Internship Final Report

Project Title: Hydrodynamical Modelling and Soil Erosion Risk Maps in Shihmen Reservoir Watershed, Taiwan

Company: Nelen & Schuurmans (zakkendragershof 34-44, 3511 AE utrecht)

Intern: Cheng Wei

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ABSTRACT

As mentioned by Chiang et al. (2019) [1], the balance of sediment transport in rivers is affected by land development in a watershed. Especially during the rainy season, Taiwan confronts typhoons with heavy rainfall that wash hillslopes, causing landslides, soil erosion and debris flow into downstream areas. As a result, the overloaded sediment frequently causes serious river bank damage and bed scours. Moreover, the risk of erosion in watersheds increase and hydraulic structures, such as dams and reservoirs could be damaged. Therefore, it is crucial to have insight into the risk levels of erosion of the various areas.

Shihmen reservoir watershed, northern Taiwan is chosen as the research area in this study. In terms of the hydrodynamics model, we would like to use 3Di to simulate Typhoon Aere in 2004 to investigate the influence of severe typhoon events due to the significant role of sediment production of the study area.

These areas will be determined based on soil parameters, bed coverage and land use in combination with velocity fields from 3Di. And then an erosion risk map is derived with indications, e.g. very high, high, medium and low risk, and considers the spatial distributions of bed shear stress as a risk indicator to evaluate the effect of soil erosion after the typhoon event.

Our study indicates that most areas of Shihmen reservoir watershed are under moderate or high-risk level of soil erosion in the case, while few areas in hillslope or lowland region would suffer very-high-risk and low-risk level of soil erosion hazard. The map provides an evaluation reference for decision making, when it comes to such typhoon events in the future. It is evidenced to be a valuable reference for the reservoir authority to plan future soil conservation engineering as well.

CONTENTS

Chapter 1 Introduction

Soil erosion is the transportation and detachment of the soil by water removing soil particles causing the soil to deteriorate. Additionally, it is a naturally occurring phenomenon and a common geological process associated with the hydrologic cycle. The most important causes of soil erosion are driven forces of wind, precipitation, and following runoff on the land surface. Land use, soil types and living-being activities are also responsible for such erosion occurrence.

After heavy rainfall and typhoon events, the eroded soil will be carried into water courses and result in tremendous sediment inflow into streams. Soil erosion in catchment areas and the subsequent deposition in rivers, lakes, and reservoirs are of great concern for various reasons such as eroding the fertile and rich soil in the catchment areas, reducing the capacity in the storage reservoirs as well as degradation of downstream water quality. Soil erosion can never be stopped completely, but it can be mitigated to some extent. [2,3]

Therefore, it is important to evaluate the soil erosion and find the susceptible area in watershed catchments. And then systematically classify the eroded areas for the hazard assessment and future management. [4]

In 2004, Typhoon Aere crossed northern Taiwan during 23– 26 of August. The maximum four-day cumulative rainfall reached up to 1607 mm. The Baishi precipitation measurement station located in the upstream area of the Hsiuluan sub-watershed, recorded 1262 mm in 24 hr. Typhoon Aere was the strongest typhoon to strike northern Taiwan in the past ten years, and the high intensity of the rainfall triggered most of the potential landslides and soil erosion. Figure 1 shows the landslide locations before (areas in blue) and after (areas in red) Typhoon Aere, it can be seen that more landslides occurred after the typhoon event.

Shihmen reservoir watershed is suitable for investigation of erosion phenomena. According to Tsai et al. [5], the ratio of the total landslide volume in Yunfeng and Hsiuluan watersheds, sub- watersheds of the Shihmen catchment, to the one in the whole Shihmen reservoir watershed reached 46.7% from 1968 to 1975, 62.2% from 1976 to 1985, 59.2% from 1986 to 1997, 40.5% from 1998 to 2003, and 61.7% from Typhoon Aere in 2004. Therefore, in the following, Shihmen reservoir watershed is chosen for simulating Typhoon Aere and investigating the erosion potential.

Most studies ([5-8]) explored how typhoons affected the mountainous region in Taiwan, focusing on the effect of landslide erosion and the post-failure sediment yields in landslide sites. In fact, there are few studies investigate the effect of soil erosion in watershed areas. Therefore, it is worth exploring the aspect of soil erosion in mountainous region, because it also plays an essential role in soil conservation planning and risk management. When Taiwan confronts challenges from natural disasters in the future again, both landslide and soil erosion studies could provide useful reference for solutions.

Due to the fact that Taiwan has young geological properties, high terrain, and fragile rock formation combined with typhoon and storm events, resulting in massive landslides and sediment yields in estuary areas after typhoon events. It is crucial to have insight in the risk levels of flood hazard rating as well to find out the possibilities of being destroyed by the following flooding after typhoon events in the watershed areas.

Therefore, it is of great importance to construct an erosion risk map to firstly estimate the sediment yields after intense rainfall events for the purposes of disaster prevention, hazard mitigation, and watershed management for further risk control procedures.

The physics behind soil erosion, landslides, sediment transport and debris flow are partly unknown and the uncertainties are quite large since sediment yield from a watershed is involved with numerous parameters such as local topography, soil, lithology, meteorological conditions, vegetation cover, land use, watershed morphology, and flow hydraulics. It is very complicated and highly variable in both time and hydro-morphological location of watersheds.

However, it is crucial to have insight into the risk levels to erosion of the various areas. Despite all the complexities and uncertainties on river systems, it should consider more aspects besides hydrological variability. Although every time when disasters occur, further works are often restricted due to the limited historical data or lacks of following field measurements. Based on these reasons, it remains challenging to determine the impacts in the first phase of the occurrence of natural disasters. Therefore, it is of great significance to derive a risk evaluation reference for determining the degrees of being impacted by the disaster in the areas of concern. Through this research, an erosion risk map is derived to present the risk levels after a typhoon event to provide a first-hand reference for determining the risk degrees and further decision making.

The primary objective of this research is to derive an erosion risk map to investigate soil erosion risk in Shihmen reservoir watershed, northern Taiwan, to address the potential erosion problems after the typhoon event. The map shows indications, e.g. very high, high, moderate and low risk levels, for erosion assessment. These areas will be determined based on soil parameters, bed coverage and land use in combination with velocity fields from the 3Di model, and suitable critical shear stress criteria. The circumstances of typhoon Aere in 2004 are used to give these indications.

Chapter 2 Methodology and Materials

2.1 Study Area

Located at the junction of the Philippine Sea Plate and the Eurasian Plate and passing routes of typhoons, this unique geographic location not only created an extremely diversified topography and frequent seismic activity, but also result in extreme rainfall and floods to Taiwan.

Besides, Taiwan has young geological properties, high terrain, and fragile rock formation due to the active and strong orogeny, which combined with high intensity rainfall events from typhoons or plum rains would result in massive soil erosion, landslides and sediment yields in estuary areas, generating large amounts of sediments eroded from the upstream watershed.

These sediments are transported mainly by water to the downstream reservoir areas, and the decrease of flow velocity causes sediment deposit, which would reduce the reservoir capacity and shorten the lifespan of reservoirs. [6]

Figure 2 shows the map and sub-watersheds of the study area—the Shihmen reservoir watershed. It is located in the northern Taiwan, on the middle reaches of the Dahan River, having one of the largest and most important reservoirs in Taiwan.

The watershed area of the reservoir watershed is 760.2 km^2 with elevation ranging from 158 m (Shihmen reservoir dam site) to 3524 m and average slope angles of about 30 degrees, sloping down from the southeast to the northwest, and it covers latitudes from 24°25'32.29" N to 24°51'37.98" N and longitudes from 121°11' 32.18" E to 121°28'44.16" E.

In the lower areas of the watershed, the lithology is mainly composed of gravel, muddy sand, and alternations of sandstone and shale. In the middle of the watershed, argillite, sandy shale, and slate are present; the upper watershed has broken and complex strata. The rock layer materials consist of argillite, slate, massive sandstone, alternations of shale and sandstone, and thick-bedded metasandstone. [5]

According to meteorological statistics (WRA, 1964 – 2004): the annual average temperature in this area is 19°C and the annual average humidity is approximately 82%. The average annual rainfall is approximately 2580 mm, with the wet season from May to September and the dry season from October to April in the next year, and is highly concentrated between May and September due to heavy rainfall from typhoons.

This study will focus specially on the Typhoon Aere, which hit Taiwan with a total precipitation of 1607 mm in the Shihmen reservoir watershed on 23-26 August in 2004. It crossed northern Taiwan bringing heavy rainfall to the watershed. It was the worst typhoon to strike northern Taiwan in recent years compared with other typhoon events.

The high intensity of the rainfall not only triggered a great number of landslides, as shown in Figure 1, and soil erosion in Shihmen reservoir watershed, but also caused turbidity currents in the reservoir areas, brought approximately $2.8 \times 10^7 m^3$ sediments into the reservoir, and interrupted the water supply for 17 days, not to mention the subsequent economy loss of agriculture, forestry, fishery and animal husbandry which was approximate 1.8 billion dollars.

In this situation, the role of erosion risk assessment needed to be identified for the purpose of evaluating the impact after such major typhoon event.

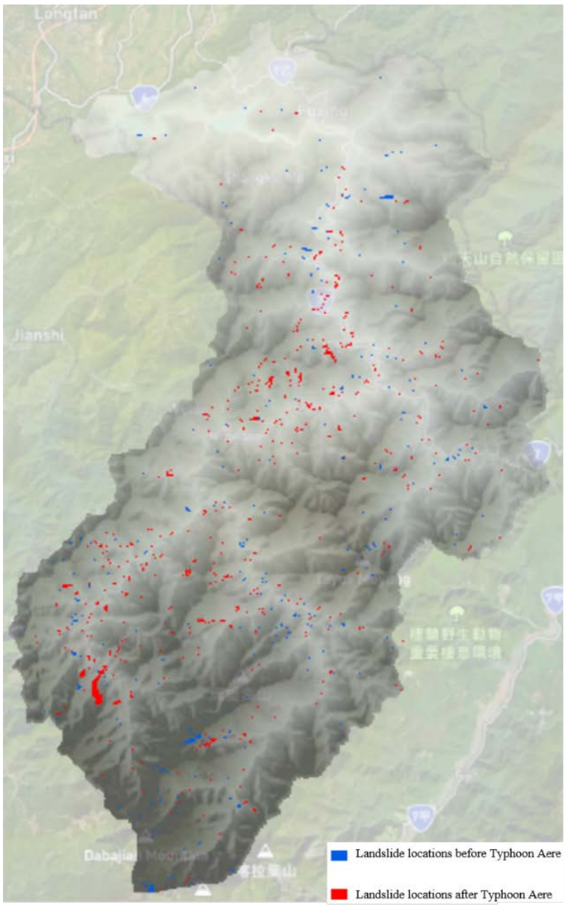


Figure 1 Landslide inventory before and after typhoon Aere in Shihmen Reservoir watershed.

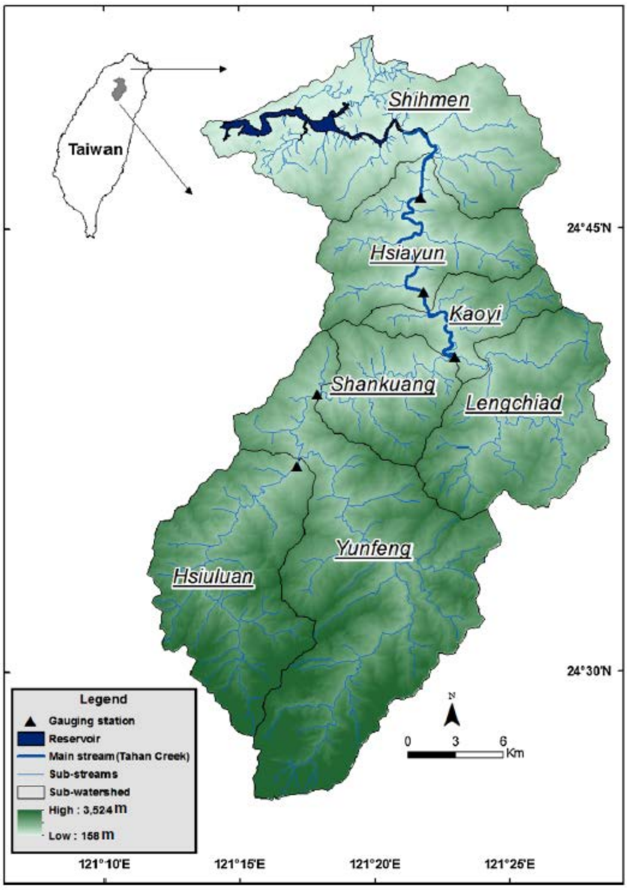


Figure 2 Sub-watersheds of the study area, Shihmen reservoir watershed, Northern Taiwan (Tsai et al. 2013). [6]

2.2 Proposed Model

In this study, a hydrodynamic model, 3Di, was used to simulate the catchment flows and to determine the velocity field, water depth, water-level of the watershed. 3Di is developed by a consortium of Stelling Hydraulics, Deltares, TU Delft and Nelen & Schuurmans. It is a process-based, hydrodynamic model for flooding, drainage and other water management studies and can be used for the computation of water flow in 1D and 2D.

The data and analytics platform, Lizard, was used to manage and download the results of raster data to integrate and combine data from different sources and domains. Other geo-based software such as Q-GIS and Arc GIS were utilized for further analysis in order to evaluate the risk level after the typhoon event scenario.

Figure 3 illustrates the flowchart for the model simulation and analysis procedure to estimate soil erosion and evaluate the risk levels of in the study areas.

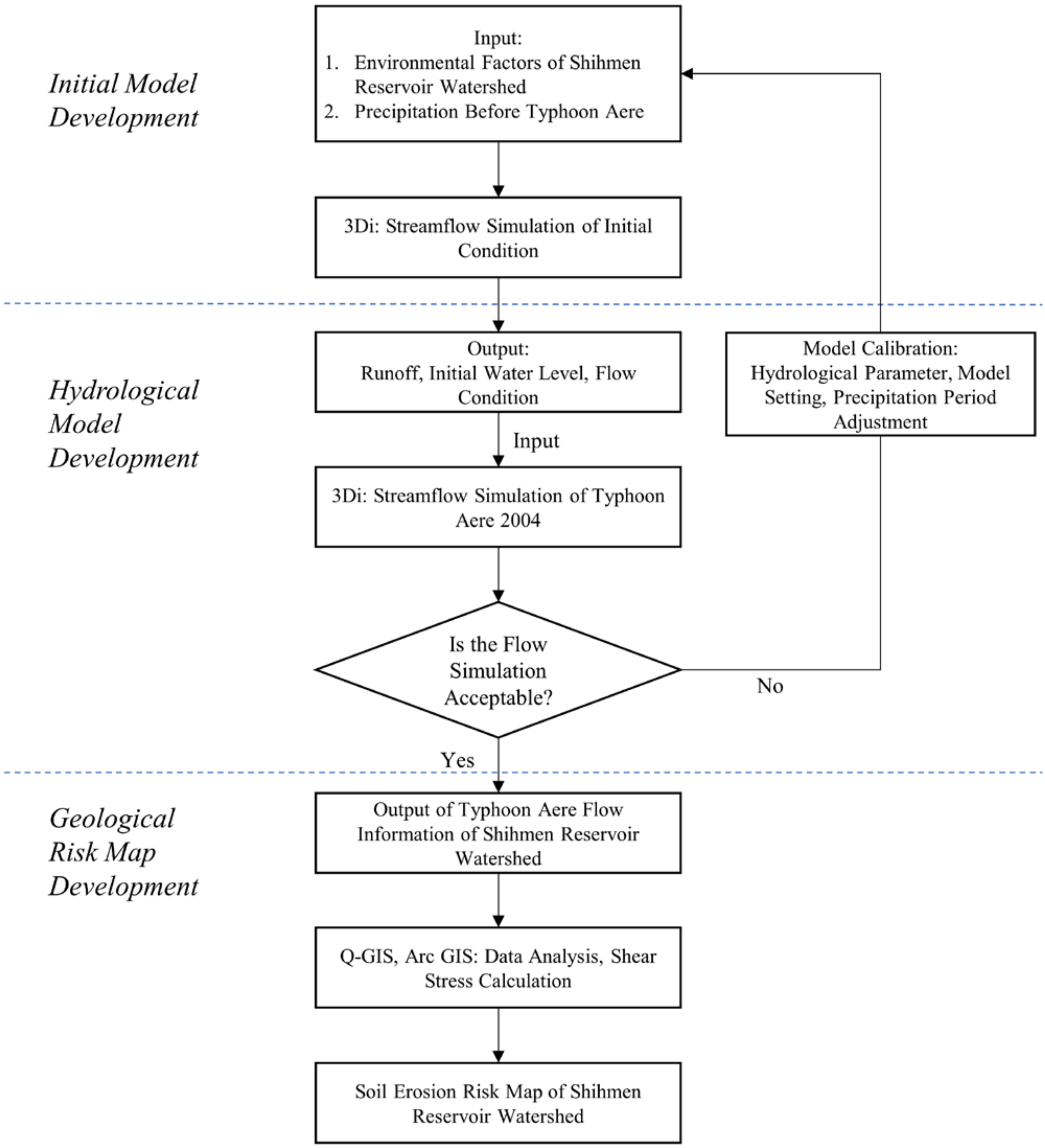


Figure 3 Framework for the development of erosion risk map.

2.3 Model Scenario

2.3.1 Precipitation data

To investigate the influence of severe typhoon events, Typhoon Aere in 2004 was chosen due to the significant role of sediment production of the study area including both landslide and soil erosion. Therefore, it deserves more attention to get more insights into this typhoon event.

Typhoon Aere crossed specifically over northern Taiwan, bringing extreme heavy rainfall. Precipitation data indicate that the total rainfall during the typhoon was 1607mm, with 1262mm occurring at the Baishi rainfall station of the Hsiuluan sub-watershed (Central Weather Bureau and Water Resources Agency). The typhoon runoff to the reservoir carried extremely high concentrations of sediment, considerably increasing the turbidity of the Shihmen Reservoir. [7]

The 3Di model was adopted to simulate the rainfall-runoff processes, thus providing the behavior of overland flow in surface runoff. In the study, the precipitation 14 days before the typhoon event as shown in Figure 4 was used to generate the initial flow condition for the purpose of making the model more precise and stable. And then use the hourly precipitation during Typhoon Aere period as shown in Figure 5 for modeling the typhoon scenario.

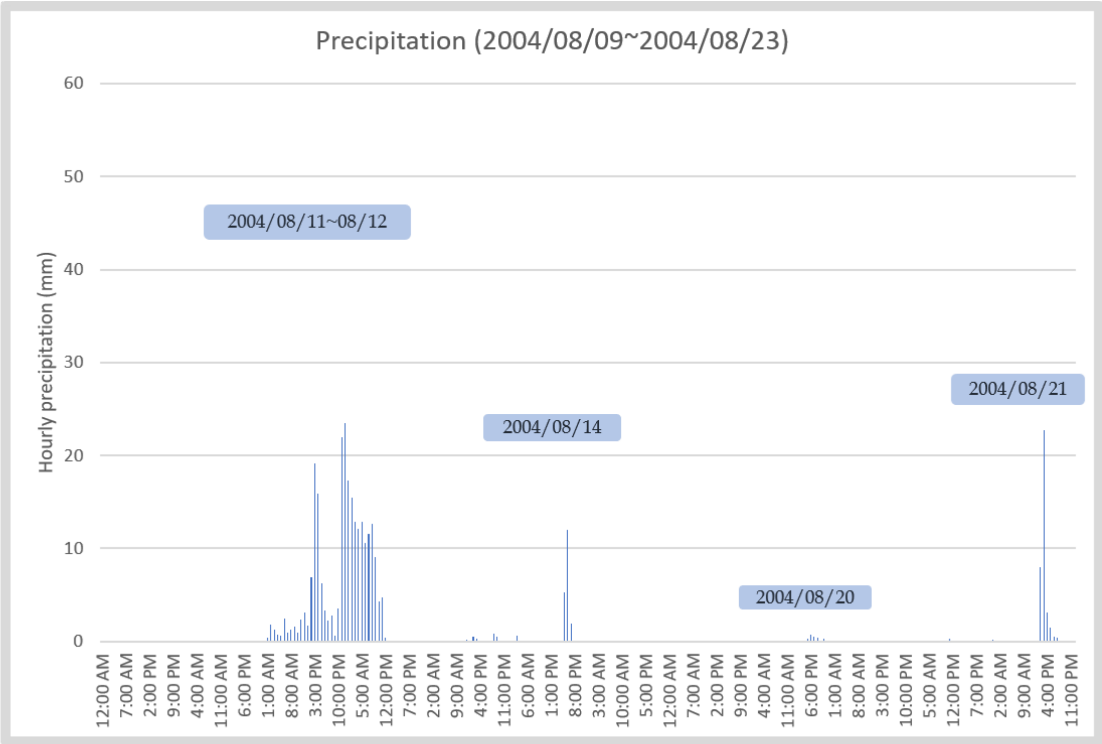


Figure 4 Hourly precipitation of the Shihmen reservoir watershed from August 9 to August 23 in 2004

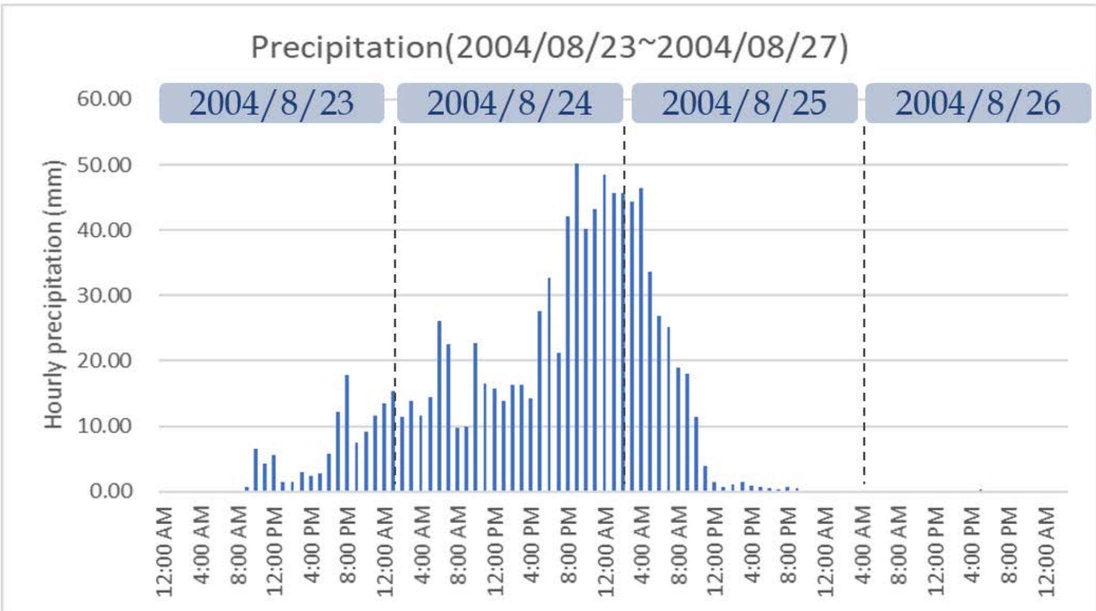


Figure 5 Hourly precipitation of the Shihmen reservoir watershed during Typhoon Aere in 2004

2.4 Hydrodynamic computations using 3Di

The detail model settings are shown in appendix including v2_global_settings and v2_numerical_settings.

In 3Di to allow flow to be computed numerically, space and time need to be discretized. For time are time-steps defined, and for space is a grid defined. It makes use of a so-called structured, staggered grid. This implies for the surface water domain that computational cells are perfect squares, where the pressure/ water levels and volumes are defined in the cell centers and velocities and discharges are defined at the cell edges. This also yields for the vertical coupling.

The hydrodynamic computations are based on the conservation of volume and momentum. The computational cost of a simulation is strongly related to the number of computational cells.

Because there are often regions where the flow is more complex or where one requires results with a finer resolution, to optimize the computational cost and grid resolution, the grid can be refined locally. 3Di uses a method called quad-tree refinement. This is a simple refinement method that forces smooth grid variations, which enhances an accurate solution of the equation.

In the study, the refinement of the grid is assigned along the main streams in the Shihmen reservoir watershed to investigate the variation near the main streams as shown in Figure 6.

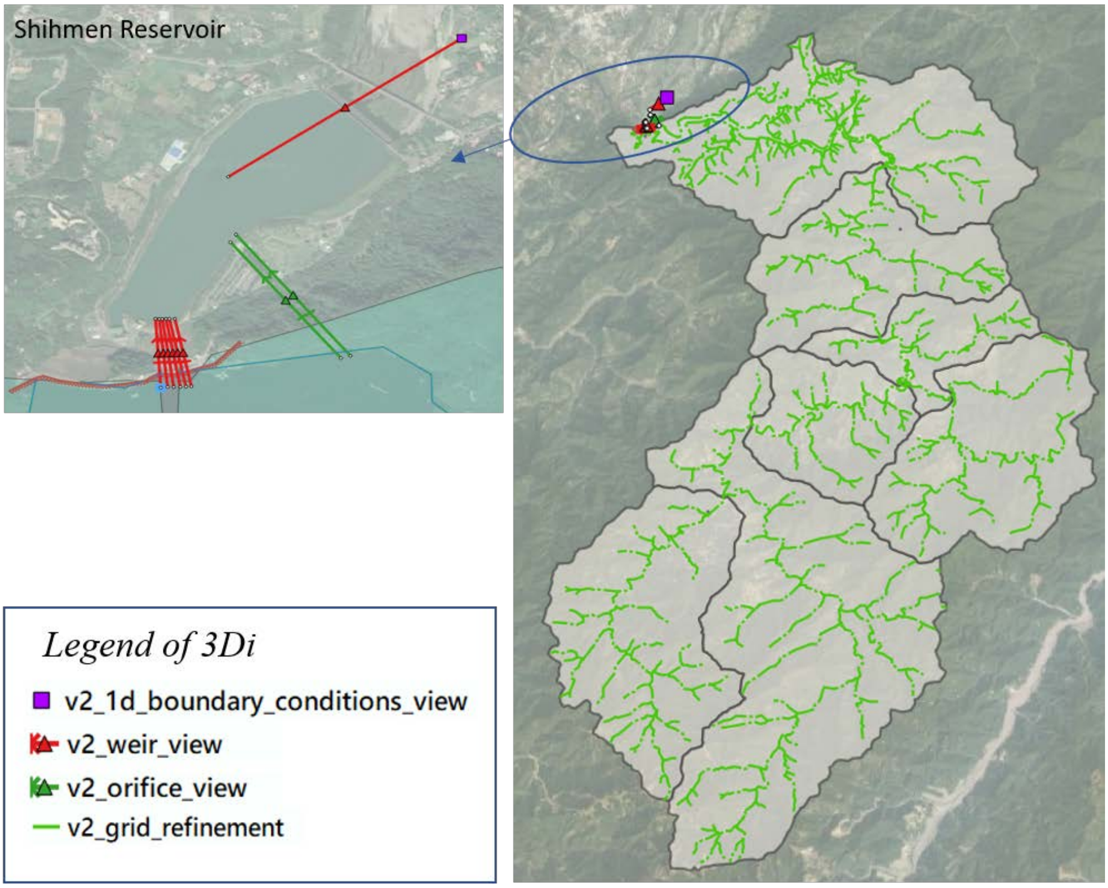


Figure 6 Modeling environment of Shihmen reservoir watershed Displayed in 3Di Modeller Interface

2.5 Analysis procedure

2.5.1 Catchment flow

The velocities throughout the catchments are often unknown. With the 3Di model, not only the velocity field, but the water depth and water level can also be determined by the results. Generally, water levels in the rivers are monitored, so the measured values of water level can be used as calibrations of the model. Besides, by calibrating simulations based on the peak water levels will indicate that the flow to the river is quite good as well. In order to evaluate the erosion risk of the study areas, the maximum values of the results will be selected to calculate the following evaluation indicators.

2.5.2 Determination of shear stress

To determine whether or not erosion will take place, the critical shear stress should be determined. It depends on a wide range of parameters such as the top soil layer, the land coverage and possibly more variables based on bed slope, wet/dry conditions etc.

Hsu et al. (2016) [9] conducted a flume experiment to analyze the threshold condition of bottom-silt entrainment by turbidity currents focusing on Shihmen reservoir watershed. During typhoon events, the state of the bottom silt on the river bed would be entrained by the debris flows and the erosion capacity of the inflowing turbidity current both might play key roles to the influence of erosion condition after such events. In view of these facts, a flume experiment was conducted to analyze the threshold condition of bottom-silt entrainment by turbidity currents.

At present, there is no theoretical equation for the mechanism of incipient motion of underwater viscous clay or silt. Due to a big uncertainty occurring in the analysis on high-turbidity condition during typhoon events, it remains a challenge to find out the critical shear stress in watershed areas.

Then, to evaluate and validate muddy water phenomena during storm rainfall events, a flume experiment was set to find out an empirical equation for evaluating the relationship between the critical shear stress and bed concentration.

For the same water depth and under average bed shear stress, the turbidity current is more likely to roll up the bottom sediment than an open-channel flow would. Therefore, the mentioned experiment evaluates the critical shear stress τ_c on the cohesive clay eroded by the turbidity current, and the bed of cohesive clay with various concentrations C_b was prepared to establish the relationship between critical shear stress τ_c and cohesive clay concentration C_b.

According to the test results, the higher the concentration of kaolin on the laid bed, the greater the bed shear stress required for occurring resuspension. The following equation to determine the critical shear stress is obtained by regression:

$$\tau_c = 2 \times 10^{-10} \times C_b^{3.75} \quad (1);$$

$$C_b = 150 \sim 300\ g/L;$$

, where τ_c = critical shear stress (Pa) at which the density current entrains the kaolin clay; C_b = concentration of the bed kaolin clay (g/L); and α = adjustment coefficient

In this study, based on the soil type and land cover of Shihmen reservoir watershed because the lithology of the area is mainly composed of muddy sand, and alternations of sandstone and shale, which are less cohesive than kaolin clay, to determine the critical shear stress in the study, the lower limit to calculate the critical shear stress with substituting $C_b = 150$, is chosen to be the threshold condition of calculation.

Besides, if adopt the above equation directly may lead to overestimate the critical shear stress value based on the experiment results. It indicates that the triggered shear stress on the bed cannot be determined solely by the concentration. Therefore, the shear stress evaluated with Eq. (1) was multiplied by an adjustment coefficient α and expressed as Eq. (2). When the silt was not yet consolidated, it was corrected with α values between 0 and 1. When the silt was completely consolidated, an α of 1 was used.

$$\tau_c' = \tau_c \times \alpha \quad (2);$$

$$\alpha = 1.22 \times 10^{-2} t^{1.18} \text{ ; if } t > 42 \text{ days, } \alpha = 1$$

To determine the bed shear stress, Julien, P. Y., and Simons, D. B. (1985) [10] points out the relationship existing between the mechanics of overland flow and soil erosion by rainfall. The authors addressed the problem of estimating the sediment transport capacity for rainfall erosion based on the mechanics of overland flow.

In this study, turbulent stream flows were used as a basis for the analysis of the typhoon condition, and choose the type of turbulent rough flow (Manning equation) for bed shear stress calculation.

The bed shear stress and related variables are defined as:

$$\tau_b = \rho g h S_f \quad (3);$$

, where ρ = specific mass of water (Pa); g = gravitation acceleration; h = water depth; and S_f is the slope of the energy line or friction slope.The slope of the energy line can be defined by the Darcy-Weisbach relationship (Manning), where f = fiction coefficient (take f= 0.03 in correspond with the 3Di model setting):

$$S_f = \frac{f}{8}\left(\frac{u^2}{gh}\right) \quad (4);$$

, then the bed shear stress can be reduced to the following form:

$$\tau_b' = \frac{\rho f}{8} u^2 \quad (5);$$

Chapter 3 Results

3.1 Model Validation of Initial Condition

Figure 7 shows the locations of the selected hydrological stations of Shihmen reservoir watershed. And these five hydrological stations are respectively Hsiayun, Kaoyi, Linjia, Yunfeng, and Hsiuluan, which have sufficient data of measured values.

By applying the 3Di to model Shihmen reservoir watershed during Typhoon Aere event in 2004, the results of simulated water level of the chosen five hydrological stations are shown in Figure 8 to Figure 12.

In the graphs, the simulated water levels are shown with the hourly precipitation during the typhoon event of four days to find out whether the trends are consistent. The results indicate that the trends of the simulated water level at each hydrological station are similar to the precipitation during the typhoon event except for some slight difference in Kaoyi and Linjia station. It can be inferred that the simulation results are reasonable and the model is applicable for other analysis outputs.

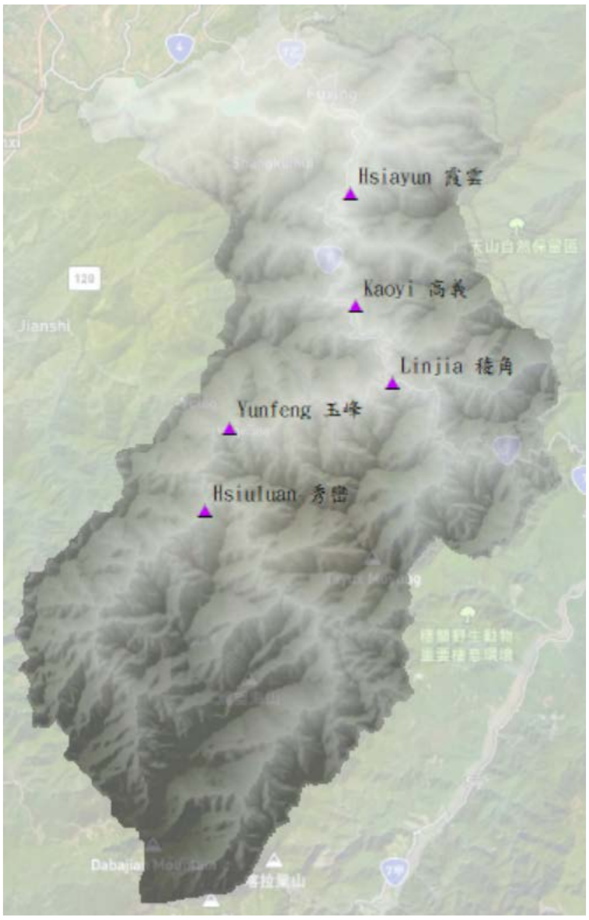


Figure 7 Locations of the chosen five hydrological stations of the Shihmen reservoir watershed

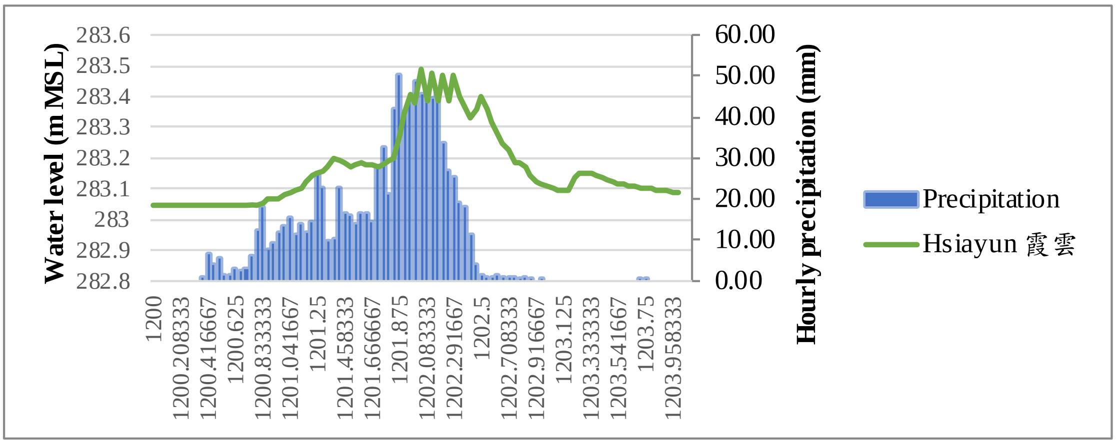


Figure 8 water level of Hsiayun hydrological station

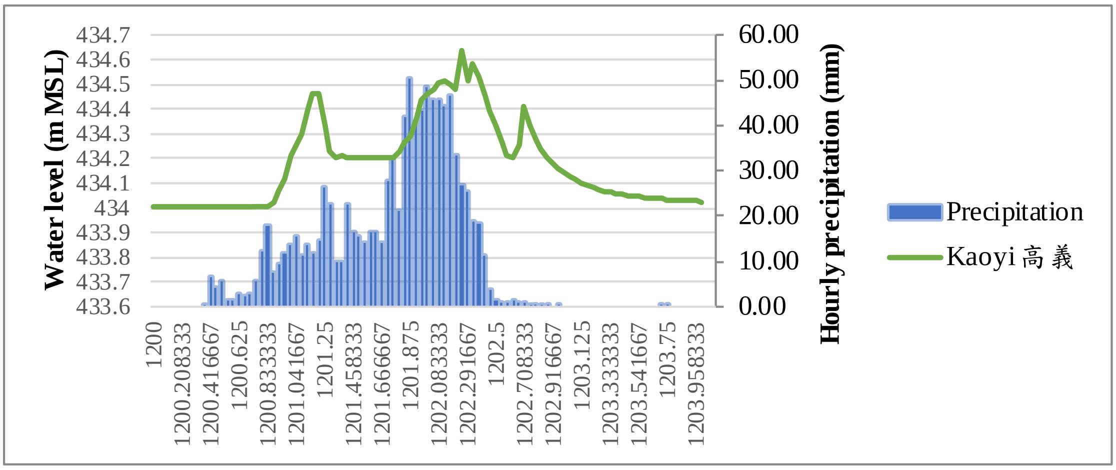


Figure 9 water level of Kaoyi hydrological station

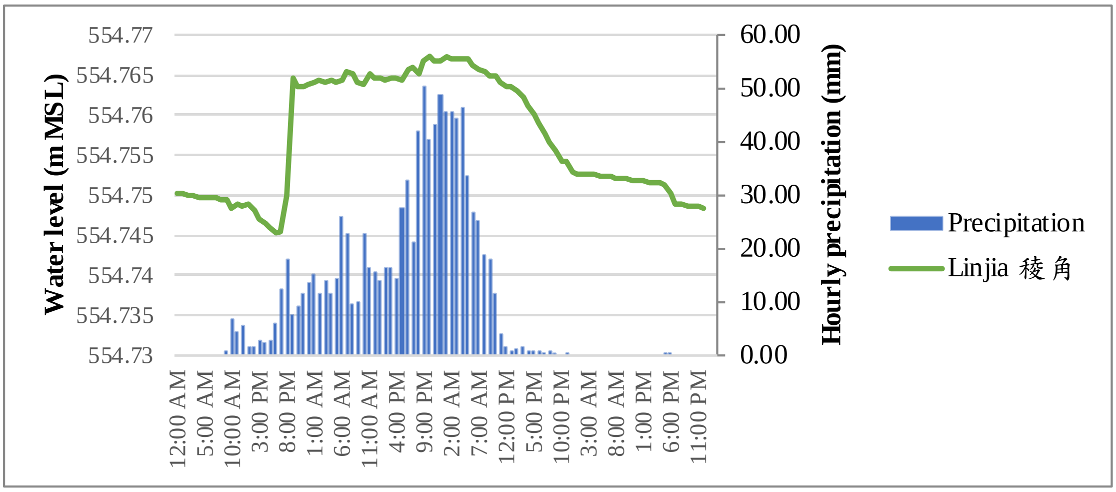


Figure 10 water level of Linjia hydrological station

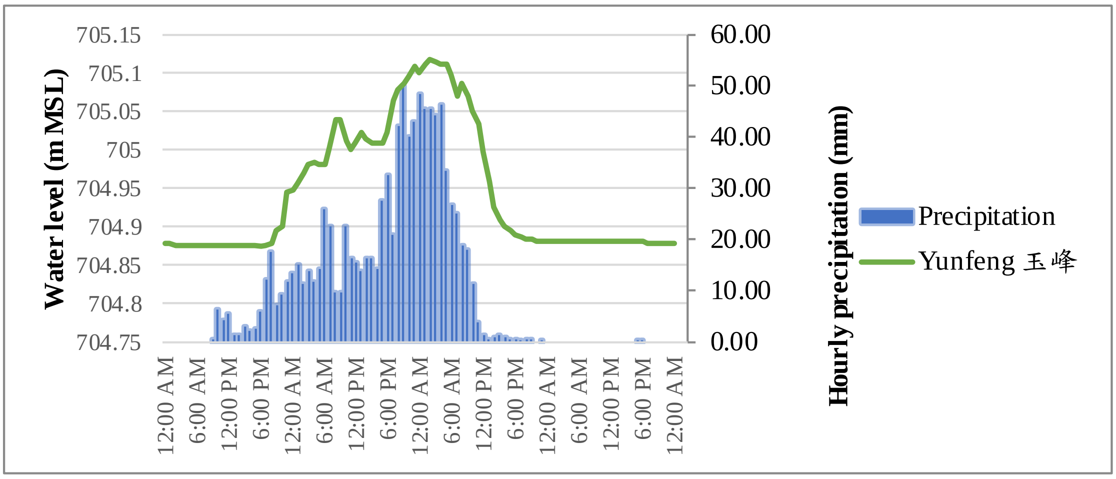


Figure 11 water level of Yunfeng hydrological station

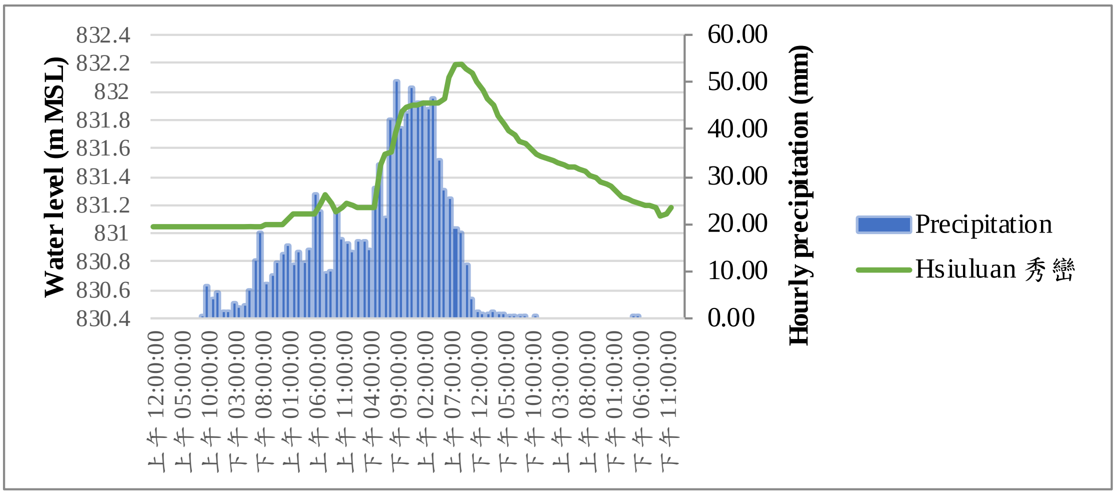


Figure 12 water level of Hsiuluan hydrological station

It is important to realize whether the simulated results are within reach to the measured values. Therefore, compare the simulated results with measured water levels of each gauge station in Shihmen reservoir watershed at the specific measured timing.

Figure 13 to Figure 17 show the comparison of water level between measured and simulated values of the chosen five hydrological stations of the Shihmen reservoir watershed during Typhoon Aere.

It indicates that there is inconsiderable difference between the measured water levels and simulated values. Among these five hydrological stations, Hsiayun station has the largest difference of about 30 meters, the difference of Linjia and Yunfeng stations range between 15 to 20 meters, while Kaoyi and Hsiuluan stations have the least difference of 0.5 to 10 meters. While some of the hydrological stations may display a slight value of overestimate or underestimate, the results are acceptable in this case.

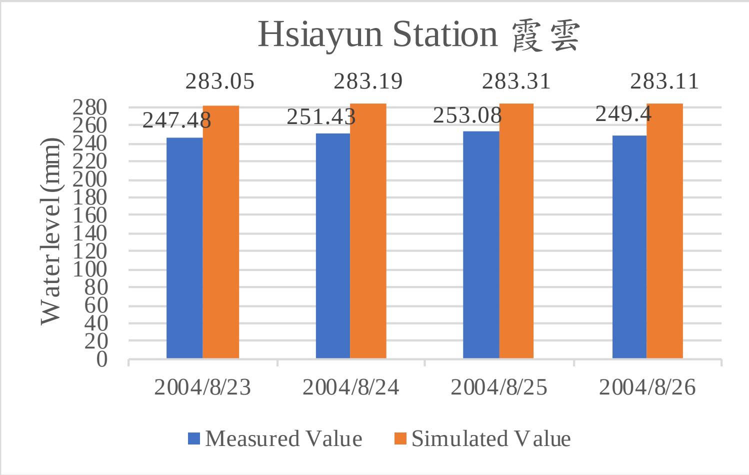


Figure 13 Comparison of water level between measured and simulated value of Hsiayun hydrological station during Typhoon Aere.

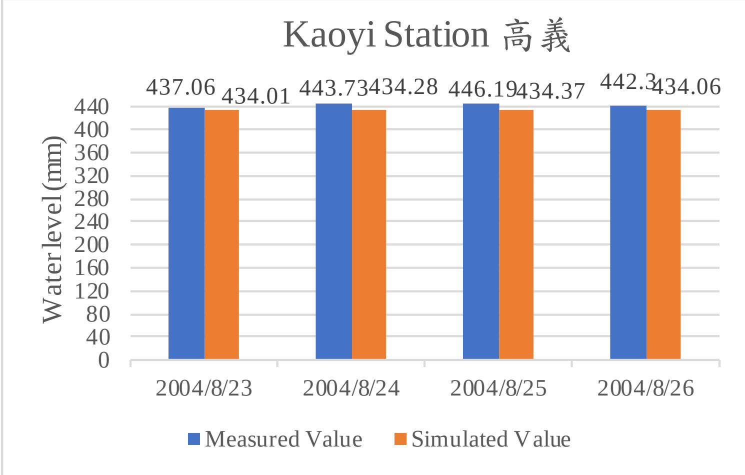


Figure 14 Comparison of water level between measured and simulated value of Kaoyi hydrological station during Typhoon Aere.

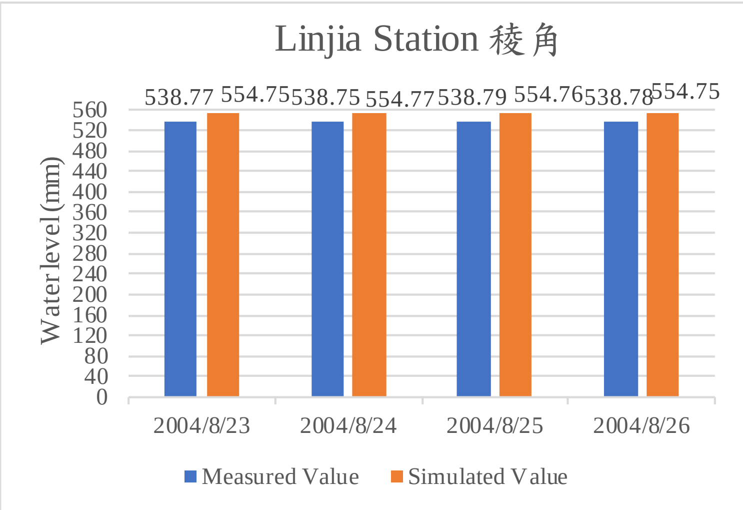


Figure 15 Comparison of water level between measured and simulated value of Linjia hydrological station during Typhoon Aere

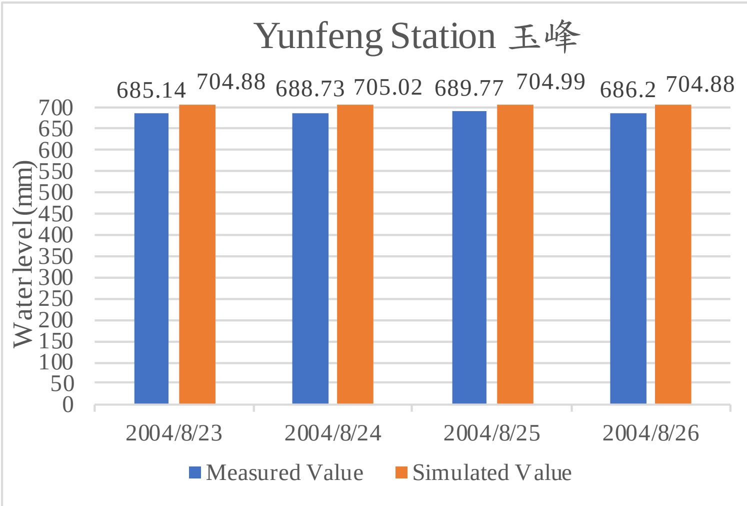


Figure 16 Comparison of water level between measured and simulated value of Yunfeng hydrological station during Typhoon Aere

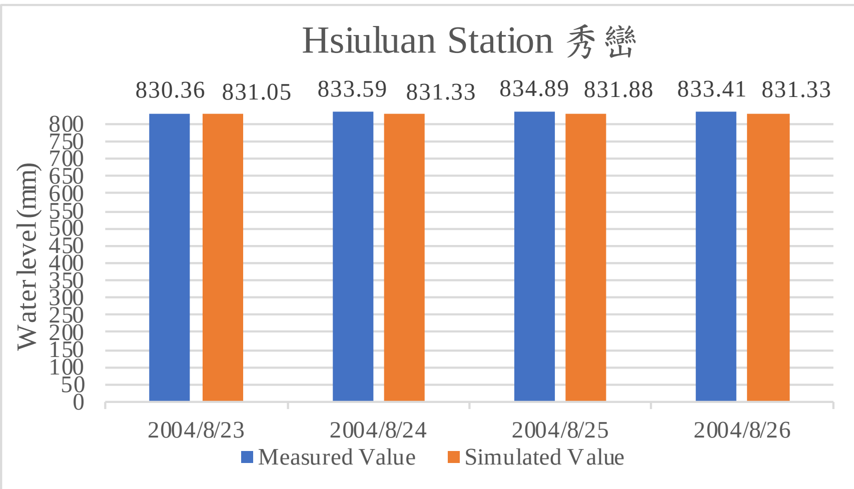


Figure 17 Comparison of water level between measured and simulated value of Hsiuluan hydrological station during Typhoon Aere

3.2 Catchment flows outputs

Figure 18 and Figure 19 present the maximum velocity field, and maximum water depth of the Shihmen reservoir watershed during Typhoon Aere in 2004, respectively.

From Figure 18, the spatial distribution of the higher values of maximum velocity field mainly concentrates in the main upstream river channels and the central mountainous regions, which have steep slopes. Velocity values gradually decreases from the main streams to tributaries with some higher values scattering on the lowland areas and hillslope.

The spatial distribution of maximum water depth during Typhoon Aere is shown in Figure 19. The water depth variation mostly depends on the fluvial topography in Shihmen reservoir watershed. For example, rivers near the central of the Shihmen watershed area have deeper land forms than other areas, it can be seen that there are some extreme high values, over 5m, scattering around main upstream streams near the central ridge in Shihmen watershed, and lower values, 0 to 0.5m, distributing in the areas downstream near the Shihmen reservoir.

In this case, the soil erosion is mainly controlled by precipitation during the typhoon event, flow conditions, soil types, and land use. The 3Di model simulated Typhoon Aere event in Shihmen reservoir watershed, and the simulated results are in good agreement with the measurement over the four days during the typhoon event. In addition to those, somewhat limited observation points, the trends of the results are intuitively as expected based on the precipitation. The simulated water levels of initial condition provide reasonable results for the model to generate other outputs for analysis.

The intense rainfall from Typhoon Aere in 2004 resulted in both high flow velocities and water depths in Shihmen reservoir watershed. The simulation indicates that the maximum values of flow velocity mainly distributed in areas with steep slope, high terrain, or most of all in regions near the main upstream rivers. While larger water depths existed in areas having deeper land forms, lower water depths mainly found near the Shihmen reservoir dam site.

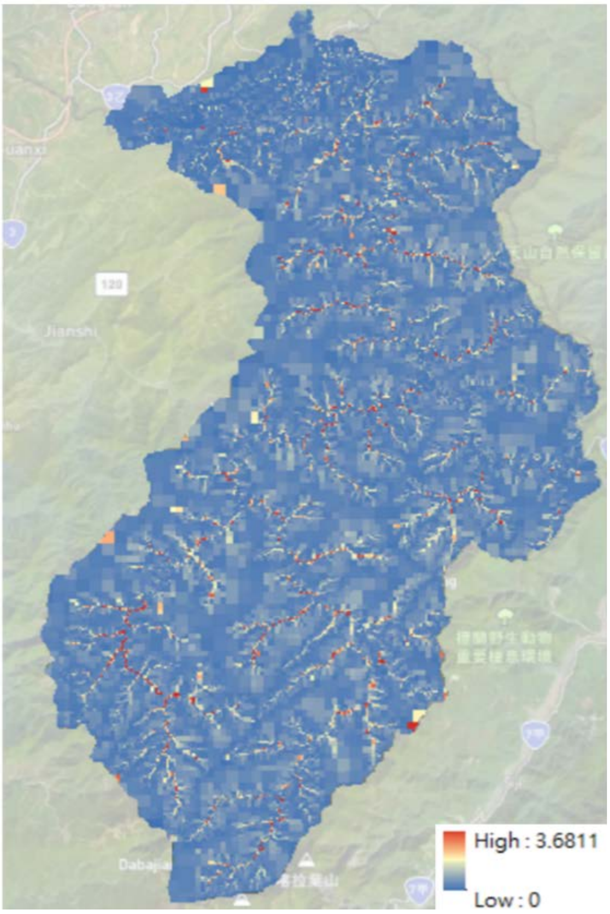


Figure 18 Maximum flow velocity of Shihmen reservoir watershed during Typhoon Aere (unit: m^2/s)

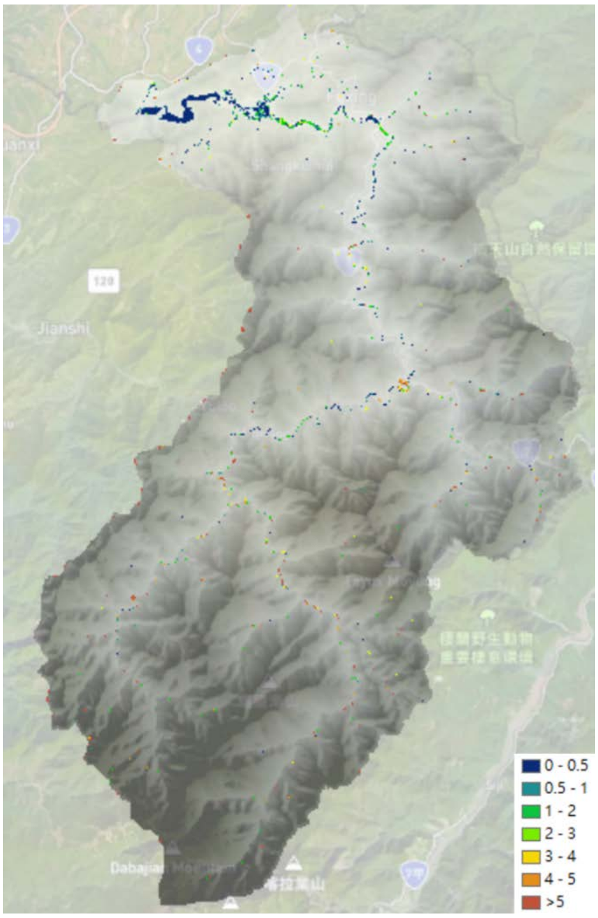


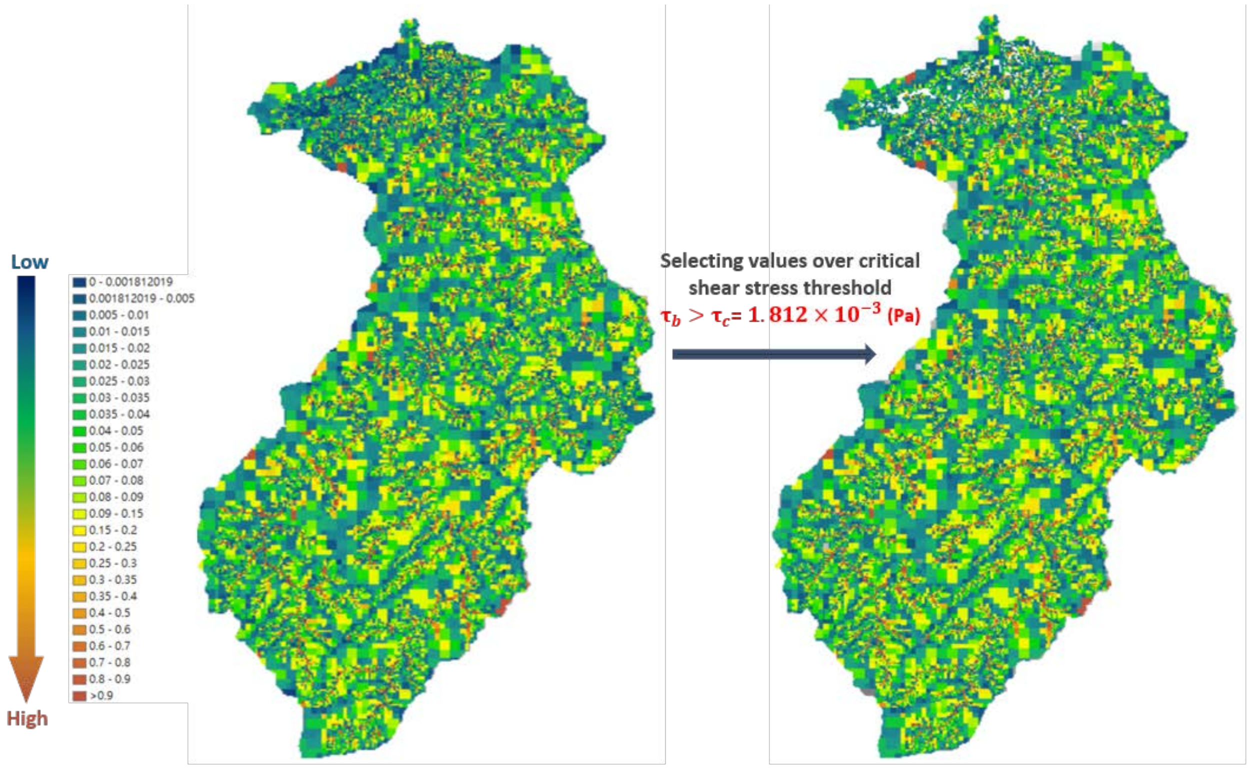
Figure 19 Maximum water depth of Shihmen reservoir watershed during Typhoon Aere (unit: m)

3.3 Soil erosion risk map

The critical shear stress threshold calculated with Eq. (2) was approximately 1.812×10^{-3}(Pa). And the bed shear stress calculated with Eq. (5) ranges from 0 to 50.04 (Pa), mostly concentrated between 0.001 to 0.224(Pa), and has a mean value equaling to 0.04886(Pa).

The bed shear stress values are classified from low to high into 26 intervals to investigate the minor variation between each sub-watershed areas. Figure 20(a) displays the spatial distribution of the bed shear stress results of the Shihmen reservoir watershed after Typhoon Aere, while Figure 20(b) shows the spatial distribution of selected shear stress values based on the critical shear stress threshold mentioned above, values below the threshold are removed, and become blank grid on the map. There are only values over the critical shear stress left on the map.

The difference between Figure 20(a) and (b) mostly presents at the downstream areas of the watershed, where the location is near the dam site of Shihmen reservoir, lowlands nearby, locations near the outer boundary, and some scatter areas in the hillslope far from rivers. Nevertheless, most of the area is in some way vulnerable based on this analysis. Based on Figure 20(b), we can find that the Shihmen sub-watershed located downstream would suffer the least soil erosion hazard after this typhoon event.



(a) Bed shear stress map ($\boldsymbol{\tau_b}$) (b) Selected bed shear stress map ($\boldsymbol{\tau_b} > \boldsymbol{\tau_c}$)

Figure 20 Maps of bed shear stress and selected values over critical shear stress, which can be regarded as a soil erosion risk indicator to show the erosion hazard potential

In order to investigate the influence of soil erosion after the typhoon event, the risk levels are classified to evaluate the detail of each area within the Shihmen reservoir watershed. To find out the value variation of the shear stress more precisely, intervals are divided again from 26 to 4 levels of the spatial distribution of bed shear stress.

Table 1 lists the classification of soil erosion risk level in Shihmen reservoir watershed based on the bed shear stress values and suitable intervals. The soil erosion risk levels are classified into "Low", "Moderate", "High", "Very High" separately from the lowest hazard degree to the highest possibility for soil erosion to occur. And the detail divided intervals can be found in Table 1. Note that the "Low" risk level includes the areas, where the bed shear stress values are below the critical shear stress threshold.

Table 1 Risk level classification of soil erosion

Risk level	Description
Low	**Soil erosion unlikely.** Areas classified as "no-risk" ($\tau_b < \tau_c = 1.812 \times 10^{-3}$), and areas classified as bed shear stress τ_b between 0.001812 and 0.03(Pa)
Moderate	**Soil erosion possible.** Areas classified as bed shear stress τ_b between 0.03 and 0.09(Pa)
High	**Soil erosion likely.** Areas classified as bed shear stress τ_b between 0.09 and 0.7(Pa)
Very High	**Soil erosion existing.** Areas classified as bed shear stress τ_b higher than 0.7(Pa)

Based on the soil erosion risk level classification criterion mention in Table 1, the new risk evaluation of Shihmen reservoir watershed after Typhoon Aere was remapped into Figure 21 to find out the soil erosion risk levels in a more straightforward way.

Because the soil erosion risk map is composed of at most four risk levels, it turns out to be a simpler map and easier to understand the distribution of soil erosion risk levels and depict the most vulnerable areas. Additionally, when there comes such typhoon event like Typhoon Aere in the future, the map could provide a risk indicator of Shihmen reservoir watershed for both future management and decision making.

Based on the simulation results for both maximum values of velocity and water depth, soil erosion risk maps of Shihmen reservoir watershed are made. The significance is that, the soil erosion risk map provides an acceptable hazard evaluation and reference of risk in this case.

From Figure 21, the map indicates that most areas of Shihmen reservoir watershed are under moderate or high-risk of soil erosion in the case. Only some scattering areas in steep hillslope or near main streams would be likely to suffer from significant soil erosion as very-high-risk level, while areas within the lowland region or location near the reservoir dam site downstream would suffer low-risk of soil erosion hazard.

In general, the whole watershed is under moderate and high-risk after Typhoon Aere in 2004 and has potential hazard for the time period. More protection procedures are needed to implement for preventing future erosion in Shihmen reservoir watershed area.

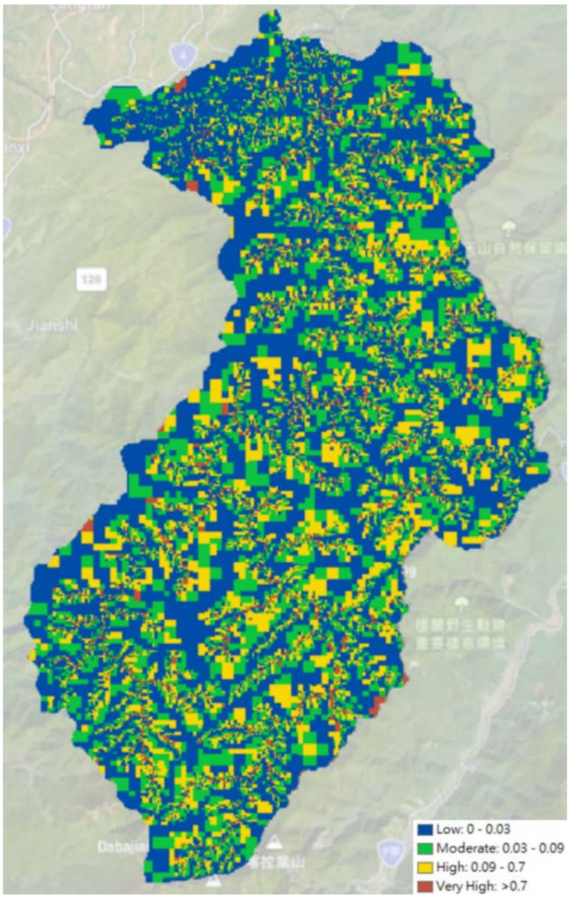


Figure 21 Soil erosion risk map of Shihmen reservoir watershed after Typhoon Aere in 2004 based on risk level classification in Table 1.

Chapter 4 Discussion

The intended use of this soil erosion risk map is to identify the relative susceptibility to soil erosion of Shihmen reservoir watershed. The map is designed to provide information for regional planning and localities where more detailed soil erosion mapping is required. When a disaster occurs in the future, this map can provide first-hand information for disaster assessment.

In this study, because the grid refinement was added along the main stream, it emphasizes the value distributions near the main stream and areas nearby to evaluate the variation more precisely. While add the coarser grid cells the water depth is averaged out.

Limitations of the input data and modeling methods used to make the map are such that the map is appropriate to make decisions of the watershed areas, but not suitable to answer larger regional or community scale questions.

The map is based on three primary sources:

a) four days of precipitation during Typhoon Aere,

b) maximum flow velocity field, and

c) bed shear stress of Shihmen reservoir watershed.

The following is a list of specific limitations:

Factors that can affect the level of detail and accuracy of the final susceptibility map include:

1. Lack of detailed soil erosion field measurements and no comparison with

actual soil erosion observations,

2. Too much or too little generalization of geology, such as Manning coefficient, land cover of the whole watershed, uncorrected depths,

3. Refinements along the main streams and the size of grids resulting in variable accuracy of the simulating model, which would under- or overestimate the output results, and limited calibration of the model,

4. Large grid cells for velocity-based maps may decrease the precision, and

5. Map based on only maximum values of variables, critical shear stress criterion, and only one typhoon event.

Nevertheless, as one point to improve, uncertainties in the rainfall resulted in the water levels simulation over- and underestimated among these five hydrological stations in the case, but this problem could be fixed by improving the model through further parameter calibration or other detailed model settings.

The objective of the soil erosion risk map is to identify Shihmen reservoir watershed that may be more or less at risk for future soil erosion, and to provide first-hand information for disaster assessment. Some soil erosion areas on the map may have been mitigated, reducing their level of susceptibility/vulnerability due to the model grid refinement.

Despite the limitations mentioned above, the derived soil erosion risk map still has referred to value of evaluate the risk levels immediately when natural disasters occur in Shihmen reservoir watershed. The soil erosion risk map provides an indication about the areas to focus on due to a higher risk classification. Therefore, it is significant as being the reference of soil erosion hazard assessment.

Chapter 5 Conclusion

To investigate the effect of soil erosion after a typhoon event, an erosion risk map was derived to indicates the areas of erosion risk levels, focusing on watershed areas. The erosion risk map is determined based on soil types, bed coverage and land use in combination with a velocity field from 3Di. The 3Di model was utilized to directly simulate catchment flow conditions in Shihmen reservoir watershed with the precipitation data of Typhoon Aere in 2004.

By comparing with measurements of water level from the five chosen hydrological stations, which are Hsiayun, Kaoyi, Linjia, Yunfeng, and Hsiuluan, the simulation successfully captured the trend of hydrographs and the simulated values were acceptable. The modeling outputs, such as the maximum flow velocity, and the maximum water depth, we can gain insight into the behavior of the system and the assessment of disaster risk degrees in Shihmen reservoir watershed. The soil erosion risk map considers the spatial distributions of bed shear stress as a risk indicator.

Our study indicates that most areas of Shihmen reservoir watershed are under moderate or high-risk level of soil erosion in the case, while few areas in hillslope or lowland region would suffer very-high-risk and low-risk level of soil erosion hazard. The map provides an evaluation reference for decision making, when it comes to such typhoon events in the future.

A soil erosion risk map of bed shear stress spatial distribution is evidenced to be a valuable reference for the reservoir authority to plan future soil conservation engineering. Furthermore, without a lot of effort, the soil erosion risk map can be easily extended to other watershed of interest, and provide first-hand assessment of disaster risk under any given rainfall input of any engineering or scientific interest.

Chapter 6 Improvements for future work

The following is a list of works which can be improved for future works:

I. Comprehensive geology considerations:

1. Manning coefficient, n, can be determined to different values and assigned into more to reflect regional property which could be closer to the reality; likewise, the land cover and soil type of the whole watershed can also be done by similar methods, and

2. It is suggested that detailed soil erosion field observations can be found to compared with the simulated results.

II. Detailed model settings:

1. Smaller grid cells for velocity-based maps can be determined to increase the precision of the simulating model, which would decrease the situations of under- or overestimation of the output results

2. Uncertainties of input data, such as the precipitation; uncorrected depths and measured water levels, can be calibrated by finding field data or other suitable methods of calibration to improve the limitation of the simulation, and

3. the grid refinement can be changed to along different objectives, such as hillslope or central mountains regions, to find out different influence under the simulating scenarios

III. Determination of critical shear stress and classification of risk assessment

1. Further research could include the effects of multiple variables to determine the bed shear stress and find out better threshold to select the values of critical shear stress because there is still big uncertainties exsisting,

2. The modeling situation could be added more typhoon events to investigate longer term effect of influence after such natural disasters, and

3. Risk levels could be classified via different aspects of establishment which would reflect interesting behaviors of the surveyed research areas.

APPENDIX

- Model setting of 3Di

I. v2_global_settings

General	
Setting	**Value for this model**
id	1
name	shihmen_project_cw
use_0d_inflow	0: do not use 0d inflow
use_1d_inflow	☑
use_2d_rain	☑
use_2d_inflow	☑
Grid	
Setting	**Value for this model**
grid_space	40
kmax	5
table_step_size	0.5
Terrain information	
DEM	
dem_file	rasters/ShihmenWatershed_5m.tif Shihmen reservoir watershed area (with the grid size of 5 m × 5 m)
epsg_code	3826
Friction	
frict_coef_file	NULL

frict_coef	0.03
frict_type	2: Manning
frict_avg	☐
Groundwater	
initial_groundwater_level_file	NULL
initial_groundwater_level	NULL
initial_groundwater_level_type	average
Initial waterlevel	
initial_waterlevel_file	NULL
initial_ waterlevel	228
water_level_ini_type	average
Interception	
interception_file	NULL
interception_global	NULL
Wind	
Wind_shielding_file	NULL
Time	
Setting	**Value for this model**
sim_time_step	30
minimum_sim_time_step	0.1
maximum_sim_time_step	60
nr_timesteps	99999
output_time_step	3600
Settings id's	
Setting	**Value for this model**

interflow_settings_id	NULL
groundwater_settings_id	NULL
numerical_settings_id	1
simple_infiltration_settings_id	1
control_group_id	NULL
Extra options 1D	
Setting	**Value for this model**
advection_1d	0: Do not use advection 1d
dist_calc_points	100
manhole_storage_area	NULL
max_angle_1d_advection	NULL
table_step_size_1d	NULL
Extra options 2D	
Setting	**Value for this model**
advection_2d	1: Use advection 2d
dam_obstacle_detection	☐
guess_dams	☑
dam_obstacle_height	NULL
embedded_cutoff_threshold	NULL
flooding_threshold	0.001
table_step_size_volume_2d	NULL

II. v2_numerical_settings

General	
Setting	**Value for this model**
id	1
Limiters	
Setting	**Value for this model**
limiter_grad_1d	1
limiter_grad_2d	0
limiter_slope_crossectional_areas_2d	3
limiter_slope_friction_2d	1
Matrix	
Setting	**Value for this model**
convergence_cg	1e-09
convergence_eps	1e-05
use_of_cg	20
use_of_nested_newton	1: When the schematization includes 1D-elements with closed-profiles
max_degree	7: for 1D and 2D flow
max_nonlin_iterations	20
precon_cg	1
integration_method	0
Threshollds	
Setting	**Value for this model**

flow_direction_threshold	1e-06
general_numerical_threshold	1e-08
thin_water_layer_definition	0.05
minimum_friction_velocity	0.05
minimum_surface_area	1e-08
Miscellaneous	
Setting	**Value for this model**
cfl_strictness_factor_1d	1
cfl_strictness_factor_2d	1
frict_shallow_water_correction	3
pump_implicit_ratio	1
preissmann_slot	0

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