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AUTOMATIC INTEGRATION OF HYDRAULIC AND HYDROLOGIC MODELS BASED ON GEOGRAPHIC INFORMATION

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We propose automatic model generation and model-coupling methods for integrated simulation of distributed runoff, one-dimensional (1D) river, and two-dimensional (2D) inundation models. We developed a software product, the DioVISTA® Flood Simulator that integrates a four-dimensional global geographic information system (4D global GIS) and a modeling system. This integration enables us to implement not only graphical user interfaces, but also the following four functions: (1) Dynamic Domain Definition Method (Dynamic DDM) for automatic domain definition and fast calculation of a 2D inundation model, (2) the Dynamic Watershed Delineation Method (Dynamic WDM) for automatic watershed delineation, (3) automation methods for coupling between distributed runoff and 1D river models, and (4) automation methods for coupling between 1D river and 2D inundation models. The Dynamic DDM defines the calculation domain of the 2D inundation model to include the flooded area and to eliminate the non-flooded area during the simulation. The Dynamic WDM generates channel networks in the target river's catchment area. Introduction of spatial coordinates to the distributed runoff, 1D river, and 2D inundation models enables automatic model coupling. Users only need three steps to generate a system for water levels and flooded area simulation using precipitation data with 1-km horizontal and 10-min temporal resolution and river cross sections. It is clear that the automations enable users to easily integrate the latest modeling technologies without extensive knowledge and experience, and assist interdisciplinary collaboration.

Introduction

Interdisciplinary collaboration is needed to solve water-related problems. For example, flood insurance, which has become a hot issue in many countries, is a reasonable solution only if it accompanied with adequate loss prevention measures (Kron [1]). Thus, some insurance companies simulate floods, estimate losses, and propose adequate countermeasures to their clients (Yamaguchi *et al.* [2]). Water-related information is important for professionals both with and without extensive backgrounds on hydroinformatics.

Because a wide spectrum of models and data are needed to simulate hydrologic and hydraulic processes, standardizations are conducted; e.g., OpenMI [3] for model linkage, ArcHydro [4] and WaterML [5] for data exchange. In a similar context, the Japanese government promotes the CommonMP project (Odaira *et al*. [6], Kikumori [7]), which will provide interfaces for model linkage, linkable hydrologic and hydraulic models, interfaces of database access, geospatial data, and a geographic information system (GIS) with spatiotemporal (4D) global data management functions (4D global GIS). These flexible frameworks enable integration of models, and therefore it will assist collaborative research and development across professions.

However, professionals not having modeling or GIS knowledge may need another solution, such as easy-to-use and easy-to-understand but accurate simulation software. Martin *et al*. [8] reviewed 36 state-of-the-art modeling software products, and found that most were made of two separate systems: GIS and modeling. This means that users should learn both GIS and modeling systems. An ideal system suggested by Martin *et al*. [8] is the integration of GIS and modeling systems: GIS with multidimensional and time series display capabilities and modeling environments inserted into the GIS.

We further discuss the advantages of this integration based on our software product, DioVISTA® Flood Simulator. This integration enables us to implement not only user-friendly interfaces but also (1) a fast calculation method of a 2D inundation model, (2) an automatic watershed delineation method, (3 an automatic coupling method between distributed runoff and 1D river models, and (4) an automatic coupling method between 1D river and 2D inundation models. We introduce the components that make up our software and the workflow, discuss the above-mentioned four methods and their advantages, and present our conclusions.

Software components and their workflow

Our software integrates Windows-based graphical user interfaces, 4D global GIS engine and modeling engine (Figure 1). Because each module has its own 4D coordinate, the data coordinate is converted among the modules. The GIS engine displays global data as the earth (Figure 2a). The modeling engine includes a model controller and generator. The model controller has distributed runoff, 1D river, 2D inundation models derived from a base model (with physical variables and governing equation solvers), and model connectors derived from a base connector (with references of models and governing equation solvers). The model generator fetches data from the GIS and creates and populates the models and connectors. The runoff and inundation models consist of 2D square cells, and the river model consists of 1D cells along with a digital representation of a target river. The runoff model represents unsaturated, saturated, and overland flows in each cell along channel networks (Tachikawa *et al.* [9]) derived from a digital elevation model (DEM).

Screen transition and interaction between a user and the software are shown in Figures 2 and 3, respectively. After the launch of the software (Figure 2a), a user loads data of target rivers, which are composed of the river centerline and river cross sections (Figure 2b, Figure 3a1). The user clicks on the Simulation Settings button, then the Settings dialog box is displayed (Figure 2c, Figure 3a2). Through the dialog box, the user sets the simulation date, grid sizes, etc. Then the user clicks on the Simulation start button (Figure 3a3), and the software starts the simulation. The modeling engine fetches precipitation data with 1-km horizontal and 10-min temporal resolutions at the specified date in the Settings dialog, and advances the time in the three models. The latest results are automatically displayed on the GIS (Figure 2d). As shown in Figure 3, the user only needs to perform three steps. The software automatically performs other steps, such as grid generation, watershed delineation, connecting the models, model domain definition, population of the models based on GIS data, solving the equations, and displaying the results on the GIS.

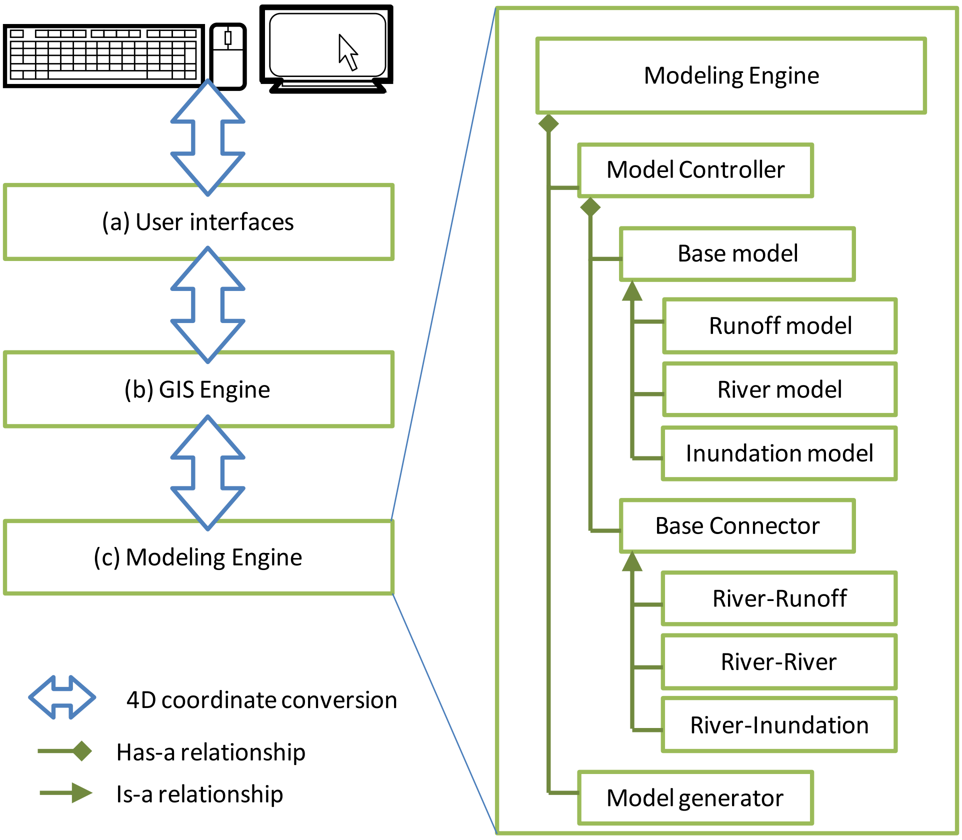
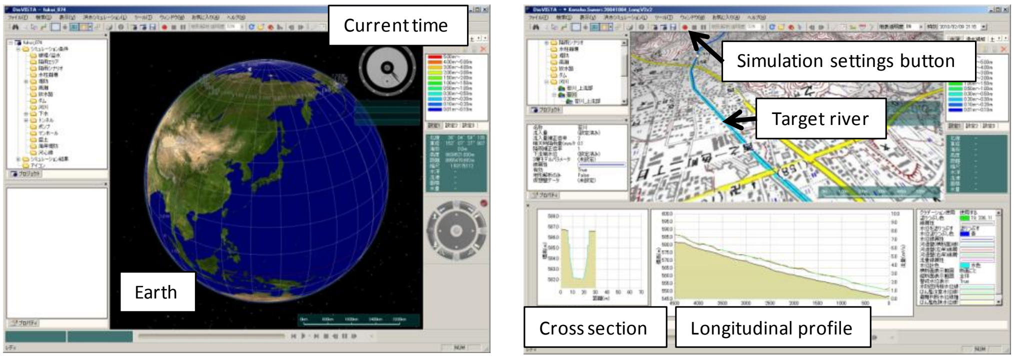


Figure 1. System architecture of our flood simulation software

(a) Launched Application (b) Loaded data



(c) Setting dialog (d) Visualized results on map

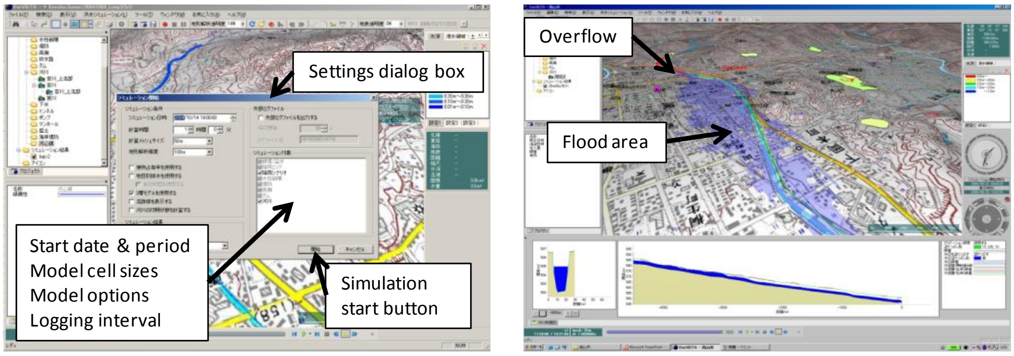


Figure 2. Screen transition of our flood simulation software. (a) after launch of application, (b) after loading of river data, (c) setting simulation options before starting simulation, and (d) after starting of simulation. Latest simulated result is automatically displayed as time progresses.

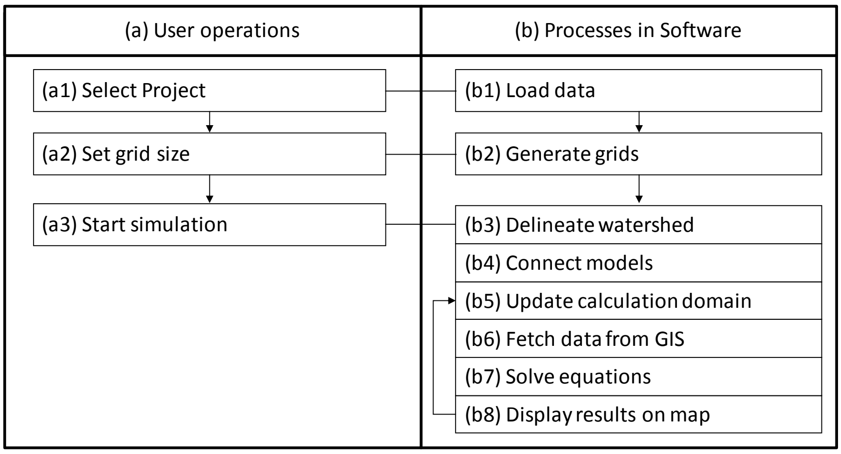


Figure 3. Interaction between user and our software

Automatic generation of inundation and runoff models

The major advantage of the integration of the GIS and modeling engines is automation of Steps b1 - b8 in Figure 3. We developed our Dynamic Domain Defining Method (Dynamic DDM) and Dynamic Watershed Delineation Method (Dynamic WDM) for Steps b3 and b5, respectively.

In Step b5, the calculation domain (i.e., cells in the target area of the simulation) of the inundation model is automatically defined using our Dynamic DDM. In a conventional inundation model, a user must define the calculation domain in advance of the simulation (Figure 4a1). The domain must include the flood areas but eliminate non-flooded areas for faster processing. In Figure 4a3, the water reaches the boundary of the domain. In such cases, the simulation fails and the user must simulate again after expanding the calculation domain. In our Dynamic DDM, the calculation domain is automatically defined to include the flooded areas and to eliminate the non-flooded areas during the simulation. The modeling engine divides the entire space into sub-domains composed of two or more cells. The modeling engine detects the cells with water (Figure 4b1), and loads the sub-domains in which those cells are included (Figure 4b2). Data in the sub-domain is fetched from the GIS. Neighboring sub-domains are automatically loaded when the water reaches the current domain boundary (Figure 4b3). Using our Dynamic DDM, the simulation never fails because the domain boundary expands automatically. In addition, because non-flood areas are automatically eliminated from the calculation domain, the calculation time is drastically reduced [2].

In Step b3, the calculation domain of the watershed delineation is automatically defined using our Dynamic WDM. In a conventional method (e.g., Jenson and Domingue [10]), a user must define the calculation domain in advance of the delineation. The workflow of the conventional method is: (1) defining of the calculation domain that must include the catchment area, (2) generating a ‘hydrologically correct’ DEM from the original DEM by using the so-called Sink-Filling method, and (3) searching upstream from the drain of the catchment area. The original DEM includes cells that are lower than the surrounding cells and are known as sinks. Since sinks cause errors in hydrological analysis, detection and correcting sinks is required. In a conventional method, a user must define the target area of the correction as the calculation domain. In our Dynamic WDM, the calculation domain is automatically defined. As shown in Figure 5a, upstream searches are conducted from the drain of the catchment area (Cell 1). Because Cells 4 and 5 are lower than the surrounded cells (sinks), Cell 3 is estimated as a watershed. For the validation of the estimation, a downstream search with the Sink-Filling operation is conducted from the estimated watershed (Cell 3, Figure 5b). Cells 4 and 5 are detected as sinks and corrected, and the downstream search reaches the estimated watershed (Cell 3, Figure 5c). This means that Cell 3 is not a watershed. The upstream search is conducted again, and the estimated watershed is now Cell 9 (Figure 5d). The downstream search reveals that the most downstream cell of the watershed is the sea (Cell 11, Figure 5e). This means that Cell 9 is the correct watershed. During upstream and downstream searches, we use our Dynamic DDM. Thus watershed delineation is automatically conducted using our Dynamic WDM.

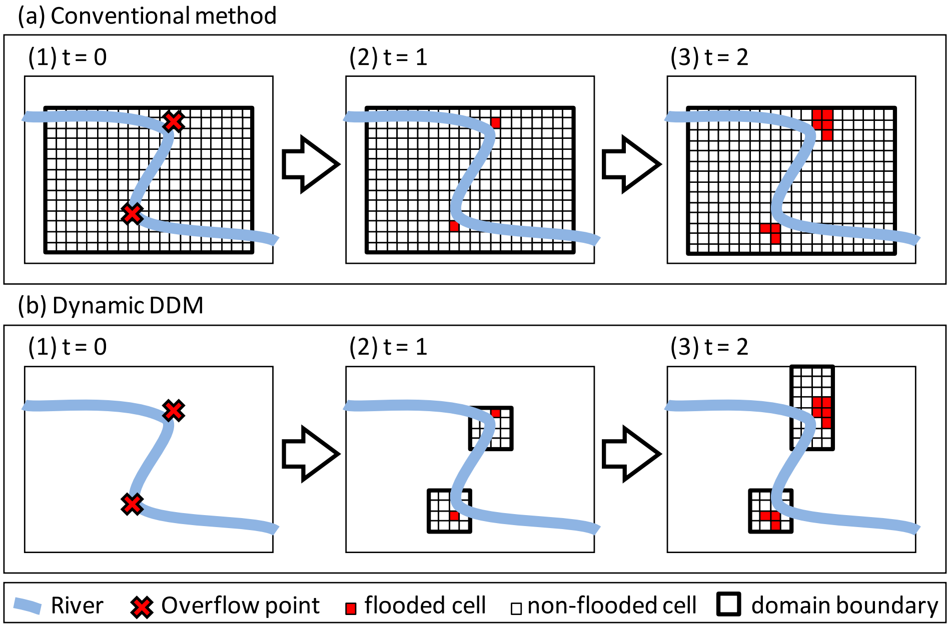


Figure 4. Workflows of inundation models with (a) conventional method and (b) our Dynamic Domain Defining Method (Dynamic DDM)

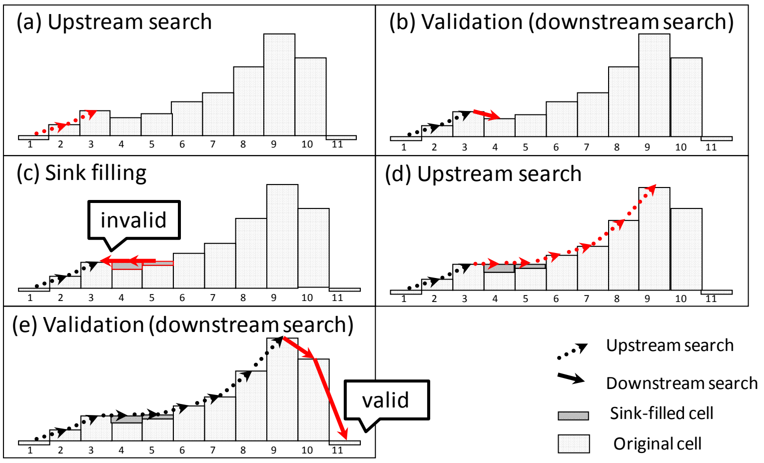


Figure 5. Workflow of our Dynamic Watershed Delineation Method (Dynamic WDM). (a) Upstream search from drain (Cell 1), (b) validation by downstream search from estimated watershed (Cell 3), (c) filling sink (Cell 4-5) during downstream search, (d) retry upstream search from false watershed (Cell 3), (e) retry validation by downstream search from estimated watershed (Cell 9) to sea (Cell 11)

Automatic generation of model connections

Because all models have spatial coordinates, the modeling connection can be automated (Figure 3b4). Connection between the river and the runoff models (Figure 6a) and between the river and the inundation models (Figure 6b) are automatically generated. Two models are connected at the connection points, at which the distance between a cell in the river model and the corresponding cell in the other model is assumed to be zero. River centerlines are connected to the runoff model, and the river's left and right levee lines are connected to the inundation model, respectively. The river-inundation connection allows all river cells to be laterally linked to inundation cells. Flow through the connection is calculated using a Weir equation.

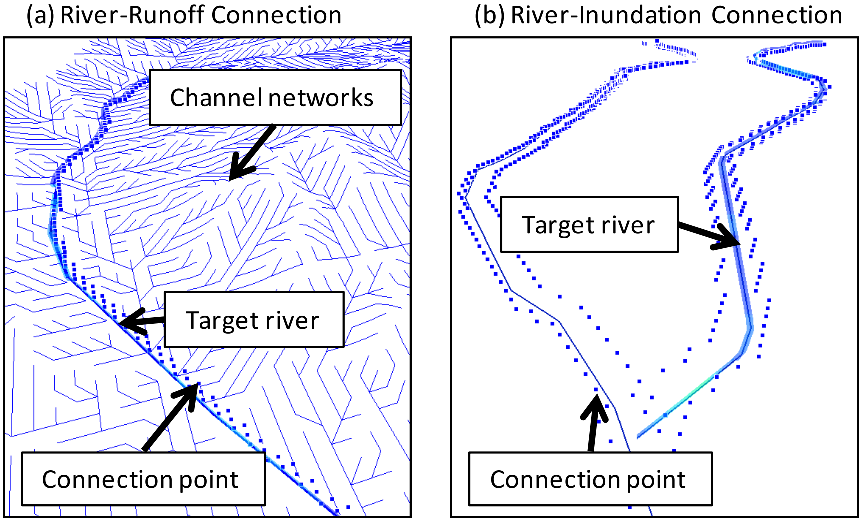


Figure 6. Connection points (a) between river and runoff models and (b) between river and inundation models

Conclusions

The major advantage of the integration of GIS and modeling engines demonstrated using our software is automation: the user only needs to perform three steps (select project, set grid size, and start simulation) to conduct integrated simulation of distributed runoff, and 1D river and 2D inundation models using precipitation data with 1-km horizontal and 10-min temporal resolution and river cross sections. The key methods for automation are:

(a) Dynamic Domain Definition Method for automatic domain definition and fast calculation of 2D inundation model

(b) Dynamic Watershed Delineation Method for automatic watershed delineation

(c) Introduction of spatial coordinates for automatic coupling between distributed runoff and 1D river models

(d) Introduction of spatial coordinates for automatic coupling between 1D river and 2D inundation models

As shown in Figure 2, the system displays simulated water levels and flooded area on maps. It is clear that the automations enable a user to easily integrate the latest modeling technologies without extensive knowledge and experience. Since a wide variety of spatial data is available and frequently updated on a global scale, the integrated system of GIS and modeling will assist interdisciplinary collaboration for solving water-related problems.

Acknowledgments

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