2016 TCCIP Workshop on Applications of Climate Change Projection

Modeling of Urban Inundation and its Application Potential to Climate Change Impact

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New Taipei, Taiwan

Disaster Prevention Research Institute,
Kyoto University, Japan

SOUSEI Program for Risk Information on Climate Change 気候変動リスク情報創生プログラム

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Introduction

Program for Risk Information on Climate Change – SOUSEI Program

Theme A: Prediction and diagnosis of imminent global climate change

Theme B: Climate change projection contributing to stabilization target setting

Theme C: Development of basic technology for risk information on climate change

Theme D: Precise impact assessments on climate change

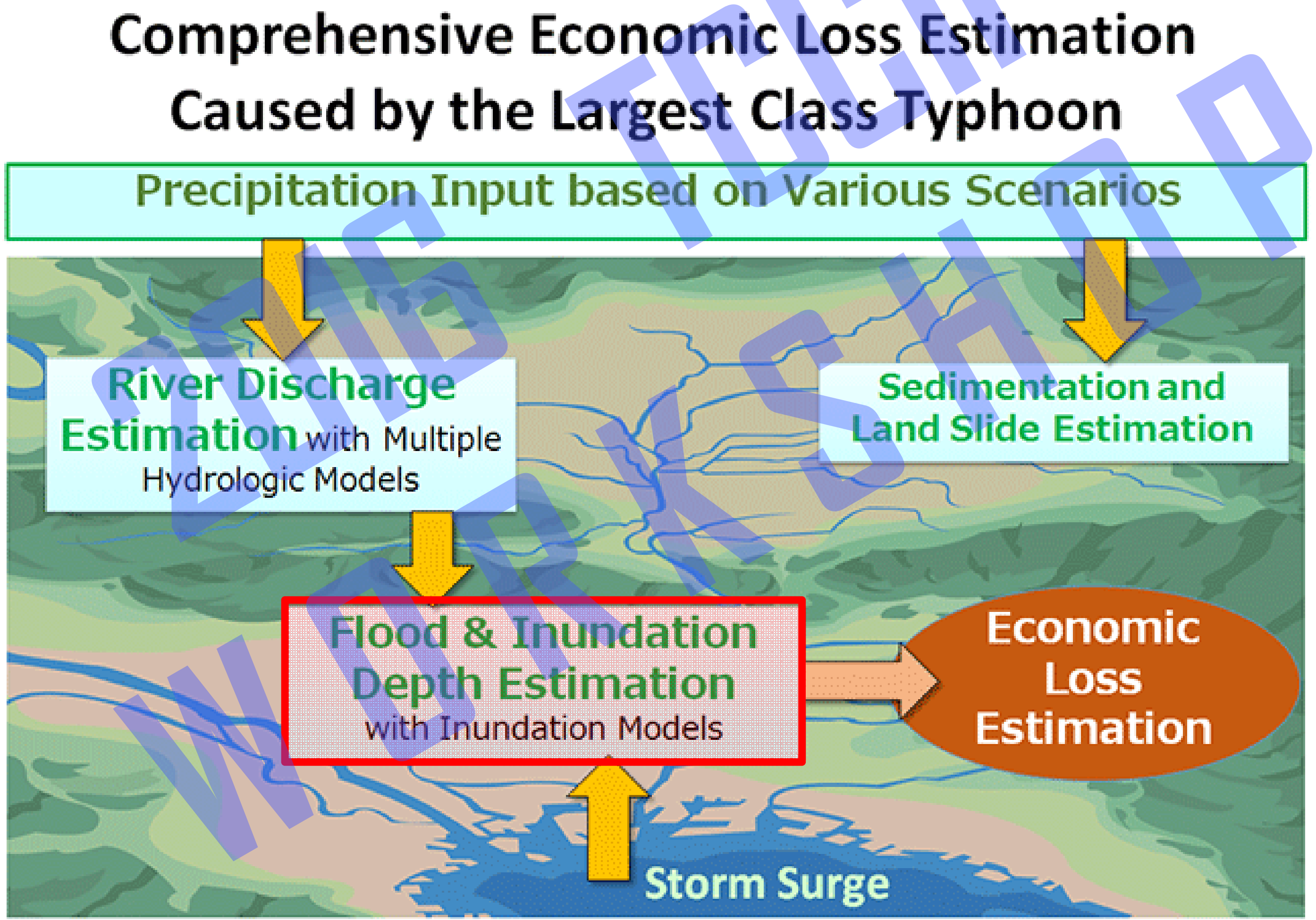
Climate change impacts on Natural Hazards

Climate change impacts on Water Resources

Climate change impacts on Ecosystem and Biodiversity

Introduction

Program for Risk Information on Climate Change – SOUSEI Program



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Introduction

River flood inundation – application of predicted flood discharge

Urban inundation – potential application of rainfall prediction

Summary

Kanto Regional Development Bureau,
Ministry of Land, Infrastructure, Transport and Tourism, Japan

River flood inundation – application of predicted flood discharge

Collaborative simulation within the SOUSEI program

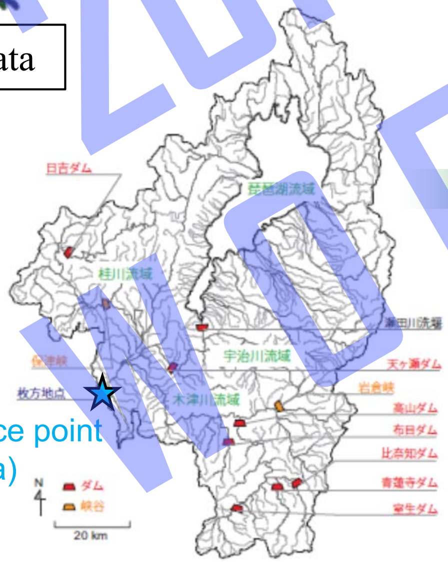
Typhoon simulation

WRF/ARW Ver. 3.3.1

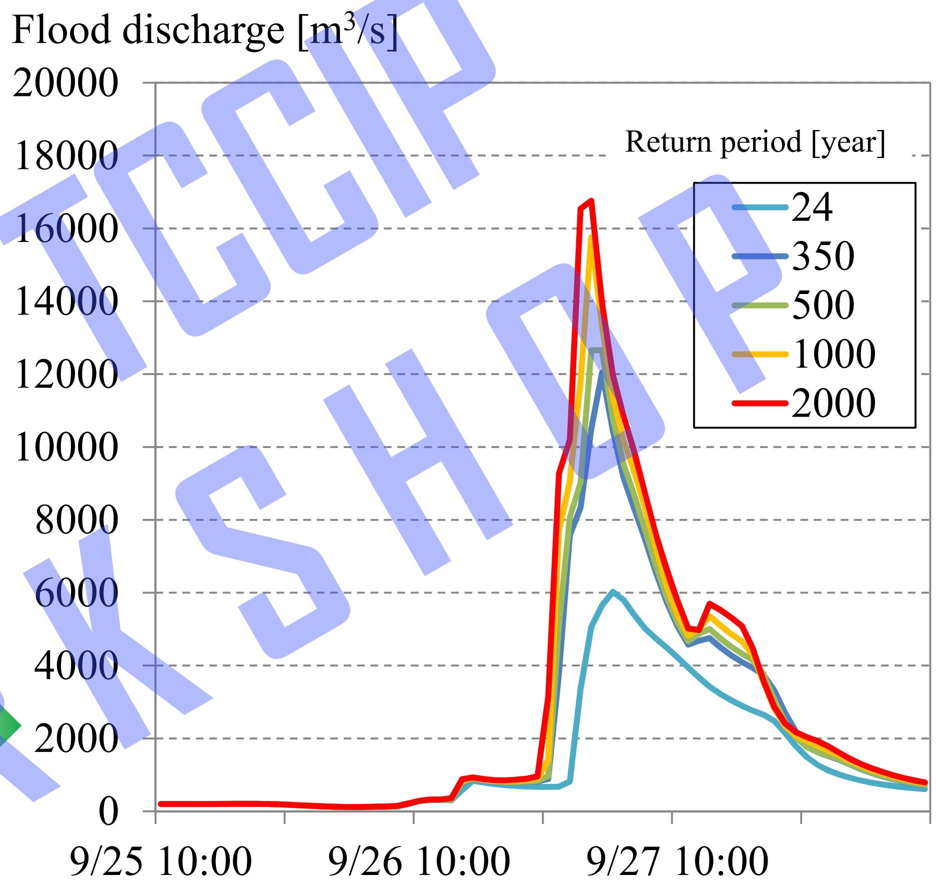
Reproducing simulation of the Isewan Typhoon under the condition of pseudo global warming

Rainfall data

Rainfall-Runoff simulation



Reference point (Hirakata)

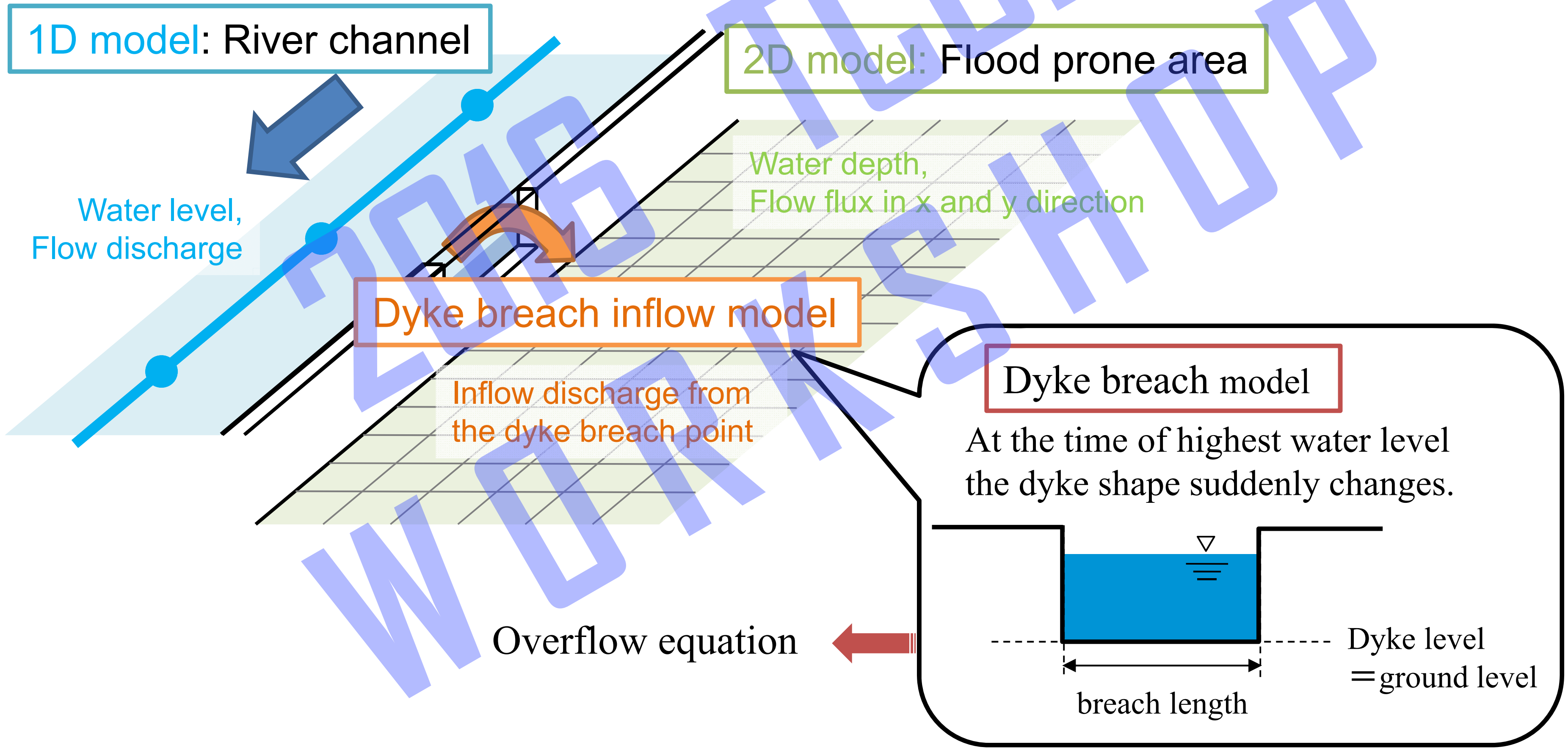


Predicted flood discharge

Figures and results are cited from Miyawaki et al. (2016)

River flood inundation – application of predicted flood discharge

River flood flow and inundation flow are simultaneously calculated. Inundation flow is calculated using the inflow discharge from the breach point as the boundary condition.



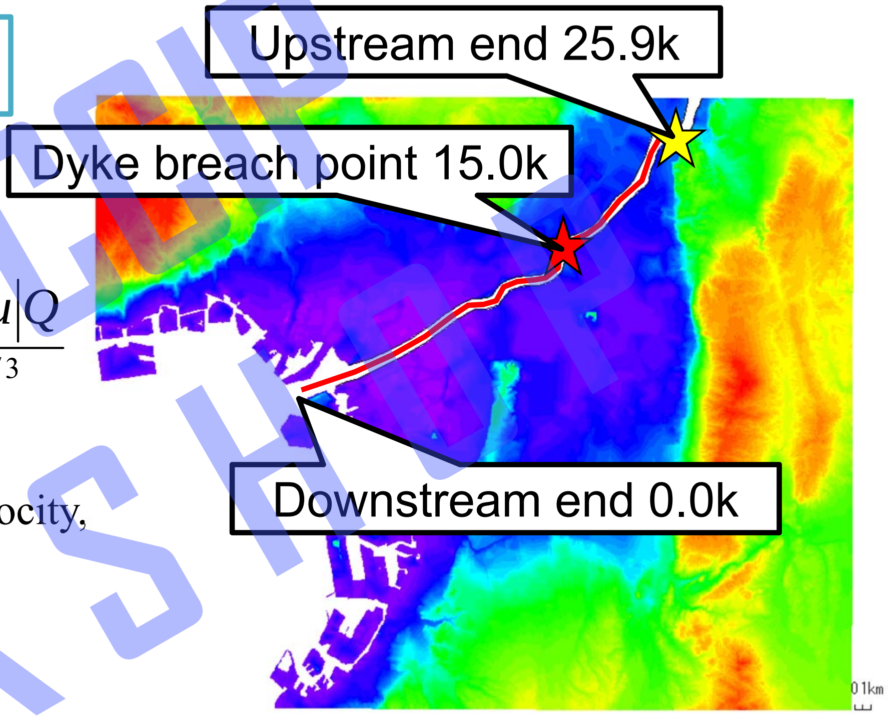
River flood inundation – application of predicted flood discharge

1D model of the river flood

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

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

A: cross sectional area, Q: flow discharge,
q: inflow discharge per unit length, u: flow velocity,
h_R: water depth, z_b: river bed elevation,
n: Manning's roughness coefficient,
R: hydraulic radius



A dyke breach is assumed at 15 km point upstream from the river mouth.

Inflow discharge from the dyke breach point

$$h_2/h_1 \leqq 2/3 \quad q = \mu L h_1\sqrt{2gh_1}$$

$$h_2/h_1 > 2/3 \quad q = \mu' L h_2\sqrt{2g(h_1 - h_2)}$$

$h_1 = H_r - H_0$, $h_2 = H_f - H_0$
H_r: river water level,
H_0: top crown level of river embankment,
H_f: water level of residential area

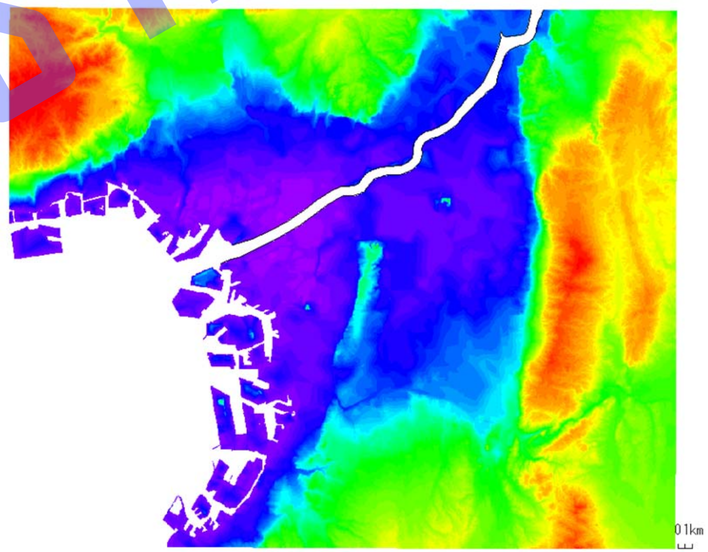
2D model of overland inundation

$$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=-q_0$$

$$\frac{\partial M}{\partial t}+\frac{\partial uM}{\partial x}+\frac{\partial vM}{\partial y}=-gh\frac{\partial (z_G+h)}{\partial x}+\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial M}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial M}{\partial y}\right)-\frac{\tau_{bx}}{\rho}$$

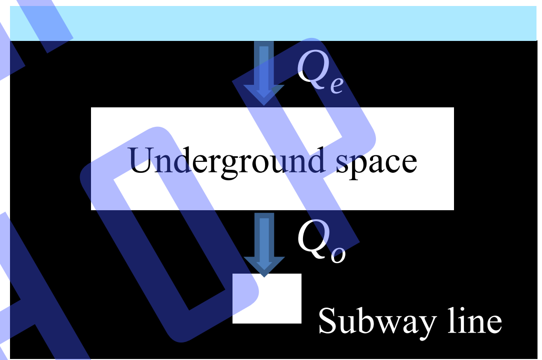
$$\frac{\partial N}{\partial t}+\frac{\partial uN}{\partial x}+\frac{\partial vN}{\partial y}=-gh\frac{\partial (z_G+h)}{\partial y}+\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial N}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial N}{\partial y}\right)-\frac{\tau_{by}}{\rho}$$

u, v: flow velocity, h: water depth, M, N: flow flux,
z_G: elevation, τ_{bx}, τ_{by}: bottom shear stress,
ρ: water density, q_0: outflow discharge per unit area
($q_0 = \sum q_n l_n/\Delta x\Delta y$,
q_n: inflow discharge per unit length of the mesh,
l_n: river length included in the mesh, $\Delta x\Delta y$: mesh area),
ε_x, ε_y: eddy viscosity coefficient



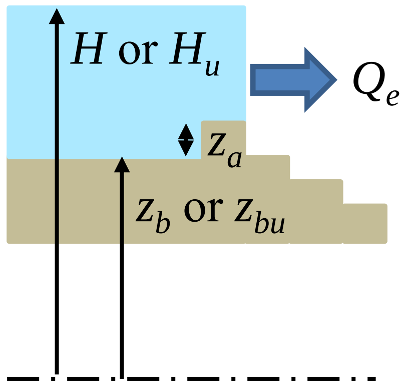
Modeling of underground shopping mall and subway station

$$A_u \frac{\partial h_u}{\partial t} = \sum Q_e - \sum Q_o$$



A_u: floor area of the underground space,
h_u: water depth of the underground space,
Q_e: inflow discharge at the entrance to the underground space,
Q_o: outflow discharge to the subway line

$$h_2/h_1 \leqq 2/3 \qquad Q_e = \mu L h_1 \sqrt{2gh_1}$$
$$h_2/h_1 > 2/3 \qquad Q_e = \mu' L h_2 \sqrt{2g(h_1 - h_2)}$$



h_1/h_2: larger/smaller water depth derived from the followings,
$h_1/h_2 = H - z_b - z_a$ or $H_u - z_{bu} - z_a$
H: water level on the overland, H_u: water level of the underground space,
z_b: overland elevation, z_a: step height of the entrance, z_{bu}: bottom level of the underground space,
L: entrance width

River flood inundation – application of predicted flood discharge

Modeling of subway lines – 1D slot model

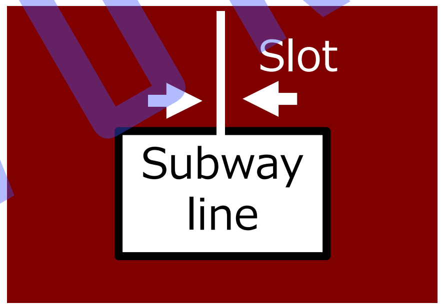
$$\frac{\partial A_s}{\partial t}+\frac{\partial Q_s}{\partial x}=q_o$$

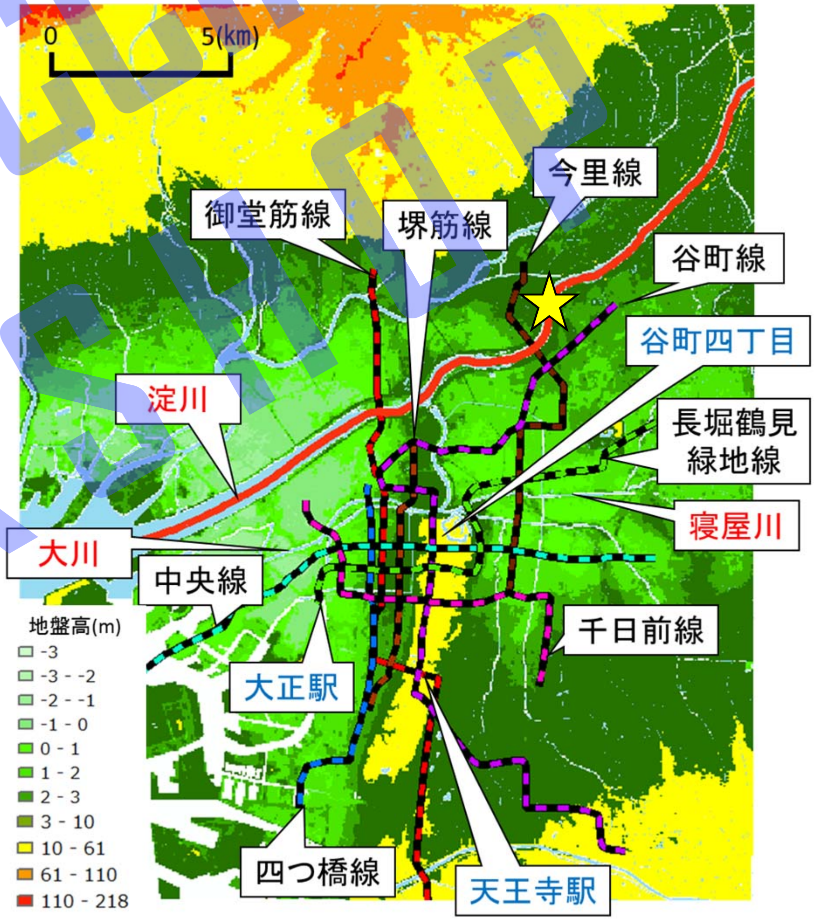
$$\frac{\partial Q_s}{\partial t}+\frac{\partial U_s Q_s}{\partial x}=-gA_s\frac{\partial (h_s+z_{bs})}{\partial x}-\frac{gn^2 Q_s|U_s|}{R_s^{4/3}}$$

A_s: cross sectional area, Q_s: flow discharge,
h_s: water depth of the subway line,
q_o: inflow discharge per unit length

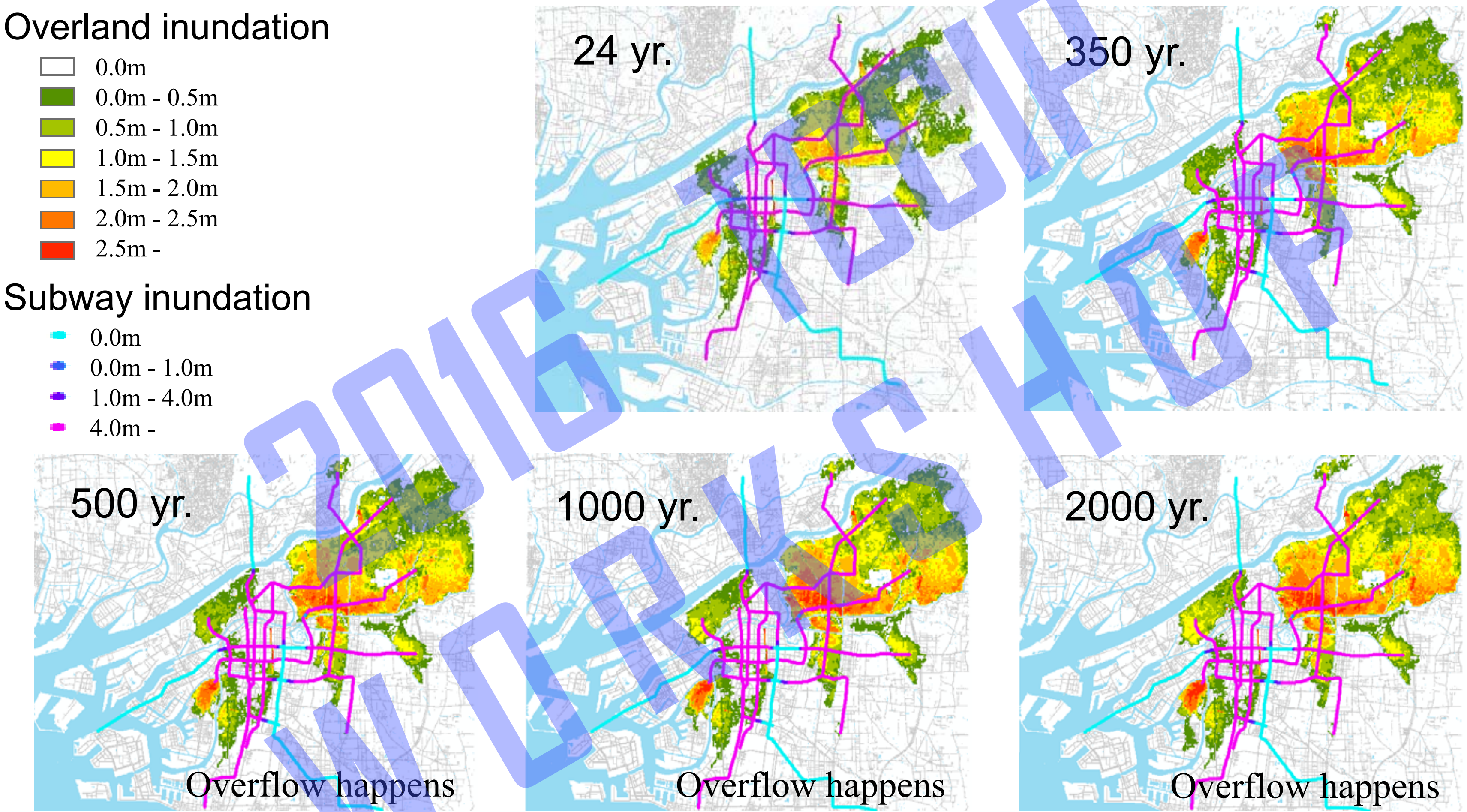
slot width $B=\frac{gA_s}{C^2}=\frac{9.8\times(4\times 7)}{20^2}=0.6(m)$

A_s: cross sectional area of subway line,
C: propagation speed of pressure wave





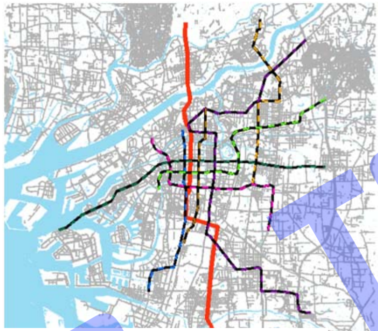
River flood inundation – application of predicted flood discharge



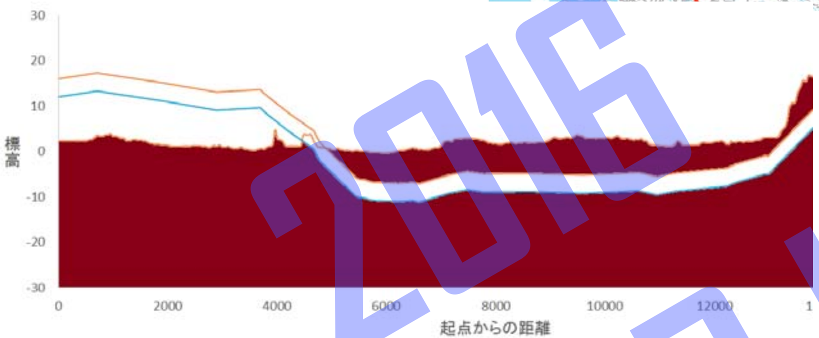
- Some part of inundation water on the ground flows into the subway line.
- Inundation occurs in some areas apart from the river through the subway lines.

River flood inundation – application of predicted flood discharge

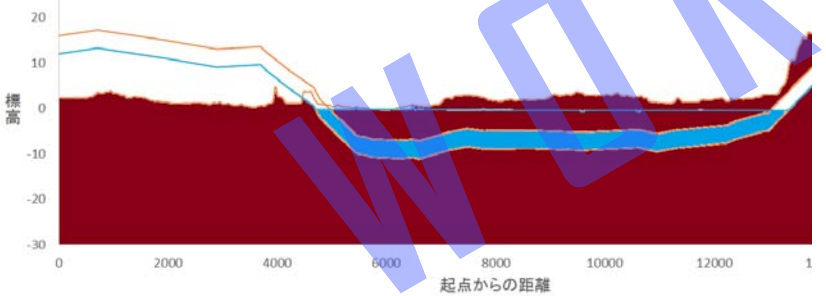
Subway Midousuji-Line



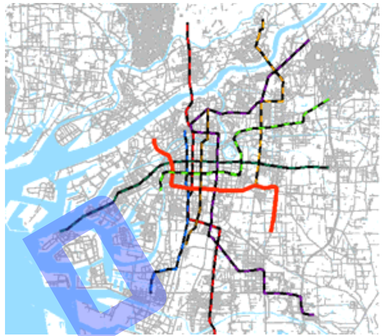
9 hours after the breach



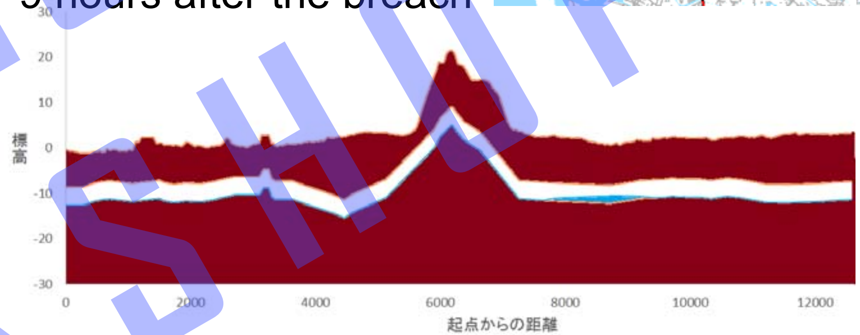
42 hours after the breach



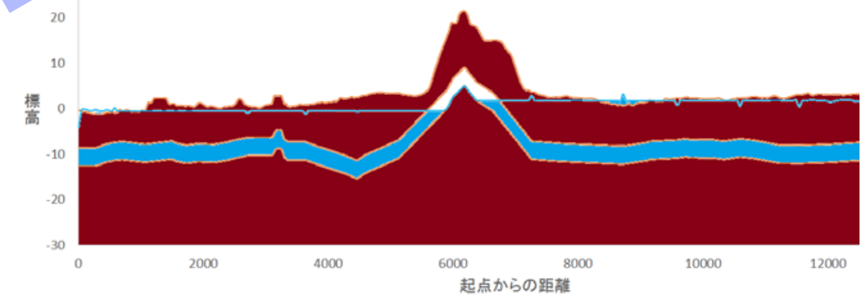
Subway Sennichimae-Line



9 hours after the breach



42 hours after the breach



※different simulation case from the previous page

River flood inundation – application of predicted flood discharge

Summary of River flood inundation

In the SOUSEI program, collaborative simulations of

① Typhoon,
② Rainfall-Runoff, River flood,
③ Overland and underground inundation

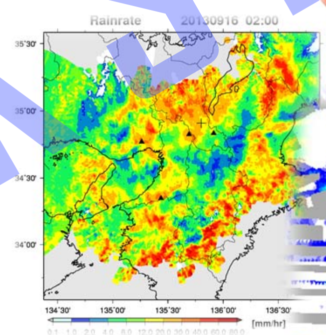
can be implemented. In addition, another team of the program is planning to estimate ④ economic loss using the above inundation results.

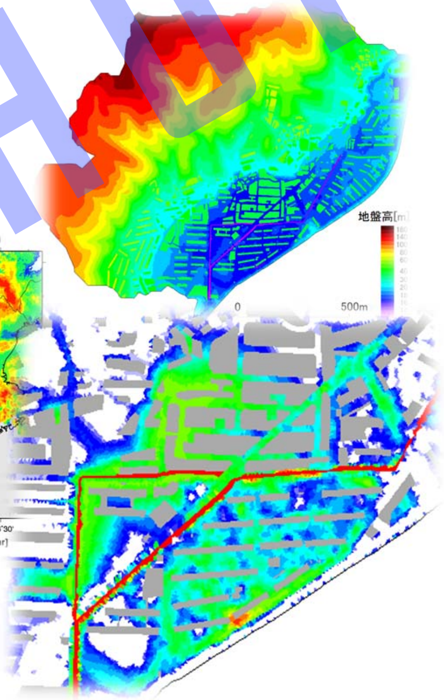
Introduction

River flood inundation – application of predicted flood discharge

Urban inundation – potential application of rainfall prediction

Summary





Urban inundation – potential application of rainfall prediction

River flood inundation might result in a severe damage of large area.

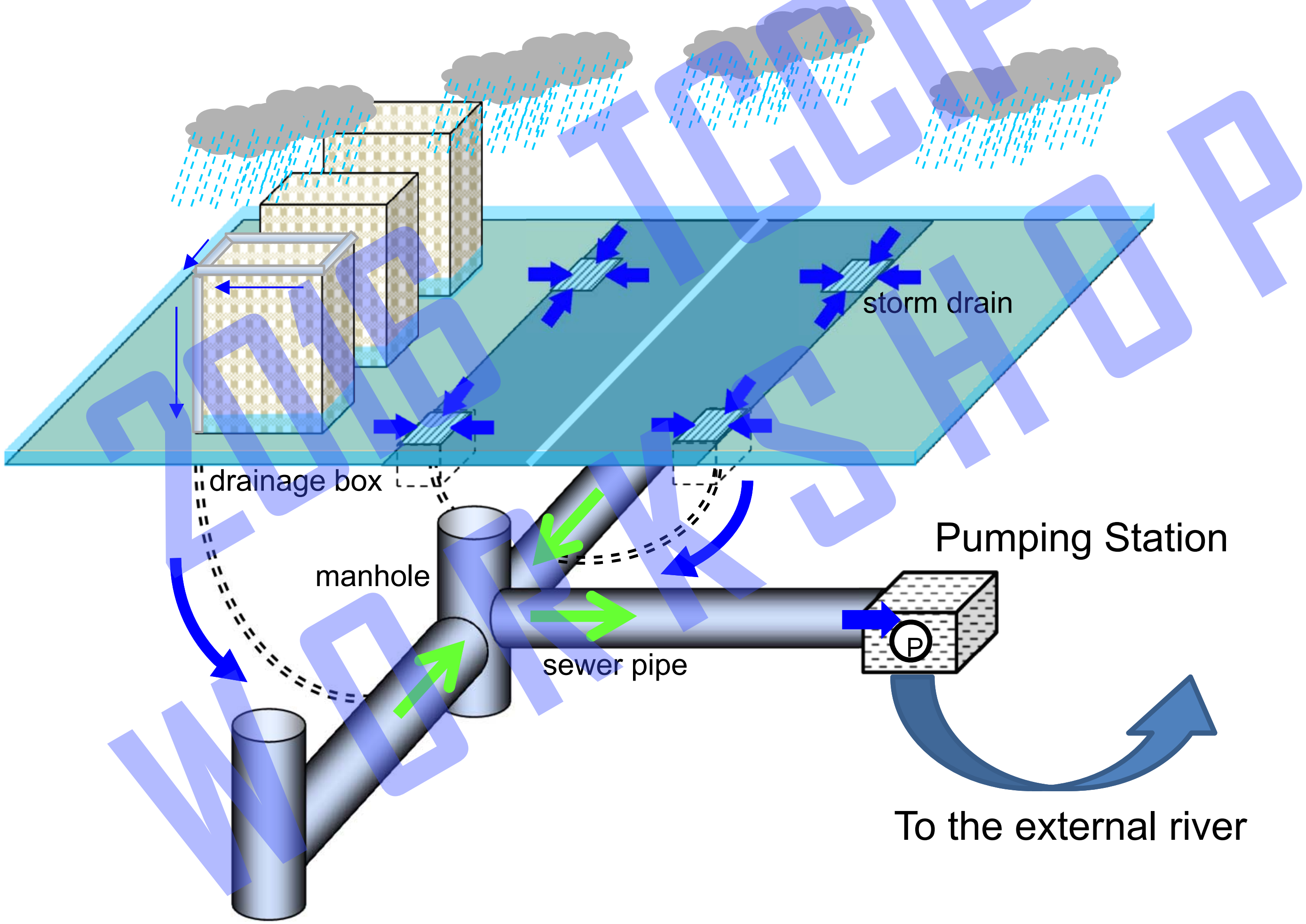
Another important issue is
local torrential rainfall during a short time period.

Such rainfall events are anticipated to be more torrential and more frequent.

It is also worried that resultant inundation disasters would occur more severely and more frequently.

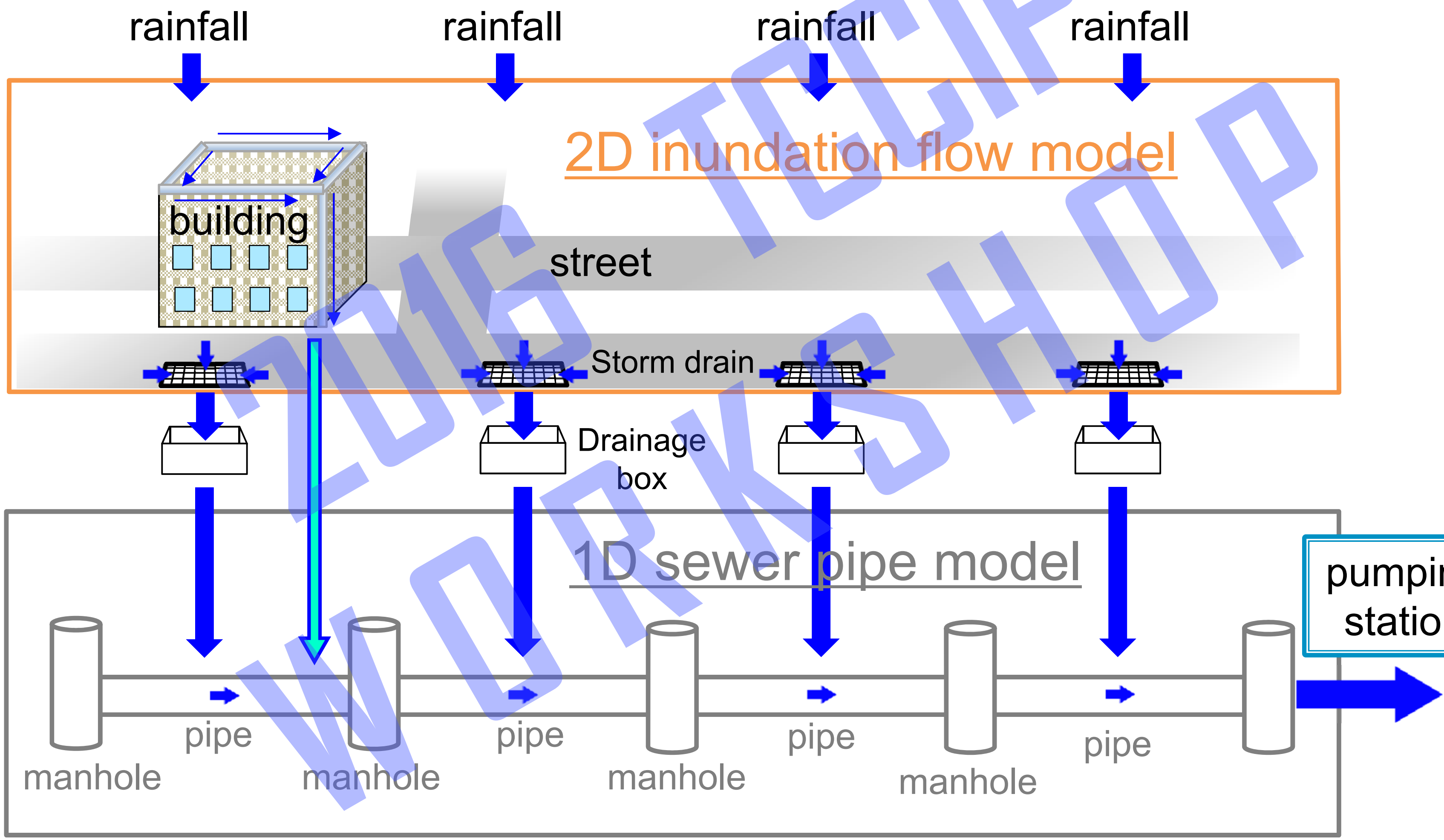
Urban inundation – potential application of rainfall prediction

Modeling of urban inundation



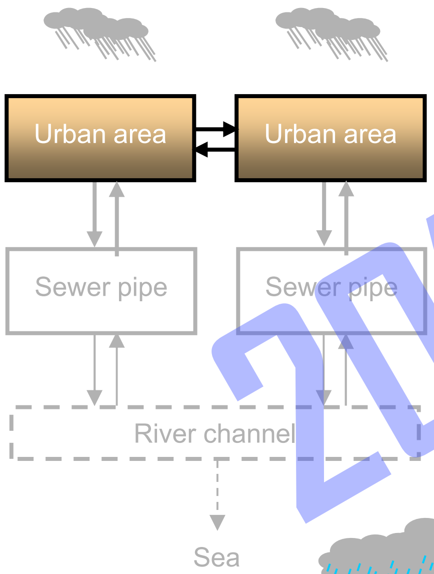
Urban inundation – potential application of rainfall prediction

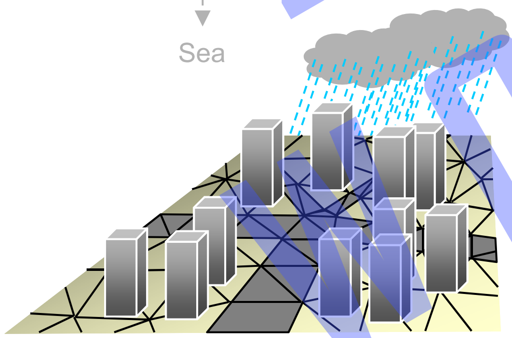
Modeling of urban inundation



Urban inundation – potential application of rainfall prediction

2D inundation flow model





2D shallow water equations

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

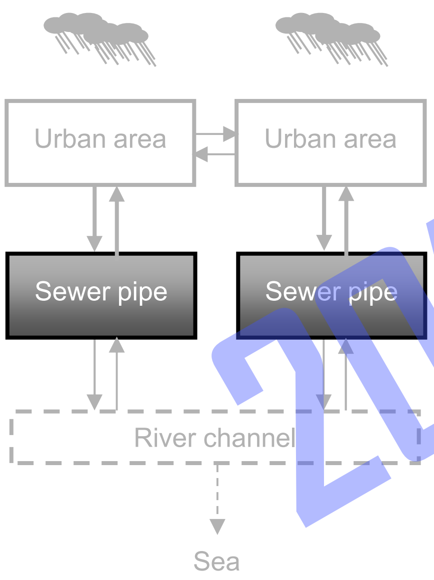
$$\frac{\partial M}{\partial t}+\frac{\partial (uM)}{\partial x}+\frac{\partial (vM)}{\partial y}=-gh\frac{\partial (z_b+h)}{\partial x}-\frac{gn^2M\sqrt{u^2+v^2}}{h^{4/3}}$$

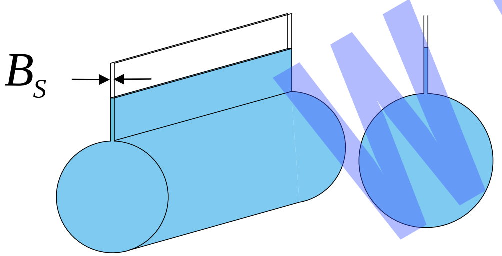
$$\frac{\partial N}{\partial t}+\frac{\partial (uN)}{\partial x}+\frac{\partial (vN)}{\partial y}=-gh\frac{\partial (z_b+h)}{\partial y}-\frac{gn^2N\sqrt{u^2+v^2}}{h^{4/3}}$$

M, N: discharge flux in x,y-directions
M^*, N^* (= βM, βN): corrected discharge flux in x, y-directions
β: correction coefficient of discharge flux r_e: effective rainfall
h: water depth z_b: ground elevation
u,v: flow velocity in x,y-directions g: gravity acceleration
n: Manning' roughness coefficient
q_{sew}: drainage discharge per unit area from the ground surface to the sewerage system

Urban inundation – potential application of rainfall prediction

1D sewer pipe model





1D unsteady flow equations (slot model)

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

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

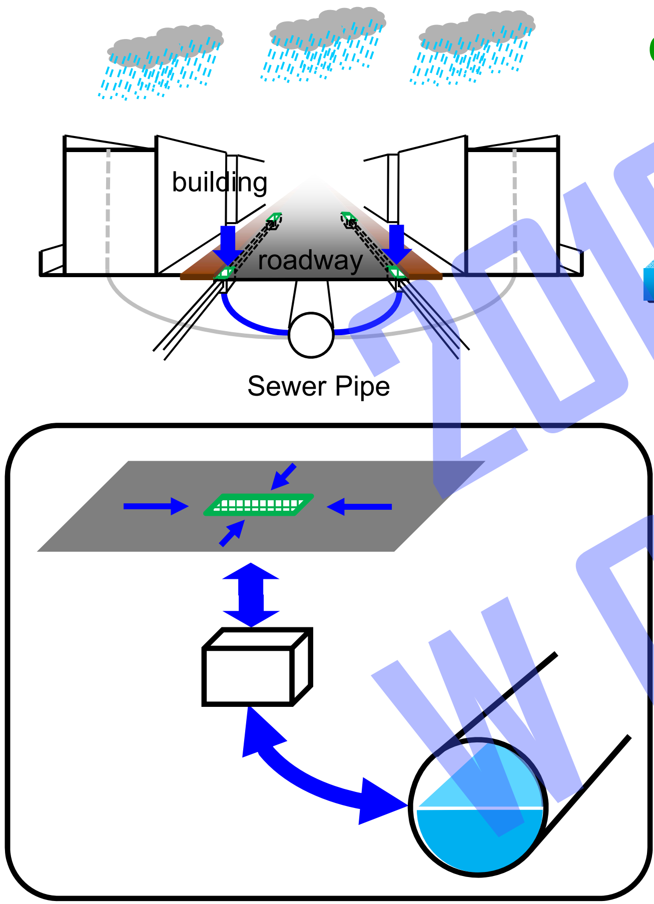
$$h=\begin{cases} f(A) & : A\le A_0 \\ D+(A-A_0)/B_s & : A>A_0 \end{cases} \qquad B_S=\frac{gA_0}{a^2}$$

A: flow area A_0: cross sectional area of the pipe Q: flow discharge
q: lateral inflow discharge u: flow velocity R: hydraulic radius
$H_p(=z+h)$: water level z: pipe bottom elevation a: pressure wave speed
B_s: slot width D: pipe diameter f: h-A relation function

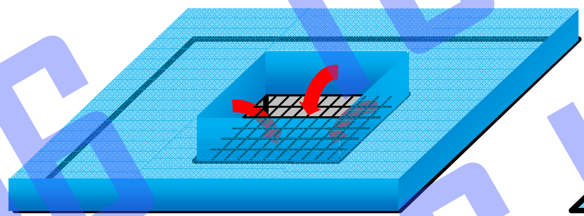
Assuming a slot on the top of the pipe, pressurized flow can be treated as hypothetical open channel flow.
Using this slot model, both pressurized flow and open channel flow can be treated by the same equations.

Urban inundation – potential application of rainfall prediction

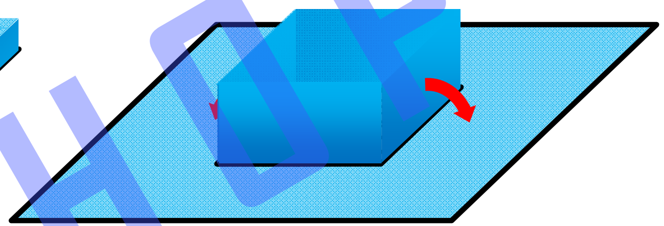
Drainage process①: ground surface ←→ drainage box
drainage box ←→ sewer pipe



drainage

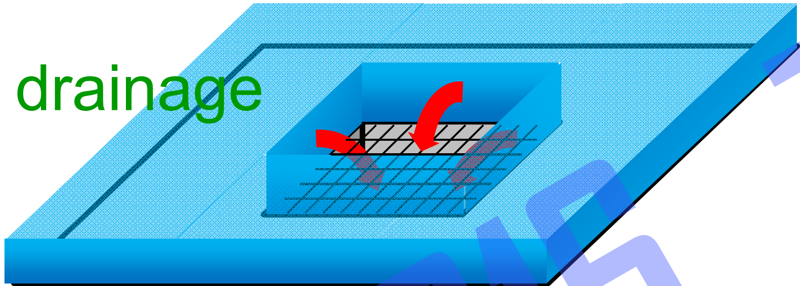


overflow



Urban inundation – potential application of rainfall prediction

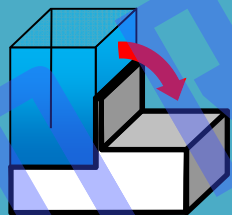
Drainage process①: ground surface ←→ drainage box
drainage box ←→ sewer pipe



weir

$$Q = \frac{2}{3} C_{dw} L \sqrt{2g} (H_t)^{\frac{3}{2}}$$

$$H_t = \left(h + \frac{v^2}{2g} \right)$$

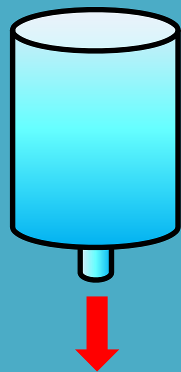


Q : flow discharge
C_{dw} : weir discharge coefficient
L : length of the storm drain
H_t : total water head
h : piezometric head
V : average flow velocity

orifice

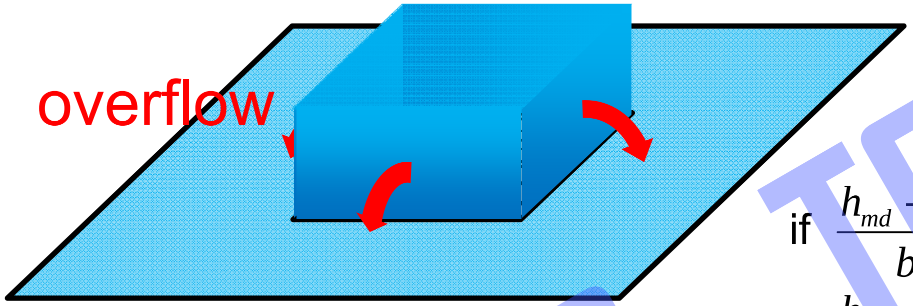
$$Q = C_{do} A \sqrt{2gh}$$

$$C_{do} = C_c \times C_v$$



Q : flow discharge
C_{do} : orifice discharge coefficient
A : orifice cross section area
h : piezometric head
C_c : account for energy losses
C_v : contraction coefficient

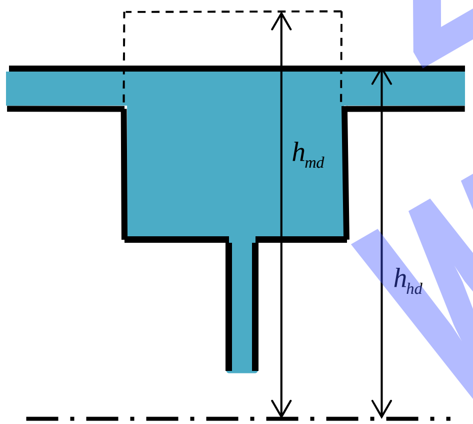
Urban inundation – potential application of rainfall prediction



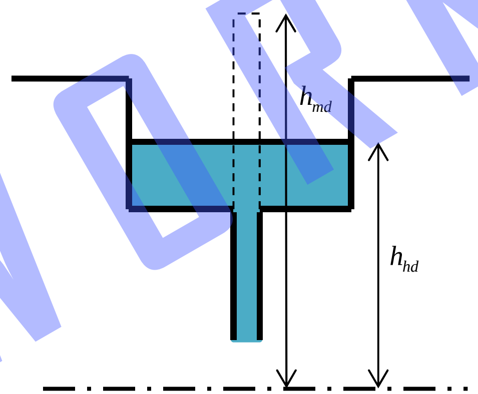
if $\dfrac{h_{md} - h_{hd}}{b_o} \geq 0.5 \quad Q = -C_{do} \times A \times \sqrt{2g(h_{md} - h_{hd})}$

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

Ground surface
↑
Drainage box



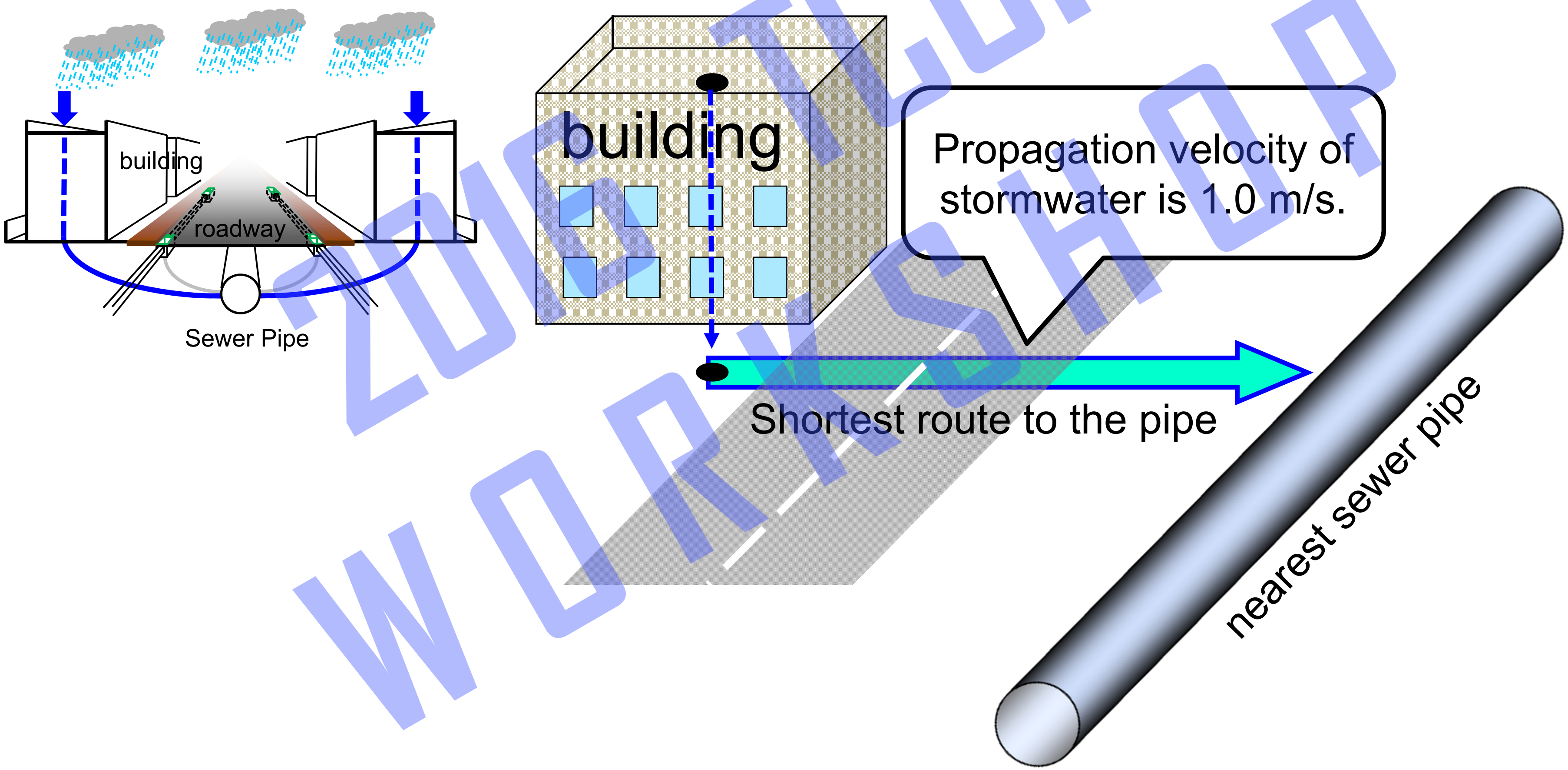
Drainage box
↑
Sewer pipe



C_{do} : orifice discharge coefficient
C_{dw} : weir discharge coefficient
Q : flow discharge
h_{hd} : water level of the drainage box or the ground surface
h_{md} : piezometric head of the sewer pipe or the drainage box
A : cross sectional area of the drainage box or the drainage pipe

Urban inundation – potential application of rainfall prediction

Drainage process②: building roof → sewer pipe



Urban inundation – potential application of rainfall prediction

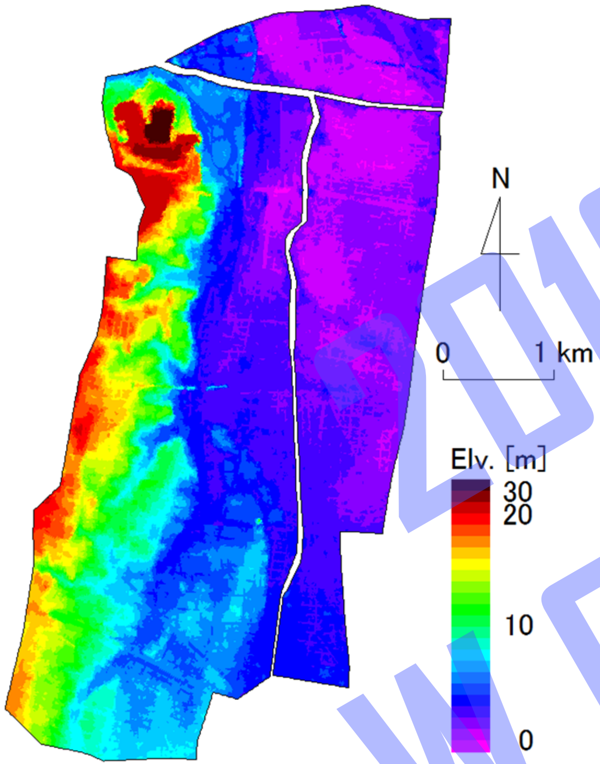
Target area

Nakahama area

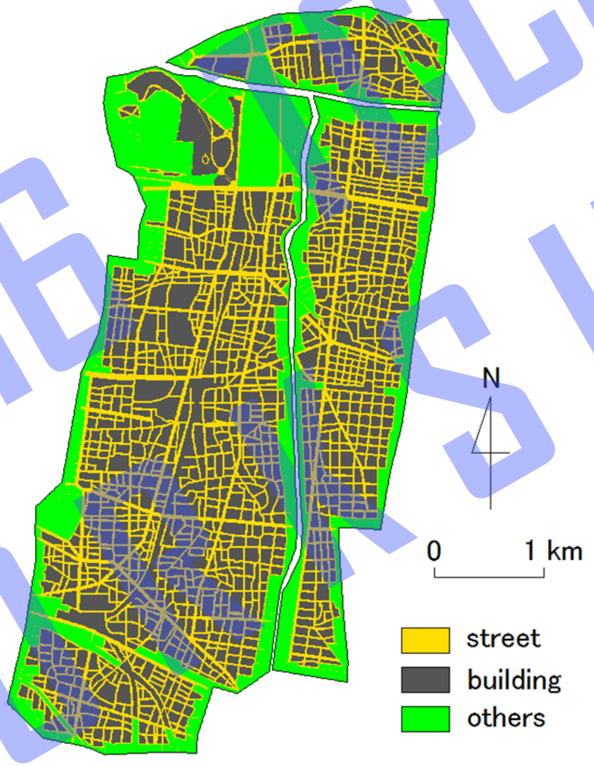
Highly urbanized
Population: 300,000
Area: 18.1 km^2

Urban inundation – potential application of rainfall prediction

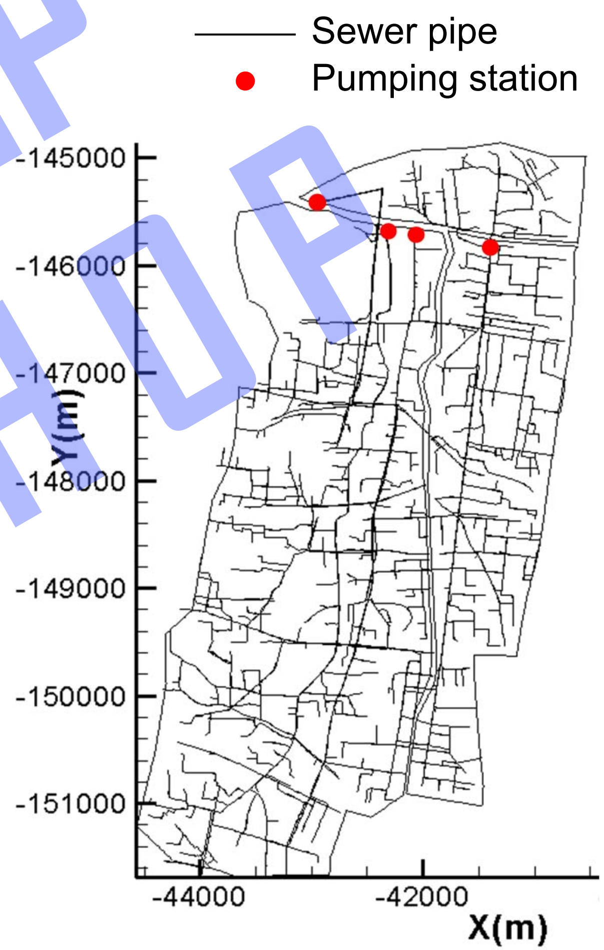
Geographical data



Mesh elevation



Mesh category



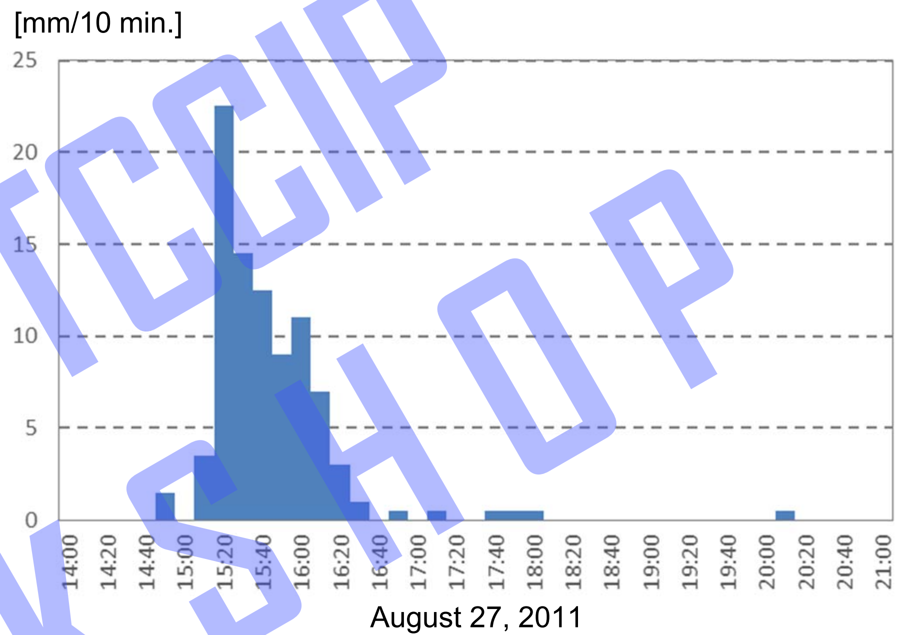
Sewer pipes

Urban inundation – potential application of rainfall prediction

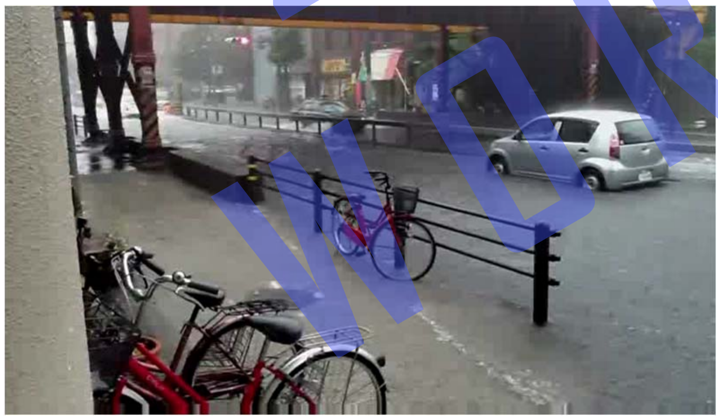
Input data

Rainfall observed at
Osaka Regional Headquarters,
Japan Meteorological Agency
during 14:00 – 21:00, Aug. 27, 2011

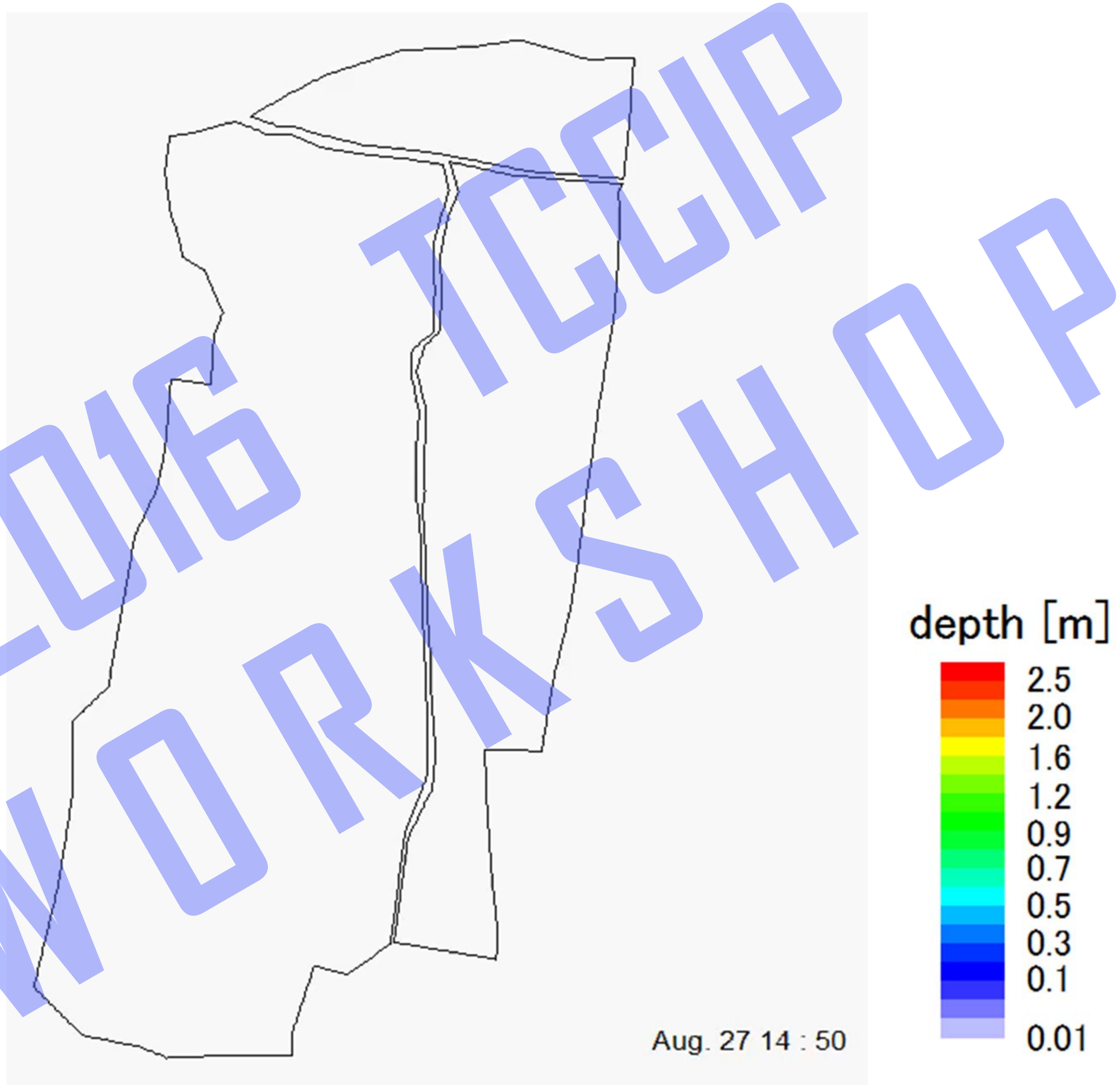
Maximum record of 1 hour rainfall since 1889!



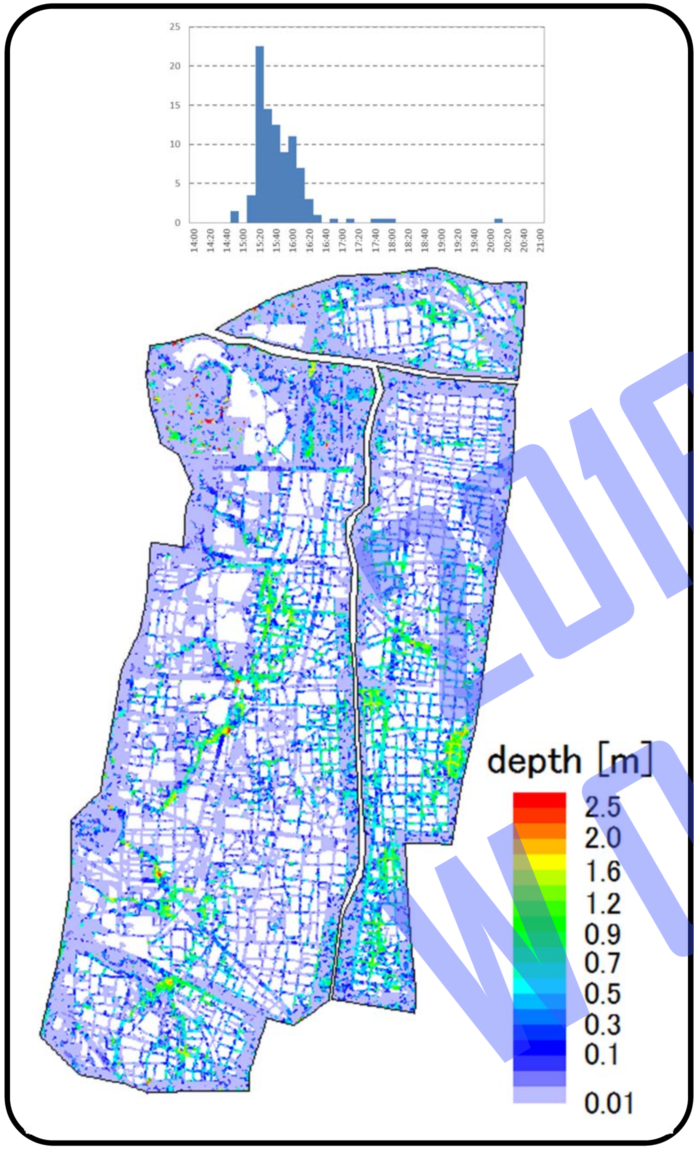
This rainfall pattern is given to the whole target area.

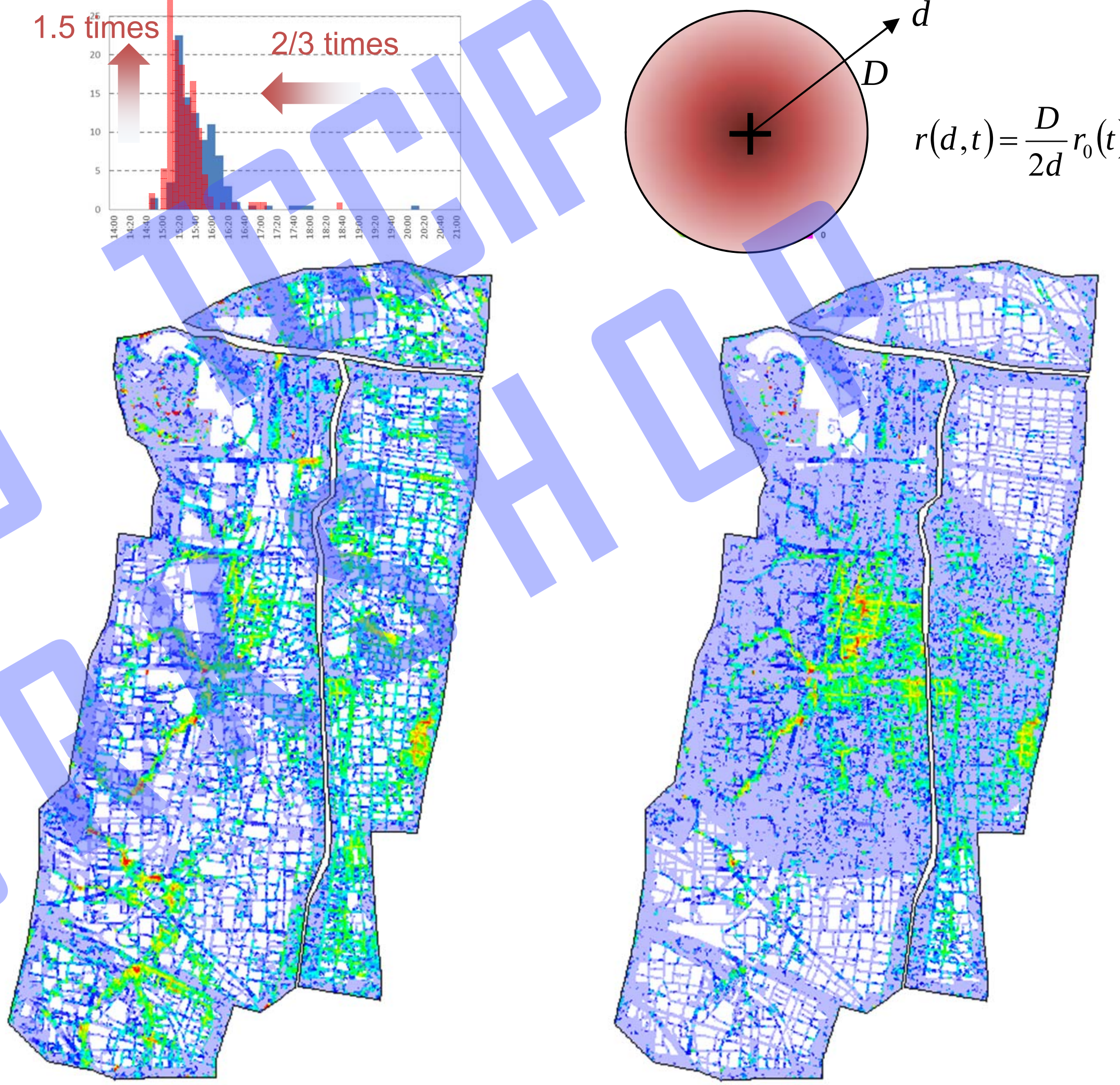


Urban inundation – potential application of rainfall prediction



Urban inundation – potential application of rainfall prediction

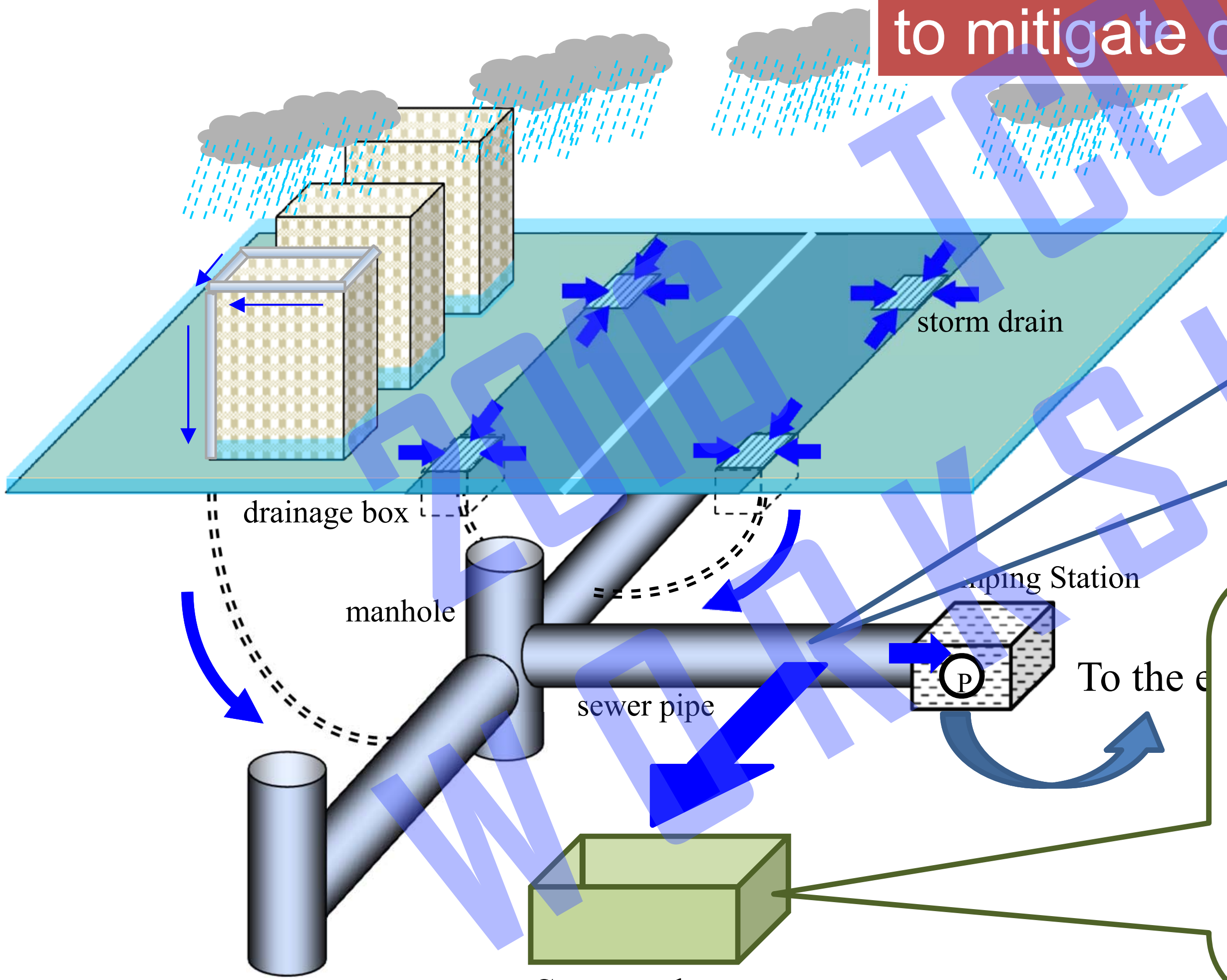


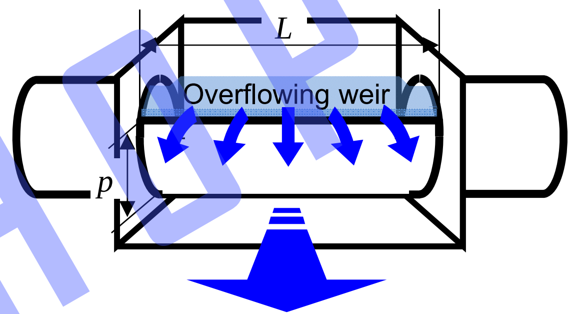


$$r(d,t) = \frac{D}{2d} r_0(t)$$

Urban inundation – potential application of rainfall prediction

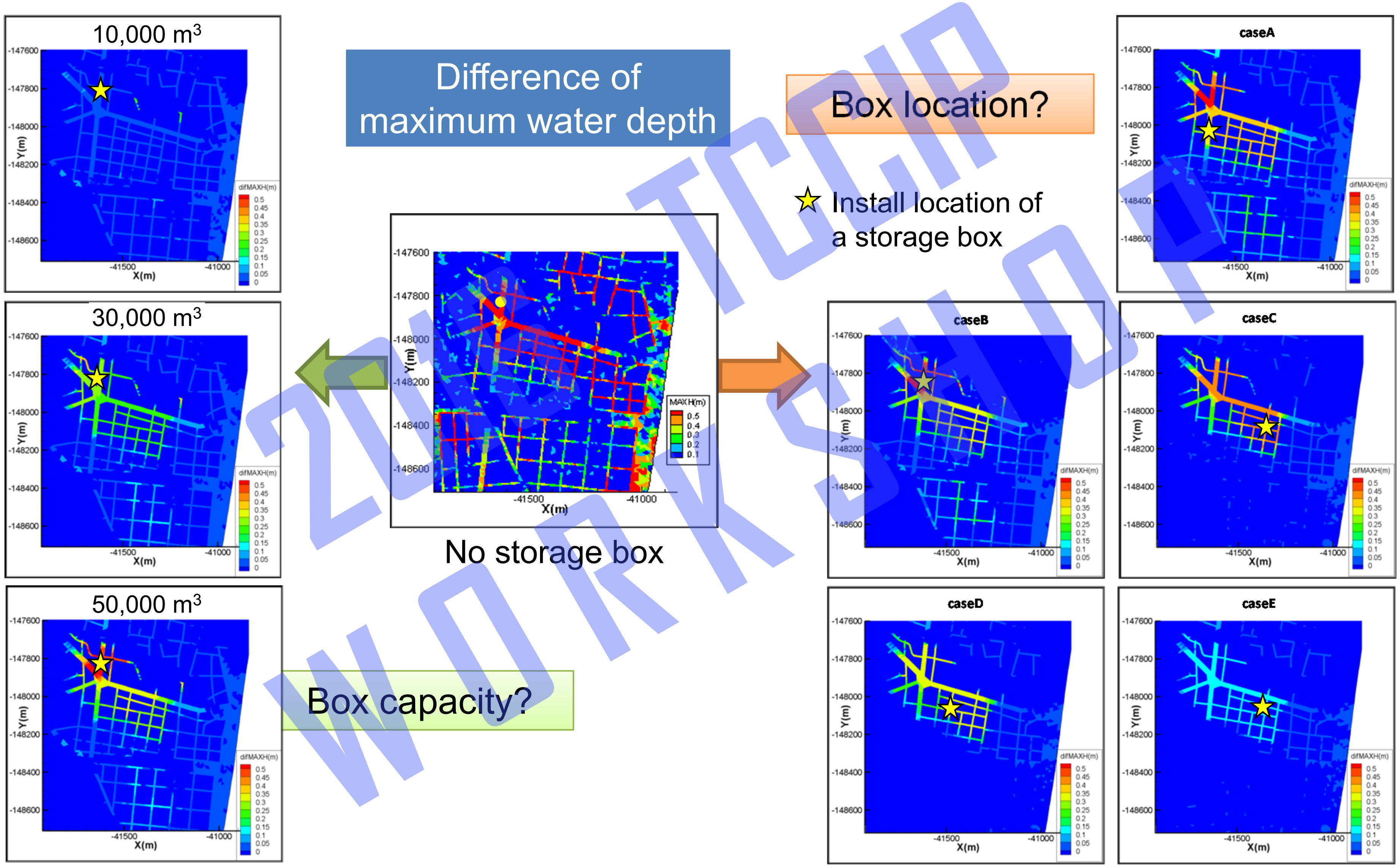
What if a storage box is installed to mitigate overland inundation?





Storage box

Urban inundation – potential application of rainfall prediction

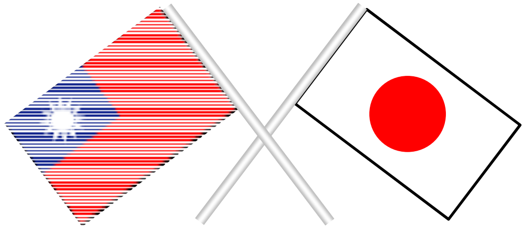


Summary of Urban inundation

- Simulation model is getting more and more sophisticated to predict urban inundation due to torrential rainfall.
  Once rainfall hyetograph is given to the model, we can estimate the time series of inundated area, depth, and flow velocity
- In order to mitigate such urban inundation disasters, suitable countermeasures should be prepared.
  Using the above mentioned model, we can have a planning and evaluate the effects of enhanced drainage system, or various storage facilities.

Summary

- Numerical simulation for both river flood and urban inundations can be carried out.
  If a boundary condition of upstream end discharge or rainfall intensity is given, inundated area, depth, and flow velocity can be estimated.
- Especially in the case of river flood inundation, a series of simulations of typhoon, rainfall-runoff, overland and underground inundation can be carried out.
- Using those models, mitigation effects of flood control facilities can be evaluate.



謝謝!

감사합니다!

Thank you very much for your kind attention!

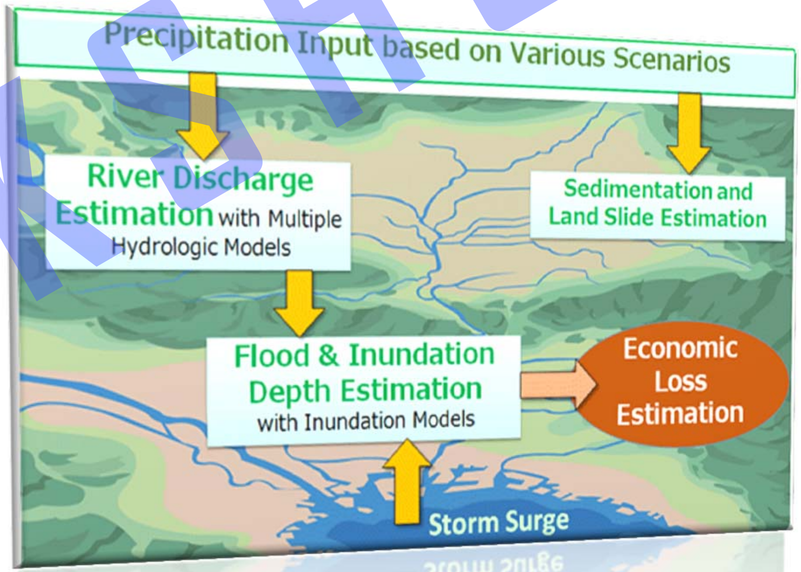
ご清聴ありがとうございました

Introduction

River flood inundation – application of predicted flood discharge

Urban inundation – potential application of rainfall prediction

Summary



What happened in Ogurisu?

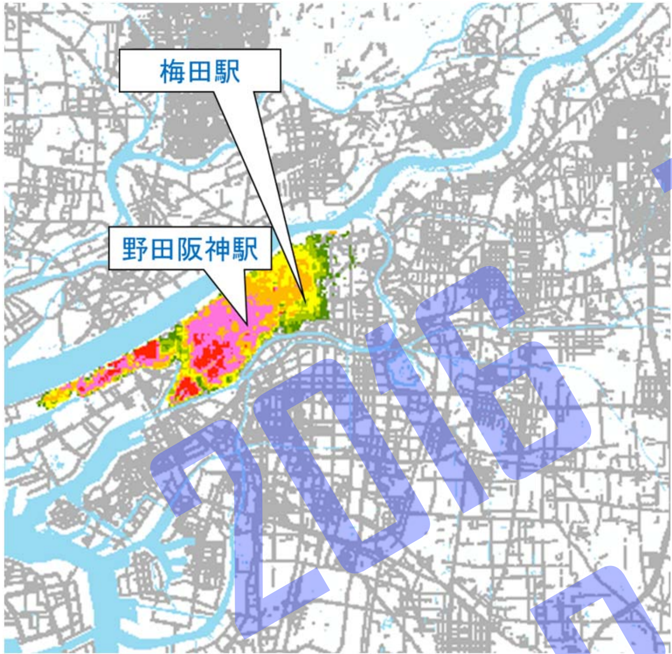
Numerical modeling of the Ogurisu area

Application and Results

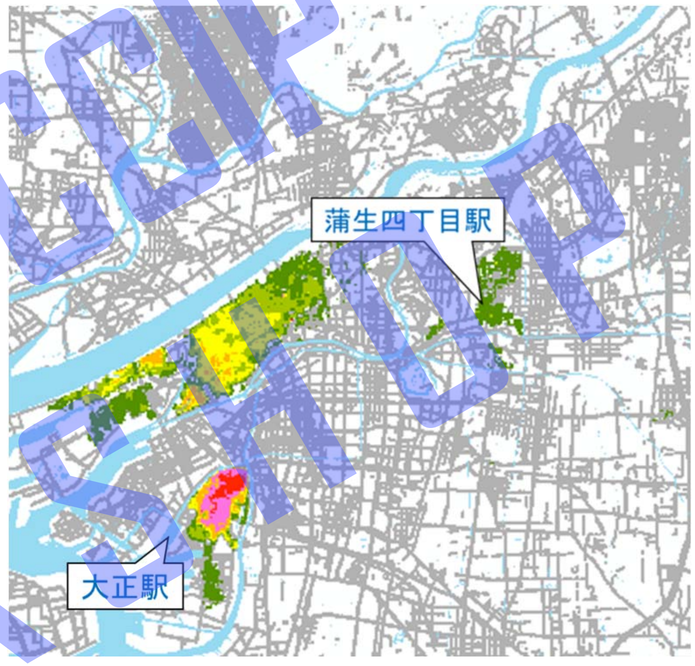
Summary

River flood inundation – application of predicted flood discharge

42 hours after the dyke breach



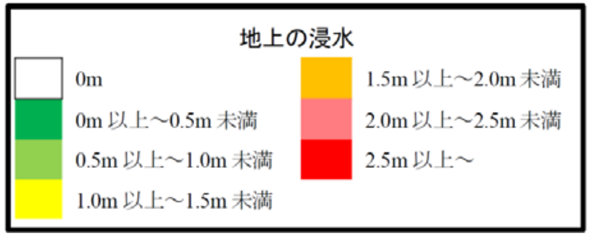
Subway lines are NOT considered.



Subway lines are considered.

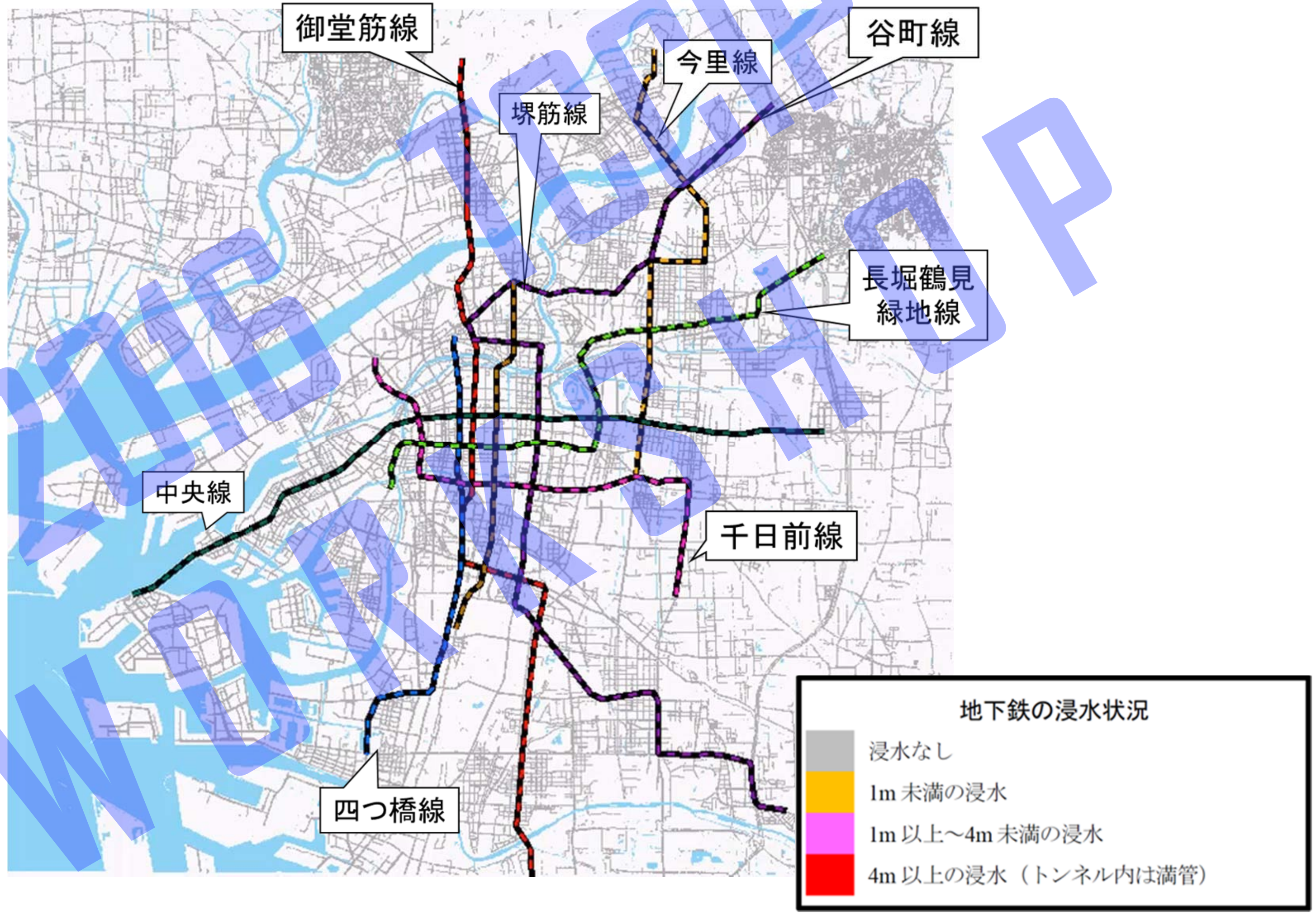
Because the inundation depth is decreased, some part of inundation water flows into subway lines.

The inundation water overflows from some subway entrances far from the dyke breach point.



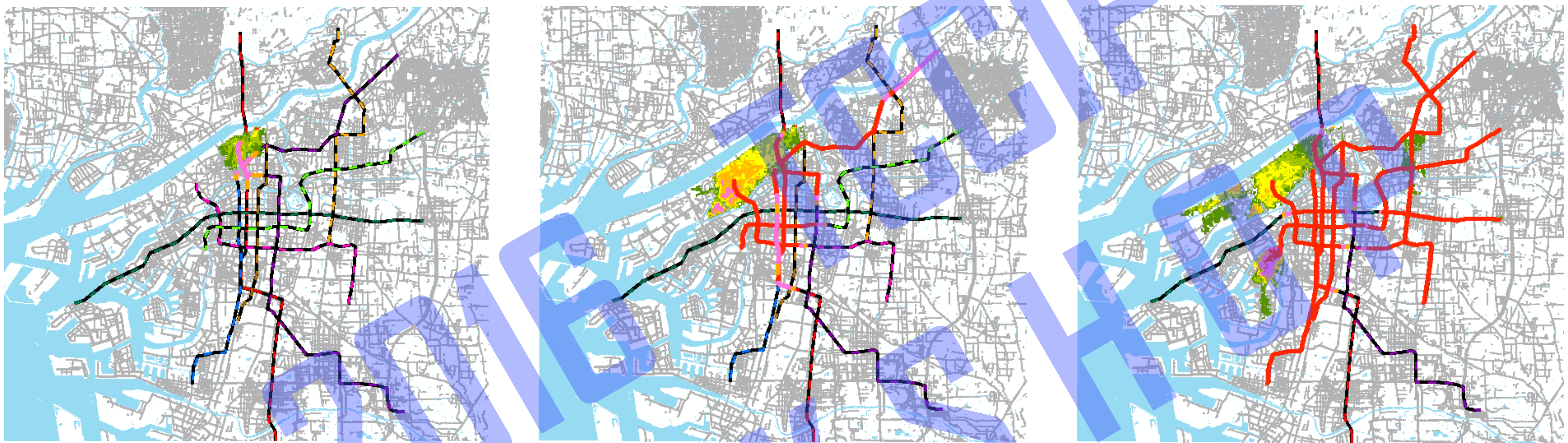
River flood inundation – application of predicted flood discharge

Inundation of the subway lines



River flood inundation – application of predicted flood discharge

Inundation of the subway lines overlapping on the overland inundation



1 hour after the breach　　5 hours after the breach　　42 hours after the breach

地下鉄の浸水状況

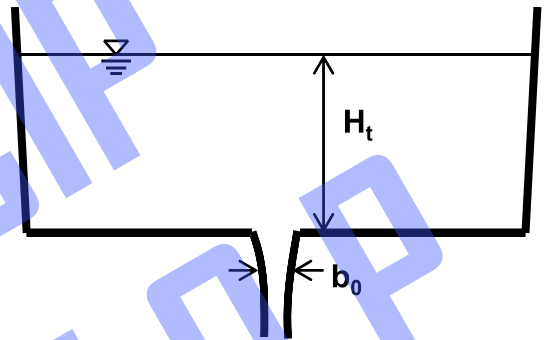
- 浸水なし
- 1m 未満の浸水
- 1m 以上～4m 未満の浸水
- 4m 以上の浸水（トンネル内は満管）

地上の浸水

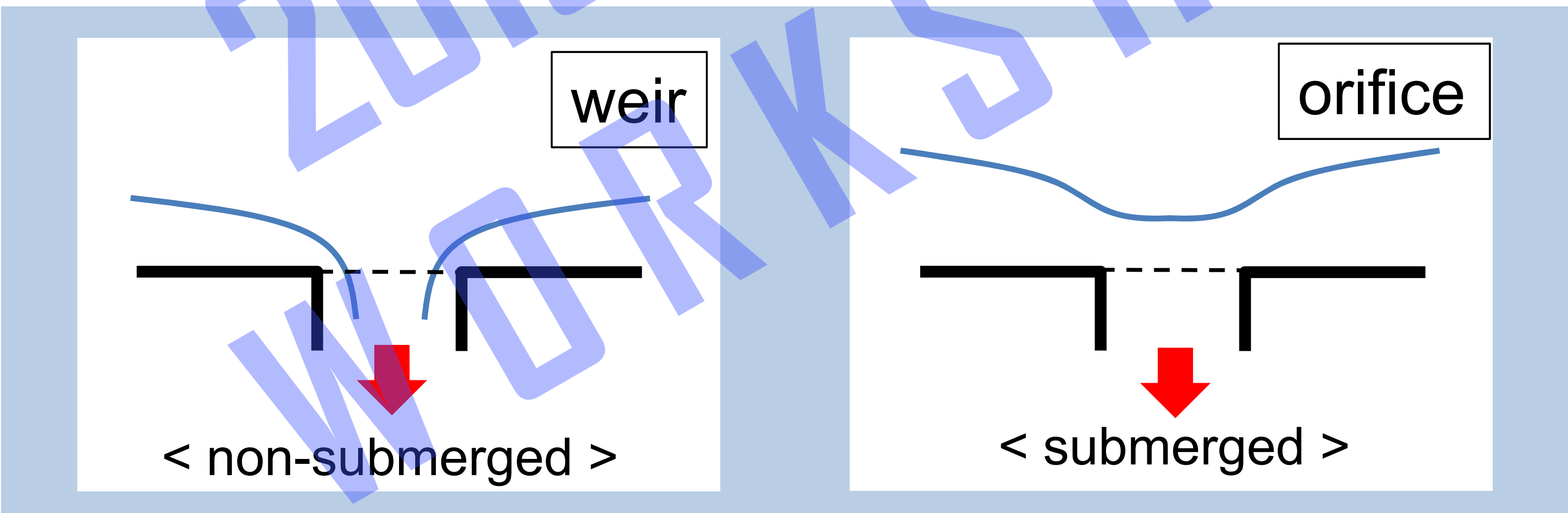
- 0m
- 0m 以上～0.5m 未満
- 0.5m 以上～1.0m 未満
- 1.0m 以上～1.5m 未満
- 1.5m 以上～2.0m 未満
- 2.0m 以上～2.5m 未満
- 2.5m 以上～

Numerical modeling of the Ogurisu area

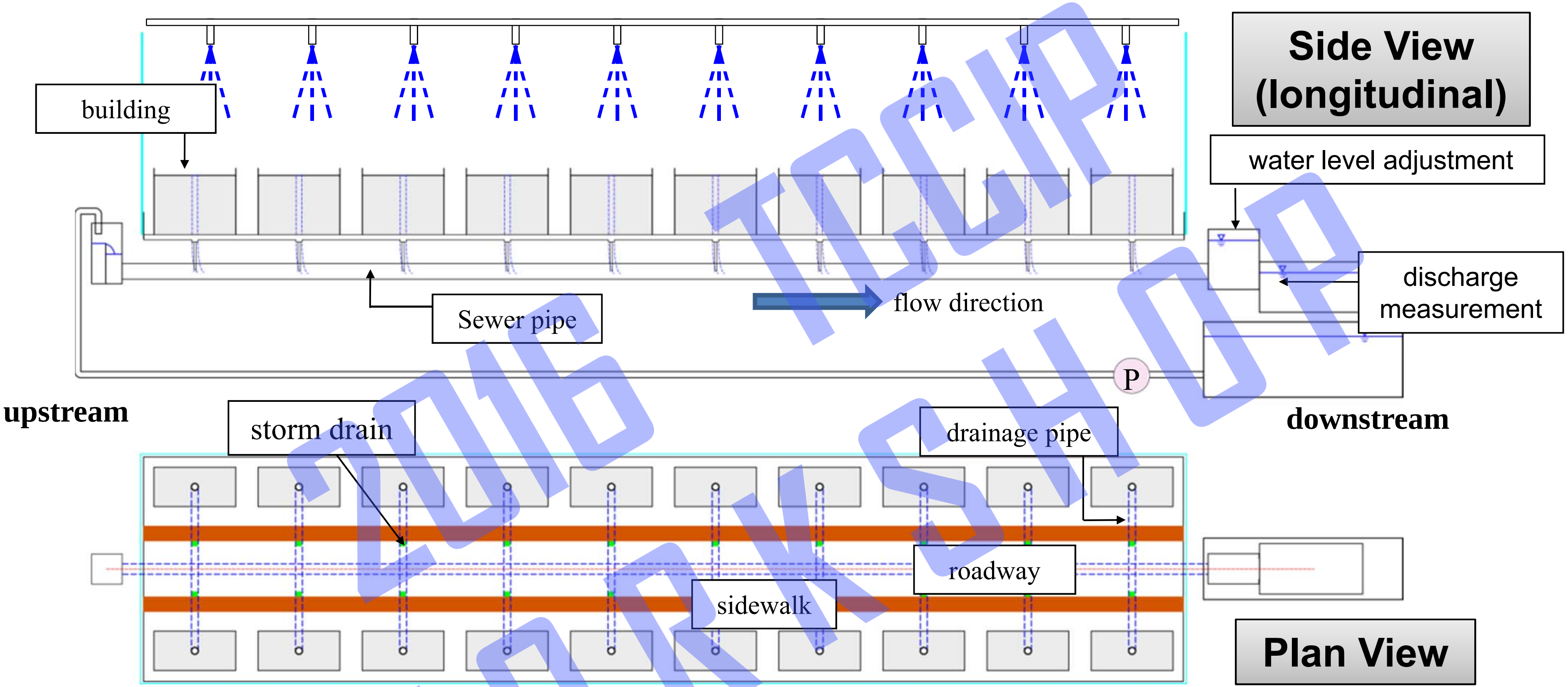
- Depending on whether the storm drain is submerged or not, weir formula or orifice equation will be switched.
- According to H. Chanson et al.(2002), the switching criteria is ‘$H_t/b_0 \approx 0.43 \sim 0.51$’.
- In this study, ‘$H_t/b_0 = 0.5$’ is adopted.



Sketch of the experiment and definition sketch (Chanson et. al.(2002))



Numerical modeling of the Ogurisu area



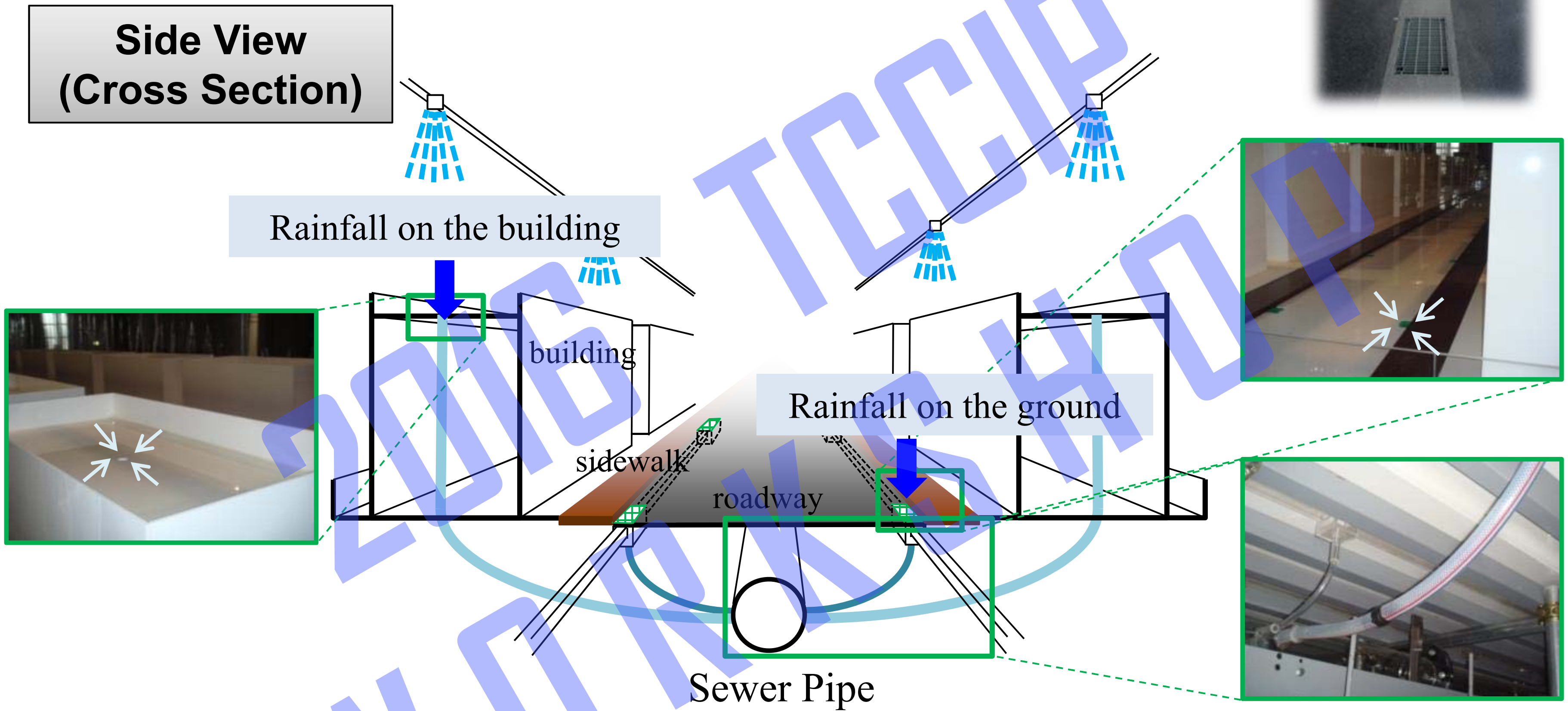
Rainfall simulator
Number of nozzles 20
Max. rainfall intensity 37.12 mm/hr

scale 1/20

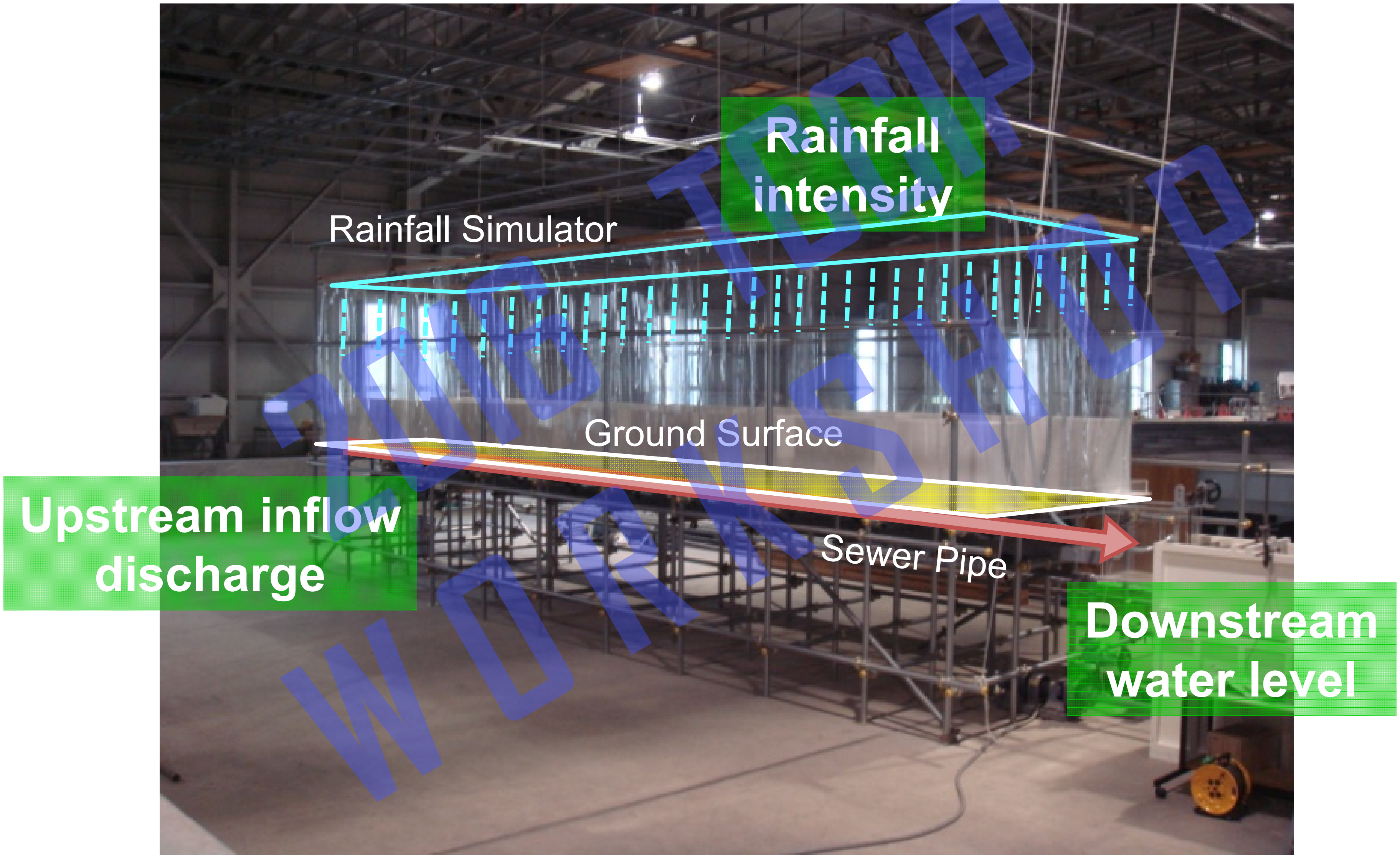
Ground surface
inundation basin 2.0 × 10.0 m
Roadway 0.5 × 10.0 m
Street inlet 0.025 × 0.05 m
buildings 20 0.8 × 0.4 × 0.5 m

Sewer pipe
Cross section Circular
Length 10.43 m
Diameter 0.0935 m
Gradient 1/877

Numerical modeling of the Ogurisu area

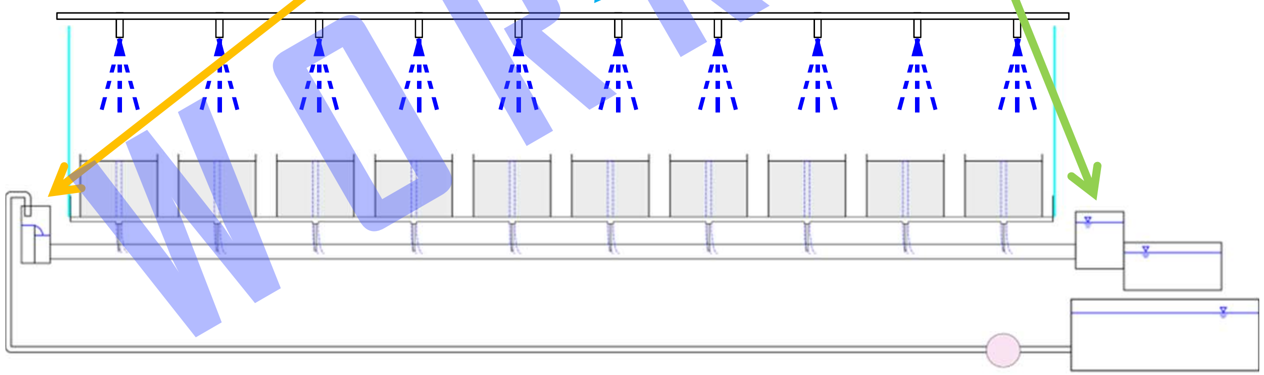


Numerical modeling of the Ogurisu area



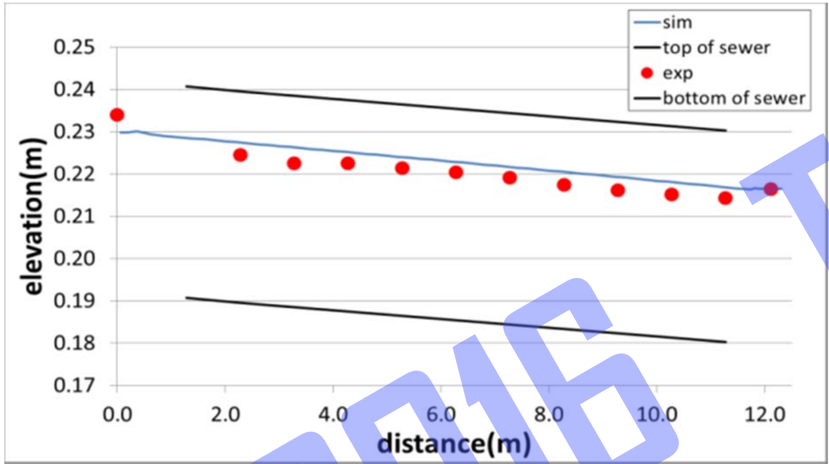
Numerical modeling of the Ogurisu area

Case	Steady / Unsteady	Inflow discharge (l/s)	rainfall (mm/h)	Downstream water level (cm)	Flow regime
Case – 1	Steady	0.30	0.0	21.6	Open channel
Case – 2		1.00	0.0	19.7	Transient
Case – 3		0.85	0.0	22.1	Transient
Case – 4		0.95	0.0	27.6	Pressurized
Case – I	unsteady	1.34	0.0	variation (↗ ↘)	All

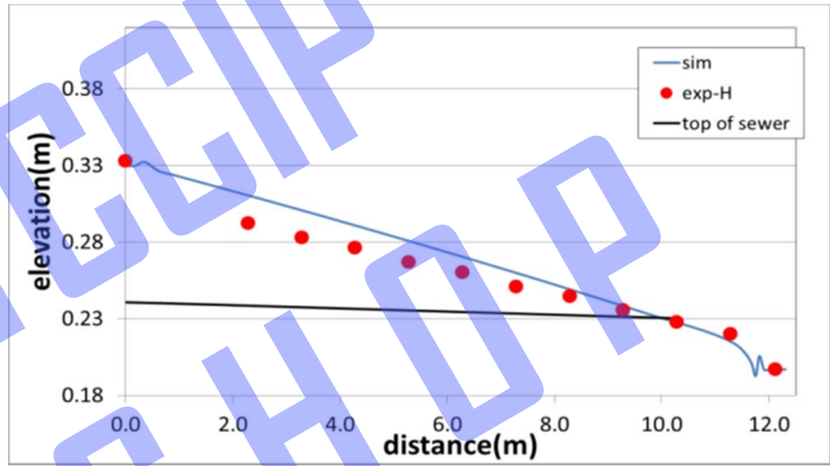


Numerical modeling of the Ogurisu area

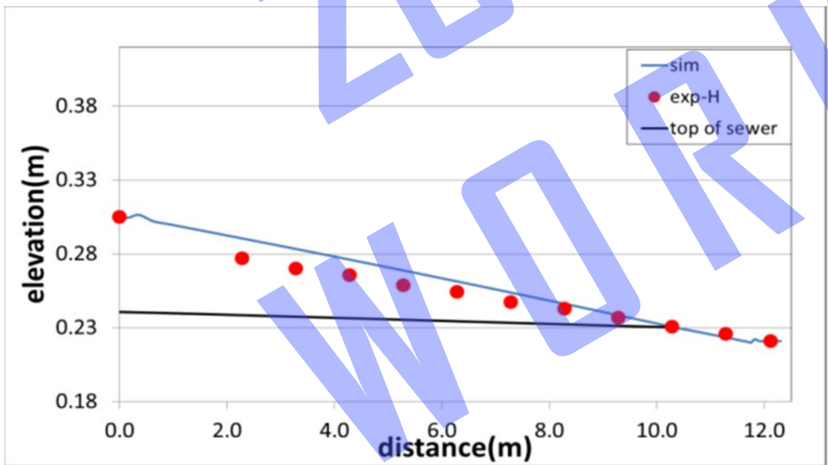
- Comparison between experimental and simulation results (steady flow)



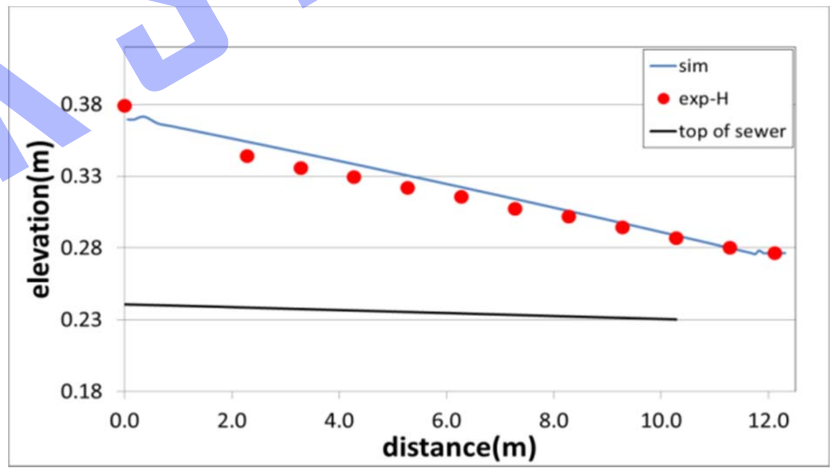
(a) Case-1



(b) Case-2



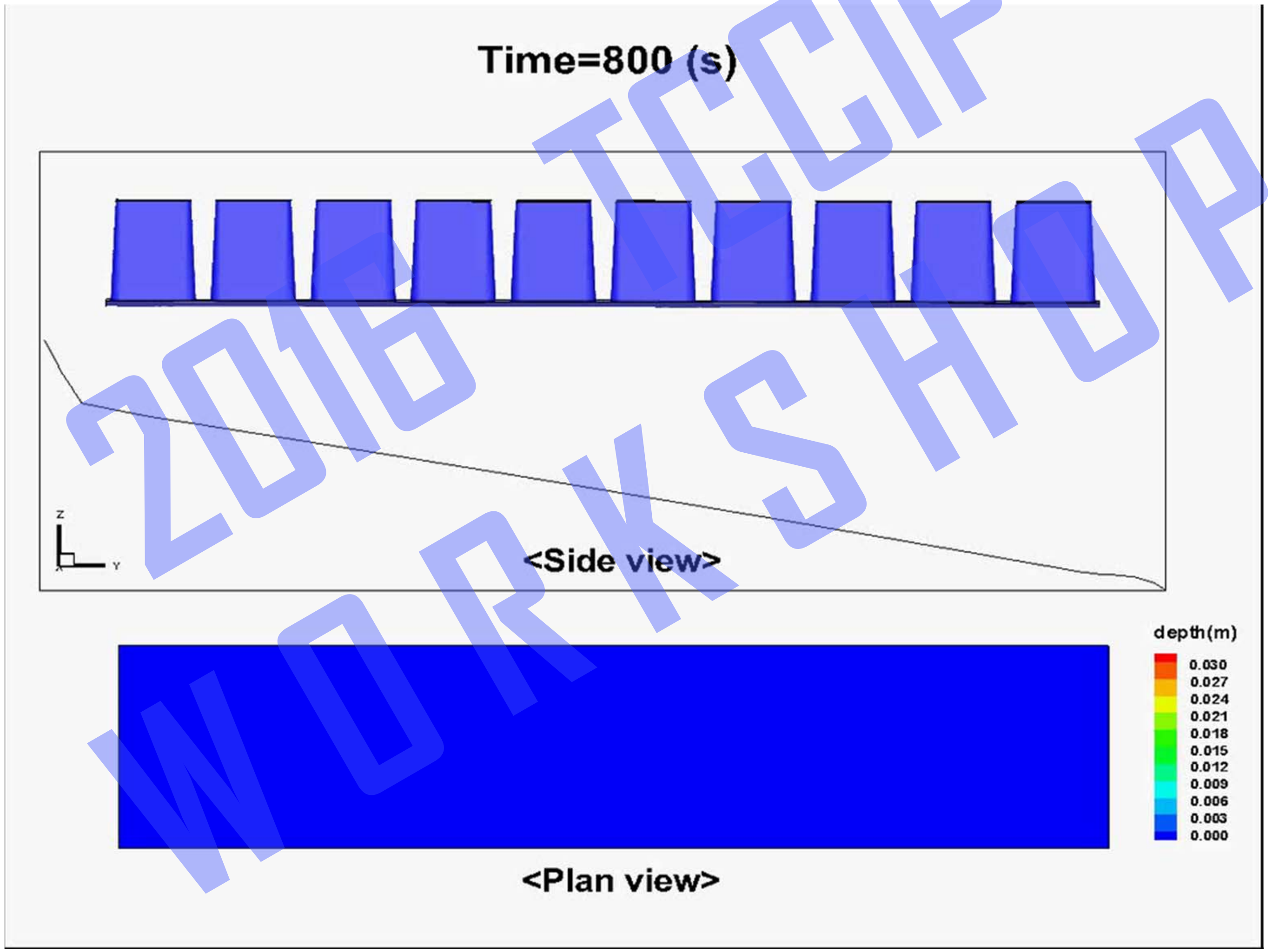
(c) Case-3



(d) Case-4

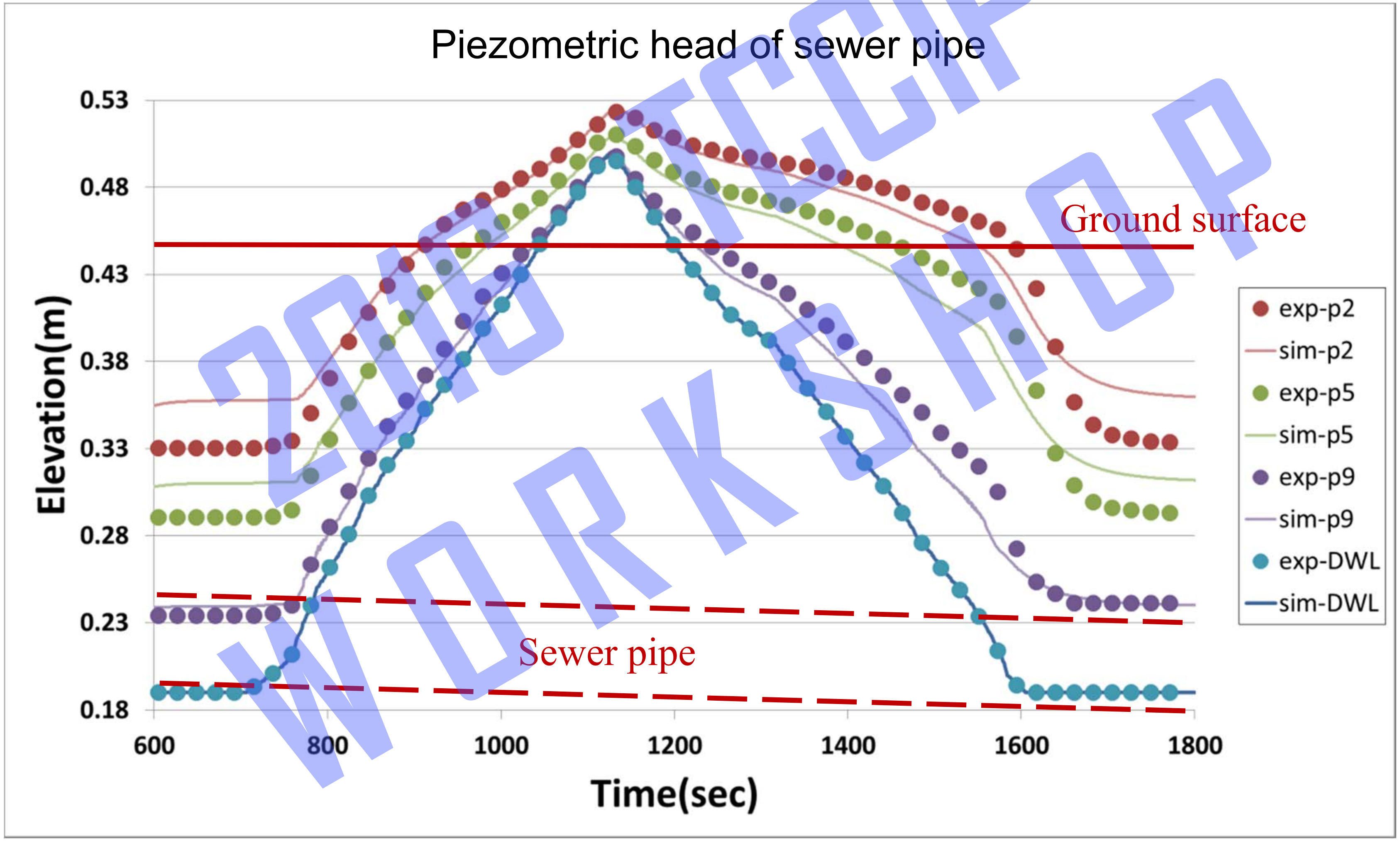
Numerical modeling of the Ogurisu area

- Comparison between experimental and simulation results (unsteady flow)



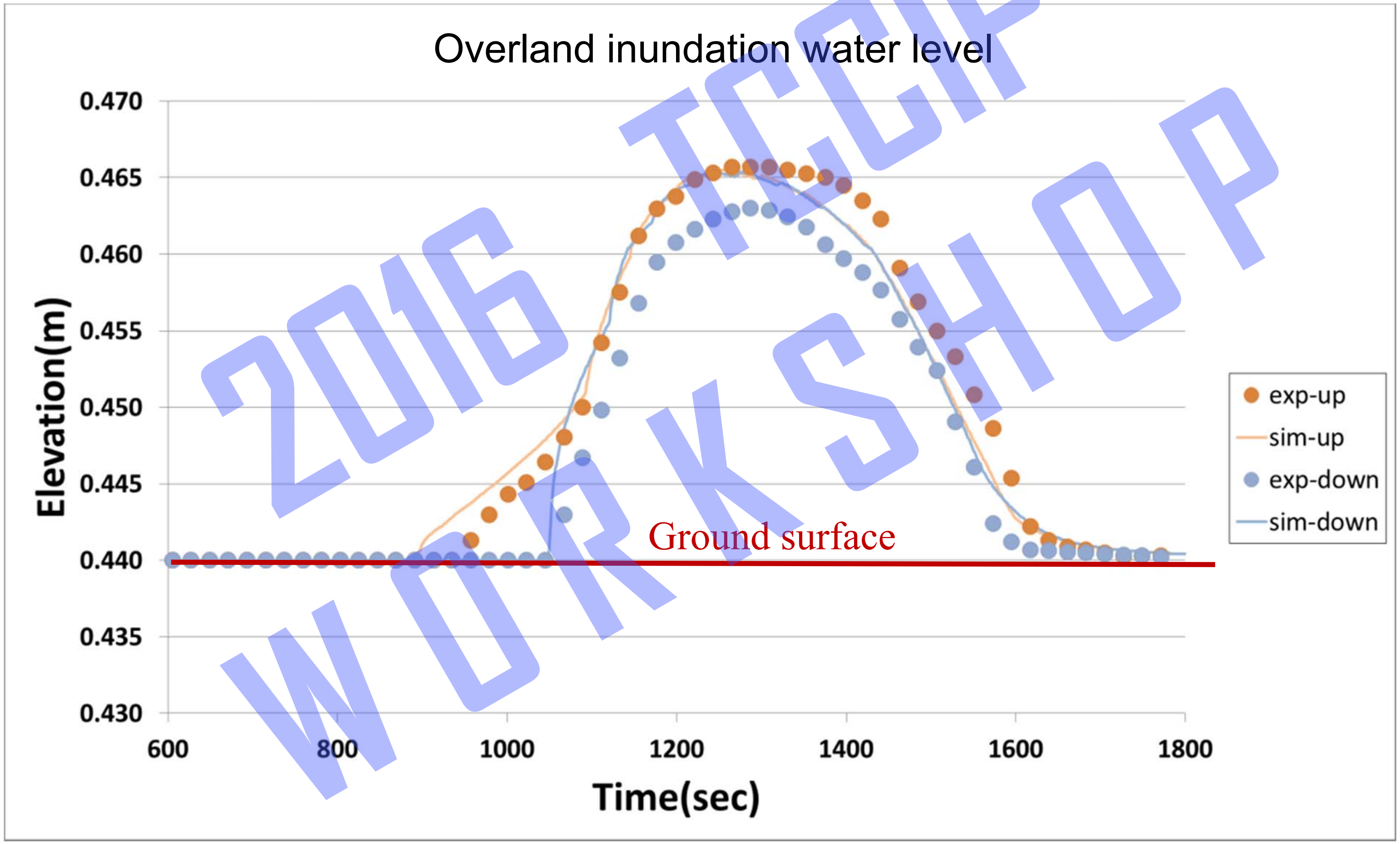
Numerical modeling of the Ogurisu area

- Comparison between experimental and simulation results (unsteady flow)



Numerical modeling of the Ogurisu area

- Comparison between experimental and simulation results (unsteady flow)



Application and Results