A Nature-Based Modelling of Fluid-Flow, Heat and Mass Transport for Watersheds Management Practices

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Introduction

To practice Integrated Water Resource Management (IWRM), it is essential to understand the terrestrial fluids behavior under the wide range of spatial and temporal scales. We have developed a terrestrial fluid-flow simulator named as ***GETFLOWS*** (**GE**neral-purpose **T**errestrial **F**luid-f**LOW** **S**imulator). It enables "**Nature-Based Modelling**" of fluid flows (water, gas, and NAPL), heat and mass transport in watersheds. Remarkable feature of "Nature Based Modelling" is to avoid the simplifications of hydrological processes and to integrate them as much faithful to the nature as possible. At this end, it is expected that simulated results should provide us new findings or better understandings of the targeted system. To maintain such expectations, following implementations in the numerical simulation become more crucial.

- Direct and flexible representation of the system by means of 3-dimensional discretization
- Synthesize the various hydrological processes and their interactions
- Solve such synthesized and comprehensive phenomena using High Performance Computing (HPC) environment
- Visualization of the results with high impacts

Conceptual Model

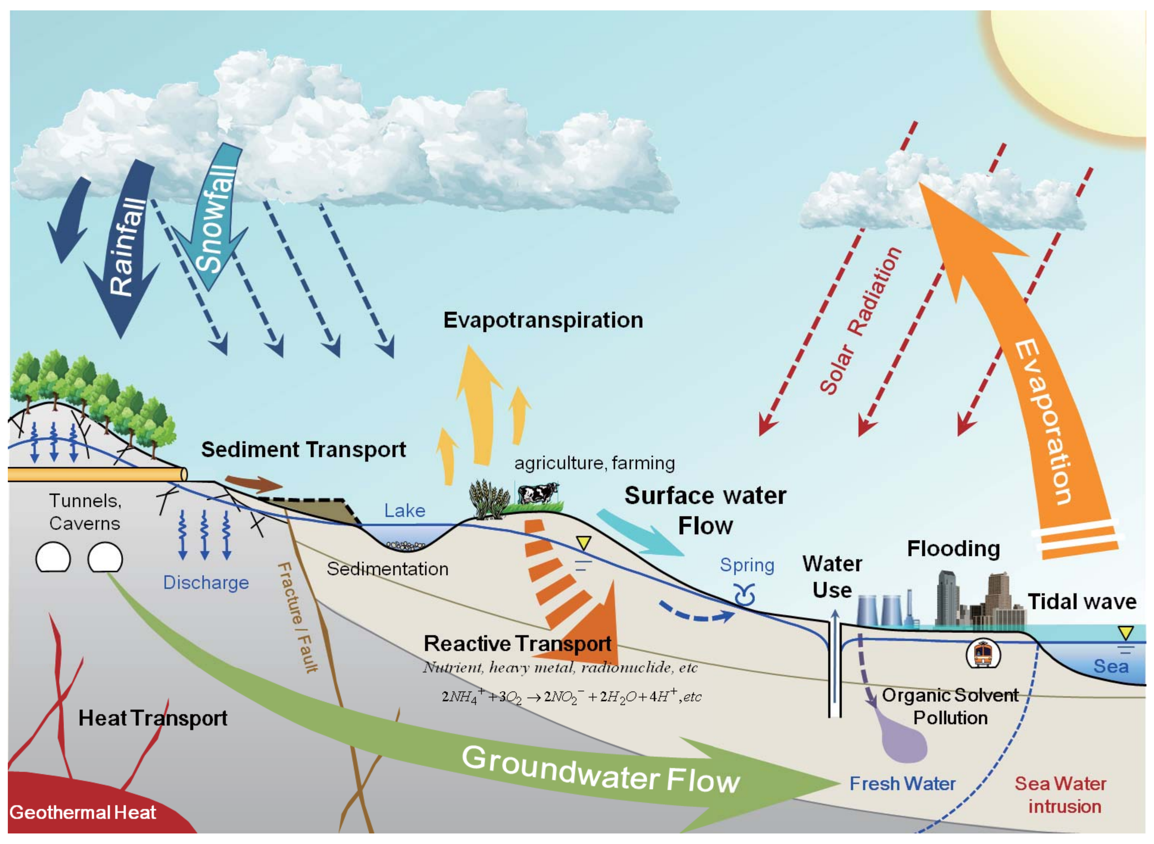

Fig.1 Main hydrogeological processes in the present day hydrosphere that GETFLOWS can treat

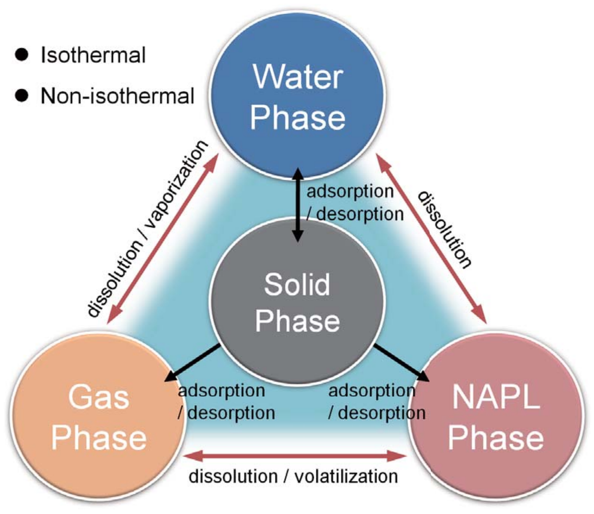

Fig.2 Interaction between phases

Governing Equations

Equations of Continuity for water, gas and NAPL	$\nabla \cdot \boldsymbol{M}_p - \rho_p \boldsymbol{q}_p = \frac{\partial}{\partial t}(\phi \rho_p S_p)$
Solute transport equations	$\nabla \cdot (R_p^\kappa \boldsymbol{M}_p) - \nabla \cdot (D_p^\kappa \nabla R_p^\kappa) - \rho_p R_p^\kappa \boldsymbol{q}_p - \boldsymbol{f}^\kappa = \frac{\partial}{\partial t}(\phi \rho_p S_p R_p^\kappa)$
Thermal convection-diffusion equation for liquid	$\sum_p \nabla \cdot (H_p \boldsymbol{M}_p) + \nabla \cdot (\lambda_f \nabla T_f) - \sum_p \rho_p H_p \boldsymbol{q}_p - \boldsymbol{W} = \frac{\partial}{\partial t}\left(\sum_p \phi \rho_p S_p U_p\right)$
Thermal convection-diffusion equation for solid	$\nabla \cdot (\lambda_s \nabla T_s) + \boldsymbol{W} = \frac{\partial}{\partial t}[(1-\phi)\rho_s U_s]$

D : hyrodynamic dispersion coefficient
f : mass transfer rate between phases
H : enthalpy
$\boldsymbol{M}$: mass flux
q : sink / source
R : mass fraction
S : saturation
T : temperature
U : internal energy
W : heat exchange rate between liquid and solid phase
ρ : density
ϕ : porosity
λ : heat conductivity

superscript
κ : fluid component
subscript
f : fluid
p : fluid phase (w:water, g:gas, n:NAPL)
s : solid

How to couple surface and subsurface fluid flows

Analogous expressions of surface and subsurface fluid flows based on Darcy's equation

$$M^* = -K^* \cdot A^* \cdot f_1[P_w] \cdot f_2[S_w] \cdot f_3[P_w, S_w]$$

	Permeability K^*	Area A^*	Compressibility Viscosity $f_1[P_w]$	Relative permeability $f_2[S_w]$	Potential gradient $f_3[P_w, S_w]$
Groundwater	K	A	$\frac{\rho_w}{\mu_w}$	k_{rw}	$\frac{\partial \Psi_w}{\partial x}$
Surface water (Diffusion Wave)	$\frac{\mu_w}{\rho_w g n}\left(\frac{WH}{2H+W}\right)^{\frac{2}{3}}$	WH	$\frac{\rho_w}{\mu_w}$	$S_w^{\frac{5}{3}}\left(\frac{2H+W}{2S_w H+W}\right)^{\frac{2}{3}}$	$(\rho_w g)^{\frac{1}{2}}\left\lvert\frac{\partial \Psi_w}{\partial x}\right\rvert^{\frac{1}{2}} \mathrm{sgn}\left(\frac{\partial \Psi_w}{\partial x}\right)$
Surface Water (Linearized Diffusion Wave)	$\frac{\mu_w}{\rho_w g n \lvert i_g\rvert^{1/2}}\left(\frac{WH}{2H+W}\right)^{\frac{2}{3}}$	WH	$\frac{\rho_w}{\mu_w}$	$S_w^{\frac{5}{3}}\left(\frac{2H+W}{2S_w H+W}\right)^{\frac{2}{3}}$	$\frac{\partial \Psi_w}{\partial x}$

A : cross-sectional area
g : gravity acceleration
h : water depth ($= S_w H$)
H : channel height
i_g : slope of river bed
K : absolute permeability
k_r : relative permeability
n : Manning's roughness coefficient
W : channel width
Ψ : hydraulic potential ($\Psi_w = P_w + \rho_w g Z$)
μ : fluid viscosity

The surface water flow is modeled by Diffusion Wave Approximation (Tosaka, 2000).

References

[1] Tosaka, H. et al., Fully Coupled Formulation of Surface Flow with 2-phase Subsurface Flow for Hydrological Simulation, Hydrological Processes, 14(3), 449-464, 2000.

[2] Tosaka, H. and Matsumoto, Y., An Efficient Reservoir Simulation by the Successive Explicitization Process, Journal of Japan Association of Petroleum Technology, 52(4), 307-313, 1987.

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Numerical Solution Procedures

- **Integral finite difference method (IFDM)** with 3-dimensional corner-pointed grid blocks
- **Fully-implicit upstream-weighted** discretization
- **Newton-Raphson method** to solve the strong non-linear equations
- **Preconditioned conjugate residual (PCR)** solver for the non-symmetrical Jacobian matrix
- **Nested Factorization** as preconditioner (Appleyard et al., 1981)
- **Successive Locking Process (SLP)** which can exclude the converged grid-blocks from calculation during nonlinear iterations (Tosaka and Matsumoto,1987)
- **Parallel Computing** using Domain Decomposition (DD) method in a PC cluster

Interactions of surface/subsurface fluid flows

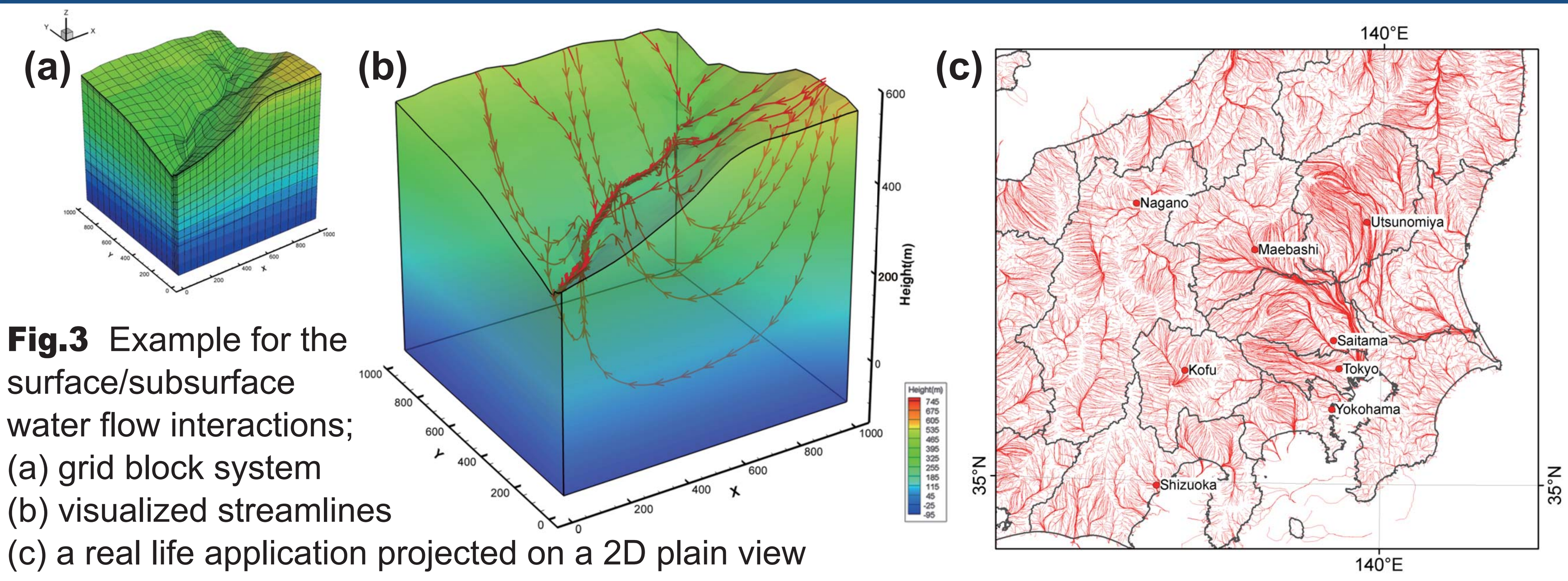

Fig.3 Example for the surface/subsurface water flow interactions;
(a) grid block system
(b) visualized streamlines
(c) a real life application projected on a 2D plain view

Applications

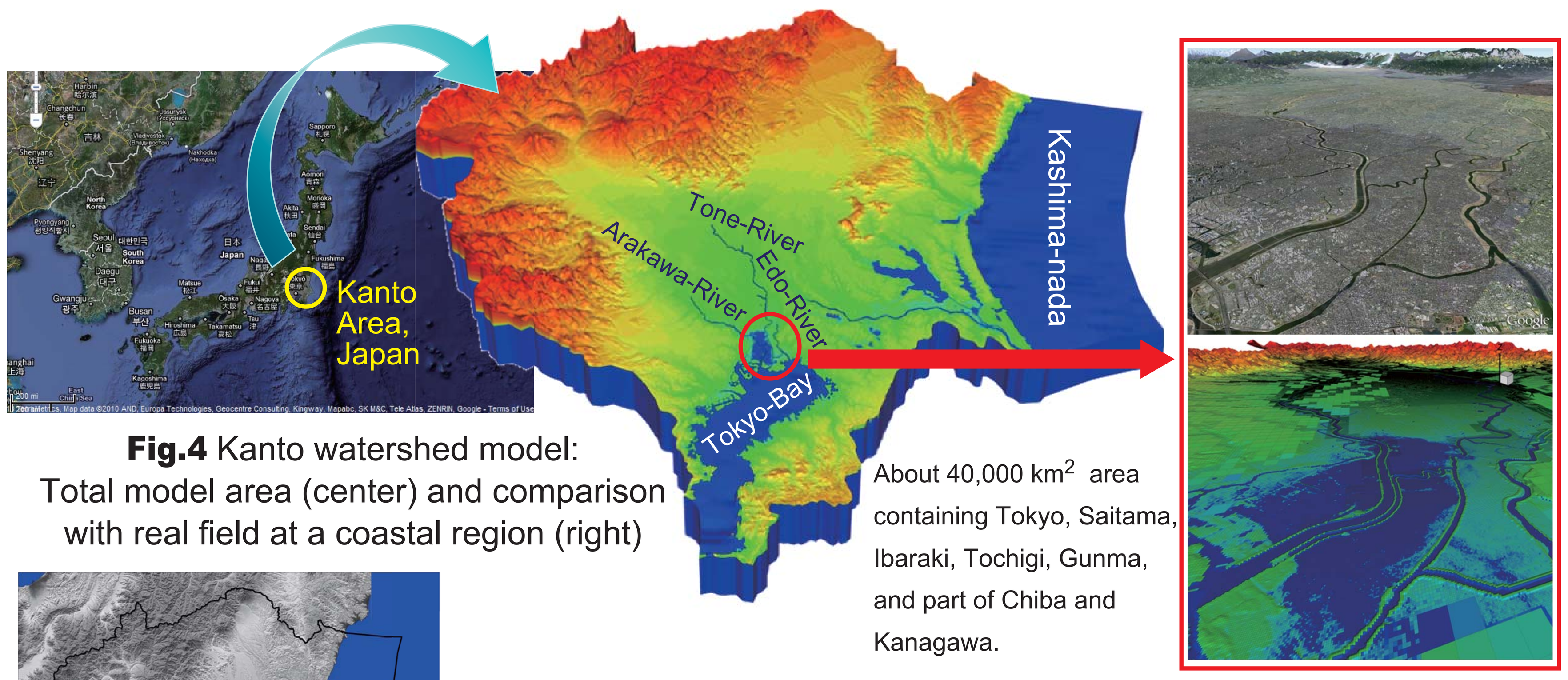

Fig.4 Kanto watershed model: Total model area (center) and comparison with real field at a coastal region (right)

About 40,000 km^2 area containing Tokyo, Saitama, Ibaraki, Tochigi, Gunma, and part of Chiba and Kanagawa.

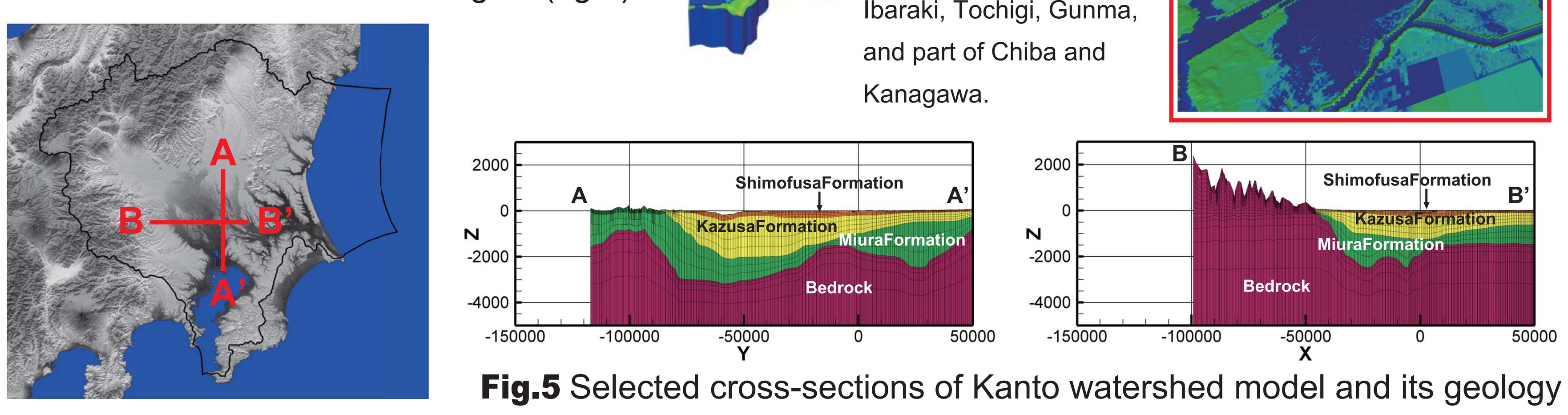

Fig.5 Selected cross-sections of Kanto watershed model and its geology

A watershed model is developed for Kanto area (water-air 2 phase fluid flow problem) as shown in Fig.4 and Fig.5. It simulates the basins of Tone-river and Arakawa-river. Appropriate hydro-geological and land use informations are assigned. Hydrological structures such as dams and dikes along the main rivers are considered. Total number of grids is 3,657,774.

Provided daily precipitation data for two years, the calculated results of the hydrographs at two observation points along Tone-River are shown in Fig.6. A reasonable match can be seen. Other calculated data not shown here are also consistent with the observed ones . We will use this model to conduct case studies to evaluate the risk of flooding by heavy rain or the water resource distribution change in future draught periods.

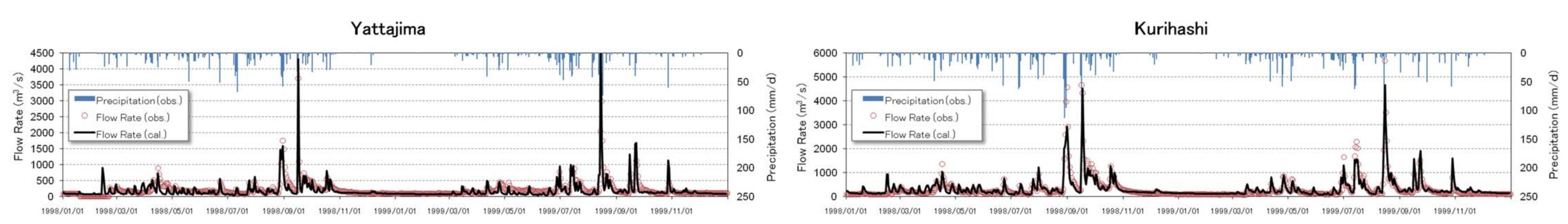

Fig.6 Hydrographs of Tone-River Yattajima (left) and Kurihashi (right)

Concluding Remarks

1) GETFLOWS has been applied to watershed simulations for more than 10 years in Japan.
2) Holistic model that covers the total area of Japanese land is in progress to provide evaluation and prediction tools for nation-wide water issues.
3) It is planned to expand the capabilities of the simulator to develop a global model which comprises major international river basins.
4) GETFLOWS will be a very sophisticated tool to understand the hydrologic characteristics of the watersheds and it should contribute to the IWRM practices for sustainable water management.