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G2D 침수해석 모형을 이용한 시나리오 기반 도시 침수예측 연구

A Study on Scenario-based Urban Flood Prediction using G2D Flood Analysis Model

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[요 약]

본 논문에서는 2차원 침수해석 모형인 G2D를 이용하여 모의 도메인을 구성하고, 전주시 전역을 대상으로 시나리오 기반 도시 침수예측을 수행하였다. 도메인 구성과 격자별 조도계수 설정은 DEM과 토지피복도를 이용하고, G2D 모형의 입력은 수위, 수심 및 유량 등을 적용하였다. 가상 강우는 10분당 3 mm로 5시간 동안 모든 격자에 부여하였고, 가상 유량을 적용하여 지표면 침수해석 모의를 진행하였다. 또한 대상 지역의 침수해석 모델 실행 여부를 판단하기 위해 GPU 가속 기법을 적용하였다. 모의 결과 고해상도 침수해석 시간의 대폭 단축 및 모의 시간별 시각적인 침수 판단을 위한 침수심을 생성할 수 있음을 확인하였다.

[Abstract]

In this paper, scenario-based urban flood prediction for the entire Jinju city was performed, and a simulation domain was constructed using G2D as a 2-dimensional urban flood analysis model. The domain configuration is DEM, and the land cover map is used to set the roughness coefficient for each grid. The input data of the model are water level, water depth and flow rate. In the simulation of the built G2D model, virtual rainfall (3 mm/10 min rainfall given to all grids for 5 hours) and virtual flow were applied. And, a GPU acceleration technique was applied to determine whether to run the flood analysis model in the target area. As a result of the simulation, it was confirmed that the high-resolution flood analysis time was significantly shortened and the flood depth for visual flood judgment could be created for each simulation time.

색인어 : 수치표고모형, 침수분석모형, G2D 모형, GPU 가속, 도시 침수예측

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Ⅰ. Introduction

Today, the number of typhoons and torrential rains is increasing all over the world, and floods and inundation damages are experienced repeatedly every year due to abnormal climate phenomena caused by global warming [1],[2]. In order to minimize flood damage based on these experiences, major organizations are providing flood forecasting and information by establishing a flash flood forecasting system, an integrated flood management system, and a road flood warning system.

However, existing flood prediction studies are mainly limited to research on river and urban flood prediction methods and monitoring of flooded areas [1]. In addition, there is a lack of research on the establishment of a regionally customized urban flood system that combines various technologies such as prediction data with rainfall and flow information, and AI specialized in road and urban flood prediction and response.

Therefore, in this paper, simulation for road flood prediction is performed using past rainfall data and visualized by time. In particular, Jinju city was selected for inundation analysis simulation, and the analysis model was built and analyzed based on Grid based 2-Dimensional flood model (G2D). In addition, the GPU acceleration method was improved for the efficiency of high-resolution flood analysis, and the run-time evaluation of input/output data calculation was performed.

The composition of this paper is as follows. Section 2 describes existing inundation analysis models. Section 3 describes the selected G2D model and defines the specifications of simulation data for flood prediction. In Section 4, the results of applying the GPU acceleration technique and the G2D model were discussed and visualized with flood prediction data. Section 5 describes the conclusions and future work.

Ⅱ. Flood Analysis Models

2-1 HEC-RAS model

Hydrologic Engineering Center's River Analysis System (HEC-RAS) is a one-dimensional hydraulic analysis model developed by the US Army Corps of Engineers, and in version 5.0, two-dimensional flow analysis is possible [3]. HEC-RAS can analyze steady flow, unsteady flow, and rapid flow for a river based on the input cross-sectional terrain data, and the one-dimensional inequality flow analysis is calculated by the table-sequence method [3],[4]. In particular, in Korea, it is used for one-dimensional flow analysis when producing a flood risk map, but since it is done in a way that extends the water level in the river direction, there is a limit to precise flood analysis. In other words, HEC-RAS is capable of inundation analysis focusing on the river and its surroundings, and has limitations in simulating flooding in the entire basin to which rainfall is applied.

2-2 FLUMEN model

FLUvial Modelling ENgine (FLUMEN) is a two-dimensional flood analysis model developed in Switzerland [5]. FLUMEN constructs simulation domains using shallow water equations and irregular grids, and is suitable for analysis of areas with complex hydraulic aspects, such as river confluences or curved areas. In Korea, FLUMEN is applied to two-dimensional flow analysis for important areas such as the vicinity of downtown areas when producing flood risk maps.

2-3 MIKE FLOOD model

MIKE FLOOD model is developed at DHI [6]. This model is analyzed by connecting MIKE11 for one-dimensional river flow analysis and MIKE21, a two-dimensional analysis model. The MIKE 11 and MIKE21 models use the one-dimensional Saint-Venant equation and the two-dimensional natural water equation, respectively, and construct simulation domains using a square grid. This model enables precise flow and flood inundation analysis in rivers, but it is difficult to set the initial water depth for the simulated area , and to apply the scenario.

2-4 LISFLOOD-FP model

LISFLOOD-FP is a two-dimensional flood analysis model developed in the UK [7]. Flow analysis can be performed using a high-resolution digital elevation model (DEM), boundary conditions of the model, and flow conditions according to time at the flow inflow point.

2-5 G2D model

G2D is a two-dimensional overflow analysis model developed at KICT, and a simulation domain is constructed using a square grid [8]. Like LISFLOOP-FP, this model performs flow analysis using DEM, boundary conditions of the model, flow conditions according to time at the flow inflow point, and rainfall. G2D model is simple to simulate and can predict flood propagation relatively accurately.

Ⅲ. Model Selection and Data Definition

3-1 Concept of G2D model

The G2D model simulates the two-dimensional transport and diffusion of surface water by water level, water depth, flow rate or rainfall. This model uses a regular square grid for the control volume, which is the minimum unit of calculation, and constructs a domain using DEM. The governing equation for surface flow analysis uses the diffusion wave equation (or dynamic wave equation) that additionally includes a local acceleration term in the diffusion wave equation [8],[9]. In addition, the model only simulates surface flow and does not account for infiltration and runoff into the soil, and may reflect initial loss of rainfall.

Figure 1 shows the concept of the discretization of the governing equation, and the G2D model uses the finite volume method [9]. In Figure 1, (i, j) and p represent the location and center of the control volume. The upper, lower, left, and right sides of the control volume are indicated as w ($-x$ direction), e ($+x$), n ($-y$), and s ($+y$), respectively. After integrating the continuous equation with respect to x, y and time for the control volume $CV_{i,j}$, the discrete equation is written as Equation (1). At this time, the discretization method for time was applied. The momentum equation is analyzed as a grid network using one control volume $CV_{i,j}$ and adjacent control volumes. For example, the right adjacent control volume is $CV_{i+1,j}$. The equation for calculating the flow rate from $CV_{i,j}$ to e is the same as Equation (2), and the equation can be written in the same way for the w, n and s directions.

$$h_{i,j}^{t+\Delta t} - h_{i,i}^{t} + \{q_{xe} - q_{xw}\}^{t+\Delta t}\frac{1}{\Delta x}\Delta t + \{q_{ys} - q_{yn}\}^{t+\Delta t}\frac{1}{\Delta y}\Delta t - s_{i,j}^{t+\Delta t}\Delta t = 0. \tag{1}$$

$$q_{ei}^{t+\Delta t} - q_{ei}^{t} + \frac{g\,(h_f)_i \Delta t\,(z_{i+1} - z_i)^{t+\Delta t}}{\Delta x} + \frac{g n^2 \Delta t\, q_{xi}^{t+\Delta t}\left|q_{xi}^{t}\right|}{(h_f)_i^{7/3}} = 0. \tag{2}$$

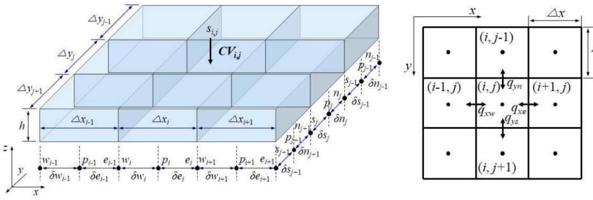


그림 1. 공간적 이산화를 위한 제어 체적 설정
Fig. 1. Control volume settings for spatial discretization

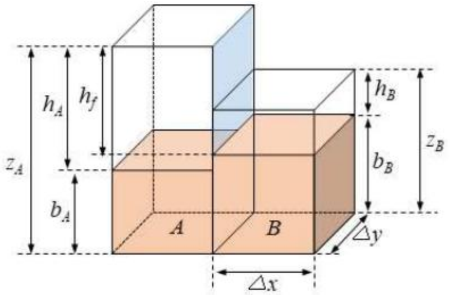


그림 2. 수심, 수위, 지면고, 흐름 수심의 관계
Fig. 2. Relationship between water depth, water level, ground elevation, and flow depth

In the control volume of the rectangular grid-based model, the altitude of the ground is not continuous and has a discontinuous value from the DEM altitude. Therefore, the water depth of the flow h_f between two adjacent grids A and B is set as shown in Figure 2 and Equation (3) using the ground elevation and water level of each grid.

$$h_f = (\left|z_{A,B}\right|_{\max} - \left|b_{A,B}\right|_{\max}). \tag{3}$$

The calculation time interval is set using the Courant Friedrichs Lewy (CFL) condition as shown in Equation (4) while the calculation is in progress [10].

$$\Delta t \le \frac{\Delta x}{u_{\max}}. \tag{4}$$

Here, $u_{\max}$ is the maximum value of flow velocity in the entire grid calculated at time t, and Δt represents the calculation time interval at time $t+\Delta t$.

3-2 Definition of input and output data

This section defines the format of input and output data used for urban flood prediction using the G2D model presented in Section 3-1. Tables 1 and 2 show input data to be applied to the model and output data formats for predicting results, respectively.

As shown in Table 1, input data are simulated environmental variables, model parameters, domain settings using DEM, and roughness coefficients for each grid using land cover map (LCM). In addition, the water level and depth can be set as initial conditions, and can be entered as boundary conditions such as water level, water depth and flow rate. Boundary conditions and average rainfall are entered as text files, and initial conditions are entered as ASCII raster format files or text files.

표 1. G2D 모델의 입력자료들
Table 1. Types of input data for G2D model

type of data	file format	notes
DEM	ASCII raster	target domain configuration
LCM		roughness coefficient for each grid
rainfall	ASCII raster	distributed rainfall – time series data
	text file	mean rainfall – time series data
flow rate	text file	boundary condition
water level	text file	boundary or initial conditions
	ASCII raster	initial conditions
water depth	text file	boundary or initial conditions
	ASCII raster	initial conditions

표 2. G2D 모델의 출력자료들
Table 2. Types of output data for G2D model

type of data	notes
water depth	water depth (unit, m)
water level	height from mean sea level to water surface (m)
flow rate	maximum flow per cell (m^3/s)
velocity	maximum flow rate in 4-way flow (m/s)
direction	direction of maximum flow
cell value	flow component value in the specified cell
log	log file

Table 2 is the resulting data format for the simulation. Calculation results of simulation experiments are saved as ASCII raster files or image files, and simulation result files can be selectively output. In the log file, the calculation time interval, the time used for calculations, the number of effective grids, and the number of grids for each designated water depth are output.

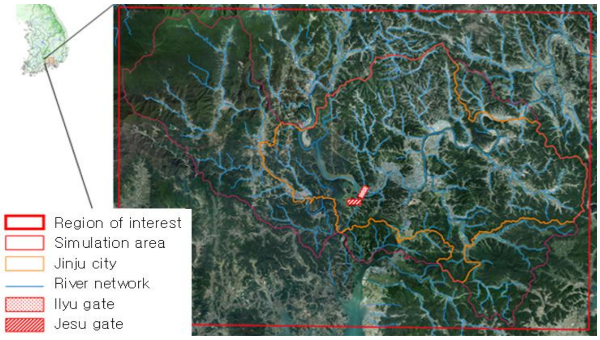
Ⅳ. Construction and Simulation of Urban Flood Analysis Model

4-1 Construction of urban flood analysis model

In this section, the results of constructing the flood analysis model using the type of input data and G2D model described in Section 3 are described. The simulation target area was set in Jinju city, Korea, which has many experiences of damage from torrential rain. The construction area is the area including Jinju city as shown in Figure 3(a). The upper stream includes the tributary basin flowing into Jinju city, and the downstream area is set to include a simulated area 2 km downstream of Jangbak Bridge in Jinju city.

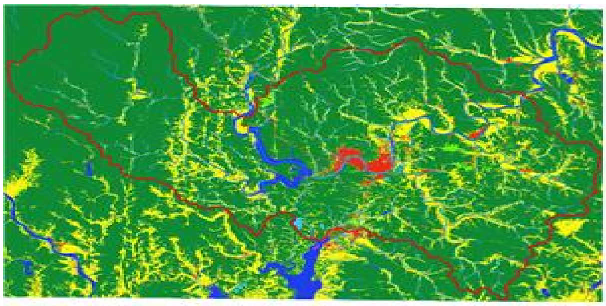
As shown in Figure 3(a) and (b), for topographical and spatial data, a model was built with a resolution of 10 m × 10 m so that important roads, rivers, and topographic relief could be distinguished. Here, the number of effective grids is composed of about 13 million. And, a simulated domain was constructed using DEM, and the ground surface roughness coefficient was set using LCM classified by the Ministry of Environment.

Boundary conditions and generation term settings are as follows. Boundary conditions and generation term settings are as follows. In order to apply the discharge scenario of Namgang Dam, the flow generation point was set at Ilyu Gate, which is the main flow gate of Namgang Dam, and Jesu Gate, which is the Gahwa Stream gate of Namgang Dam. The downstream stage applies the free surface outflow condition, and to reduce the uncertainty of the boundary, the boundary condition was set at about downstream 2 km of Jangbak Bridge in Jinju city.



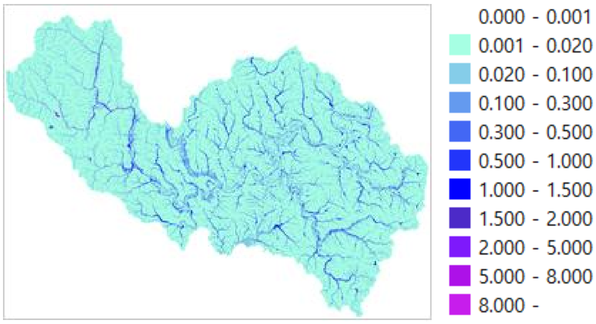
(a) target area (Jinju city)

(b) DEM of target area

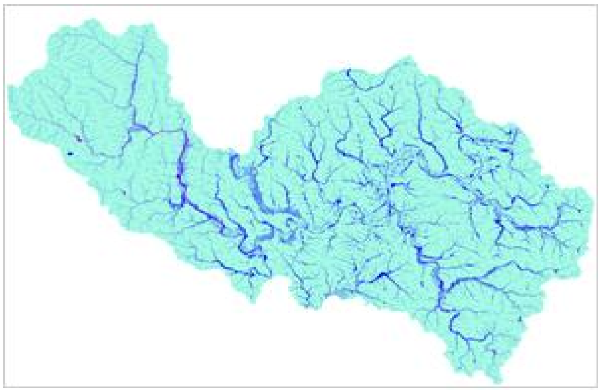


(c) land cover map of target area

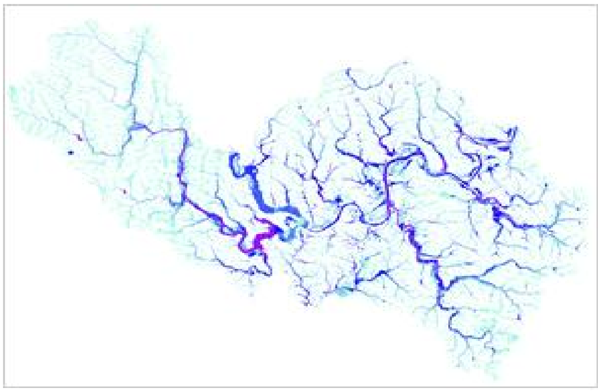
그림 3. 모의 대상 지역과 지형 및 공간자료들
Fig. 3. Areas to be simulated, topography and spatial data



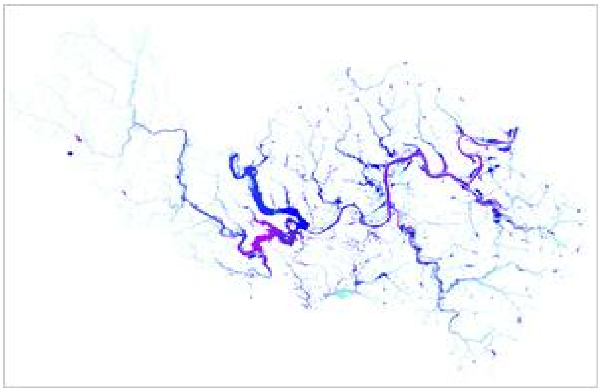
(a) + 2 hours (water depth, m)



(b) + 3 hours



(c) + 6 hours



(d) + 12 hours

그림 4. G2D 모델의 시간별 시뮬레이션 결과

Fig. 4. Simulation results of G2D model by time

The simulation period was set as the rainy season from July to August 2020, and the rainfall data was used the rain radar RKDP of the Ministry of Environment. In the simulation of the built G2D model, virtual rainfall (3 mm/10 min rainfall given to all cells for 5 hours) and virtual flow were applied, and the simulation results of the hourly G2D model are shown in Figure 4. As a result of the experiment, it was confirmed that surface flow, river flow, and undercurrent in scattered reservoirs were well simulated throughout Jinju city. The run-time evaluation using the GPU acceleration method for th flood analysis simulation is described in Section 4-2.

4-2 GPU acceleration techniques

High-resolution flood simulation takes a lot of calculation time, so it is difficult to quickly produce simulation results. In particular, the simulation area of Jinju city in this study has a vast number of effective grids of about 13 million, and rapid simulation is essential to run multiple simulations by applying various rainfall and flow scenarios. The G2D model can be used for parallel calculation using CPU by applying OpenMP, but additional run-time time reduction is required to simulate flooding in the entire Jinju city area. In this study, a GPU acceleration method was developed and adopted in the G2D model using NVIDIA's CUDA [11].

표 3. GPU 가속 기법 적용을 위한 실험 환경

Table 3. Experimental environment for applying GPU acceleration techniques

type	details
OS	Windows10 Pro. 20H2 64bit
CPU	Intel Core i9-7900X, 3.3GHz, 10 Core 20 Threads
GPU #1	NVIDIA GeForce GTX 1080Ti, 3,584 CUDA cores, Mem. 11 GB, MBW(Memory Band Width) 484.4 GB/s
GPU #2	NVIDIA GeForce RTX 3090, 10,496 CUDA cores, Mem. 24 GB, MBW 936.2 GB/s

표 4. GPU 가속 기법을 적용한 런-타임 평가

Table 4. Run-time evaluation using GPU acceleration techniques

grid size / number of cells	type	CPU serial	CPU parallel	GPU #1	GPU #2
10 × 10 (m) / 13,243,084	run-time (m)	35,389	3,503	1,255	517
	Speedup_CPU serial (1)	1	10	28.2	68.4
	Speedup_CPU parallel (2)	–	1	2.8	6.8

⁎ Speedup_CPU serial (1) = (CPU serial time) / (CPU parallel time) or (CPU serial time) / (GPU time)

⁎ Speedup_CPU parallel (2) = (CPU parallel time) / (GPU time)

Table 3 is the specification and environment of the main system for run-time evaluation in the flood analysis process, and Table 4 compares CPU and GPU-based run-time evaluation to visualize the results in Section 4-1. The run-time evaluation result of the flood analysis model is variable depending on the applied equipment, and parallel calculation using GPU is well executed in the environment presented in Table 3, and it was confirmed that the simulated flood depth can be generated as shown in Figure 4. As a result of the simulation, it was possible to reduce the time required for high-resolution flood simulation by reducing the run-time by about 39 to 72 times compared to CPU serial and about 6 to 8 times compared to CPU parallel.

Ⅴ. Conclusions and Future Works

In this paper, scenario-based urban flooding prediction using rainfall forecasting, topography and spatial data was performed. The wide-area surface inundation analysis simulation applied the G2D model developed by KICT, and constructed and visualized the flood analysis model based on Jinju city in Korea. In addition, the flow was calculated by applying the GPU acceleration method for high-resolution inundation simulation. For the simulated area, it took about 2.4 days for one day of simulation in parallel calculation using CPU. However, calculation using GPU could reduce run-time by about 39 to 72 times and 6 to 8 times, respectively, compared to CPU serial and CPU parallel. And it was confirmed that surface flow, river flow, and undercurrent in scattered reservoirs were well simulated for the entire Jinju city, the target area.

For future research, we plan to perform model calibration and evaluation to secure the reliability of the flood analysis model in Jinju city, and build a model for the construction of a flood prediction mapusing the InfoWorks ICM [12] model. In addition, since urban flood analysis is greatly affected by the temporal and spatial changes of precipitation, we plan to create an accurate rainfall scenario and build a database for road facilities.

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