Development of efficient and cost-effective distributed hydrological modeling tool MWEasyDHM based on open-source MapWindow GIS

Xiaohui Lei [a], Yuhui Wang [a,b,*], Weihong Liao [a], Yunzhong Jiang [a], Yu Tian [a,c], Hao Wang [a]

[a] China Institute of Water Resources and Hydropower Research, Beijing 100038, China
[b] School of Environmental Science and Engineering, Donghua University, Shanghai 201620, China
[c] School of Civil Engineering, Tianjin University, Tianjin 300072, China

ARTICLE INFO

ABSTRACT

Many regions are still threatened with frequent floods and water resource shortage problems in China. Consequently, the task of reproducing and predicting the hydrological process in watersheds is hard and unavoidable for reducing the risks of damage and loss. Thus, it is necessary to develop an efficient and cost-effective hydrological tool in China as many areas should be modeled. Currently, developed hydrological tools such as Mike SHE and ArcSWAT (soil and water assessment tool based on ArcGIS) show significant power in improving the precision of hydrological modeling in China by considering spatial variability both in land cover and in soil type. However, adopting developed commercial tools in such a large developing country comes at a high cost. Commercial modeling tools usually contain large numbers of formulas, complicated data formats, and many preprocessing or postprocessing steps that may make it difficult for the user to carry out simulation, thus lowering the efficiency of the modeling process. Besides, commercial hydrological models usually cannot be modified or improved to be suitable for some special hydrological conditions in China. Some other hydrological models are open source, but integrated into commercial GIS systems. Therefore, by integrating hydrological simulation code EasyDHM, a hydrological simulation tool named MWEasyDHM was developed based on open-source MapWindow GIS, the purpose of which is to establish the first open-source GIS-based distributed hydrological model tool in China by integrating modules of preprocessing, model computation, parameter estimation, result display, and analysis. MWEasyDHM provides users with a friendly manipulating MapWindow GIS interface, selectable multi-functional hydrological processing modules, and, more importantly, an efficient and cost-effective hydrological simulation tool. The general construction of MWEasyDHM consists of four major parts: (1) a general GIS module for hydrological analysis, (2) a preprocessing module for modeling inputs, (3) a model calibration module, and (4) a postprocessing module. The general GIS module for hydrological analysis is developed on the basis of totally open-source GIS software, MapWindow, which contains basic GIS functions. The preprocessing module is made up of three submodules including a DEM-based submodule for hydrological analysis, a submodule for default parameter calculation, and a submodule for the spatial interpolation of meteorological data. The calibration module contains parallel computation, real-time computation, and visualization. The postprocessing module includes model calibration and model results spatial visualization using tabular form and spatial grids. MWEasyDHM makes it possible for efficient modeling and calibration of EasyDHM, and promises further development of cost-effective applications in various watersheds.

© 2011 Elsevier Ltd. All rights reserved.

1. Current conditions and barriers of applications on distributed hydrological model system in China

Many regions in China are still threatened with frequent floods and water resource shortage problems. Consequently, it is helpful to reproduce and predict the hydrological process in watersheds for reducing the risk of damage and loss. However, it seems a high cost to adopt developed commercial tools in such a large developing country. Thus, to develop an efficient and cost-effective hydrological tool in China is necessary.

1.1. The development of distributed hydrological modeling systems

Since the appearance of the first hydrological model called the Stanford Watershed Model, many similar models have been created and used in various applications around the world. Recently, attributed to the rapid development of computational

technology, several successful applications of distributed hydrological models were developed such as SWAT (Shen et al., 2009; Romanowicz et al., 2005; Schuol et al., 2008). Except for a few widely used distributed hydrological models, many of these models lack an integral software system for model building and calibration (Viviroli et al., 2009). These traditional models instead manually adopt ways to achieve model building, computation, and calibration. Generally speaking, the steps can be summarized as follows:

(1) First, preprocessing all underlying hydrological, meteorological, and social–economic data with commercially developed GIS software like ArcView, ArcGIS, etc., or depending on some other software for the purpose of model building. The main concerned steps are probably the DEM extraction and burning with surveyed river networks, slope calculations, flow direction determinations, accumulation computations, digital stream extractions, catchment delineations, etc. The processes of hydrological or meteorological data involve data interpolation temporally such as linear interpolation and spatially Thiessen polygon (Croley and Hartmann, 1985) or kriging interpolation (Kebaili Bargaoui and Chebbi, 2009).

(2) Then manually carrying out sensitivity analysis of the model parameters and calibrating model parameters to find a global optimum in feasible parameter space. This process involves quite complicated calculation procedures with many data types, each containing a large amount of information. Some global well-known models like SWAT may take advantage of optimization tools like SWATCUP (SWAT-CUP2 manual (SWAT-CUP2, 2008)) that can be adopted to enhance the model calibration. For others, Elias G. et al. (2007) present a diagnostic study on the multiobjective, automatic calibration of the SWAT model. The calibration routine is developed using a NSGA-II algorithm (nondominated sorting genetic algorithm II). However, some widely accepted models in China such as the Xinanjiang (Ren-Jun, 1992) model may have been developed without integrating any autocalibration tools. As a result, only senior professionals who are very familiar with the model structure can smoothly finish the model building process and carry out calibrations without optimization algorithms.

(3) Postprocessing of calculation results. Generally speaking, the result presenting and analysis of hydrography can be obtained using mathematical tools (Matlab and Excel, etc.), which may require additional effort.

However, with the rapid development of spatial technology, especially GIS and RS, there are some quite well GIS integrated distributed hydrological models, e.g., Mike SHE (Abbott et al., 1986) and SWAT (Neitsch et al., 2005). These models can greatly simplify the modeling and calibration process, and enable users to reduce repetitive steps in establishing distributed hydrological models, upgrading the efficiency of modelers, and to reach an ideal simulation precision (Hormann et al., 2009).

Hydrological models, which are integrated with GIS software providing users with useful interfaces, can be categorized into three classes: (1) distributed hydrological model systems based on commercial GIS software, (2) open-source GIS software-based distributed hydrological model systems, and (3) distributed hydrological model systems independent of GIS software. These categories will be described in more detail below.

(1) *Distributed hydrological model systems based on commercial GIS software*: Well-known distributed hydrological models like ArcSWAT are developed on the commercial software ArcGIS (Schuol et al., 2008), that can provide good integration for model building and greatly decrease the modeling difficulties for users. The spatial data calculation of ArcGIS is quite reliable, however, usually not affordable for users especially for small labs. In addition, commercial full-functional GIS software may require large disk space but actually not necessary in hydrological modeling.

Some other existing distributed hydrological models, for example, ArcView SWAT and the preprocessing functions of the Wetspa model (water and energy transfer between soil, plants, and atmosphere model) developed at the University of Brussels (Wang et al., 1997; Batelaan et al., 1996), have taken advantage of ArcView GIS. ArcView GIS software, although providing users with editable AVX (Arcview scripts) and not as complicated as ArcGIS, is a non-open source software which limits the capability of further development for hydrologic models and still not cost-effective enough.

(2) *Distributed hydrological model systems based on open-source GIS software*: In addition to commercial GIS software, there are many widely spread open-source software systems including GRASS (Castrogiovanni et al., 2005; McMichael et al. (2006) (Geographic Resources Analysis Support System, 2010)), MapWindow (Smakhtin and Eriyagama, 2008; Using the MapWindow ActiveX Control, 2008), QGIS (Quantum GIS Project team, 2009), OpenJUMP (OpenJUMP Geographic Information System, 2008), uDig (uDig GIS Framework for Eclipse, 2009), and SharpMap (2009), that can be used in different operating systems (OS), including MS Windows, Unix, and Linux. In addition, they are developed in various languages, i.e., Java, C++, C#, VB.Net, etc.

Different from commercial GIS software, open-source GIS software is popular among GIS tool developers due to its open-source, strong extensibility, and free to use (Coroza et al., 1997). At present, well-known distributed hydrological models developed based on open-source GIS software are listed: (1) MWSWAT (George and Leon, 2008) and (2) BASINS4 (BASIN4 Environmental Protection Angency, 2009). These models are developed on the basis of the open-source GIS software MapWindow. The main purpose of developing distributed hydrological model systems based on open-source GIS is to decrease the application cost of the model system, and to enable users to obtain the system without or at a lower cost.

(3) *Distributed hydrological model independent of any GIS software*: Moreover, there are some distributed hydrological models independent of any GIS software, which have their own professional GIS modules well integrated into their software systems such as HEC-HMS (William et al., 2010), Mike SHE (Abbott et al., 1986), and JAMS (Kralisch and Krause, 2006). Models with independent GIS software have the ability to fully integrate with hydrological models and can achieve more specialized operations in modeling. However, these model systems usually could only provide relatively simple GIS functionality and high developing cost.

(4) *Comparison between different model systems*: The three kinds of distributed hydrological model systems noted above have their own advantages and disadvantages, respectively, as listed in Table 1. Commercial GIS software-based hydrological models are usually quite powerful and have adopted some efficient hydrological analysis algorithms. Thus it can be relatively easy to develop new software modules on the basis of this GIS software through the dynamic link library (DLL). However, high software costs restrict the further application of this modeling system to some extent, especially in developing countries. The greatest advantage of open-source GIS software is that it is free of charge and draws on a large code-sharing community.

In some circumstances, commercial GIS software is more powerful than open-source GIS and enjoys continually functional

Table 1
Comparisons of the four GIS software considering their features.

| GIS software type	Functionality	Interface	Package size	Source edibility	Update frequency	Development cost	Update cost	User benefit
Commercial GIS	Comprehensive	User friendly	Large	No	High	High	High	Low
Non-open-source GIS	Limited	Not ideal	Medium	No	Low	Low	Low	Moderate
Open-source GIS	Improvable	User friendly	Medium	Yes	Not always	moderate	Low	High
Independent GIS	Professional	Professional	Small	No	When necessary	High	High	Moderate
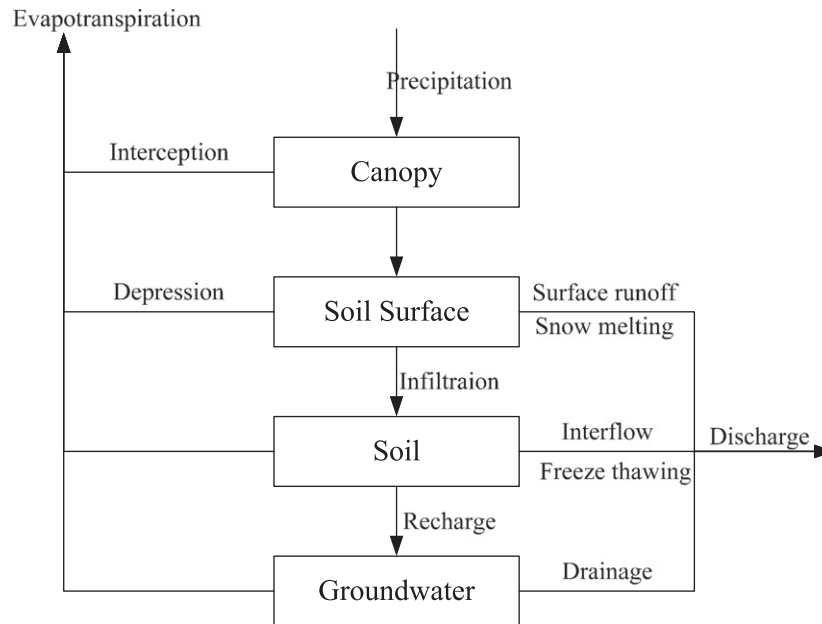
Fig. 1. Runoff algorithm of the EasyDHM hydrological model.

updates while open-source GIS may not able to keep up. However, it is worth noting that updates are usually not hydrologically purpose oriented in commercial GIS software. Moreover, the updates will cost extra expenditure on model system development. There may exist drawbacks that the development of a model system based on open-source GIS software faces: higher development costs as GIS model function improvements and modifications are comparatively harder than comprehensive commercial GIS software; and other tasks must be completed, such as bug fixing, function testing, and manual writing. However, it is true that open-source GIS-based development will create an efficient and user benefiting integration of GIS systems and hydrological models. Although codes or tools like ArcView can be alternatively accepted in GIS integration, open-source software like MapWindow is still better. In MapWindow GIS, due to its open source, code modification is possible. C# developing language used in MapWindow is a new and high-level programming tool for efficient user interface enhancement, better than C++. Without open-source software, realizing functions like multi-thread data interpolation in a GIS system may not be possible. Modeling systems built independently from comprehensive commercial GIS codes may have the best capability of integration, but they are usually less professional and not cost-effective.

1.2. Problems to be solved

As noted above, in recent years, some distributed hydrological model systems have been developed and used all over the world, while many Chinese scholars and research institutes are trying to develop their own model software systems. However, due to various reasons, there is until now no distributed hydrological modeling tool as powerful as ArcSWAT or MIKE SHE that can fully support most functions in the process of distributed hydrological modeling. Some of these reasons are explored in further detail in the remainder of this section:

(1) *Inadequate functions for spatial and attribute data analysis*: Although some well-developed GIS systems provide strong spatial and attribute data analysis and calculation functions, improvements are still required, e.g., river network coding especially using the Pfafstetter method (Pfafstetter, 1989) for EasyDHM; automatic operations on subbasin delineation; efficient interpolation of rainfall and meteorological data.

(2) *Low efficiency in distributed hydrological modeling for large scale basins*: Most distributed hydrological models are designed for medium or small-scale watersheds. When they are used in large basins such as the Yellow River Basin or Yangtze River Basin in China, they will suffer from low efficiency in modeling and calibration.

(3) *Low integration of spatial and attribute data*: Besides the friendly and convenient model-building environment and calibration functions, a distributed hydrological modeling tool should provide direct access to most of the spatial data required. Well-developed model systems could provide such functions; e.g., MWSWAT offers download links of all public data. Due to various reasons, data-sharing mechanisms in China still leave much to be desired and many spatial and attribute data are currently recorded in different formats.

It would be a long-term and difficult mission to integrate the spatial and attribute data of the whole of China required by distributed hydrological modeling in MWEasyDHM.

2. Structure of MWEasyDHM system

EasyDHM (Lei and Yu, 2009; Lei et al., 2009, 2010) is featured as containing easy rain-runoff generation processes and comprehensive preprocess and postprocess modules. As depicted in Fig. 1, the rain-runoff mechanism includes 5 main steps: interception, evapotranspiration, depression storage, infiltration, and ground water recharge. Since the model system of the distributed hydrological model EasyDHM is developed taking advantage of open-source GIS software MapWindow, we name this modeling system as MWEasyDHM (MapWindow-based easy distributed hydrological modeling tool), the system structure of which is shown in Fig. 2.

The MWEasyDHM modeling tool mainly consists of four structural parts: (1) general GIS software for hydrological analysis; (2) preprocessing module; (3) computational module; and (4) postprocessing module. MWEasyDHM contains many functions, which are involved in many algorithms and procedures. These functions are encapsulated into different modules. Besides, considering the language model developers used, the whole
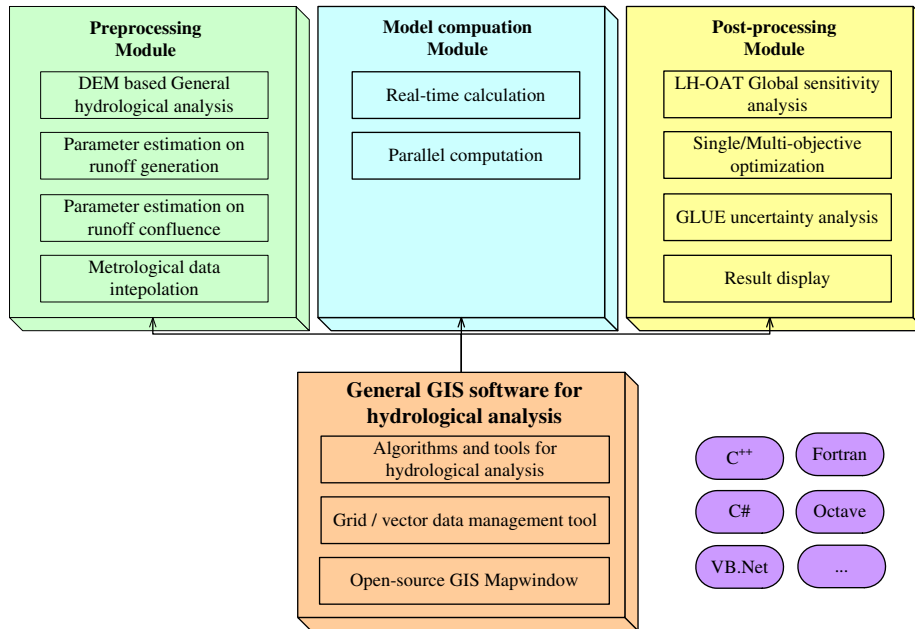

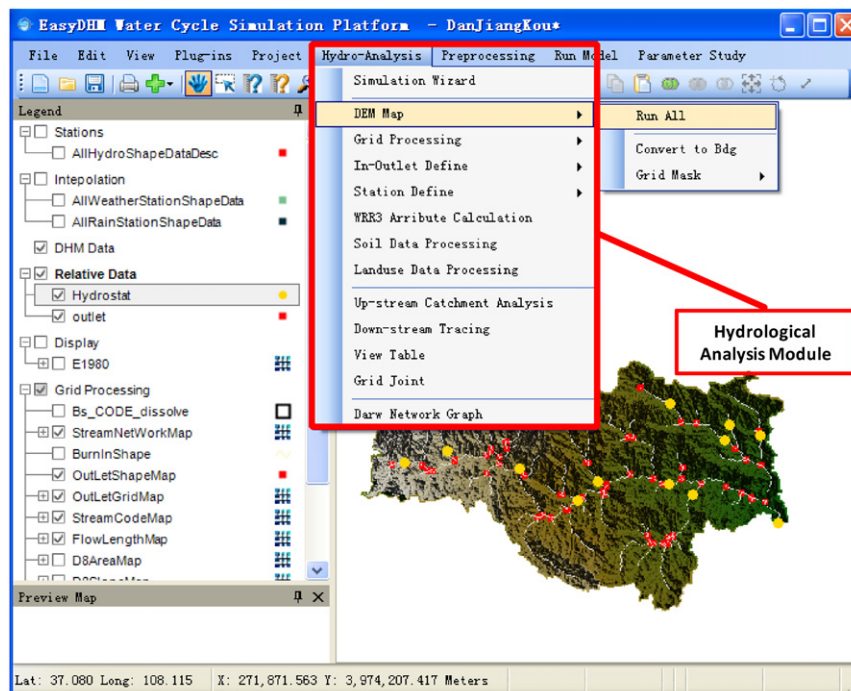**Fig. 2.** System structure of the MWEasyDHM system.

Fig. 3. Main functional menu of the MWEasyDHM system.

platform will be organized as an integration of all functional components and algorithms, and the development languages of MWEasyDHM tool includes C^{++}, $C^{\#}$, VB.Net (programming languages suitable for interface development), and Fortran (a computational efficient language for scientific research). The main function menu of MWEasyDHM system is displayed in Fig. 3.

3. Main hydrological function of MWEasyDHM system

3.1. General GIS software for hydrological analysis

General GIS software for hydrological analysis is a most important part of MWEasyDHM, which includes not only such functions as GIS spatial display, table query, and data management, but also spatial analysis, data format conversion, and projection functions required during the processing of distributed hydrological modeling.

Some new functions can be obtained by add-on functions during the development and reconstruction of MapWindow, listed as follows:

(1) Since original conversion algorithms of vector and grid data are only capable of dealing with simple objects (such as simple river networks), these algorithms are improved for various complex objects (complicated river networks with multioutlets).
(2) Improve efficiency of grid data loading and outputting. The spatial data are read and stored in the format of grids and shape files, making it easier to conduct spatial calculation and conversion between different data format.
(3) The original version of add-on functions was developed in English. Much effort has been made to convert these modules into Chinese, thus enhancing the tool to favorably support a Chinese system environment.

3.2. Preprocessing module

Preprocessing module is the most complicated part in the hydrological modeling process, including: (1) the general hydrological analysis submodule based on DEM, containing calculations of flow direction, flow accumulation, flow length, slope,

digital river networks extraction, etc.; (2) calculation of various runoff generation parameters, including parameters related to soil physical properties and parameters related to land cover and terrain; (3) calculation of various confluence parameters, including parameters related to unit characteristics and channel characteristics; (4) spatial interpolation of meteorological data, including several kinds of spatial interpolation algorithms. During the development of MWEasyDHM, difficulties in the process of distributed hydrological modeling (e.g., large number sets of data concerned, complicated algorithms, and numerous calculation steps) were classified and summarized, and the simplification of distributed hydrological modeling procedures was achieved by designing new algorithms or integrating external algorithms.

3.2.1. General hydrological analysis submodule (GHAS) based on DEM

In order to solve common problems in distributed hydrological modeling and improve the automation level of the modeling procedures, we developed GHAS based on DEM, whose main functions can be found in Fig. 4. The submodule consists of three parts: (1) basic processing functions of grid data, including grid masking, vector/grid data, and grid calculation projection; (2) DEM processing modules, including DEM digital elevation modification (burning-in) to align with surveyed river networks, DEM pit-filling, flow direction and flow accumulation calculations, extraction of digital river networks, digital river network links creation, digital river network grading, flow length calculations, slope calculations, river outlets identification, man-made inlet and outlet editing, downstream tracing and upstream catchment analysis, etc.; (3) a spatial analysis module for basin division, including river network coding and subbasin division, internal subbasin unit division, and deriving the parameter space, etc. These submodules are described in more detail below.

(1) *DEM processing module*: A detailed flowchart of the DEM processing module is shown in Fig. 5a, which not only includes common hydrological analysis modules, but also draws attention to other useful functions such as special calculations on plain area determination and river outlet identification. In the MWEasyDHM system, users can finish all steps of DEM processing modules separately or complete all the analyses and calculations at one time (Fig. 5b).
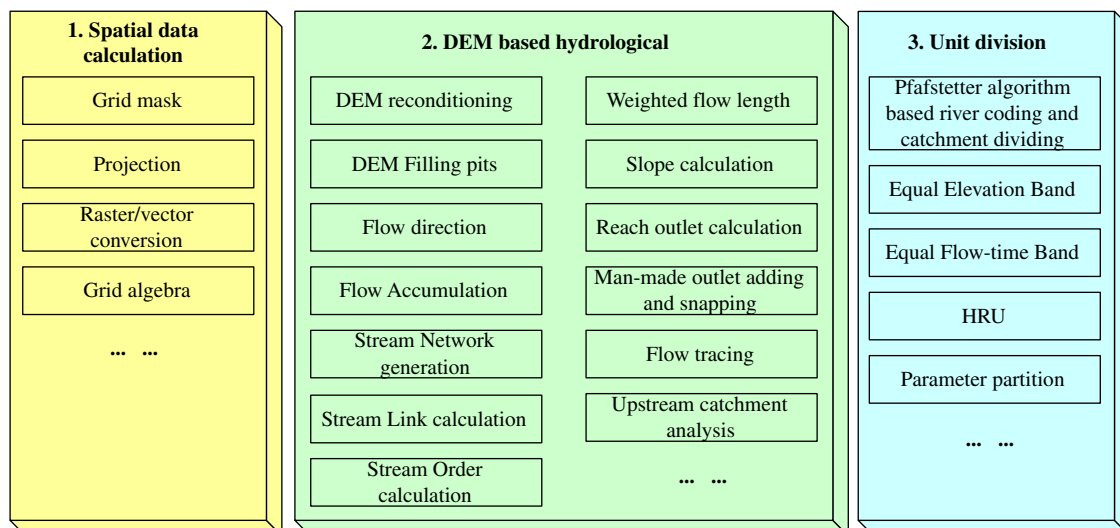

Fig. 4. Main functions of general hydrological analysis submodule in the MWEasyDHM system.
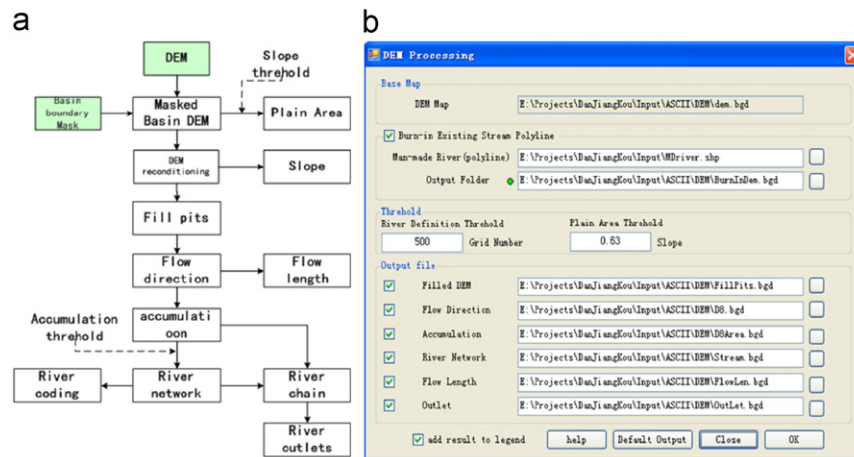
Fig. 5. DEM data processing flow and user's interface. The interface includes the main process of DEM processing steps that are sink filling, flow direction calculation, accumulation, river network extraction, etc.: (a) processing procedure of DEM digital elevation and (b) user's interface of DEM digital elevation processing.
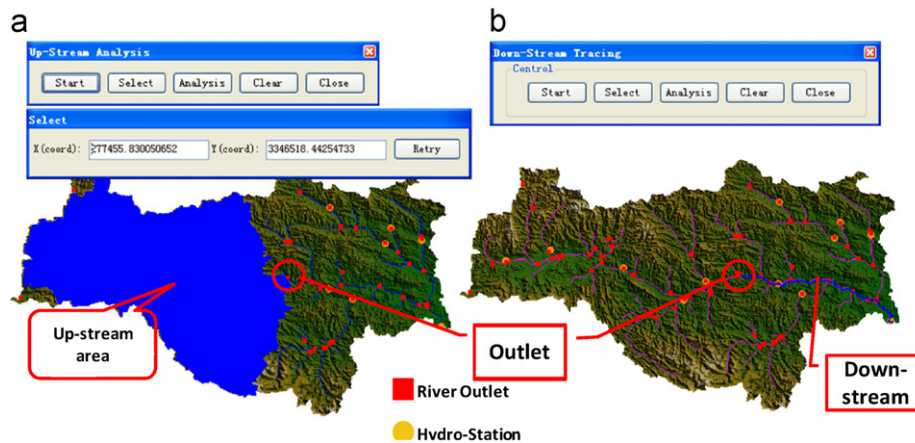

Fig. 6. Display of upstream scope and downstream river tracing function: (a) upstream analysis and (b) downstream tracing.

(2) *Upstream catchment analysis and downstream tracing functions*: Upstream catchment analysis and downstream tracing are basic functions of basin hydrological analysis, which can not only improve users' tangible experience of hydrological analysis, but also can be used for senior hydrological analysis functions.

As shown in Fig. 6, the MWEasyDHM system is enhanced with the above functions, while Fig. 6a shows the upstream catchment scope of a specified tributary outlet, and Fig. 6b indicates downstream tracing to the basin outlet corresponding to a specified tributary outlet. It can be seen that the river finally flows out of the whole basin at the outlet.

(3) *Hydrological gauges and reservoir location identification module*: Different from other distributed hydrological models, the basin outlet definition procedure in MWEasyDHM was achieved by first generating every tributary outlet along the river network and then the basin outlets could be selected from the generated outlets (the graphical user interface for this process is shown in Fig. 6a and b and describes the outlets of all river reaches in the basin). Users can choose the basin outlets from all drainage outlets highlighted (shown in Fig. 7a), other than adding basin outlet points manually. Thus this interface can greatly improve the rationality and accuracy of basin outlets selection. Meanwhile, the interface also provides the ability to import existing point shapefile descriptions of basin outlets. Finally, the MWEasyDHM system also has a function of reasonable checkups on selected outlets (Fig. 7a), which can avoid errors and save model building time.

Hydrological gauges and reservoirs are regarded as man-made outlets, and they are identified in a similar process as the basin outlets. Hydrological gauges and reservoir point layers can be created according to the imported data (ASCII grid, Shapefile, or point coordinates). Fig. 7b shows the "Identification" interface of hydrological gauges. Except for the "import" function, the interface supports automatic snapping of hydrological gauges and reservoirs to the nearest river, namely automatically move hydrological gauges and reservoirs points to the nearest river networks according to a given snapping threshold. Moreover, the interface provides a data check function (Fig. 7b). Finally, the interface supports a searching function for the upstream catchment. That allows automatic calculation of the position, control scope and area of each hydrological station or reservoir, which can facilitate further accurate error correction of the hydrological analysis.

(4) *Land use and soil data processing module*: In order to accomplish modeling in major basins of China using distributed hydrological modeling, the MWEasyDHM system provides nationwide Chinese land use data with resolution of 1 km^2 in three periods (1980, 1995, and 2000). Soil type data include two data sources, namely: (1) high-resolution (1 km^2) grain-size distribution of soil from Soil Science Institute, CAS, which divides the soil into five layers (depth, cm), 0–10, 10–20, 20–30, 30–70, > 70 cm; (2) global soil grain-size distribution

data with the resolution of 10 km from FAO, which divides soil into two layers, 0–30 and 30–100 cm.

Additionally, the MWEasyDHM automatically masks and resamples land use and soil data in accordance with the grid resolution of input DEM data, and generates a corresponding data set with the same resolution as DEM data. This is quite essential for the later hydrological analysis.

(5) *Spatial analysis module for unit division and default parameter calculation*: As noted above, MWEasyDHM is developed on the basis of the spatial structure of the internal subbasin computational units. Thus, we developed a set of general basin spatial division algorithms; refer to the detailed data flow in Fig. 8a. All basic data come from calculation results of the

previous modules. Fig. 8b shows the operation interface of subbasin division and computational unit refining. The interface integrates spatial division and default parameters calculation algorithm of EasyDHM (refer to the following part in detail).

The interface illustrated in Fig. 8b also indicates the statistics on attributes of computational units, the purpose of which is to obtain the default parameters of a unit for model parameter initialization. Before carrying out calibrations, default parameters of each computational unit should be obtained. Default parameters in MWEasyDHM can be obtained in an indexed lookup table which is related to DEM (confluence parameters), land use
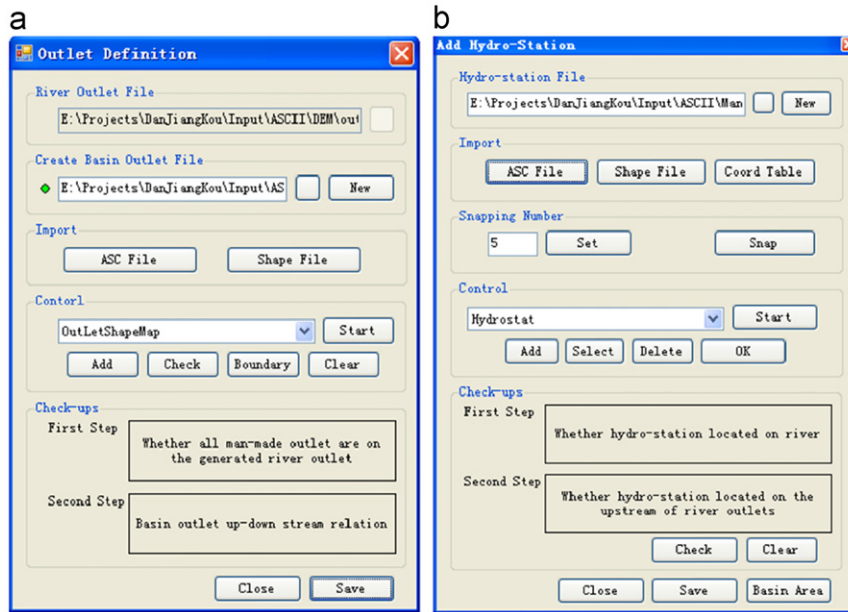

Fig. 7. Selection interfaces of basin outlets and hydrological gauges. The interface contains the outlet and station location tools that are necessary to hydrological modeling: (a) outlet definition and (b) hydrological gauges definition.
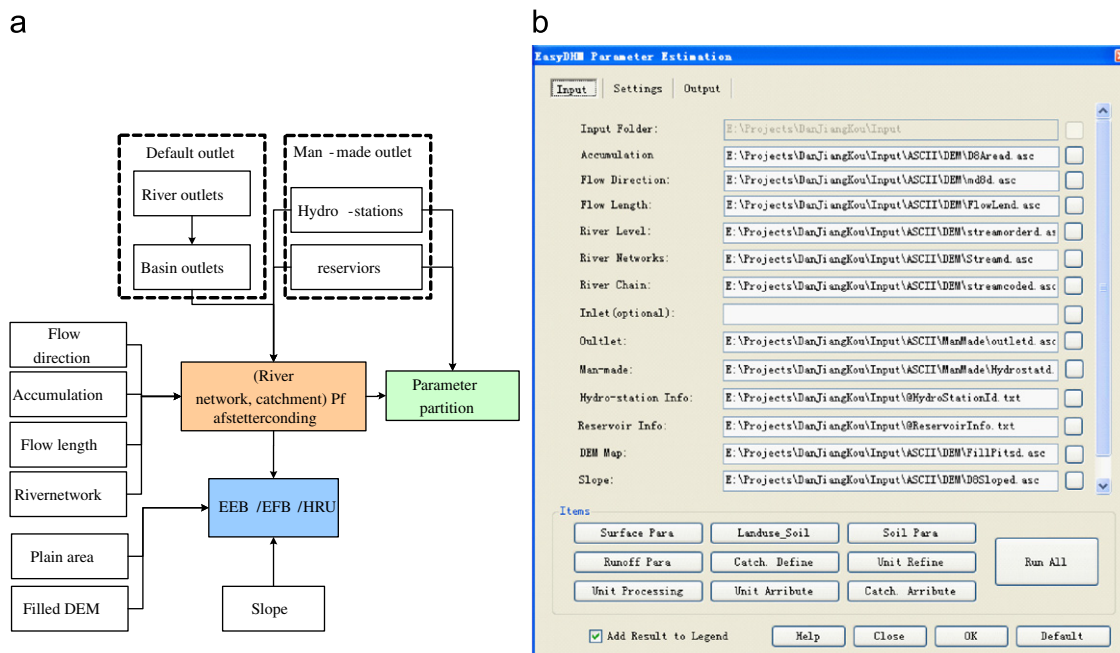

Fig. 8. Computation procedure chart and graphical user interface of basin spatial data division: (a) flowchart of spatial discrete and (b) unit physical parameter statistical interface.

(root depth, interception capacity, etc.), and soil type (conductivity, porosity, field capacity, etc.). In a catchment scale unit considered in MWEasyDHM, spatial statistics should be completed to obtain the default parameter of a catchment.

The module is called "general" in that its functions are applicable to most distributed hydrological models. Such functions as DEM processing module, upstream and downstream tracing, man-made points and outlets identification, land use, or soil data preprocessing are commonly used in all kinds of distributed hydrological models, regardless of whether they are based on a grid or the subunit scale. The function of the basin spatial division module is applicable to most distributed hydrological models that take subbasins or other units (such as HRU) as the calculation unit.

3.2.2. Default model parameter calculation

One key characteristic and advantage of distributed hydrological models is that parameters have physical meanings and can be calculated directly from underlying data. For this reason, the distributed hydrological model has the capability of being applied in ungauged basins.

Default parameter calculation of MWEasyDHM integrates the calculation of runoff generation parameters in the Wetspa model with determining the confluence parameters in the MWSWAT model system; the detailed data flowchart for these steps is shown in Fig. 9. The MWEasyDHM system is able to calculate confluence parameters of main rivers and tributaries inside the subbasin according to DEM, flow length, river network codes, and subbasin division results. Runoff generation parameters are used and calculated from all physical parameters in each grid according to DEM, land use, and soil data. Then these parameters are summarized into inner computational units (equal elevation band (EEB); equal flow band (EFB), ; or hydrological response unit (HRU)) of each subbasin.

Parameters in the MWEasyDHM model system are mainly divided into two categories that are the global parameters and the correction factor of default parameters. Default parameters are calculated by checking the lookup table (where the corresponding relationships between default parameters and topographical

information, i.e., DEM, land use, and soil type, are listed). Hence, considering the heterogeneity of different watersheds, correction factor should be introduced for default parameter adjustment. Later, global parameters and correction factors are estimated in the model calibration. Detailed descriptions of the main global parameters and the correction factors in MWEasyDHM are given in Table 2. The unit default parameter calculation interface can be seen in Fig. 8b. Besides the "input file" dialog shown in Fig. 8, there are two other setting dialogs called "calculation setting" and "output setting," respectively. Sequentially implementation of parameter calculation in MWEasyDHM can be described as steps related to topography, land cover, soil, runoff, unit division and attribute statistics, and subbasin attribute statistics. The first four steps contain the calculations of various complicated physical parameters of each grid based on the underlayer data; the purpose of spatial unit statistics is to obtain the centroid of each subbasin and calculate the statistical information onto the centroid; unit attributes and subbasin attributes are used to calculate runoff generation parameters of each unit and confluence parameter of each subbasin, respectively, according to all kinds of physical parameters in the grids. The functions of subbasin division and unit division in the interface belong to the basin spatial division module, and the functions embedded in the user interface are just for convenience in the design of interface programs to share the same input and output parameters.

3.2.3. Rainfall and meteorological data interpolation module

To use the MWEasyDHM system, it is necessary to obtain meteorological data from each subbasin by spatially interpolating meteorological data collected from gauges. Fig. 10 shows the calculation flowchart for the spatial interpolation of meteorological data in MWEasyDHM. The program integrates several meteorological data interpolation algorithms, including Thiessen polygon (TP), inverse distance interpolation (ID), kriging interpolation method (KI), elevation-modified inverse distance interpolation or a hybrid method (Zhou et al., 2006). Additionally, in the process of long-term hydrological simulation with
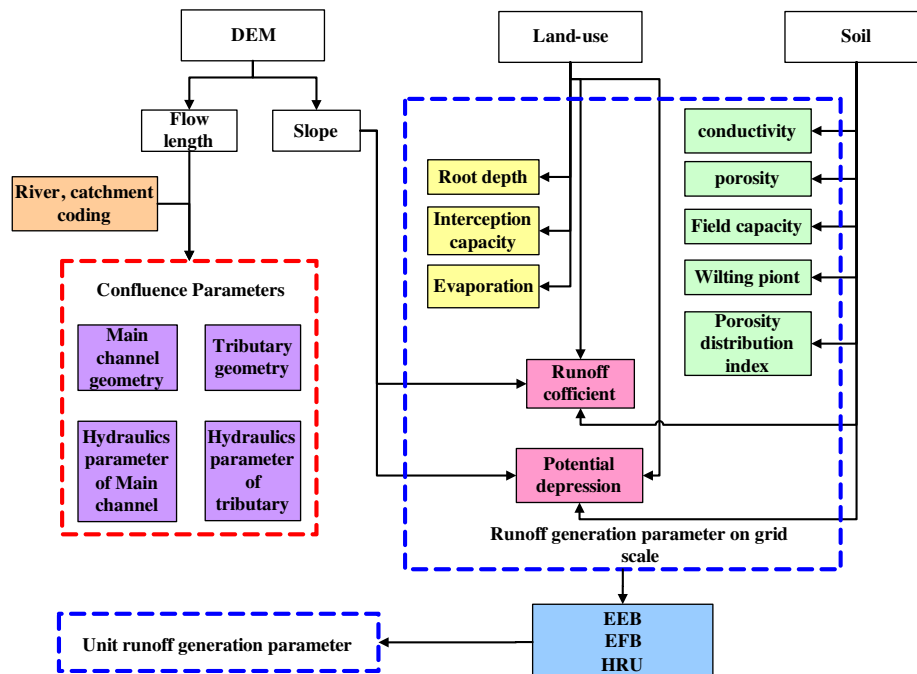

Fig. 9. Procedure diagrams of calculated parameter data.

Table 2
Global and runoff parameters of the EasyDHM model.

| Type	No.	Name	Meaning	Lower limit	Upper limit
Global parameter	1	ki	Subsurface flow computational coefficient	0.5	2
	2	kg	Global underwater recession coefficient	0.001	0.05
	3	T0	Basic snowmelt temperature	0.1	0.9
	4	ksnow	Temperature degree–daily coefficient for now melt	0.1	2
	5	krain	Precipitation degree–daily coefficient	0.0001	0.001
	6	krun	Surface runoff coefficient when rainfall intensity approaches 0	0.5	3
	7	pmax	Corresponding rainfall intensity when surface runoff coefficient is 1	100	500
Correction factor of default parameter of computational units	8	UnitSlopeM	Correction coefficient of slope of computational units	0.5	1.5
	9	RunOffCoeM	Correction coefficient of runoff coefficient	0.5	1.5
	10	ConductM	Correction coefficient of soil saturated hydraulic conductivity	0.5	1.5
	11	PorosityM	Correction coefficient of soil porosity	0.5	1.5
	12	FieldCapM	Correction coefficient of soil field capacity	0.5	1.5
	13	PoreIndexM	Correction coefficient of soil porosity indexes	0.5	1.5
	14	WiltingM	Correction coefficient of wilting coefficient	0.5	1.5
	15	ResidualM	Correction coefficient of residue water content	0.5	1.5
	16	LaiMaxM	Correction coefficient of maximum leaf area index	0.5	1.5
	17	LaiMinM	Correction coefficient of minimum leaf area index	0.5	1.5
	18	DepressM	Correction coefficient of surface sink filling capacity	0.5	1.5
	19	RootDpthM	Correction coefficient of root depth	0.5	1.5
	20	ItcmaxM	Correction coefficient of maximum canopy interception capacity	0.5	1.5
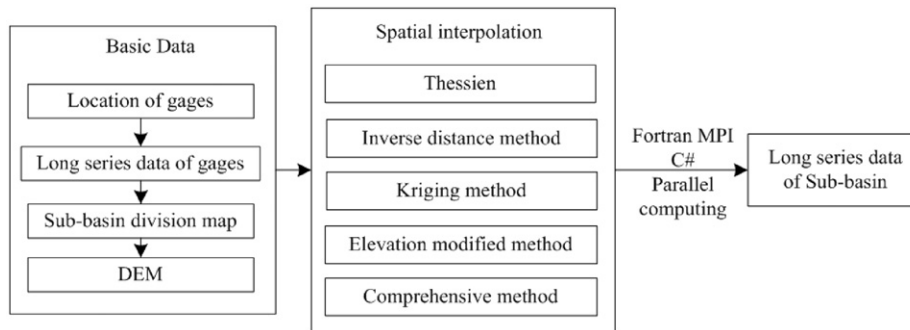
Fig. 10. Flowchart of interpolation data of rainfall and meteorological data.

MWEasyDHM, it always takes much computing time to implement spatial interpolation for long-term meteorological data. In order to solve this problem, the authors introduce windows Fortran MPI parallel technology or multithreading technology to realize fast interpolation of meteorological data. The basic idea of parallel computation is to divide long-term series of data sets into several sections, carry out parallel spatial interpolation of meteorological data for each section on different computing threads at the same time, and then rearrange the meteorological data results on different threads into one file. For example, the long-term data from 1956 to 2005 can be divided into five parallel computation tasks, where each task contains 10 years of data. Then the data can be calculated independently and the results will be rearranged into one output file.

A prerequisite task for rainfall and meteorological data interpolation is to prepare various long-term observed data from different gauging stations. In this way, MWEasyDHM provides access to the rainfall and meteorological databases covering all of China and has realized the interfaces between the MWEasyDHM system and the database, including:

(1) *National meteorological database*: The database contains long-term daily observation data from all meteorological gauges in China, including items of daily rainfall, daily average temperature, daily maximum and minimum temperature, wind speed, relative humidity, and sunshine hours.

(2) *National runoff data*: The database contains long-term monthly runoff data of major runoff gauges of China from a comprehensive planning database of national water resources.

(3) *Local rainfall and runoff data*: The database contains long-term data (including daily and hourly time steps) at rainfall gauges and runoff gauges in some basins in China, including the Hai River basin, the Yellow River basin, and the Nen River basin. Different from national data, local data gauges are of higher density and the observation time step is often shorter. National data are suitable for modeling and evaluating water resources on a large scale, while the local data are used for detailed simulation, calculation, and application in such fields as flood forecasting.

In order to obtain required data from these databases in a usable and convenient manner, two data extraction methods are developed—namely visual selection and attribute table selection. With visual selection, users can spatially select interested gauges according to the gauges' positions on a GIS window or bounding box, and for attribute selection, users can attributably select concerned gauges from tables according to query parameters from databases. In addition, the time step of outputting data can be determined by the user. After extracting the data, users could obtain average rainfall of every subbasin with the meteorological interpolation algorithm (Fig. 11).
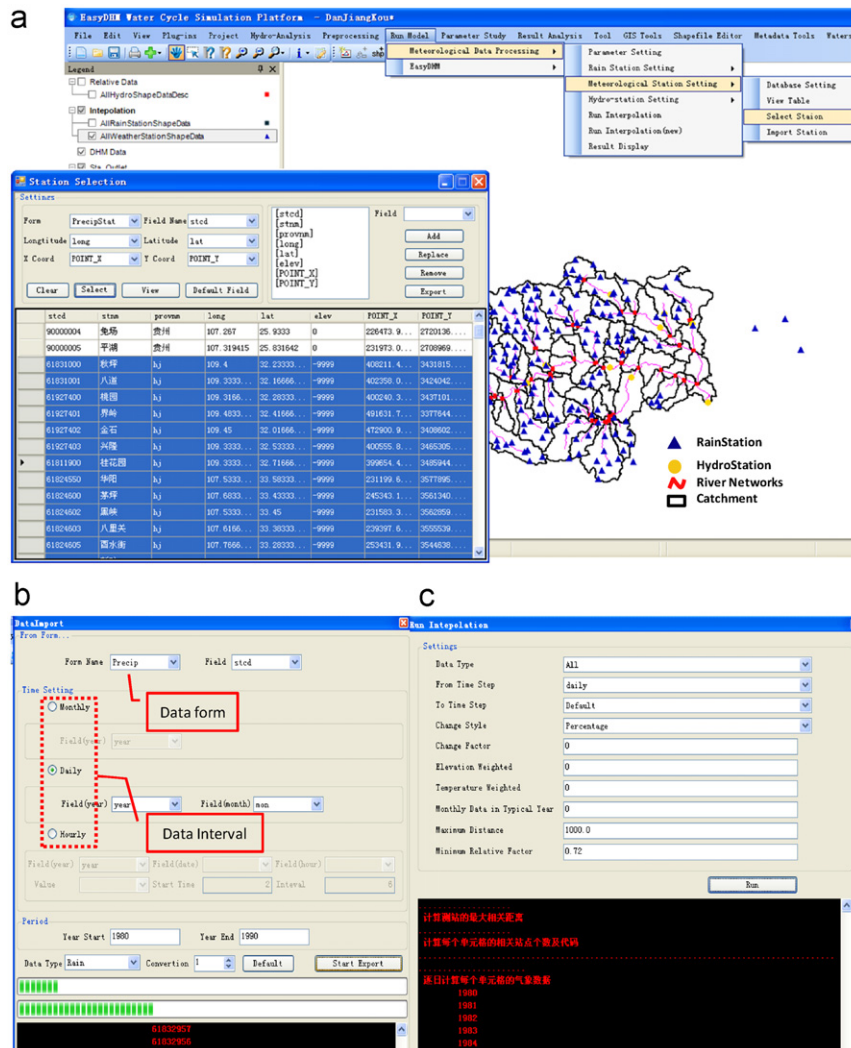
Fig. 11. Interface of rainfall and meteorological gauges, data extraction, and meteorological data interpolation: (a) interface of meteorological data space/attribute selection. The connection of database and the MWEasyDHM system can provide an easy data distribution method for users, (b) meteorological data import and (c) spatial interpolation of meteorological data.

Fig. 11a shows the selection interface for rainfall gauges. As shown in the figure, the interface not only gives selected attribute data sheets but also highlights the selected hydrological or meteorological stations in the GIS window. Fig. 11b shows the data importing interface, which can convert rainfall or meteorological elements into text files extracted from SQL Server databases according to different time steps (monthly, daily, or hourly), and provide data for the interpolation interface of meteorological data in Fig. 11c. It shows the parameters used in the spatial interpolation of various data, including the settings of parameters like data type selection (Data Type), time step ("From Time Step" and "To Time step"), changing options ("Change Style" and "Change Factor"), etc.

3.3. Computation module

Computation modules of MWEasyDHM mainly include parallel computation and real-time computation of distributed hydrological models. These models are described in the following sections.

3.3.1. Parallel computation

An autocalibration method is included in parameter estimation. Optimization algorithms may sample large numbers of candidate parameter combinations to be evaluated at a time, thus resulting in low computational efficiency. Therefore, a parallelized processing of the parameter calibration algorithm can extensively shorten the computational time in parameter estimation. One method is to divide the evaluation set into several parallel blocks, each containing several parameter combinations for a processor to evaluate. Another is to parallelize the computation in a single hydrological simulation, i.e., to parallelize runoff generation computation for topological units on different nodes. Parallel computation can improve the efficiency of model calibration and computation, and thus allows a finer resolution in the simulation of large basins with small subunits and reduce the computational burden to the highest degree.

3.3.2. Real-time computation

Real-time computation means tracing and displaying the calculation results simultaneously in the calculation process, including simulated and observed flow processes and spatial display of water circulation units at some specific units. The development of real-time computation modules also strengthens the users' visual experience in distributed hydrological models and enhances their perceptual knowledge of the model (Fig. 12). Another advantage of real-time computation included in MWEasyDHM is the real-time start–stop function. The function should

record and output current model state variables in a fixed time step for restart initialization.

Once the EasyDHM model calculation is started, the MWEasyDHM system can show real-time computation results at the same time, including screen output in the form of the console. Fig. 12 shows the real-time simulation process of rainfall runoff at Xiajiangping Hydrological gage (upstream catchment of Han River, simulation period from year 1983 to 1984), which are dynamically displayed with continuously updated hydrographs the same time as the calculation continues. Meanwhile, the real-time diagram setting could be specified through control files, including rainfall, runoff, and evaporation procedure chart, etc.

3.3.3. Model run setting

The MWEasyDHM system integrates several kinds of model calculation parameters settings into one interface, including the settings of model calculation parameters, sensitivity analysis of model parameters, and calibration of model parameters (refer to Fig. 13). After finishing parameter setup, users can complete model computations or parameter estimations (including sensitivity analysis and calibration) using real-time computation modules noted above.

(1) *Model running options*, including model "Run Type" selection (1. RunDefault—Run with default parameters; 2. Sensitivity—Run sensitivity analysis; 3. Optimization—Run autocalibration; 4. Uncertainty—Run uncertainty analysis; 5. RunBest—Run with
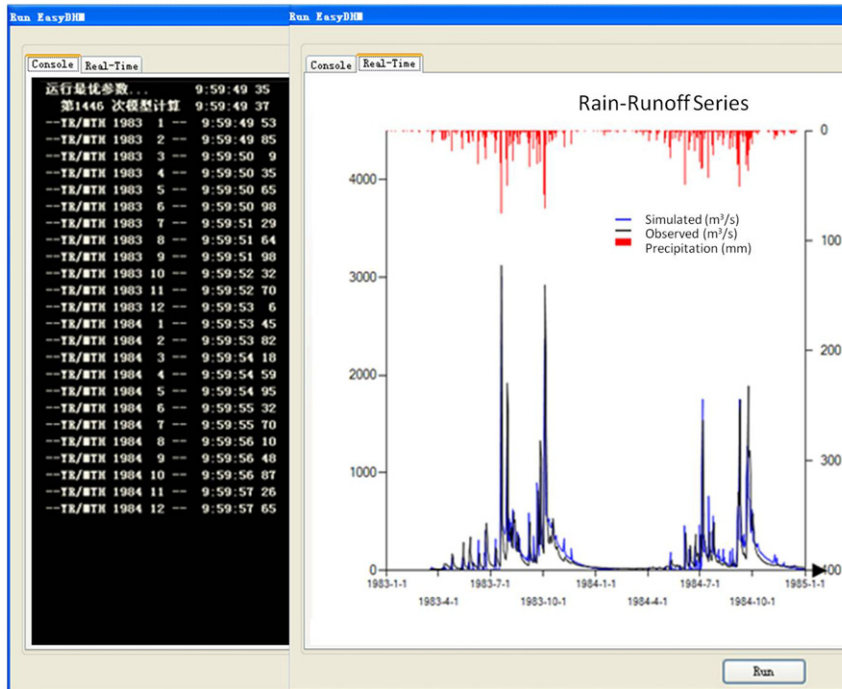

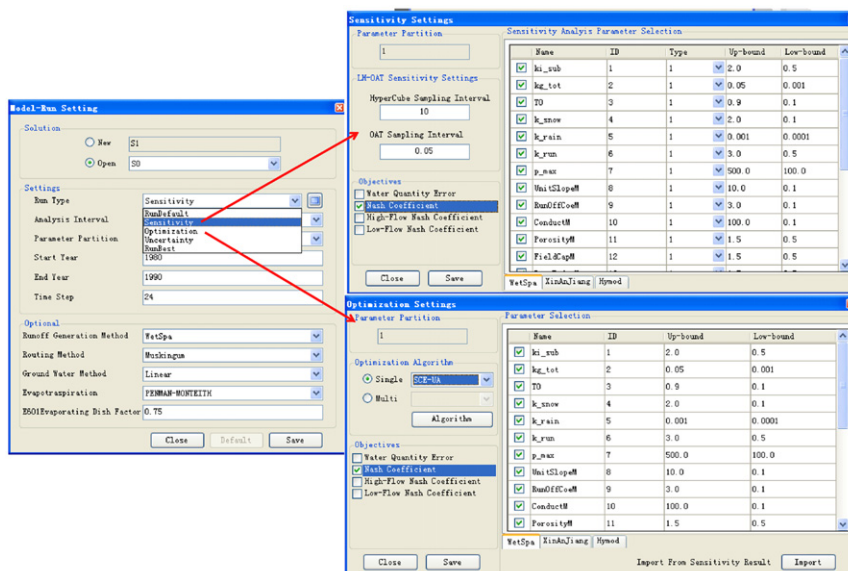**Fig. 12.** Real-time computation interface.

Fig. 13. Setup interfaces of computation, parameter sensitivity analysis, and automatic parameter calibration.

best calibrated parameters), "Parameter Partition" selection, "Start Year", "End Year," and "Time Step" setting.

(2) *Optional parameters*, including runoff generating method (1. Wetspa model; 2. Xinanjiang model; 3. Hymod Model), routing method (1. Muskingum method; 2. Variable storage method; 3. Manning routing method), groundwater simulation algorithm (1. linear reservoir; 2. nonlinear reservoir), evapotranspiration algorithm (1. Priestley–Taylor; 2. Penman–Monteith; 3. Hargreaves; 4. Use observation), and evaporation pan (E601) coefficient.

MWEasyDHM will select different simulation options in terms of selectable parameters and carry out computations, with default parameters by choosing "RunDefault" or with optimal parameters by choosing "Run BestPar." When the "Run-type" is set to "Sensitivity" or "Calibration", MWEasyDHM will carry out corresponding parameter sensitivity analysis and autocalibration within the chosen time period.

3.4. Postprocessing module

Postprocessing modules include LH-OAT global sensitivity analysis, single or multiobjective parameter calibration, spatial display, and statistical analysis of model results.

3.4.1. Parameter estimation module

The development of automatic parameter estimation modules allows the user to avoid the tedious manual model calibration, and improves the stability and reliability of parameter estimation, which can make the process more efficient. In Fig. 13, the parameter estimation of MWEasyDHM can be set. Once "Sensitivity" is chosen, a dialog box of "Sensitivity Analysis" will pop up, from which evaluation objectives and sampling parameters can be set. Similarly, when "Optimization" is chosen, the dialog box of parameter optimization setup will pop up, from which corresponding optimization methods (single/multiobjectives) can be chosen and users can choose the parameters and optimization objectives corresponding to the selected optimization method. As noted above, MWEasyDHM mainly adopts the LH-OAT global parameter sensitivity analysis method and the SCE-UA global automatic parameter calibration method to realize automatic estimation of model parameters.

3.4.2. Display of results

A convenient display of results and analysis functions can greatly improve efficiency in the analysis of results. MWEasyDHM can display and analyze calculation results in different ways, including table and chart display and GIS spatial output. Fig. 14 shows a spatial display diagram of simulation results in GIS format, in which a spatial distribution chart of the actual evaporation (ETmm) in 1983 in upstream Han River is displayed. As shown in the diagram, if display time and data item are specified, spatial distribution of data items will be quickly displayed in the way of subbasin or computation units using input or output data file.

3.5. Applications

The MWEasyDHM modeling system has been applied in many basins in China: (1) MWEasyDHM was first applied in the Han River basin for water resource simulation and prediction, to better understand the water source conditions of The Middle Route of South to North Water Diversion Project (MRP). The simulation results were used for further water resource management and operation of the water diversion projection (Lei and Yu, 2009; Lei et al., 2009). (2) The MWEasyDHM modeling system was successful in preprocessing a multioutlet basin, as exemplified by the water receiving area of MRP (Lei and Yu, 2009; Lei et al., 2009) and Songhua and Liao River Basins (Lei and Yu, 2009; Lei et al., 2009) that contain coastal terrains and multiple outlets. (3) The MWEasyDHM modeling system was also applied in the flood simulation and prediction of the Nen River located in the northeast part of China and is one of the most important agricultural areas that require flood protection. The time step of MWEasyDHM can be set to a reasonable period (e.g., hourly, daily). MWEasyDHM is capable of describing the impacts of land cover in spatial differences and in different periods. Also due to the integration of MapWindow GIS software with the EasyDHM code, the manipulation of the system is comparably easier than the traditional conceptual models.

3.6. A study case

A most successful application of the MWEasyDHM system in China is the development of a water resource management
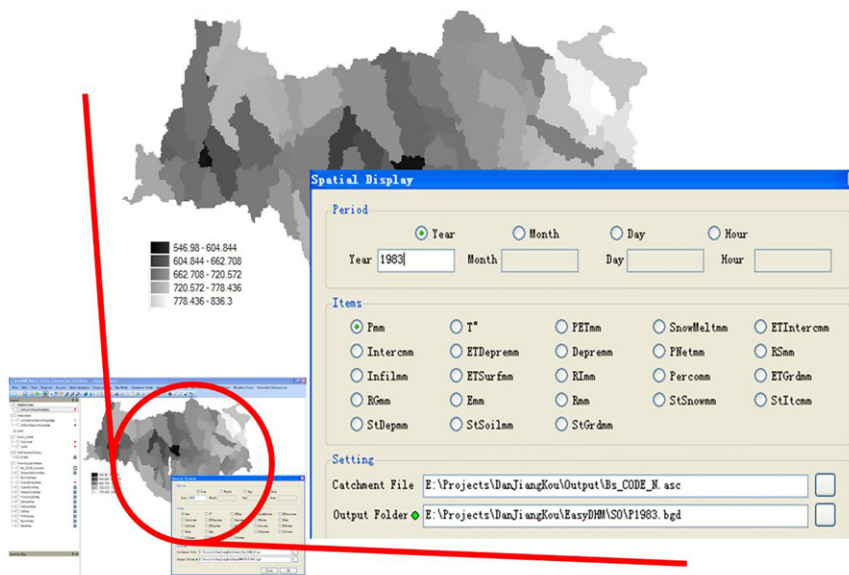

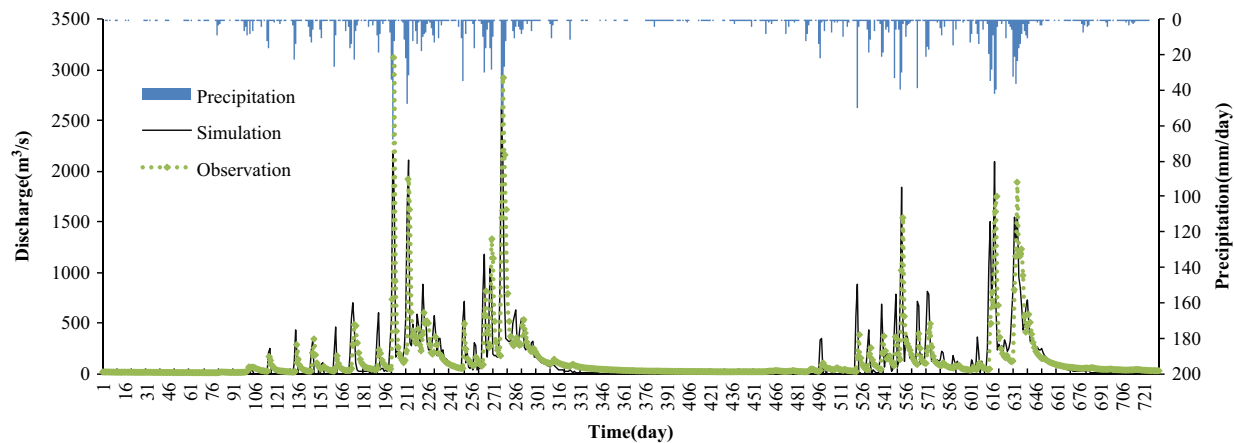**Fig. 14.** GIS display interface of model results.

Fig. 15. Simulation results of Xiangjiaping catchment (a catchment located on the upstream of the Han River Basin).

system on the upstream of the Han River Basin, which is the main functional catchment for the MRP project. The description of modeling processes can be displayed in Figs. 2 to 3. The main hydro-analysis function was added as a plug-in where multiple manipulation of DEM analysis and station identification can be handled or processed at one time (Fig. 2). After DEM processing and the catchment outlet definition, upstream and downstream analysis can be carried out. The next step is mainly focused on the model parameter calculation (Fig. 7b) relating to surface, soil, catchment, and unit statistics. The following step is mainly about data distribution and model computation start setup. The real-time display can be seen in Fig. 12. The left part of Fig. 12 shows the simulation process of Xiangjiaping catchment while the right part shows the real-time display on simulated discharge (in blue line), observed discharge (in black line), and the precipitation (in red bar). The hydrograph evaluation result at Xiangjiaping catchment with calibrated parameters is illustrated in Fig. 15. A 2-year simulation is conducted to present the good correlation between daily observation (green dot line) and simulated discharge (in black line) at the hydro-station of Xiangjiaping catchment from year 1983 to 1984. The Nash coefficient of the simulation reached to 0.84, promising a good hydrological reproduction.

4. Conclusion

The open-source GIS-based MWEasyDHM tool provides a friendly GIS-based modeling environment to carry out efficient distributed hydrological modeling with various hydrological analysis modules, computational and result visualization modules, and spatial output functions. The MWEasyDHM tool has successful applications in many watersheds of China. The application in the Han River also shows the capability of high hydrological reproduction precision and spatial visualization.

Effort should be expended to make the tool efficient for practical water resource management and flood control.

Therefore, in summary, based on MapWindow GIS, an efficient and cost-effective hydrological simulation tool with MWEasyDHM has potential in hydrological modeling and promises a foundation for further development and applications in practical water resource management and flood control.

References

Abbott, M.B., Bathurst, J.C., Cunge, J.A., 1986. An introduction to the European system: Systeme hydrologique Europeen (SHE). Journal of Hydrology 87, 61–77.

BASIN4 Environmental Protection Agency, 2009. ⟨http://www.epa.gov/water science/basins/⟩.

Batelaan, O., Wang, Z.M., De Smedt, F., 1996. An adaptive GIS Toolbox for Hydrological Modelling. Application of Geographic Information Systems in Hydrology and Water Resources Management. IAHS Publication.

Castrogiovanni, E.M., La Loggia, G., et al., 2005. Design storm prediction and hydrologic modeling using a web-GIS approach on a free-software platform. Atmospheric Research 77 (1–4), 367–377.

Coroza, O., Evans, D., et al., 1997. Enhancing runoff modeling with GIS. Landscape and Urban Planning 38 (1–2), 13–23.

Croley, T.E., Hartmann, H.C., 1985. Resolving Thiessen polygons. Journal of Hydrology 76 (3–4), 363–379.

Elias, G., et al., 2007. Multi-objective automatic calibration of SWAT using NSGA-II. Journal of Hydrology 341 (3–4), 154–176.

George, C., Leon, L.F., 2008. WaterBase: SWAT in an open source GIS. The Open Hydrology Journal 2, 1–6.

Hormann, G., Koplin, N., et al., 2009. Using a simple model as a tool to parameterize the SWAT model of the Xiangxi River in China. Quaternary International 208 (1–2), 116–120.

Kebaili Bargaoui, Z., Chebbi, A., 2009. Comparison of two kriging interpolation methods applied to spatiotemporal rainfall. Journal of Hydrology 365 (1–2), 56–73.

Kralisch, S., Krause, P., 2006. JAMS—a framework for natural resource model.

Lei, X.H., Jiang, Y.Z., Wang, H., et al., 2010. Distributed Hydrological Model EasyDHM II. Application. Journal of Hydraulic Engineering 41 (8), 893–908 (in Chinese).

Lei, X.H., Zhou, Z.H., Ding, X.Y., et al., 2009a. Study on the treatment of boundary river and coast line in the watershed subdivision of distributed hydrological model. Journal of China Hydrology 29 (6), 1–5.

Lei, X., Yu, T., 2009. General catchment delineation method and its application into the middle route project of China's south-to-north water diversion. The HKIE Transactions 17 (2), 1–7.

McMichael, C.E., Hope, A.S., et al., 2006. Distributed hydrological modeling in Geographic Resources Analysis Support System (GRASS), 2010, GRASS development team. ⟨http://grass.itc.it/⟩.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2005. Soil and water assessment tool theoretical documentation (Version 2005).

OpenJUMP Geographic Information System, 2008. ⟨http://www.openjump.org/⟩.

Pfafstetter, O., 1989. Classification of Hydrographic Basics: Coding Methodology. Departamento Nacional de Obras de Saneamento, Esri, USA.

Quantum GIS Project team, 2009. ⟨http://www.qgis.org/⟩.

Ren-Jun, Z., 1992. The Xinanjiang model applied in China. Journal of Hydrology 135 (1–4), 371–381.

Romanowicz, A.A., Vanclooster, M., et al., 2005. Sensitivity of the SWAT model to the soil and land use data parametrisation: a case study in the Thyle catchment, Belgium. Ecological Modelling 187 (1), 27–39.

Schuol, J., Abbaspour, K.C., et al., 2008. Estimation of freshwater availability in the West African sub-continent using the SWAT hydrologic model. Journal of Hydrology 352 (1–2), 30–49.

SharpMap easy-to-use mapping library for use in web and desktop applications, 2009. ⟨http://www.codeplex.com/SharpMap⟩.

Shen, Z.Y., Gong, Y.W., et al., 2009. A comparison of WEPP and SWAT for modeling soil erosion of the Zhangjiachong Watershed in the Three Gorges Reservoir Area. Agricultural Water Management 96 (10), 1435–1442.

Smakhtin, V.U., Eriyagama, N., 2008. Developing a software package for global desktop assessment of environmental flows. Environmental Modeling & Software 23 (12), 1396–1406.

SWAT-CUP2, 2008. SWAT Calibration and Uncertainty Programs, version 4, Department of Systems Analysis, Integrated Assessment and Modelling (SIAM), Eawag, Swiss Federal Institute of Aquatic Science and Technology, Duebendorf, Switzerland, 95 pp.

uDig GIS Framework for Eclipse, 2009. ⟨http://udig.refractions.net/⟩.

Using the MapWindow ActiveX Control, 2008. MapWindow Open Source Team. 〈http://www.mapwindow.org/〉.

Viviroli, D., Zappa, M., et al., 2009. An introduction to the hydrological modeling system PREVAH and its pre- and postprocessing-tools. Environmental Modeling & Software 24 (10), 1209–1222.

Wang, et al., 1997. A distributed model for water and energy transfer between soil, plants and atmosphere (WetSpa). Phys. Chem. Earth 21 (3), 189–193.

William, A., Scharffenberg, Matthew, Fleming, J., 2000. Hydrologic Modeling System HEC-HMS Technical Reference Manual. U.S. Army Corps of Engineers Hydrologic Engineering Center.

Zhou, Z.H., Jia, Y.W., Wang, H., et al., 2006. Interpolating precipitation in space and time in large-scale basin based on rain gauges. Journal of China Hydrology 26 (1), 6–11.