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ROLE OF GEOGRAPHIC INFORMATION SYSTEM (GIS) IN WATERSHED SIMULATION BY WINVAST MODEL

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Abstract. The uncertainty of modeling input will increase the simulation error, and this situation always happens in a model without user-friendly interface. WinVAST model, developed by the University of Virginia in 2003, treats an entire multi-catchment by a tree-view structure. Its extra computer programs can connect geographic information system (GIS). Model users can prepare all the necessary information in ArcGIS. Extracting information from GIS interface can not only decrease the inconvenience of data input, but also lower the uncertainty due to data preparation. The Daiyuku Creek and Qupoliao Creek in the Fei-tsui reservoir watershed in Northern Taiwan provided the setting for the case study reported herein. The required information, including slope, stream length, subbasin area, soil type and land-use condition, for WinVAST model should be prepared in a Microsoft Access database, which is the project file of WinVAST with extension mdb. In ArcGIS interface, when the soil layer, land-use layer, and Digital Elevation Model (DEM) map are prepared, all the watershed information can be created as well. This study compared the simulation results from automatically generated input and manual input. The results show that the relative simulation error resulting from the rough process of data input can be around 30% in runoff simulation, and even reach 70% in non-point source pollution (NPSP) simulation. It could conclude that GIS technology is significant for predicting watershed responses by WinVAST model, because it can efficiently reduce the uncertainty induced by input errors.

Keywords: ArcGIS, geographic information system, non-point source pollution, runoff, WinVAST

1. Introduction

The results of runoff and non-point source pollution (NPSP) simulation are the major bases for watershed management strategies, so the researchers have been keeping working on developing hydrology and water resource models. Although the cost and effort of a hydrology and water quality modeling study is a small fraction of the total management program cost, the cost of implementing an inefficient strategy based on incorrect simulation may be much larger. Because so much is at stake, reliable model results are very significant (Lung, 2001).

Runoff and water quality models are abundant. It is critical to select a suitable model based on the land-use behaviors in a watershed, available data for model input, and so on (Donigian and Huber, 1991). Model uncertainties can be concluded to consist of four components, involving uncertainty in model inputs, observations, model structure and initial values (O'Neill and Gardner, 1979; Klepper, 1997). In this study, only the uncertainty in model inputs was discussed. Uncertainties in model inputs would transport to modeling results (Faures *et al*., 1995). The crucial work for increasing the accuracy of simulation is to clearly understand all of the necessary data for models, particularly those parameters with large influence on modeling results (Drechsler, 1998). The geographic data with spatial variability is not easy to be prepared. However, it could always result in a large uncertainty in model outputs if the spatial variation is not taken into account (Vicente, 1996; Chaubey *et al*., 1999). Moreover, models without user-friendly interface can increase the uncertainty of simulation, due to its rough process of data input. Thus, whether the model interface is friendly is a criterion for determining the accuracy of modeling results.

Geographic information system (GIS) has been applied to deal with geographic data in environmental and hydrological engineering fields for many decades. Most well-known models, such as BASINS, AGNPS and WinVAST, have already been modified into a GIS interface (Donigian and Huber, 1991). This study applied WinVAST model for watershed simulation. Although WinVAST is a new model, it has some superior features, such as the tree-view structure. It is more convenient for describing the stream distribution and subbasins in a watershed by a tree-view structure than a grid system. In addition, it provides several algorithms for calculating rainfall abstraction, discharge, flood routing and pollutant export. Its extra computer programs can also connect GIS. In ArcGIS interface, model users can prepare all the necessary information for WinVAST. The process of extracting information from ArcGIS is illustrated herein. This work compared the difference of modeling results between through automatically generated input and through manual input. The objective of this study was to verify if GIS plays an important role in runoff and NPSP simulation by WinVAST model. If the simulation error through the manual input is notable, model users should be more carefully and the value of the automatically generated input system, which connects GIS technology, could be rather precious.

2. Methodology

2.1. WinVAST Model

WinVAST model, developed by the University of Virginia in 2003, is useful for predicting the water movement and pollutant transportation in a watershed. Its former version is VAST in DOS system. WinVAST model is based on windows interface, and its extra computer programs can connect GIS. WinVAST model extend the function of binary structure to a tree-view structure for displaying the stream distribution and subbasins in a watershed. Due to these improved functions, WinVAST model is more friendly to model users, particularly in the process of modeling input (Tisdale *et al*., 1996; Yu *et al*., 2003).

2.1.1. *Runoff Simulation*

The phenomenon of abstraction, depression, infiltration, and so on, can be simulated in WinVAST model. The necessary information for modeling can be in two parts: rainfall data and watershed condition. Firstly, the stream distribution and subbasin divisions should be defined by a tree-view structure. It should describe the relationship between the upstream basins and downstream basins. Model users can decide the numbers of subbasins in a watershed in accordance with their accepted accuracy of simulation results. The rainfall characteristics, land-use condition, soil type, stream length, etc. would be different in each subbasin. Through watershed division, different input parameters based on various hydrology algorithms can be applied in each subbasin. Meantime, the simulation time, interval time and system unit should be determined.

The required data for each subbasin includes base flow, subbasin area, average slope, stream length, rainfall abstraction and infiltration, unit hydrograph, and so on. WinVAST provides three methods for inputting rainfall data, three methods for calculating rainfall abstraction, and four types of unit hydrograph for evaluating the relation between rainfall and runoff. Moreover, the flood routing is also significant for runoff simulation. The Muskingum method is applied to calculate flood routing in WinVAST model. The major parameters in the Muskingum method is the weight factor, X, and routing constant, K.

2.1.2. *NPSP Simulation*

WinVAST model integrates runoff and NPSP simulation in a single interface. The calculation of predicting pollutant transportation and decay process is similar to the algorithm of STORM (Storage, Treatment, Overflow, Runoff Model) developed by the US Army Corps of Engineers. NPSP is always washed out after a rainfall storm. The pollutant accumulation on the land surface prior to a storm event is computed by the following formula:

$$P(p,l) = \mathrm{AREA}(l) * \mathrm{LR}(p,l) * \mathrm{DD} + P0(p,l) \tag{1}$$

where $P(p, \mathrm{l})$ is the accumulation of pollutant p on land use l just prior to storm event; AREA(l) is the area of land use l; LR(p, l) is the loading rate for pollutant p on land use l; DD is the number of dry days since the previous storm; $P0(p, 1)$ is the weight of pollutant p on land use l just after the previous storm.

Moreover, the pollutant wash-off from the land surface during a storm event can be computed by the following general formula:

$$\begin{aligned} M(p,l) = {} & A(p) * P(p,l) * (1.0 - \exp[-k(p) * R]) \\ & + \mathrm{FSUS}(p) * M(\mathrm{sus}) + \mathrm{FSET}(p) * M(\mathrm{set}) \end{aligned} \tag{2}$$

where $M(p, 1)$ is the wash-off rate of pollutant p from land use l; $A(p)$ is the fraction of pollutant p available for wash-off from the land surface; $K(p)$ is wash-off decay coefficient for pollutant p; R is surface runoff; FSUS(p) is the fraction of suspended solids that is pollutant p; M(sus) is the wash-off rate of suspended solids; FSET(p) is the fraction of settleable solids that is pollutant p; M(set) is the wash-off rate of settleable solids.

2.2. Connect ArcGIS with WinVAST

In addition to the main program of WinVAST, its extra computer program, named “winvast.dll”, can combine with GIS. It is called WinVAST GIS model. WinVAST GIS model is not independent software but a tool, because it must be executed on ArcGIS desktop. All the necessary information can be extracted in ArcGIS interface. First task is to call the extra program into ArcGIS, and to add the functions of spatial analysis (McCoy and Johnston, 2001). Figure 1 displays the WinVAST GIS model in ArcGIS interface. The layers of soil type, land-use condition and Digital Elevation Model (DEM) are the major maps for generating basic parameters in a watershed from ArcGIS interface to the project file of WinVAST.

One of the important tasks for GIS model is to generate the watershed and stream map from a DEM map. In order to generate watershed and stream layer, a set of rules, such as one subbasin must have only one stream, should be defined by the functions in ArcGIS. The DEM layer in grid mode can generate the map for displaying the spatial distribution of streams and sub-divisions in a watershed.

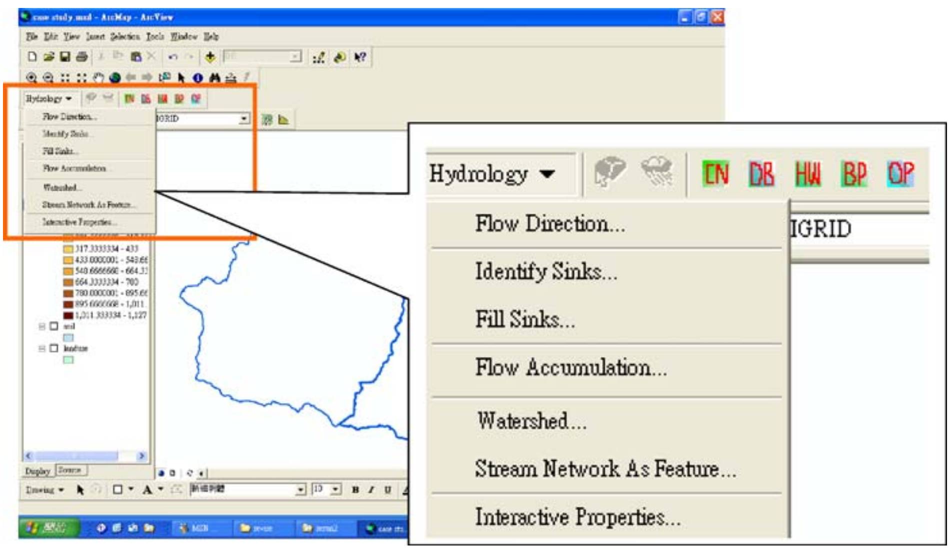

Figure 1. WinVAST GIS model in ArcGIS interface.

After calling "winvast.dll" into ArcGIS interface, it will increase a tool button, named "Hydrology", with extension functions in a pull-down menu. As shown in Figure 1, its extension functions include "Flow direction", "Identify sinks", "Flow accumulation", "Stream network as feature" and "Watershed". "Flow direction" is to determine the direction of flow from every cell in the grid. "Flow accumulation" is to calculate accumulated flow of all cells flowing into each down-slope cell in the grid. They can determine the direction of all the streams, and ascertain the topography. Thus, the layer for describing the stream distribution can be built by

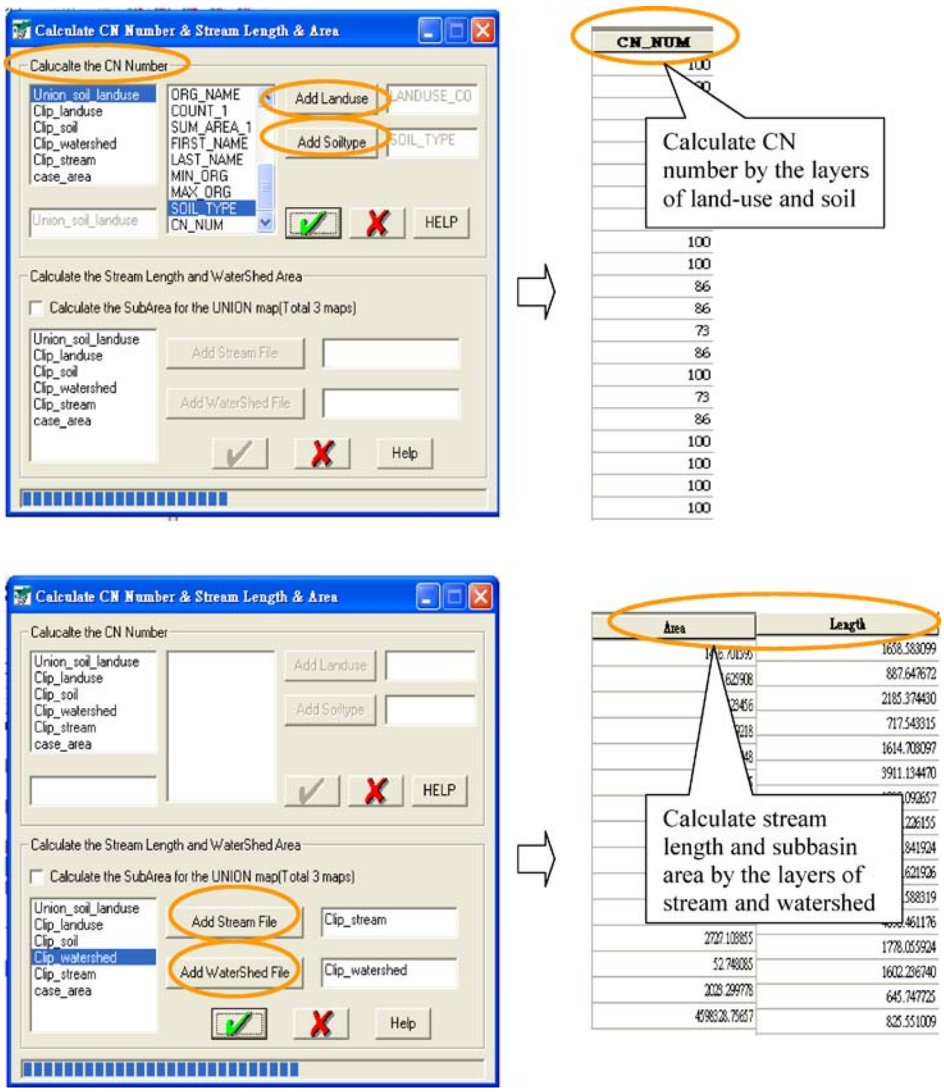

Figure 2. The interface of the "CN" function.

the function of "Stream network as feature". The stream distribution can be shown in a line layer. Moreover, the function of "Watershed" can create an area layer for displaying subbasins in a watershed.

Another important task for WinVAST GIS model is to collect the geographic data with parameter data for a watershed. The geographic data such as the relationship between each subbasin, stream length and average slope of each subbasin, can be extracted from the maps of stream and watershed. The stream lengths can be computed by the stream layer, and the subbasin areas can be calculated by the watershed layer. The parameter data, such as soil type, land-use condition and average CN for each subbasin, can be generated from the layers of soil and land-use. The themes of soil type and land-use condition are used for defining the curve number (CN) (Bedient and Huber, 2002). CN explains how moist the land surface is (Kaighn, 1993; Wanielista *et al*., 1997). It is an important parameter for predicting runoff and NPSP. Figure 2 shows the interface of the "CN" function, which can calculate the value of CN, the stream lengths, and the subbasin areas. Both geographic data and parameter data are finally gathered into a total data map, which is sufficient for WinVAST project file, as shown in Figure 3. Moreover, the tool button "DB" provides the process to create the project file of WinVAST with extension mdb in Microsoft Access database, as shown in Figure 4. The temporary file of the input file for WinVAST, named "NewMDBFile.mdb", is saved in the directory of "VAST" in program files in the Microsoft Windows. Significantly, if the data

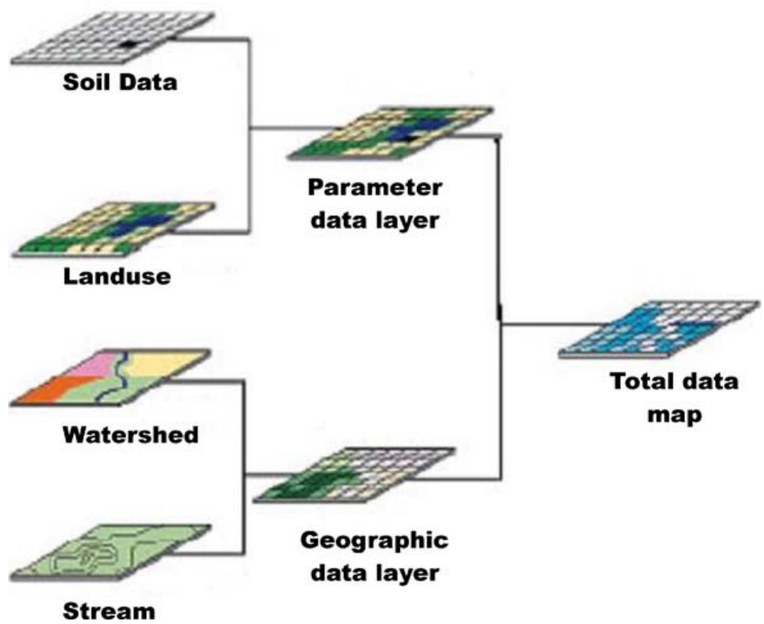

Figure 3. The process of generating project file of WinVAST model.

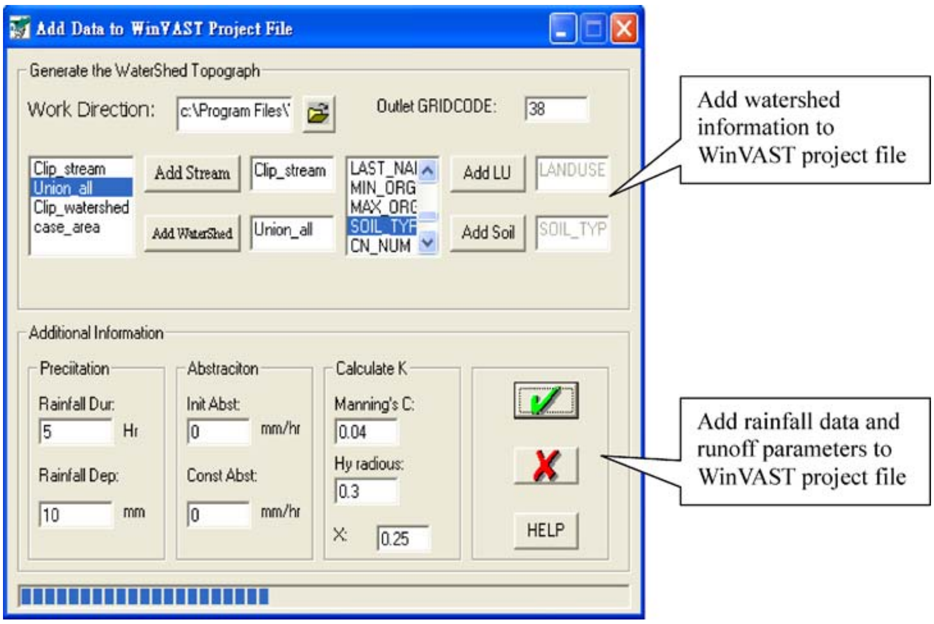

Figure 4. The interface of the "DB" function.

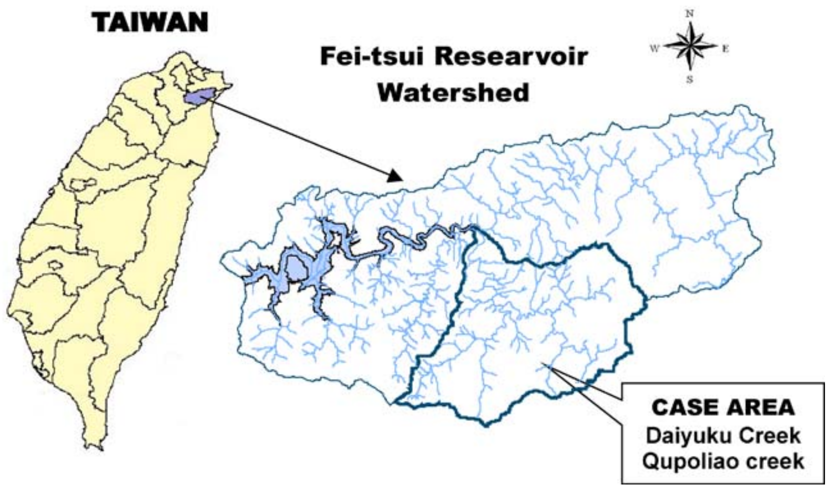

Figure 5. Case area: the Daiyuku Creek and Qupoliao creek in the Fei-tsui researvoir Watershed.

preparation process has no help from GIS technology, model users have to input all the necessary data in the project file of WinvAST by themselves. It would be rough, because artificial judgment could not be as accurate as the automatic resolution by computers.

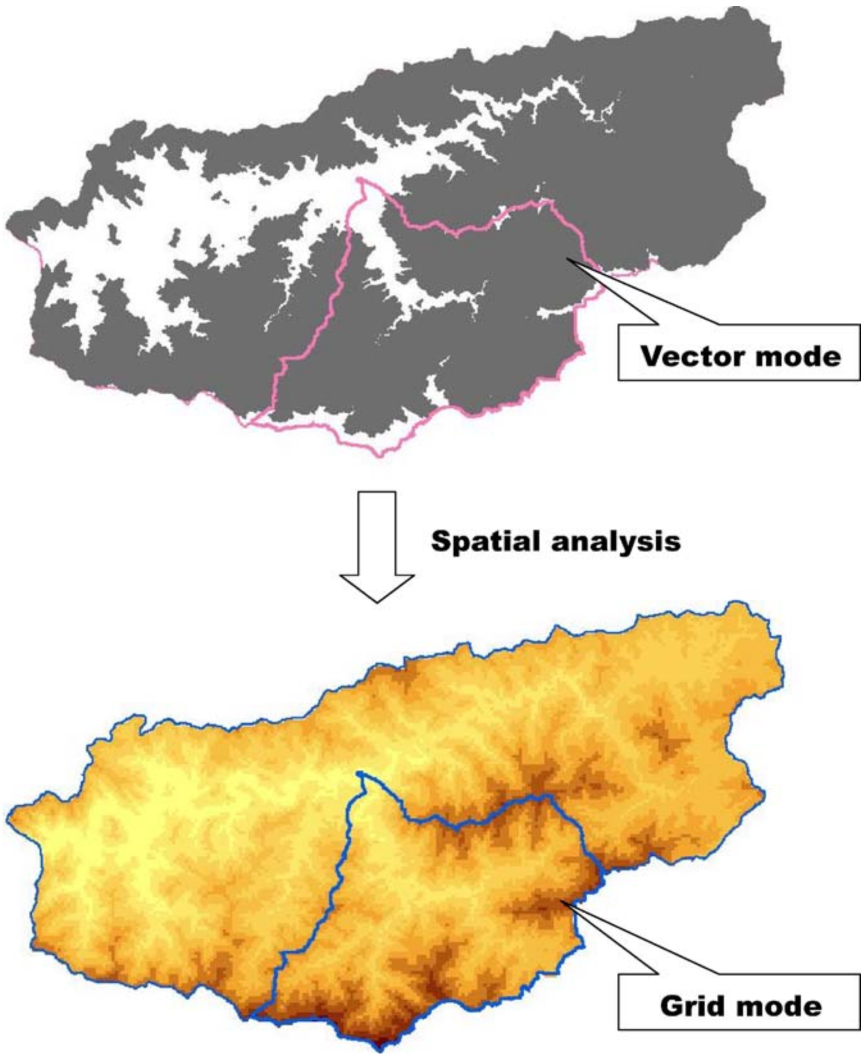

Figure 6. DEM file of the Fei-tsui reservoir watershed in the vector mode and grid mode.

3. Case Study

The Fei-tsui reservoir watershed is located on the southeast of the capital city of Taipei and has a drainage area of 303 km^2. The major land-use behavior is forest and tea garden. It consists of 7 sub-watersheds, namely Wantan Creek, main stream of Beishi Creek, Houkengzi Creek, Jinggualiao Creek, Daiyuku Creek, Huoshaozhang Creek and Qupoliao Creek. Due to the blocking effect of the Snow Mountain Range, the influence of the southwesterly wind system in Taiwan is less significant. However, the climate is generally wet due to the influence of the northeasterly wind.

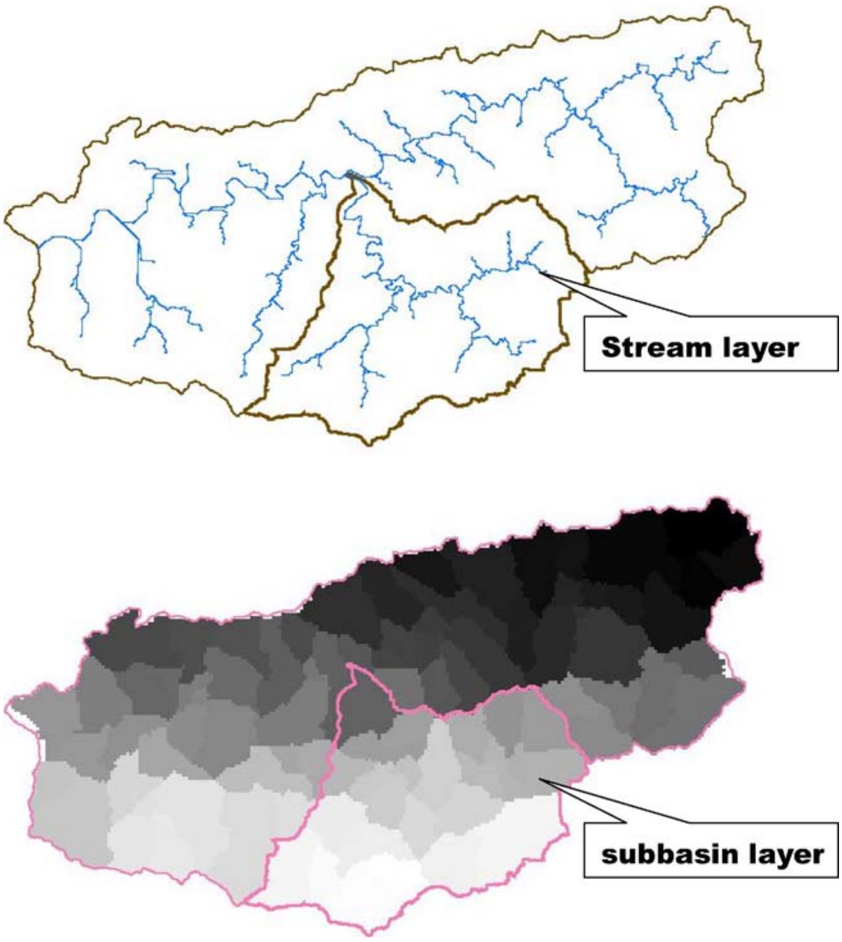

Figure 7. The stream distribution in a line layer and the subbasins in an area layer.

Thundershowers usually occur due to the abundance of wind convection resulting from radiation heating, particularly happen in summer. Moreover, typhoons would occasionally bring plentiful rainfall amounts with very large rainfall intensities. The Fei-tsui reservoir supplies most water for Taipei metropolitan in Taiwan. It is an important reservoir for the water supply system in Northern Taiwan. The Daiyuku Creek and Qupoliao Creek in the Fei-tsui reservoir watershed provided the setting for the case study in this work. The case area is about 79 km^2. The length of mainstream is about 11 kms. There is only one rainfall gauging station, Bihu station, in the case area. The Pinglin station is close to the outlet of this watershed. Figure 5 displays the relative location of this case area in the Fei-tsui reservoir watershed.

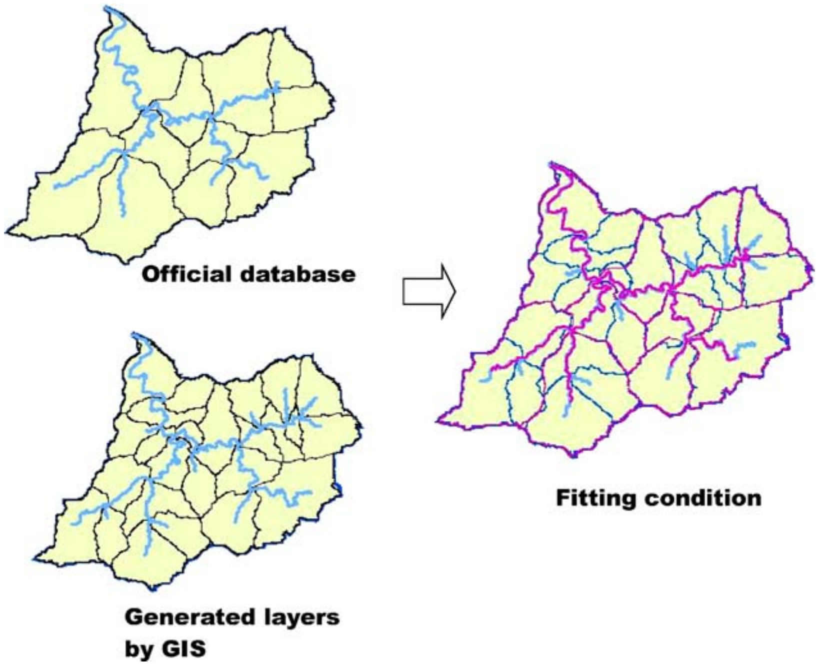

Figure 8. Comparison of generated layers and actual data.

4. Results and Discussion

Figure 6 shows the original DEM layer of the Fei-tsui reservoir watershed in the vector mode. It is required to apply the tool of "spatial analysis" to transfer the vector mode into the grid mode. The extra program of WinVAST model, which connects with GIS, can call the function of "Hydrology" in ArcGIS interface. "Hydrology" can generate the maps for displaying the stream distribution in a line layer, and the subbasins in an area layer, as shown in Figure 7. The generated layers, including the layer of stream distribution and subbasins, almost conform to the maps from official database. As shown in Figure 8, their similarity could be close to 100%. The generated themes can even be more precise than the official data.

The case area divided into 11 subbasins in the official database can be demarcated into 29 subbasins by the DEM map in ArcGIS. The spatial variability of rainfall and watershed condition can be presented through the input mode of watershed divisions. WinVAST model treats the multi-catchment in a tree-view structure, and all the input information is saved in the Microsoft Access database in a project file with extension mdb. Thus, even though the number of subbasins increases, it would not result in any additional difficulty. The number of subsbasins can be flexible based on the definition for generating streams and subbasins from the DEM map. Moreover, model users can do some adjustment in WinVAST interface, as shown

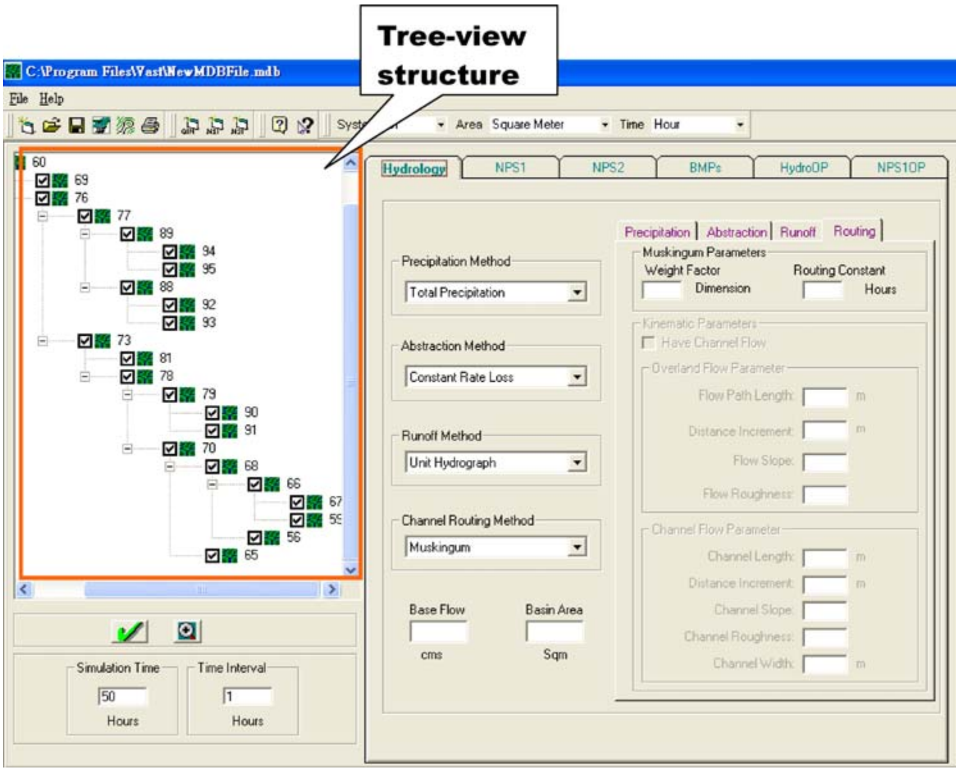

Figure 9. WinVAST interface and its tree-view structure for displaying subbasins.

in Figure 9. The tool of "Hydrology" only provides the way of "Regional rainfall" to represent rainfall information. This method, based on the database of WinVAST model, can automatically compute rainfall depth and rainfall duration. Although the generated rainfall records may not fit in with the actual rainfall records, model users still can modify the rainfall information right in the WinVAST interface.

In this study, the duration of the rainfall event was 5 hrs, and its rainfall intensity was 10 mm/hr. Also, this study assumed there are no best management practices (BMPs) in the case area. The comparison of the modeling results in runoff and NPSP simulation is shown in Figure 10. The results show that the modeling results through the data input by GIS tools, extracting information from geographic and parameter data layers, are very different from those through the artificial input process. If the modeling result based on automatically generated data is assumed to be the actual situation, the relative error of runoff simulation due to manual uncertainty can be around 30%. The relative error of suspended solids (SS), total nitrogen (TN) and orthophosphate (Orth-P) simulation can reach 43, 79 and 72% separately. The simulation error resulting from the artificial input is rather large, so it cannot be ignored. The results confirm that the importance of GIS technology

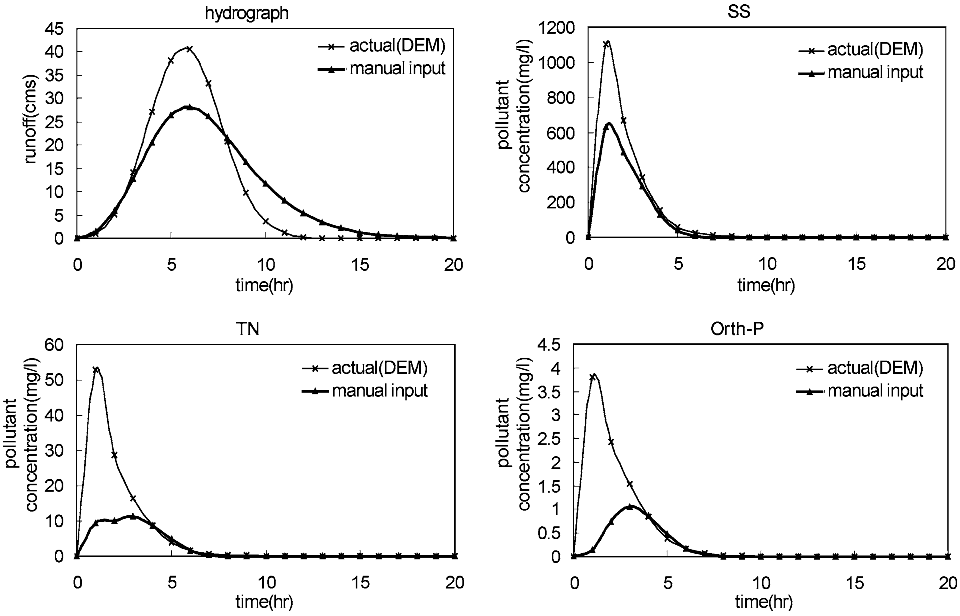

Figure 10. The difference of modeling results of runoff and NPSP simulation between two types of input process.

in watershed simulation by WinVAST model is noticeable. The friendly input interface based on GIS desktop could efficiently lower the uncertainty induced by rough input process. Therefore, the development of the features for connecting GIS tools and watershed models is significant for improving the accuracy of simulation.

5. Conclusions

GIS is a useful technology for dealing with spatial information, such as watershed information and spatial rainfall variability. Through the extra program of WinVAST, the necessary input parameters and data can be extracted in ArcGIS interface, and the layers displaying the stream distribution and subbasin divisions in a watershed can be generated automatically. The maps, which directly created from ArcGIS, almost completely conform to the layers in the official database. Besides lowering the difficulty of preparing input data, this way can also efficiently avoid the uncertainty, owing to rough manual input and inappropriate judgment, and decrease the simulation errors. Thus, the functions in WinVAST model, which can connect GIS, are significant and valuable for runoff and NPSP simulation. Reliable predictions of watershed responses would be very significant for watershed management.

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