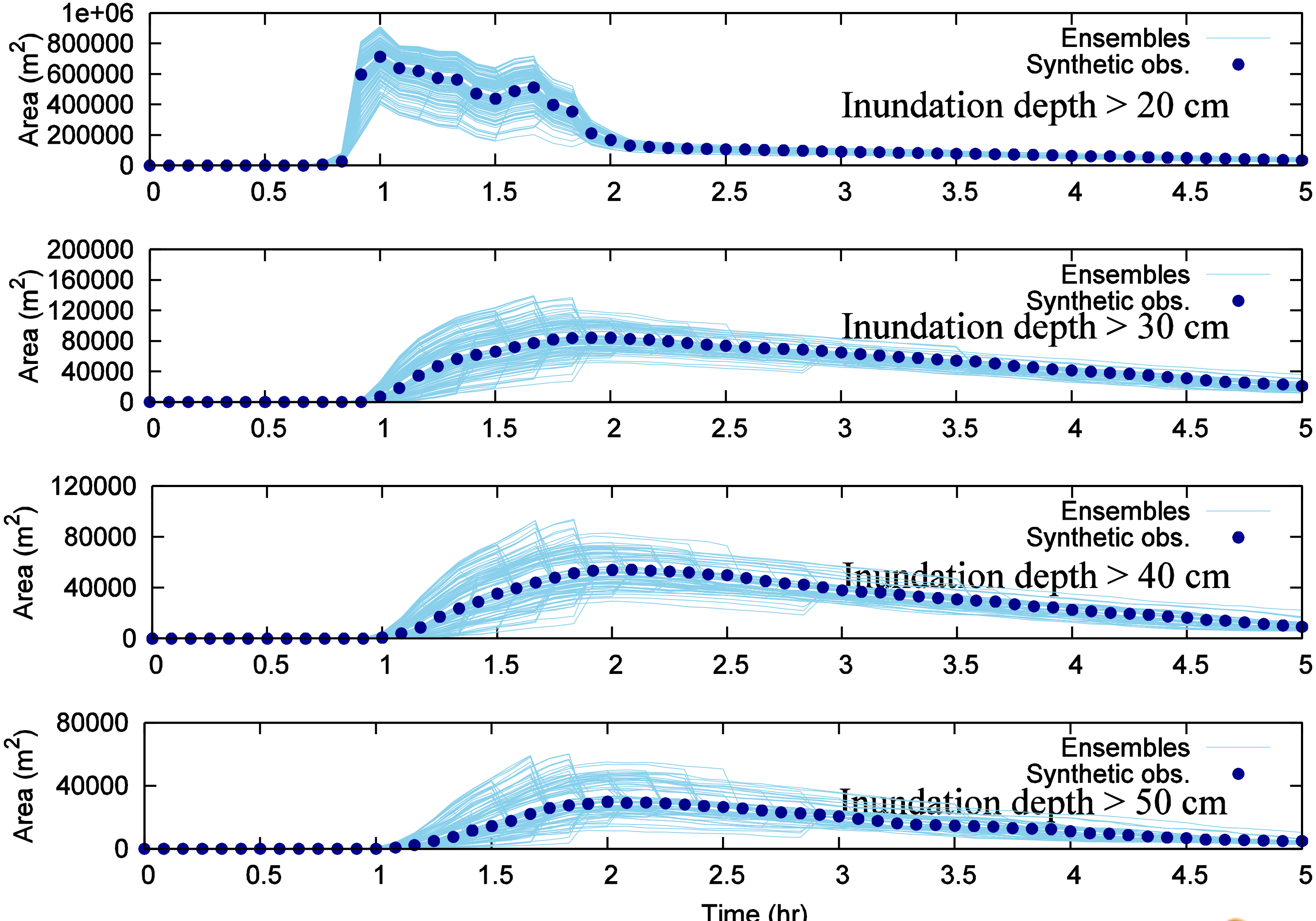
Application – Comparison on inundation area

Inundation area – with particle filtering



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Assimilation-based H-Q Relationships using 2-D Dynamic Wave Model and PF

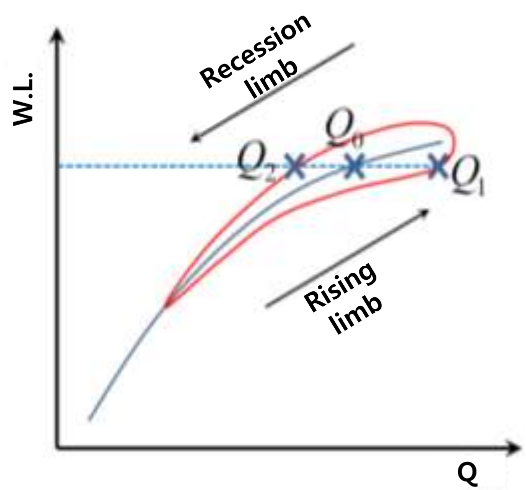
Motivation – Assimilation-based H-Q

Uncertainties

Without measuring Q

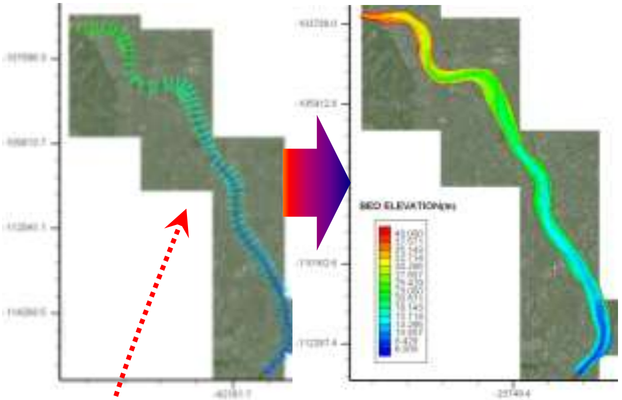
Dynamic characteristics

H-Q relationship



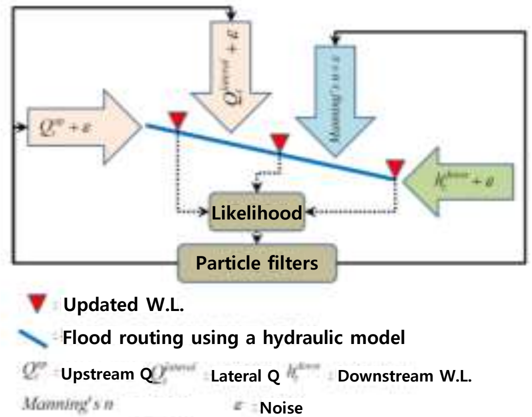
Images from www.hsc.re.kr

Methodology – DA procedures



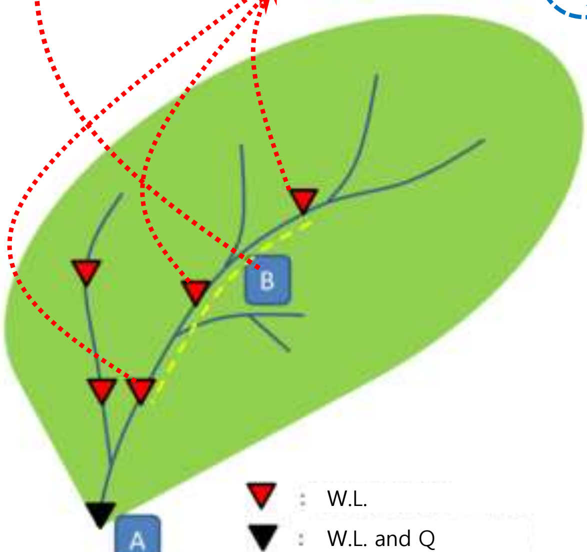
Setup of 2-D dynamic wave model
(observed data and Aerial photo)

↓



Updating ensembles using observed W.L.

Noise specification
(inflow and roughness)
+
Particle filtering using observed H



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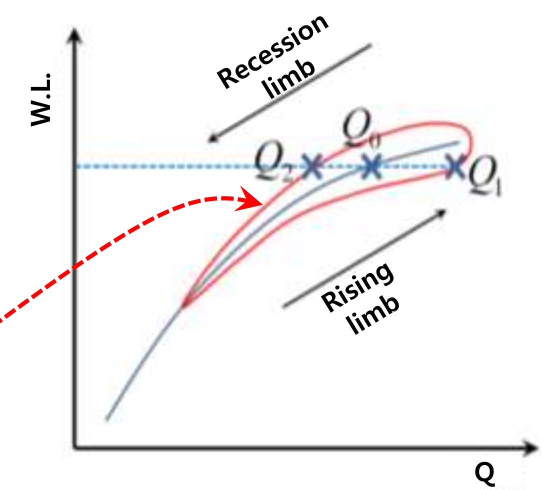
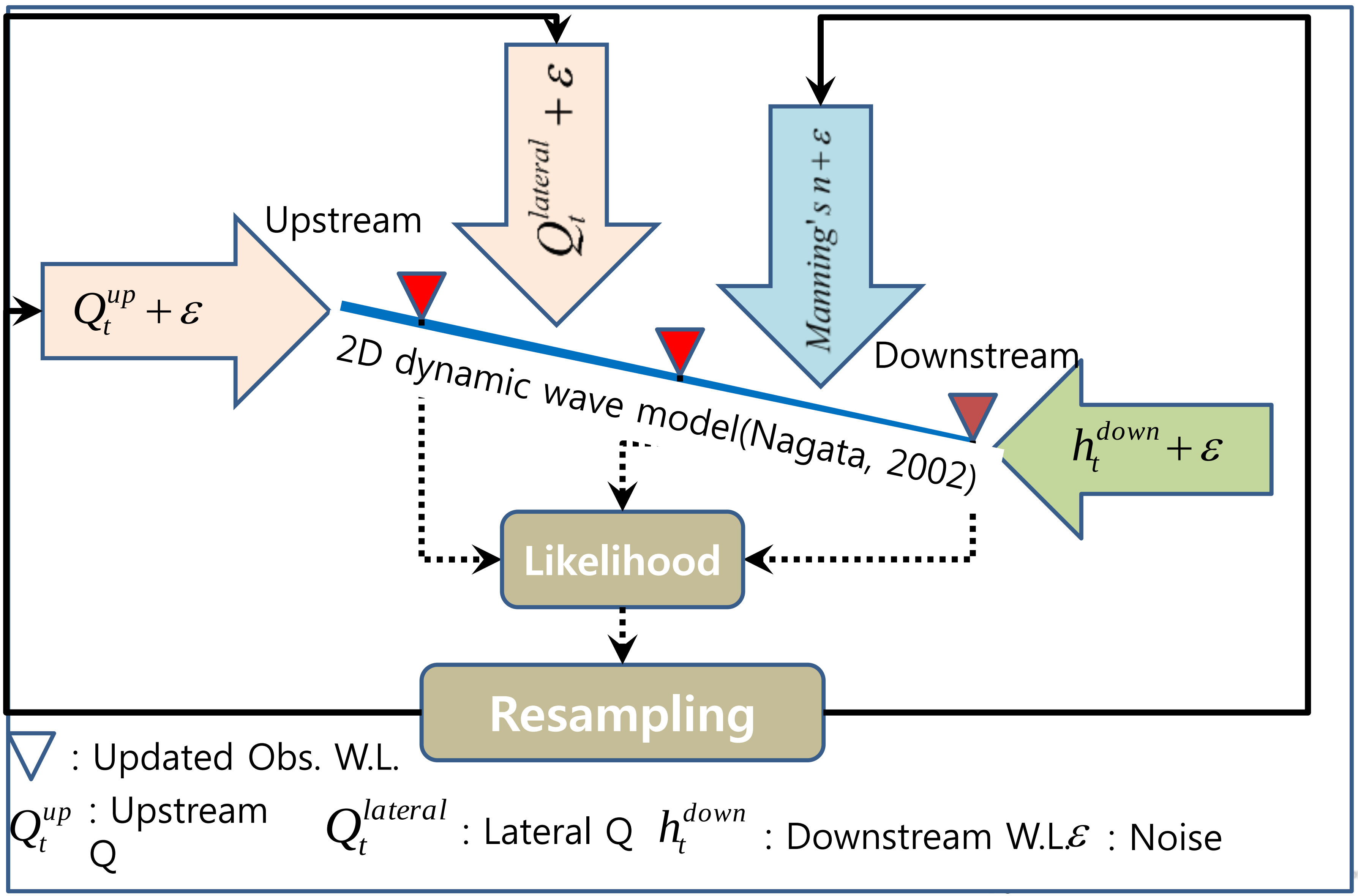
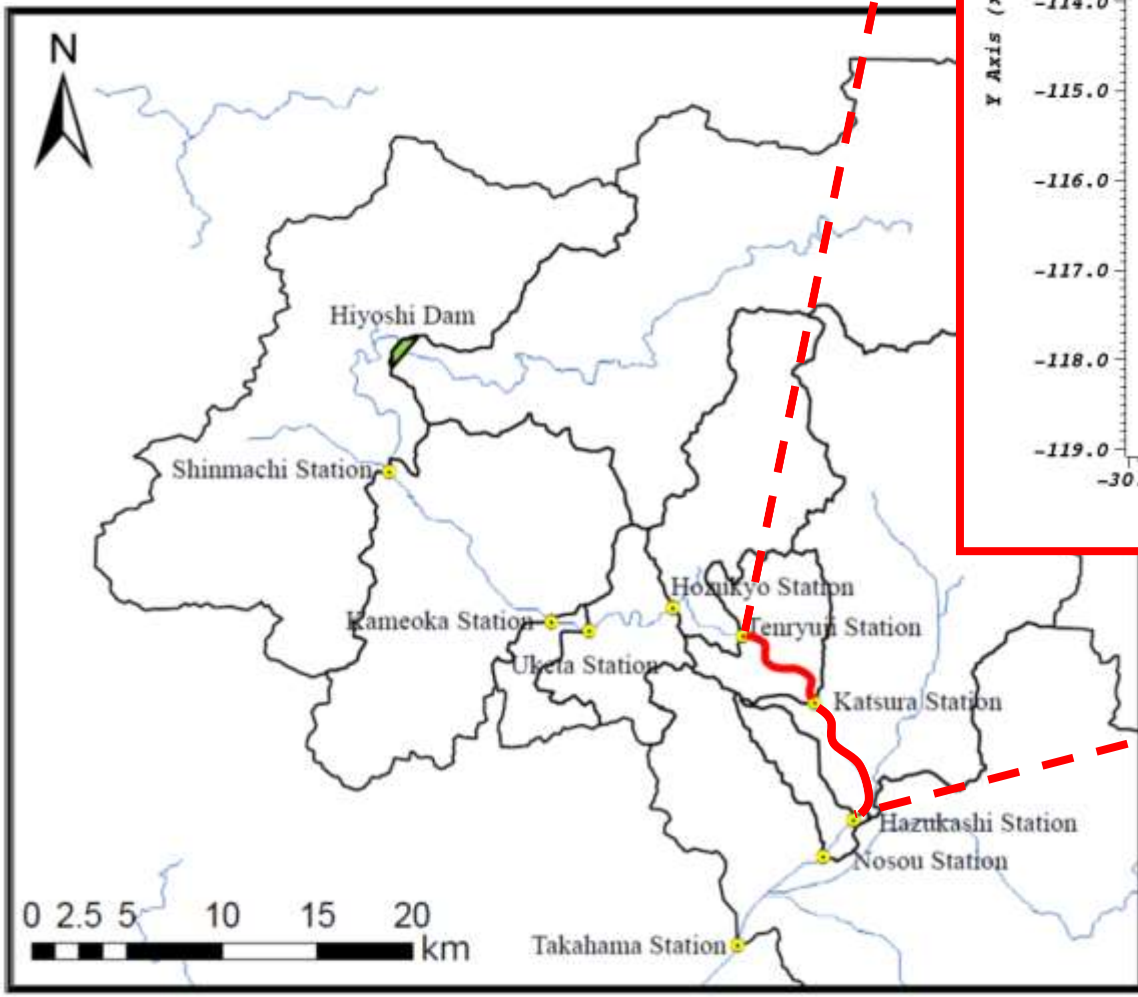
Assimilation-based H-Q

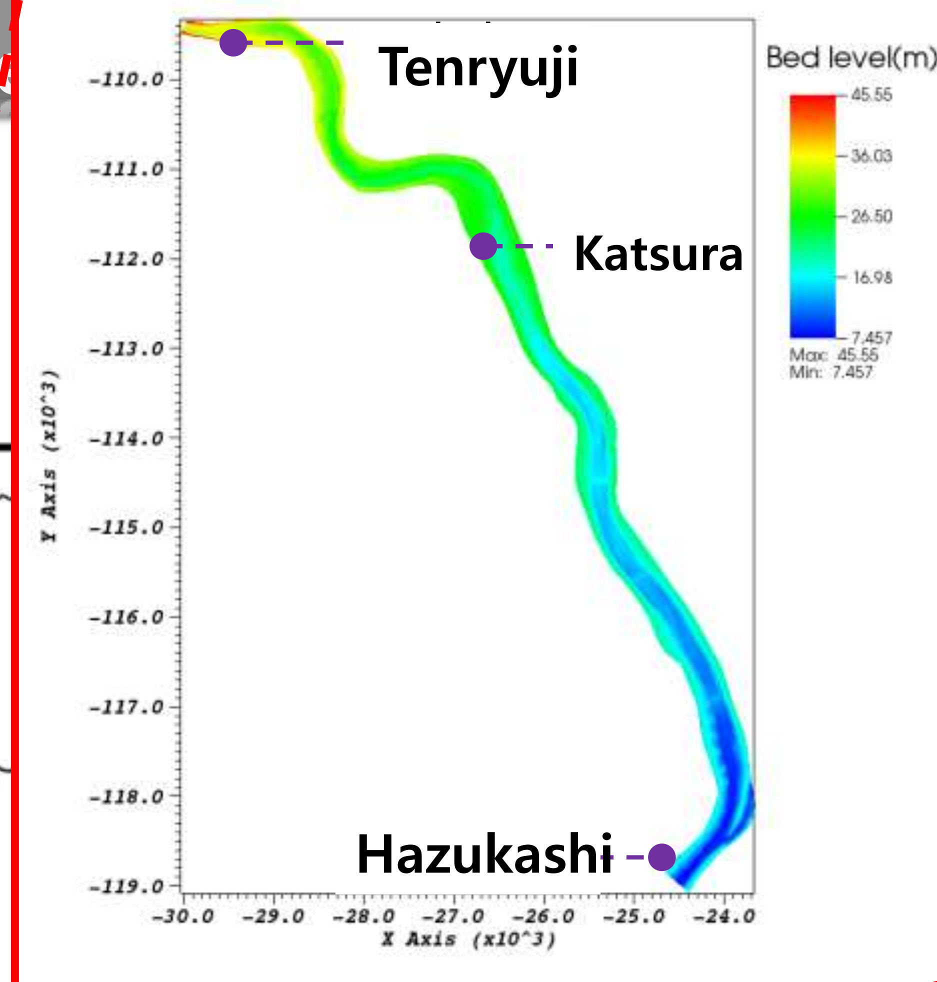


Methodology – Noise specification & PF



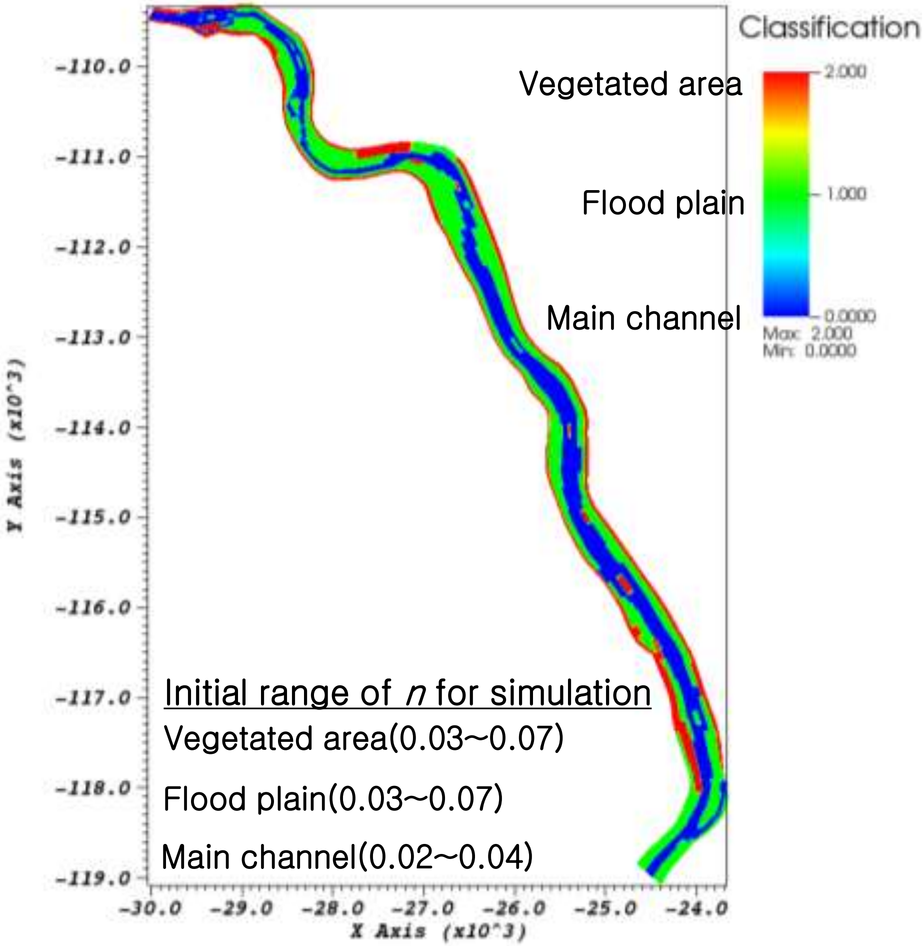
Application – Study ar





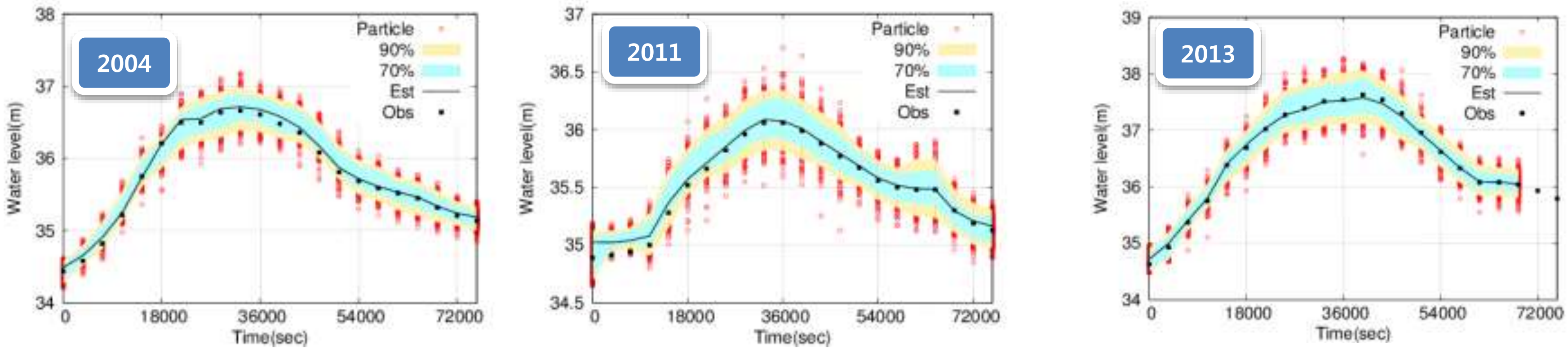
12.8km)

- Classification of Manning's *n*

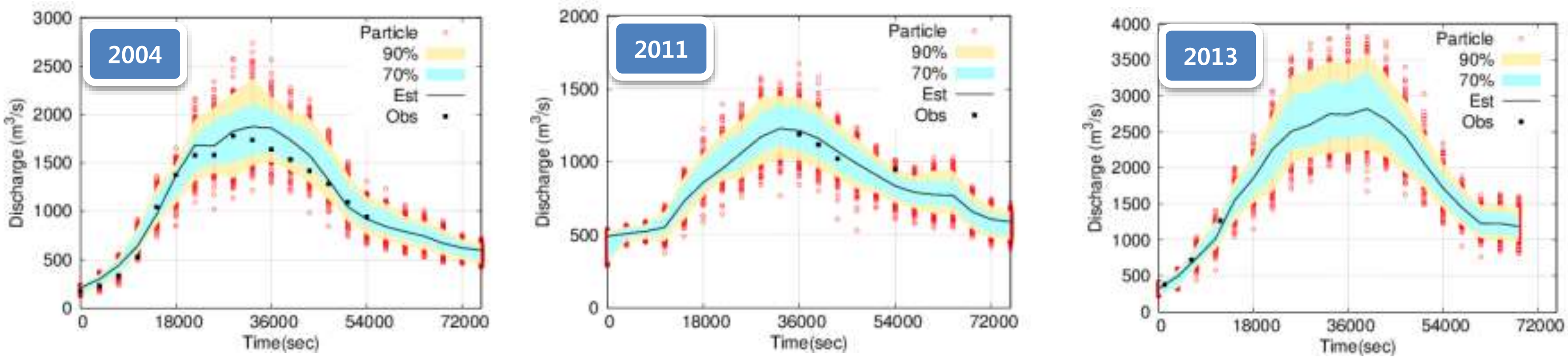


Application – Estimation of H & Q

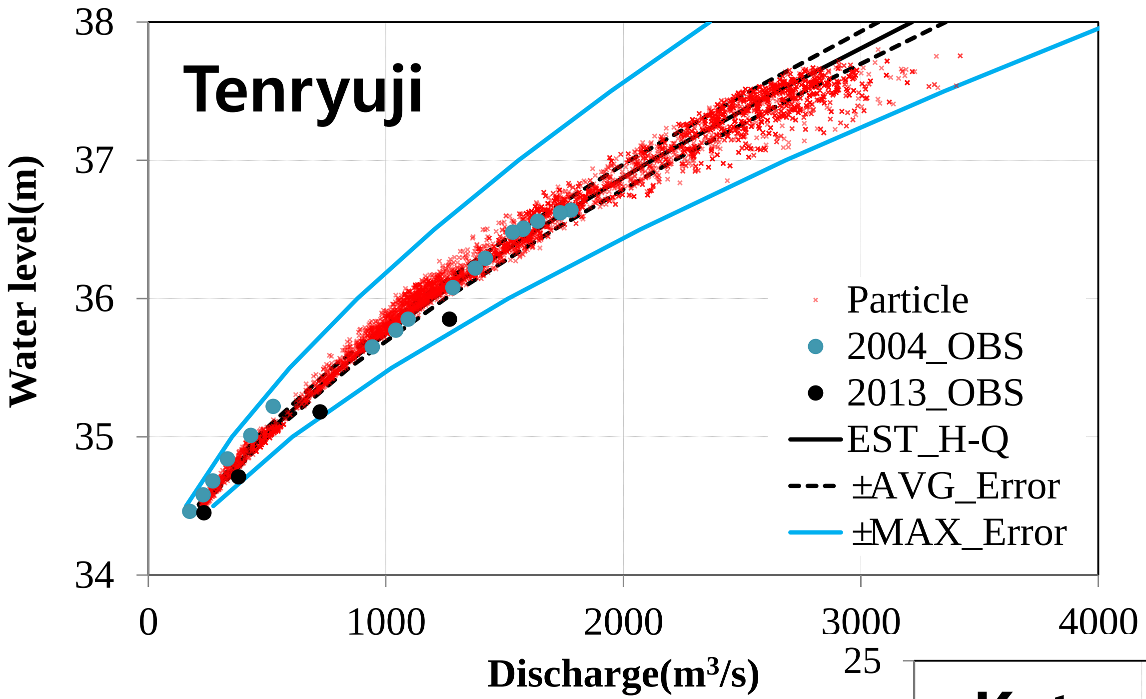
- Estimated and observed H at Tenryuji station

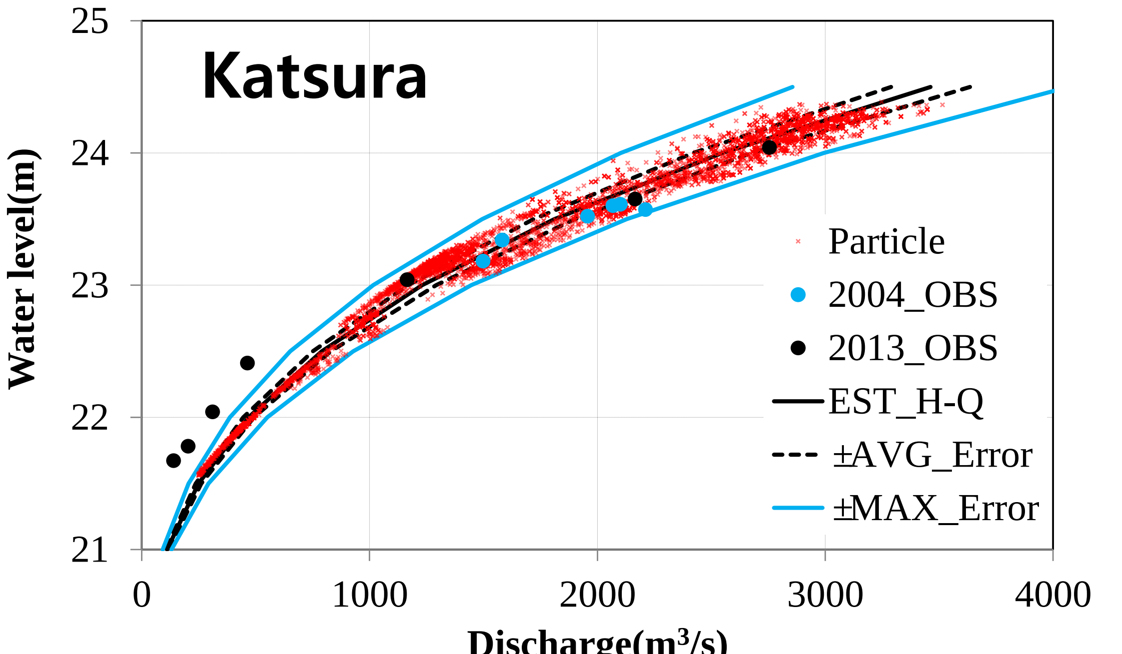


- Estimated and observed Q at Tenryuji station



Application – Assimilation-based H-Q





Conclusions

- **Applicability of particle filtering** for two hydraulic models were **evaluated**.

- **PF is sound when momentum equilibrium is important in the prediction models**

- **Assimilation-based estimation using 2-D model and PF could provide reliable H-Q relationships for poorly-gauged or ungauged basins**

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Remaining issues

- PF and dimensionality
  - Different ensembles are required for estimation of states and parameters
  - Hybrid DA to reduce dimensionality
    - PF-MLEF, PF-EnKF, …

- Real-time applications
  - Parallel computing for ensembles
  - Parallel computing within a ensemble

- More attention is needed to improve DA to consider both covariance and dynamics of the system

Thank you for your attention!

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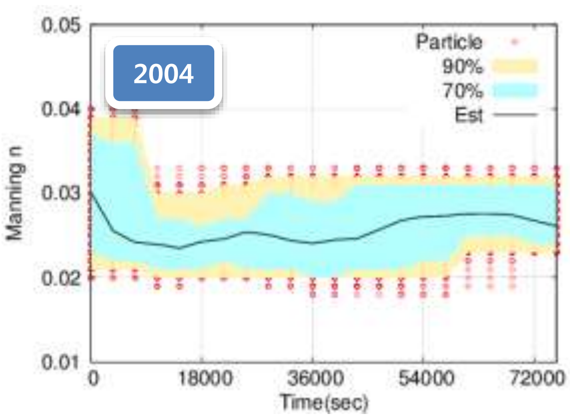
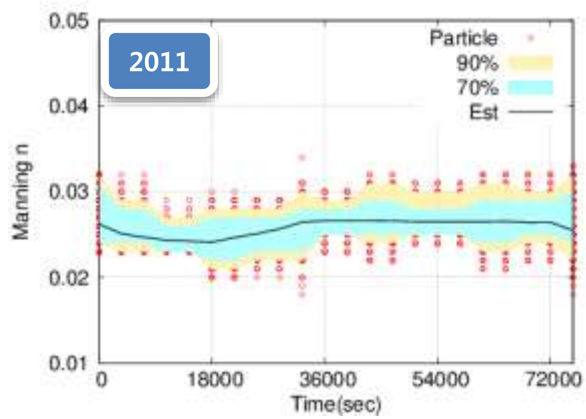
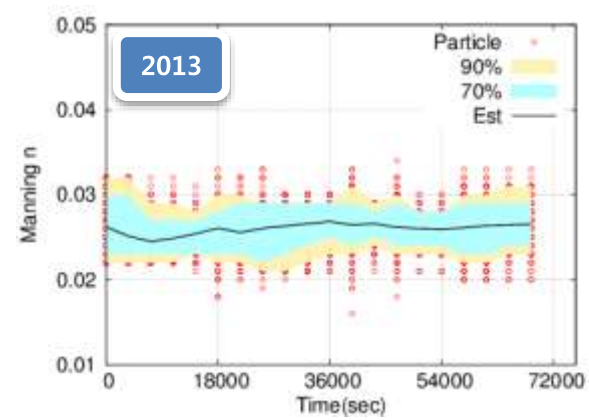
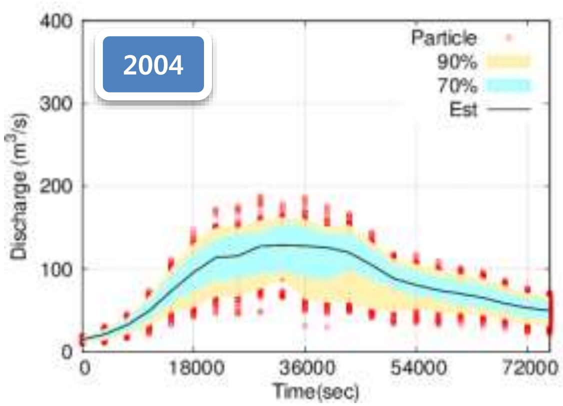
- Estimated Manning's n at main channel

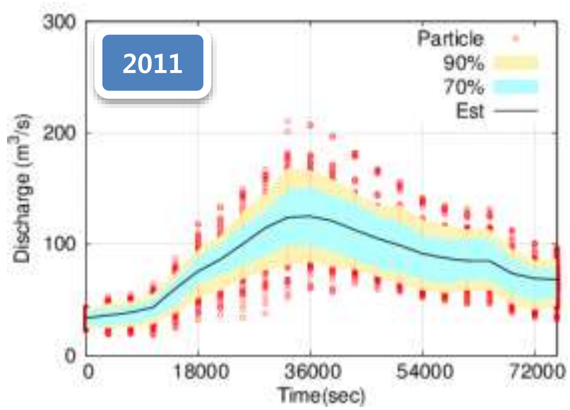


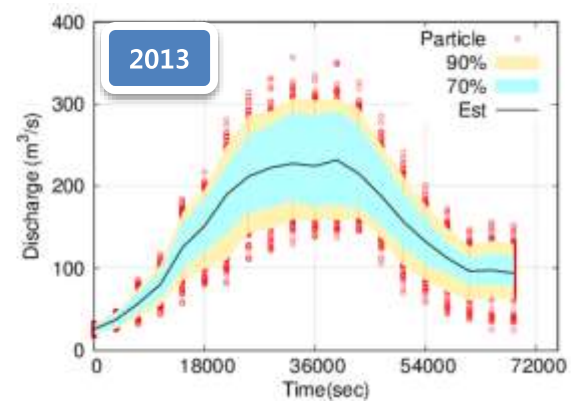




- Estimated lateral inflow from Tenryuji to Katsura station







Potential observation for data assimilation

Real-time monitoring system of sewer water level in Seoul, Korea

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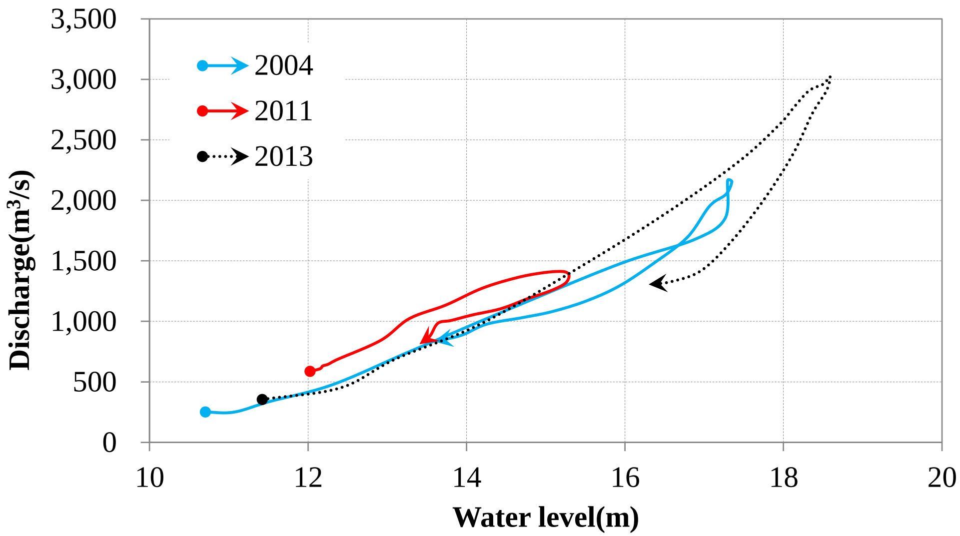
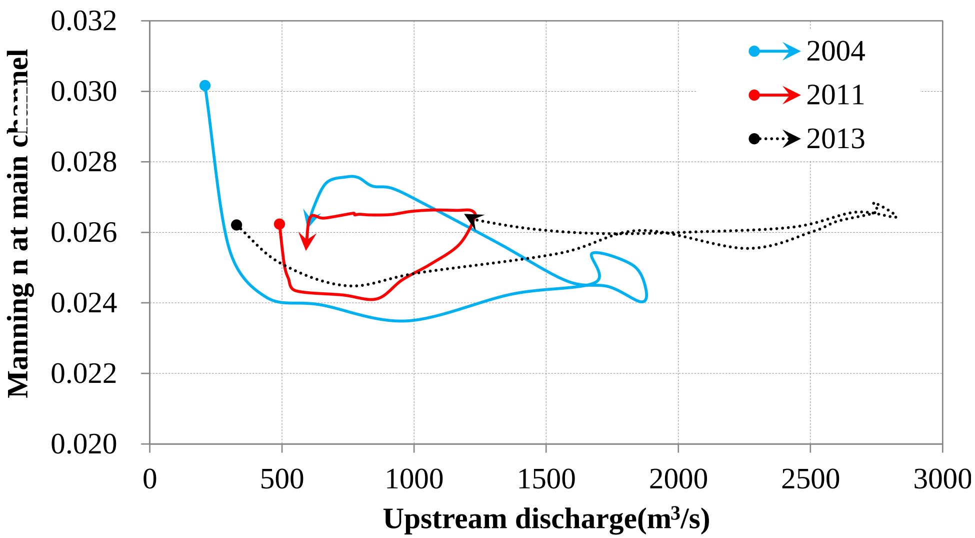
Dynamic characteristics of H-Q relationship





Connection models

- Manhole and sewer pipe

- In the case of ($h_m >= h_p$)

$$Q = 0.35 \times A_m \times \sqrt{2gh_m} \quad \textit{If } (h_p / h_m > 2/3)$$

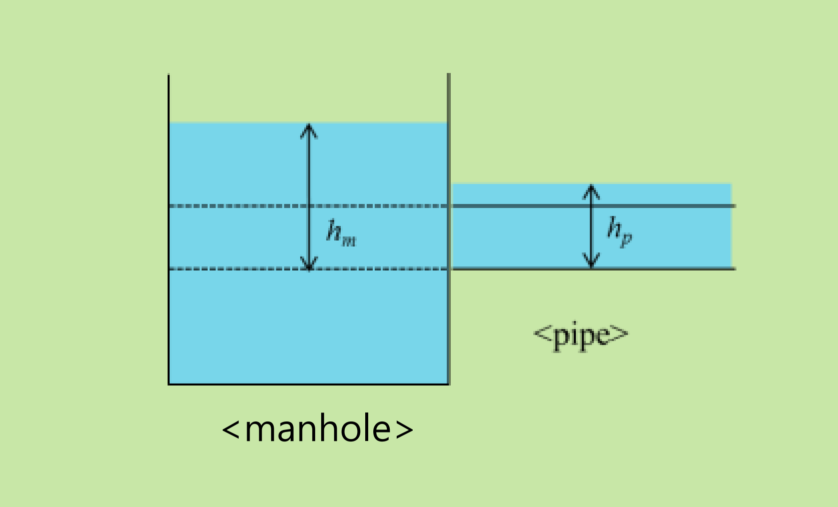
$$Q = 0.91 \times A_p \times \sqrt{2g(h_m - h_p)} \quad \textit{If } (h_p / h_m <= 2/3)$$

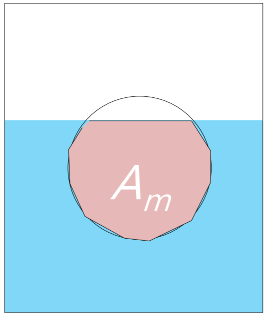
- In the case of ($h_p >= h_m$)

$$Q = -0.35 \times A_p \times \sqrt{2gh_p} \quad \textit{If } (h_m / h_p > 2/3)$$

$$Q = -0.91 \times A_m \times \sqrt{2g(h_p - h_m)} \quad \textit{If } (h_m / h_p <= 2/3)$$

z_m : elevation of manhole
h_m : water depth of manhole
v_m : velocity of manhole
g : gravity acceleration
z_p : elevation of pipe
h_{cp} : critical depth of pipe
v_p : critical velocity of pipe
h_p : critical depth of pipe + velocity head





A_m : calculated by h_m
A_p : calculated by h_{cp}

Fig. Concept of virtual area of manhole

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Introduction

- **Urban inundation** due to heavy rainfall and climate change is an inevitable problem for many cities around the world and constitutes a severe threat to residential life, property and infrastructure(Mark et al., 2004)
- Therefore, it is important **to accurately simulate urban hydrological processes** and efficiently predict the potential risks of urban floods (Lee et al., 2009)
- However, it is **insufficient to obtain accurate predictions due to various uncertainties coming from input forcing data, model parameters, and observations**.