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To Study Hydrological Variabilities by using Surface and Groundwater Coupled Model – A Case Study of PingTung Plain, Taiwan

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Abstract

The main objective of this research is to study the hydrological variabilities by using surface and groundwater coupled model. On that Taiwan is labeled as mountainous watershed with accompanying heavy rains occurred frequently, it is important to understand better the water flow conditions after extreme event occurred. The particular geology and highly concentrated river system could provide more infiltration and percolation of rainwater from surface or streams through permeable soils into water-holding rocks. It may provide useful water supply to undergrounds. In order to study the possible water storage underground in PingTung Plain, we used WASH123D watershed model to study this issue. The WASH123D numerical model is a physical based computational model with dealing surface flow and groundwater interactions competently. We firstly used field wells data to construct modeling environment, and then applied observation data to calibrate simulated parameters. Modelling environment including rivers, overland and groundwater are constructed in our model. Three examples with including extreme typhoon events insides are studied. We designed the period at last one month to calibrate our model parameters. It is because the flow condition after extreme rainfall occurred is one of the major phenomena that we are interested. The reactions of pressure head on different layers after extreme event occurred have focused. And we examined this mode to evaluate the efficiency of an ongoing groundwater supply plan in this region.

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Keywords: PingTung Plain; WASH123D; watershed. ;

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1. Preface

Due to the unevenly distributed precipitation in time and space, Taiwan is subject to the colossal variation of available water resources between wet and dry seasons. And the economic growth has made the shortage of water supply too conspicuous to ignore. To make the situation more complicated, exploration of new water resources is stumped by various conditions. As a result, groundwater has become an important water resource as a whole. According to the hydrological cycle theory, the surface water and groundwater are extremely different in hydrological features, but their alternate water transmissions are tightly bound together. In extreme events, the surface water reacts swiftly and sensitively, while the groundwater needs more time to react, and more slowly. Nevertheless, during dry seasons, the groundwater is a source of surface waters such as rivers, affecting their geological base flows. However, the groundwater pumping areas are usually not where the recharge happens, thus the over-pumping and over-use of groundwater during dry seasons can easily cause serious land subsidence along with derived social and economic issues. As a result, the southwest coasts such as the PingTung Plain has undergone serious subsidence whose consequences include weakened drainage capacity, surging tide floods, and permanent damage to the soil and water resources. The social and economic losses will be beyond estimation, and too tremendous to undertake. Therefore, effective management of groundwater resources is essential not only to consider and treat the groundwater as a whole, but also clarify the interactive mechanism and correlation between surface water and groundwater. In addition, the complete coupling of surface water and groundwater can be effectively applied to identify the areas where groundwater is used and the reasonable volumes for use, carry out effective man-made recharges, and stipulate control measures for groundwater conservation and utilization. Only through the regulated utilization and monitoring control, will the use of groundwater be sustainable.

To make robust the joint operations and management of surface water and groundwater, it is necessary to have a full insight into the interactive mechanism of surface water and groundwater, aided with a grasp of key information such as meteorological, hydrological, hydrogeological, geological, and human operation data. The simulation models with surface water and groundwater coupled can provide reference to the exploration, operations and regulations of groundwater resources in decision making. Via the numeric modelling, the one-dimension river discharge flow, two-dimension overland flow, and three-dimension groundwater flow are coupled together in the modelling for algorithms with various timescales, so that the interactive mechanism and correlation between surface water and groundwater can be clarified, and in the meantime, the results can be used for evaluation and planning on groundwater recharge programs. To actively solve the problems concerning groundwater resources, this research has applied the simulation models of coupled surface water and groundwater to evaluate the potential of groundwater resources. In the end, the Ping Tung Plain is demonstrated to evaluate potential recharge capacities of the river sections and impact of long-term man-made groundwater pumping, and find solutions to the land subsidence and deteriorated groundwater environment.

2. Description of the WASH123D Model

The WASH123D (WAterSHed Systems of 1-D Stream-River Network, 2-D Overland Regime, and 3-D Subsurface Media) is a distributed grid algorithm on catchment water flow and transmissions of biological, geological, chemical reactions. One of the advantages of the distributed physical model is its provision of space simulation features within the simulated areas and, through the complete physical calculations, various scenarios are designed for hydrological simulations so that the hydrological reactions under extreme events can be effectively grasped. In addition, the WASH123D can simulate every link of the hydrological cycles in the catchment area, including surface water evaporation, evapotranspiration, the process of surface water penetration into groundwater, overland flow, and transmission of geological and chemical reactants. This research uses the WASH123D modelling tool for coupled one-dimension river routing, two-dimension flood simulation, and three-dimension groundwater calculation. It is also used for assessment on groundwater recharge of targeted areas. The model's flow simulation adopts the control equations described as follows:

2. 1. One-dimension river routing

The governing equations of water flow in one-dimensional river/stream/canal can be derived based on the conservation law of water mass and linear momentum(Singh, 1996), and can be written as follows:

The continuity equation:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=S_S+S_R-S_E+S_I+S_1+S_2 \tag{1}$$

where S_S is the man-induced source [$L^3/T/L$], S_R is the source due to rainfall [$L^3/T/L$], S_E is the sink duo to evapotranspiration [$L^3/T/L$], S_I is the source duo to exfiltration from the subsurface media [$L^3/T/L$], S_1 and S_2 are the source terms contributed from overland flow [$L^3/T/L$].

The momentum equation:

$$\frac{\partial Q}{\partial t}+\frac{\partial VQ}{\partial x}=-gAa\frac{\partial (Z_0+h)}{\partial x}-\frac{gAh}{c\rho}\frac{\partial \Delta\rho}{\partial x}-\frac{\partial F_X}{\partial x} + (M_S+M_R+M_E+M_I+M_1+M_2) \tag{2}$$

Where h is water depth [L], Z_0 is bottom elevation [L], c is the shape factor of the cross-sectional area, F_X is the momentum flux duo to eddy viscosity [L^4/T^2], M_S is the external momentum-impulse from artificial source/sink [L^3/T^2].

2.2. Two-dimension overland calculations

The governing equations for two-dimensional overland flow can be derived based on conservation law of water mass and linear momentum [Wang and Connor, 1975]. The governing equations of dynamic wave model in conservative form can be written as follows:

The continuity equation:

$$\frac{\partial h}{\partial t}+\frac{\partial (uh)}{\partial x}+\frac{\partial (vh)}{\partial y}=S_S+S_R-S_E+S_I \tag{3}$$

Where h is water depth[L], S_S is the man-induced source [$L^3/T/L$], S_R is the source due to rainfall [$L^3/T/L$], S_E is the sink duo to evapotranspiration [$L^3/T/L$], S_I is the source from subsurface media duo to exfiltration [$L^3/T/L$].

The x-momentum equation:

$$\frac{\partial (uh)}{\partial t}+\frac{\partial u(uh)}{\partial x}+\frac{\partial v(vh)}{\partial y}=-gh\frac{\partial (Z_0+h)}{\partial x}-\frac{gh^2}{2\rho}\frac{\partial \Delta\rho}{\partial x}-\frac{\partial F_{xx}}{\partial x} -\frac{\partial F_{yx}}{\partial y}+(M_X^S+M_X^R-M_X^E+M_X^I) \tag{4}$$

The y-momentum equation:

$$\frac{\partial (vh)}{\partial t}+\frac{\partial u(vh)}{\partial x}+\frac{\partial v(vh)}{\partial y}=-gh\frac{\partial (Z_0+h)}{\partial y}-gh\frac{gh^2}{2\rho}\frac{\partial \Delta\rho}{\partial y} -\frac{\partial F_{xy}}{\partial x}-\frac{\partial F_{yy}}{\partial y}+\left(M_y^S+M_y^R-M_y^E+M_y^I\right) \tag{5}$$

M_X^S is the x-component of momentum-impulse from artificial sources/sinks [L^3/T^2], F_{xx} and F_{yx} are the water fluxes duo to eddy viscosity along the x direction [L^3/T^2].

2.3. Three-dimension groundwater calculations

For groundwater simulations, the WASH123D adopts the groundwater model FEMWATER developed by Professor Ye Gaoci as its main structure, and its control equation is the modified Richards' Equation in consideration of mass conservation and water variation in the unsaturated layer. The equation is expressed as follows:

$$\frac{\rho}{\rho_0} F \frac{\partial h}{\partial t} = \nabla \cdot \left[K \cdot \left(\nabla h + \frac{\rho}{\rho_0} \nabla z \right) \right] + \frac{\rho^*}{\rho_0} q \tag{6}$$

In the above equation, h is pressure head [L]; t is time [T]; K is hydraulic conductivity tensor [L/T]; z is elevation head [L]; q is outflow or inflow volume [$L^3/L^3/T$]; F is water content [1/L], expressed as follows:

$$\mathrm{F} = \alpha' \frac{\theta_e}{n_e} + \beta' \theta_e + n_e \frac{dS}{dh} \tag{7}$$

Where θ_e is effective soil moisture content [L^3/L^3]; n_e is effective soil porosity [L^3/L^3]; S is soil saturation; while Darcy's velocity is expressed as follows:

$$\mathrm{v} = -\mathrm{K} \cdot \left(\frac{\rho_0}{\rho} \nabla h + \nabla z \right) \tag{8}$$

The Galerkin Finite Element Method is used to solve the above groundwater flow control equations, which can be applied to confined aquifer or unconfined aquifer, or mixture of both in multilayer aquifers, for simulations. This method is currently one of the most popular numeric models for the variably saturated groundwater simulations

3. Establishment of Simulation Environment

3.1. Regional introduction

The Ping Tung Plain is taken as the simulation area for the research. Located in the southwestern tip of Taiwan, the Ping Tung Plain starts from the Alishan Range at the southern end in the north, stretching south to Taiwan Strait , the west side starts from lingkou hilly, and Dawu Mountain to the east side apart, with an area of 1,230 square kilometers and the almost area elevation is less than 100 meters.

Ping tung Plain basin average rainfall is very high, the average annual rainfall of about 2,770 mm, dry season (November to April next year) and the wet season (May to October),respectively total Rainfall annual rainfall of 7.0% and 93.0%.This rainfall substantially decreasing from east to west

The highest proportion of land use for agriculture 58.60%. Ping tung Plain region shown in Figure 1 (a) shows. In this study, the water level measurement station is Liling Bridge, Wanda Bridge, Kaoping Bridge, Kaopingsi Railway Bridge, Gangtung Second Bridge, Chaozhou Bridge, Xinpi Bridge. And part of a water flow station is Dongxi Bridge, Liouguei, Shanlin Bridge, Dajin Bridge, Sinon Bridge, Sandimen. In Figure 1 (b), the groundwater level observation wells of 66 stations. Distribution shown in Figure 1 (c) .If the simulated event flow stations with missing data, we use Hydrologic Modeling System HEC-HMS 3.5 Reckoning.

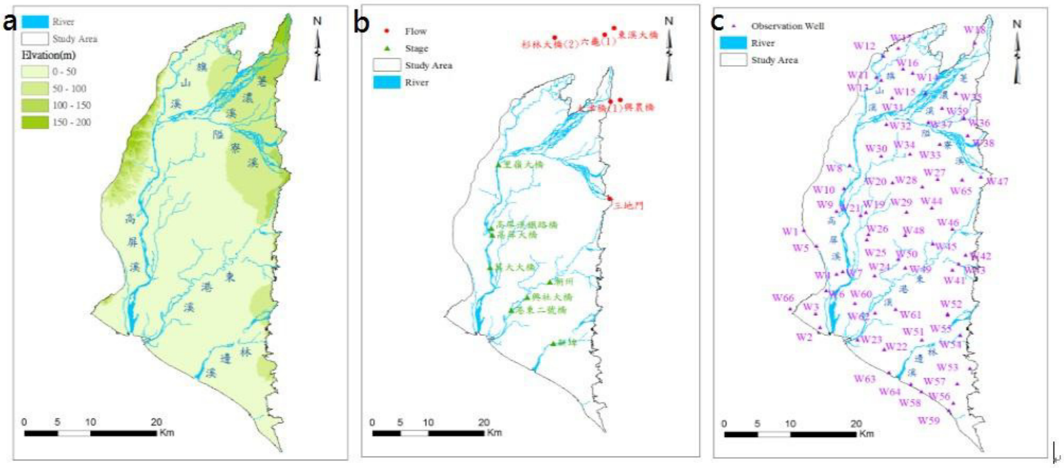
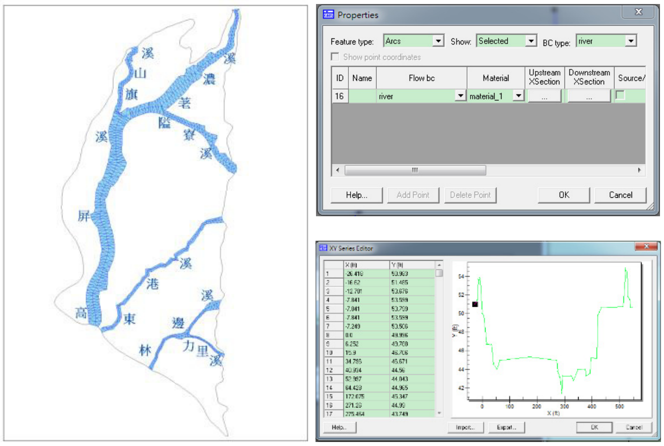


Fig. 1. (a) Ping tung Plain region; (b) Ping tung Plain water flow and level stations; (c) Ping tung Plain groundwater level observation wells

3.2. Grid setup

The one-dimension river channel simulation takes the discharge orifice of Liouguei,Shanlin Bridge, Sandimen as the upstream control point, and the estuary of coastal as the downstream control point, In this area have 3 junctions point ,according to the Water Resources Agency Great Cross Section Survey Report, Qishan River is 24 cross sections, Laonong River is 55 cross sections, Ailiao River 30 cross sections, Gaoping River is 75 cross sections, Donggang River 38 cross sections, Linbian River 46 cross sections, total cross sections is 271.
Whose geographic distribution is shown in Figure 2.



Feature type: Arcs Show: Selected BC type: river

☐ Show point coordinates

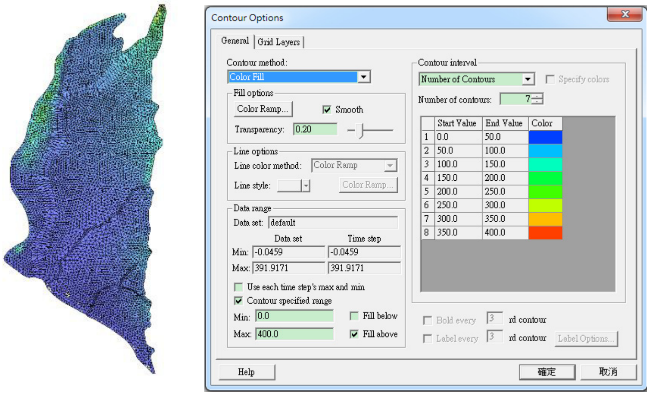
ID	Name	Flow bc	Material	Upstream XSection	Downstream XSection	Source/
16		river	material_1	...	...	☐

	X (ft)	Y (ft)
1	-26.418	50.983
2	-16.62	51.485
3	-12.701	53.676
4	-7.841	53.599
5	-7.041	53.709
6	-7.841	53.599
7	-7.249	50.506
8	0.0	49.996
9	6.252	49.768
10	15.9	46.706
11	34.795	46.671
12	40.934	44.56
13	52.987	44.043
14	64.429	44.965
15	172.075	45.347
16	271.26	44.99
17	275.464	43.749

Fig. 2. Distribution of River Cross Sections of Surface Water Simulation

The two-dimension surface simulation extension of one-dimensional simulation. The geographic distribution of the simulation is shown in Figure 3. A non-uniform grid is used to solve the overland flood problems. To begin with, triangular grids with finite element method is set up, and on the earth's surface are 4,859 grid points and 9,350 triangular grids, as show in Figure 3. In two-dimension surface simulation, each grid system node has corresponding elevation information, and each element also have corresponding land utilization. According to the Ministry of the

Interior Report, the Ping Tung Plain land utilization can be divided into 9 species, the land utilization contains Agricultural, forest, traffic, Water conservation, architecture, public, Recreation, Rock salt and other land utilization.



Contour method: Color Fill

Fill options: ☑ Smooth

Transparency: 0.20

Line options

Line color method: Color Ramp

Line style:

Data range

Data set: default

	Data set	Time step
Min:	-0.0459	-0.0459
Max:	391.9171	391.9171

☐ Use each time step's max and min

☑ Contour specified range

Min: 0.0 ☐ Fill below

Max: 400.0 ☑ Fill above

Contour interval: Number of Contours ☐ Specify colors

Number of contours: 7

	Start Value	End Value	Color
1	0.0	50.0	🟦
2	50.0	100.0	🟦
3	100.0	150.0	🟩
4	150.0	200.0	🟩
5	200.0	250.0	🟩
6	250.0	300.0	🟨
7	300.0	350.0	🟧
8	350.0	400.0	🟥

☐ Bold every 3 rd contour

☐ Label every 3 rd contour

Fig. 3. Distribution of Elevations of Two-Dimension Surface Simulation

The three-dimension groundwater simulation continues the use of the surface grids used in the surface water simulation. According to the "Planning of Groundwater Recharge Geological Sensitive Designation Areas published in 2014 by the Central Geological Survey, Ministry of Economic Affairs., descriptions of the Lin yuan- Fangshan cross section and Chaoliu - Daxiang cross section are extracted for illustration. The top-down alluvium layers of the Ping Tung Plain contains interlocking aquifer F1 (note: the report uses the term groundwater, but this research uses the term aquifer), aquiclude T1, aquifer F2, aquiclude T2, aquifer F3-1, aquifer F3-2, aquiclude T3. These hydrogeological units are used throughout this research. Also taken into account are the established fourteen hydrogeological layers as shown in Figure 4, where each layer has 9,350 elements and 4,860 nodes and, as a result, the 14 layers have a total of 130,900 elements and 72,900 nodes.

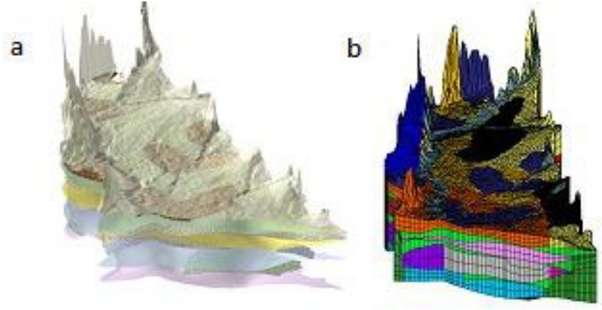


Fig. 4. (a) Conceptual Layers of Three-Dimension Groundwater Simulation; (b) Three-Dimension Grid Establishment .

Result and discussion

Parametric test of surface water groundwater integrated numerical model and verification, we choose case Typhoon Morakot to be simulation. We collect whole rainfall data of 19 long term observation rainfall stations which offer streamflow routing and Surface analog input conditions. Channel analog required given Manning coefficient to simulate water flow velocity.

1D simulationIn this 1D Channel simulation, we choose Gaoping river basin's water level station Liling bridge and Wanda bridge, simulation results are shown in Figure 5.There is an obvious error between the change of the water level after displaying the peak and the observation .Simulation in water Recession is Slower than the Actual observation water level. Liling bridge's RMSE (Root Mean Square Error) is 0.98m, CE (Nash-Sutcliffe model efficiency coefficient) is 0.68. R^2(R Square) is 0.97. Wanda bridge's RMSE is 0.97, CE is 0.69, R^2 is 0.90. The 1D simulation results shown in Figure 5.

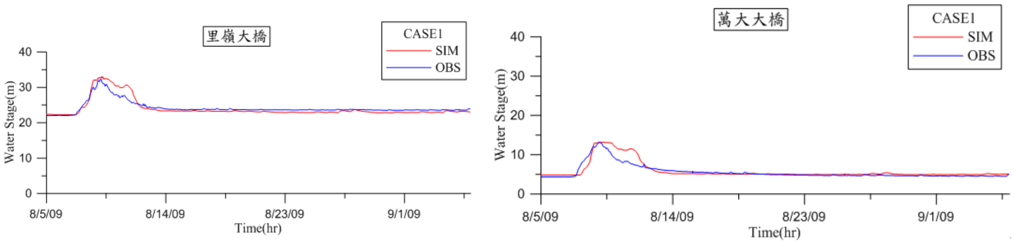


Fig.5. Liling bridge and Wanda bridge 1D Channel simulation result

- 2D simulation

This study discusses surface water situation in the area. The flooding data is referring to the report about "Pingtung County Disaster Assessment and Environmental Investigation to survey flooding area". Flooding area is equal with the fact approximately, the 2D simulation results shown in Figure 6.

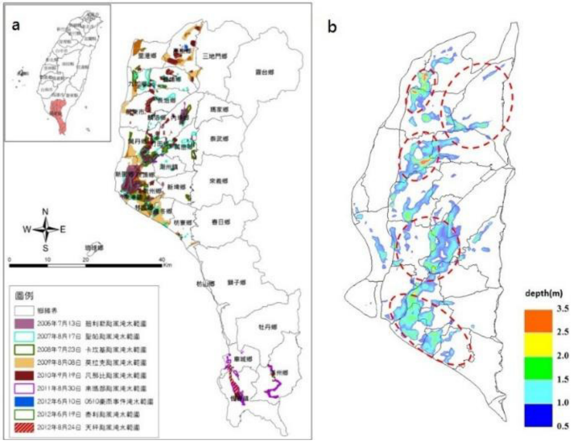


Fig.6. (a) Pingtung County Disaster Assessment and Environmental Investigation to survey flooding area; (b) surface water situation result

- 3D simulation

In this study, we will analyze groundwater observation wells and simulation data. The mountainous part Groundwater level simulation value of the maximum error 2-3 meter. Because of terrain affection, the error is acceptable. River Plain part Groundwater level simulation value of the maximum error 2 meter. Hydraulic conductivity need to adjust .The 3D simulation results shown in Figure 7.

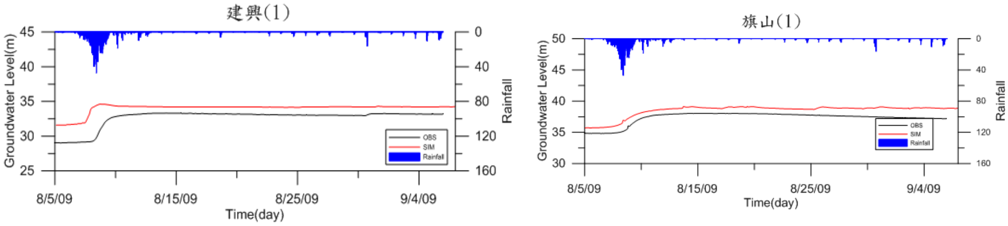


Fig.7. Kam Hing and Qishan Groundwater simulation

- Analysis of pressure head

analyze result of 3d simulation groundwater Aquifer 1 pressure head in the typhoon Morakot event. , Figure 8 is Aquifer 1’s pressure head, when no rain time, under the surface layer of mud aquifer 1‘s pressure head is higher than other place In the rest area , pressure head reach highest when it is rainstorm time. It displays that after raining, pressure head increase in river area.

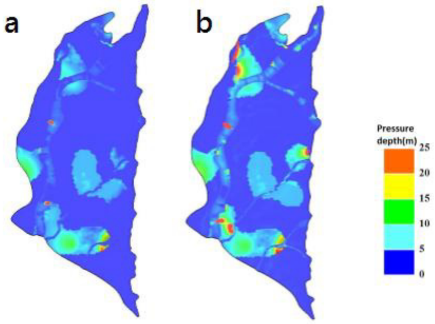


Fig.8. 3d simulation groundwater Aquifer 1 pressure head in the typhoon Morakot event (a) when no rain time; (b) Maximum rainfall

- Analysis velocity of groundwater

analyze result of 3d simulation groundwater flow situation in the typhoon Morakot event., Figure 9 is Aquifer 1’s XY direction Velocity distribution. When Start rainfall, the mountainous part and river junction part’s Groundwater velocity is higher than other place. When it is rainstorm time, Groundwater velocity reach highest. It display that Rainfall has a direct impact on groundwater.

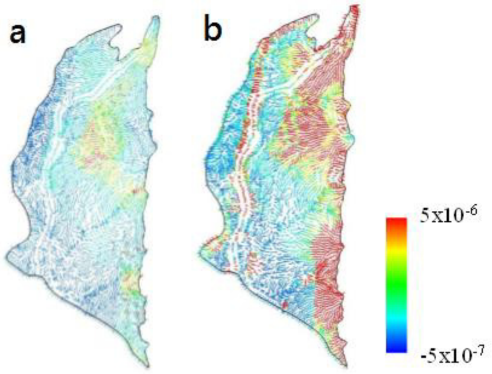


Fig.9. 3d simulation groundwater Aquifer 1 velocity in the typhoon Morakot event (a) when no rain time; (b) Maximum rainfall

Conclusions

Morakot event shows that the simulation results are consistent with the facts, the overall simulation trend of the landscape and observed values are in good agreement. Besides, the peak time is consistent and the surface flooding situation is almost the same as reported. For the groundwater part, the whole underground water level has been simulated, in the future, there will be a more in-depth understanding and research about each aquifer’s stratified flow conditions and the overall groundwater recharge.

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