Development of SPAWM: selection program for available watershed models

Yongdeok Cho and Larry A. Roesner

ABSTRACT

A selection program for available watershed models (also known as SPAWM) was developed. Thirty-three commonly used watershed models were analyzed in depth and classified in accordance to their attributes. These attributes consist of: (1) land use; (2) event or continuous; (3) time steps; (4) water quality; (5) distributed or lumped; (6) subsurface; (7) overland sediment; and (8) best management practices. Each of these attributes was further classified into sub-attributes. Based on user selected sub-attributes, the most appropriate watershed model is selected from the library of watershed models. SPAWM is implemented using Excel Visual Basic and is designed for use by novices as well as by experts on watershed modeling. It ensures that the necessary sub-attributes required by the user are captured and made available in the selected watershed model.

Key words | selection program, SPAWM, user selected attributes, watershed model

Yongdeok Cho (corresponding author)
Executive Director,
Korea Water Forum,
Dogokro 111,
Gangnam,
Seoul,
South Korea
E-mail: *choyong@kwater.or.kr*

Larry A. Roesner
Department of Civil Engineering,
Colorado State University,
Fort Collins, CO 80523-1372,
USA

INTRODUCTION

The development of watershed models began in the 1970s to estimate non-point sources of pollution in the United States and their impacts on receiving water quality (Leon & Lam 2000). From the middle of the 1980s, a variety of models were developed due to advancements in computers and science. Many watershed models have been developed for specific pollutants based on each watershed conditions (EPA 2008).

Since the advancement of computers in the mid-1980s, increasingly sophisticated watershed models have been constructed. These include pollutant specific watershed models (EPA 2008). Each watershed model can include components such as: areal precipitation, watershed representation, surface runoff, infiltration, subsurface flow and interflow, groundwater flow and base flow, evaporation and evapotranspiration (ET), interception, depression storage, detention storage, rainfall-excess/soil moisture accounting, snowmelt runoff, stream-aquifer interaction, reservoir flow routing, channel flow routing, and water quality (Singh & Frevert 2004).

Watershed models can be classified into several groups such as field scale, physically based models, lumped models, mechanistic models, numerical models, steady state models and dynamic models. They can range from very simple to extremely complex. Some watershed models are intended for the simulation of urban runoff while others are intended for the simulation of agricultural runoff. None of the models can properly simulate both urban and agricultural runoffs at the same time. Each watershed model has its own complexities, strengths and weaknesses. It is important to note that watershed models are often unique to the specific project for which they were developed. The distinctiveness of individual watershed models almost ensured that they are not interchangeable. Since the use of watershed models is probably the best approach to evaluate and establish watershed management plans, the selection of the appropriate watershed model by various stakeholders (such as the modeler and decision maker) becomes critical. Unfortunately most of the models are not well documented and some models are no longer available (Borah *et al.* 2009). Therefore the selection process for a suitable watershed model becomes difficult in the absence of guidance. At this point, the need for a watershed model selection program is apparent (Bai *et al.* 2009).

In this paper, we present our selection program for available watershed models (also referred to as SPAWM). Given the user selected sub-attributes (such as urban land use

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versus agricultural land use), SPAWM selects the most appropriate watershed models from a library of thirty-three commonly used watershed models.

WATERSHED MODELS AND THEIR ATTRIBUTES

Leslie *et al*. (2005) suggested that five factors be taken into account in reviewing a watershed model. The factors are shown in Table 1.

Leveraging on the five factors shown in Table 1, we extracted eight attributes that would provide more vital descriptions and hence represent the watershed models more accurately: land usage, lumped/distributed, event/continuous, time steps, over sediment transport, subsurface, water quality, and best management practices (BMP).

The land usage attribute can be further classified into sub-attributes such as urban, rural, agriculture, forest, river, lake, and reservoir/impoundment. The temporal scale attribute can also be classified into events and continuous (which can be further classified into time steps of seconds, minutes, hours, days, months, and years). Each watershed model can consist of a one-dimensional grid-channel network and overland elements, two-dimensional square overland grids or three-dimensional finite-difference meshes, etc. Depending on the watershed model, rainfall excess overland can be estimated using a variety of methods. Generally, runoff curve number and water balance methods (surface detention, interception and ET loss, and infiltration) are used. Some watershed models use a WDM file, USLE and MUSLE. They are able to obtain soil profiles and estimate the effective rooting depths for water, precipitation distribution and generic balance.

Table 1 | The five separate factors for watershed model evaluations

Factors	Attributes	
Type	Land-based	Simulate only land-based process
	Comprehensive	Including land and rivers, pipes (conveyance systems)
Complexity	Export coefficient	Loading based on limited factors such as land use, etc.
	Loading functions	Empirically load based on generalized meteorological factors such as temperature, precipitation, etc.
	Physically based	Physically based representations of runoff, pollutant accumulate and wash off, and sediment detachment and transport
Time steps	Single-event	Limited to simulation of individual events
	Continuous	Second, minute, hour, day, month, year
Hydrology	Includes surface runoff only	
	Includes surface and groundwater inputs	
Water quality	Based on the pollutants or parameters simulated by the model complexity	

Runoff can be simulated using a variety of methods such as the runoff curve number method, coefficient method, flow peak, SCS (TR-55 method), Manning's equation, continuity equations, explicit finite-difference, explicit or implicit numerical scheme, flow routing equation, unidirectional flow, dynamic wave routing, kinematic wave, steady-state routing, diffusive wave equation, overland flow routing, unit hydrograph, GIUH method, empirical equations, time delay histogram, grid-based runoff, approximate method, etc.

Among these methods, the runoff curve number was first used by AGNPS, AnnAGNPS, GISPLM, GLEAMS, GWLF, Mercury Loading Model and STORM. Subsequently SCS (TR-55) was used by AGNPS, AnnAGNPS, EPIC, P8-UCM, SWAT and SWMM. Flow peak was used by AGNPS, AnnAGNPS, EPIC, SWAT and SWMM. Manning's equation was used by ANSWERS, HSPF, WAMVIEW and WARM. Overland flow routing used by CASC2D, GLEAMS, GSSHA and LSPC.

There are several methods that are suitable for simulating overland sediments such as USLE, RUSLE, MUSLE, HUSLE, steady-state continuity, Bagnold stream power equation, Manning's equation, Horton's equation, runoff curve number, SCS TR-55, Yalin's equation, explicit numerical solution, sediment module equations (accumulation/attachment, detachment, transport, and scour of soil matrix), Kilinc–Richardson equation, conservation of mass, water balance, sediment transport capacity, the order kinetics model, empirical equation, advection equation advection-dispersion equation, etc. USLE was used most often for predicting overland sediment and sediment transport capacity, and MUSLE was used for several watershed models. The remaining methods have only been used in one or two watershed models.

In addition, watershed models have various BMPs based on their field scales. The types of BMPs vary and are listed as follows: agricultural practices, forest, wetlands, ponds, grass water ways, tile drainage, vegetative field strips, vegetated swales, riparian buffers, irrigation, filter strips, bioretention systems, infiltration practices, land use planning, sediment and pollutant load reductions, nutrient and pesticide management, subsurface drainage system,

Table 2 | Summary of watershed models

MODEL/Developer	Model usage	Temporal scale/lumped or distributed	Type of model	Reference
AGNPS/USDA-ARS	Rural, Agricultural	Event/distributed	Grid-based, stream routing included	Borah *et al.* (2002)
AnnAGNPS/USDA-ARS, National Sediment Laboratory	Rural, Agricultural	Daily/distributed	Stream routing included	Shamshad *et al.* (2008)
ANSWERS/USEPA	Agricultural	Storm event; variable constant step depending numerical stability/ distributed	Grid-based	Beasley & Huggins (1980)
BASINS/USEPA	Urban, Rural, Agriculture, Forest, River, Lake, Reservoir	BASINS consists of four models having different temporal scales[a]/lumped	Dynamic, stream routing included	EPA (2000)
CASC2D/Prof. Pierre Y. Julien at Colorado State University -> USEPA	Rural, Agriculture, Forest, River, Lake, Reservoir/ impoundment	Long-term & storm event; variable steps depending numerical stability/ distributed	Two-dimensional overland flow routing algorithm	Julien (1998)
DIAS/IDLAMS/Argonne National Laboratory	Rural, Agriculture, Forest	Annual step depends on models integrated in the system/distributed	Dynamic	Leslie *et al.* (2005)
DRAINMOD/North Carolina State University	Rural Agriculture Forest Reservoir/ Impoundment	Sub-daily step: hourly and daily/lumped	One-dimensional water balance	Sinai & Jain (2006)
DWSM/Illinois State Water Survey	Rural, Agriculture, Forest, River (Reservoir/ impoundment)	Several days of storm events divided into constant time intervals ranging from few minutes to few hours/ distributed	Dynamic, stream routing included	Borah *et al.* (2001A)
EPIC/Texas A&M University–Texas Agricultural Experiment Station	Rural, Agriculture, Forest	Daily time step, long-term simulations (1–4,000 years)/lumped	-	Williams *et al.* (1983)
DWSM/Illinois State Water Survey	Rural, Agriculture, Forest, River (Reservoir/ impoundment)	Several days of storm events divided into constant time intervals ranging from few minutes to few hours/ distributed	Dynamic, stream routing included	Borah *et al.* (2001A)
EPIC /Texas A&M University–Texas Agricultural Experiment Station	Rural, Agriculture, Forest	Daily time step, long-term simulations (1–4,000 years)/lumped	-	Williams *et al.* (1983)
GISPLM/College of Charleston, Stone Environmental, and Dr William Walker	Rural, Forest Agriculture, (Urban, Lake, Reservoir/ impoundment)	Daily time step	Dynamic, stream routing included	William (1997)
GLEAMS/U.S EPA	Agriculture	Daily/lumped	Continuous simulation	Leonard *et al.* (1987)

(*continued*)

Table 2 | continued

MODEL/Developer	Model usage	Temporal scale/lumped or distributed	Type of model	Reference
GSSHA/U.S. ACE	Rural, Agriculture, Forest, River, Lake, (Urban, Reservoir/ impoundment)	Sub-daily step Variable time step (seconds to minutes)/ distributed	Dynamic, grid-based, stream routing included	Ogden *et al.* (2008)
GWLF/U.S. EPA	Urban, Rural, Agriculture, Forest, (River)	Input: daily Output: monthly/ distributed	Stream routing included	Haith *et al.* (1992)
HSPF/U.S. EPA	Urban, Rural, Agriculture, Forest, River, Lake, Reservoir/ impoundment	User-defined time step, typically hourly/semi-distributed	Dynamic, stream routing included	Bicknell *et al.* (2001)
HEC-HMS/HEC US Army Corps of Engineers	Urban, Rural, Agriculture, Forest, River, Reservoir/ impoundment	Sub-daily step User-defined/lumped	Stream routing included	Scharffenberg & Fleming (2009)
KINEROS2/USDA-ARS	Rural, Agriculture, Forest, (Urban, River, Reservoir/ impoundment)	Sub-daily step Variable time step (normally in minutes)/ distributed	Stream routing included	Woolhiser *et al.* (1990)
LSPC/EPA and Tetra Tech, Inc.	Urban, Rural, Agriculture, Forest, River, Lake, Reservoir/ impoundment	Sub-daily step User-defined time step, typically hourly/lumped	Dynamic, stream routing included	Tetra Tech, LSPC Users' Manual
Mercury Loading Model/U.S. EPA	Rural, Agriculture, Forest, (Urban River, Lake, Reservoir/ impoundment)	Annual and long-term average/distributed	Spatial and temporal dynamic	Dai *et al.* (2005)
MIKE SHE/DHI Software (MIKE SHE 2003)	Urban, Rural, Agriculture, Forest, River, Reservoir/ impoundment	Sub-daily step User-defined, variable time step/distributed	Stream routing included	DHI (2007)
MUSIC/Monash University, Cooperative Research Center for Catchment Hydrology	Urban	Sub-daily step 6 minutes to 24 hours/ distributed	-	MUSIC brochure version 4
P8-UCM/U.S. EPA	Urban, Reservoir/ impoundment, (Rural, Agriculture, Forest, River)	Hourly/lumped	Continuous water & mass balance	Tetra Tech, Inc. (2007)
PCSWMM/U.S. EPA	Urban, Rural, River, Reservoir/ impoundment, (Agriculture, Forest, Lake)	User-defined time step, typically hourly/lumped	Dynamic	NHC (2010)
PGC-BMP/Prince George's County, MD	Urban, Rural, Agriculture, Forest, (Reservoir/ impoundment)	Hourly input and output time series/distributed	-	Chen *et al.* (2010)
SHETRAN/Water Resource Systems Research Laboratory, School of Civil Engineering and Geosciences, University of Newcastle upon Tyne	Urban, Rural, Agriculture, Forest, River	Daily, Sub-daily step User-defined, variable time step/distributed	Dynamic, stream routing included	Ewen *et al.* (2000)

(*continued*)

Table 2 | continued

MODEL/Developer	Model usage	Temporal scale/lumped or distributed	Type of model	Reference
SLAMM/U.S EPA	Urban, Rural, (Forest)	Sub-daily step Variable time step (hourly or sub-hourly)/ distributed	-	Pitt & Voorhees (2002)
SPARROW/USGS,NAWQA Hydrologic Systems Team	Urban, Rural, Agriculture, Forest, River	Annual step User-defined modelling period/stochastic and probabilistic	Spatially calibrated regression model	Schwarz *et al.* (2006)
HEC-HMS/HEC US Army Corps of Engineers	Urban, Rural, Agriculture, Forest, River, Reservoir/ impoundment	Sub-daily step User-defined/lumped	Stream routing included	Scharffenberg & Fleming (2009)
STORM/USACE (mainframe version), Dodson & Associates, Inc. (PC version)	Urban	Sub-daily step Hourly/lumped	Quasi-dynamic	U.S. ACE (1997)
SWAT/USDA Agricultural Research Service	Urban, Rural, Agriculture, Forest, (River, Lake Reservoir/ impoundment)	Long term/a daily time step/an hourly time step/distributed	Quasi-dynamic, stream routing included	Neitsch *et al.* (2005)
STORM/USACE (mainframe version), Dodson & Associates, Inc. (PC version)	Urban	Sub-daily step Hourly/lumped	Quasi-dynamic	U.S. ACE (1997)
SWAT/USDA Agricultural Research Service	Urban, Rural, Agriculture, Forest, (River, Lake Reservoir/ impoundment)	Long-term/a daily time step/an hourly time step/distributed	Quasi-dynamic, stream routing included	Neitsch *et al.* (2005)
SWAT/USDA Agricultural Research Service	Urban, Rural, Agriculture, Forest, (River, Lake Reservoir/ impoundment)	Long-term/a daily time step/an hourly time step/distributed	Quasi-dynamic, stream routing included	Neitsch *et al.* (2005)
SWMM/U.S. EPA	Urban, Rural, Reservoir/ impoundment, (Agriculture, Forest, River, Lake)	User-defined time step, typically minutes to hourly/Semi-distributed	Dynamic, stream routing included	Rossman (2010)
TOPMODEL/Lancaster University (UK), Institute of Environmental and Natural Sciences	Rural, Agriculture, Forest, (River)	Variable, from 1 to 24 hours/Semi-distributed	Dynamic	Bevel (1997)
WAMview/Soil and Water Engineering Technology (SWET) and U.S. EPA	Urban, Rural, Agriculture, Forest, River, Lake, Reservoir/ impoundment	User-defined time step: typically, a day/-	Dynamic, grid-based, stream routing included	Bottcher & Hiscock (2001)
WARMF/Systech Engineering, Inc.	Urban, Rural, Agriculture, Forest, Lake, Reservoir/ impoundment, (River)	Daily step/lumped	Dynamic, stream routing included	Keller (2007)
WEPP/USDA ARS	Rural, Agriculture, Forest	Daily, monthly or annual/ distributed	Continuous simulation	Abaci & Papanicolaou (2008)

[a]**HSPF** (user-defined time step, typically hourly, continuous simulation from days to years), **SWAT** (daily time step, continuous simulation for months to years), **PLOAD** (export coefficient model, annual), and **KINEROS** (single-storm event, part of AGWA, variable time step typically in minutes).

detention basins, septic systems, combined sewer overflows (CSOs), sanitary sewer overflows (SSOs), low impact developments (LIDs), etc.

From the five factors proposed by Leslie *et al.* (2005), we have extracted eight attributes (see Figure 1):

- **Land use (1)** can be segregated into urban, rural, agriculture, forest, river, and lake/reservoir.
- **Complexity** is changed to **lumped and distributed (2)**.
- **Temporal scale** is divided into **single-event model and continuous simulation model (3)**. The period of steps include seconds, minutes, hours, days, months, and years (**Time steps (4)**).
- **Hydrology** is divided into **overland sediment transport (5)** and **subsurface flow (6)**. For overland sediment transport, there are many equations that have been put into practice such as USLE, RUSLE, MUSLE, Manning's equations, etc. In the case of subsurface flow, some watershed models were applicable while others were not.
- **Water quality (7)** will be used based upon available water quality parameters.
- **BMPs (8)** are carried out based upon land type/use characteristics like agricultural, forest, wetlands, etc.

WATERSHED MODELS LIBRARY FOR SPAWM

As already mentioned, each of the watershed models used in the library is classified by its attributes such as land usage (urban, rural, agricultural, etc.), temporal scale (event or continuous), type of model (grid-based, stream routing included, dynamic), watershed representation, rainfall on overland, subsurface flow, overland sediment, BMP evaluation etc. The complete list of watershed models and their attributes used in SPAWM is shown in Table 2 and in Supplementary Information Table S1 (available online at http://www.iwaponline.com/wst/070/184.pdf).

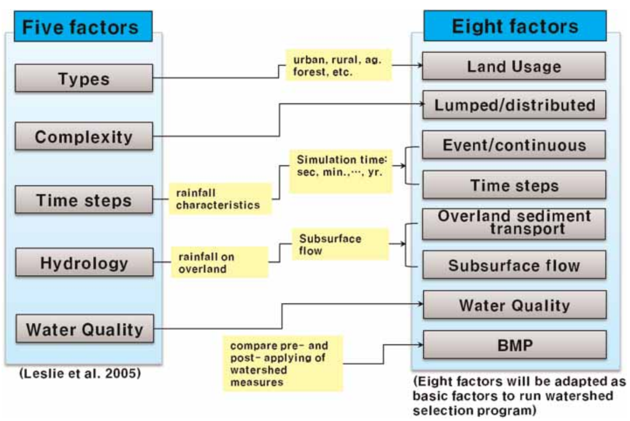

Figure 1 | Extraction of eight attributes to be used in SPAWM from the five factors by Leslie *et al*. (2005).

ARCHITECTURE AND OPERATION OF SPAWM

SPAWM was developed using Excel Visual Basic. Its architecture is shown in Figure 2. It has a very simple architecture which performs a match-and-show function with the watershed models stored in the library.

Watershed model capabilities

The watershed model capabilities are rearranged to select the pertinent watershed model according to watershed characteristics and user's needs based on Table 2. Table 3 shows the capabilities of watershed models with regard

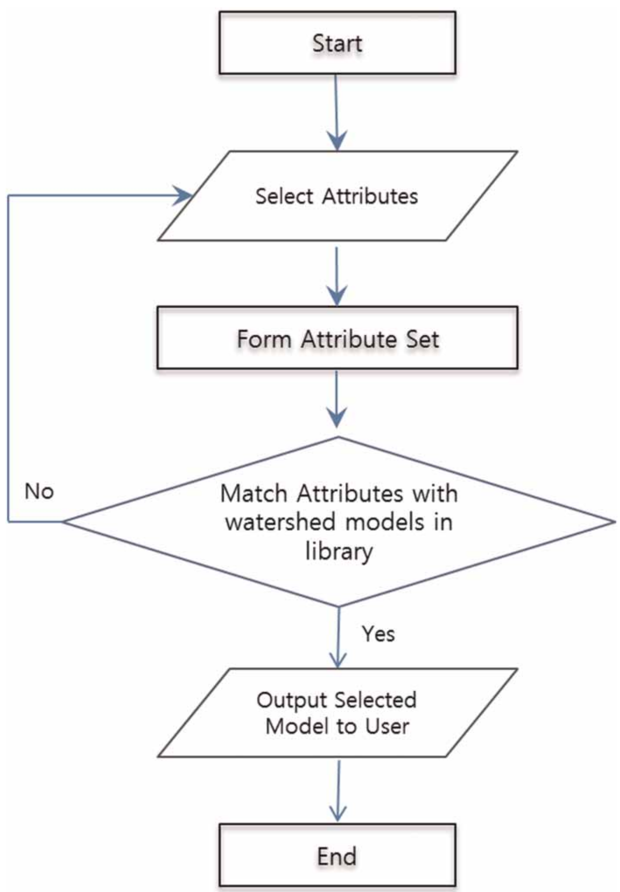

Figure 2 | Architecture of SPAWM.

Table 3 | Watershed model capabilities with regard to land type, distributed/lumped, event/continuous and time steps

Component		AGNPS	AnnAGNPS	ANSWERS	BASINS	CASC2D	DIAS/IDLAMS	DRAINMOD	DWSM	EPIC	GISPLM	GLEAMS	GSSHA	GWLF	HSPF	HEC-HMS	KINEROS2	LSPC	Mercury Loading Model	MIKE SHE	MUSIC	P8-UCM	PCSWMM	PGC-BMP	SHETRAN	SLAMM	SPARROW	STORM	SWAT	SWMM	TOPMODEL	WAMVIEW	WARMF	WEPP
Land type	Urban				0									0	0	0		0		0	0	0	0	0	0	0	0	0	0	0		0	0	
	Rural	0	0		0	0	0	0	0	0	0		0	0	0	0	0	0	0	0			0	0	0	0	0		0	0	0	0	0	0
	Agriculture	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0	0		0		0		0	0	0	0
	Forest				0	0	0	0	0	0	0		0	0	0	0		0	0	0				0	0		0		0		0	0	0	0
	River				0				0				0		0	0		0		0			0		0		0					0		
	Lake reservoir				0	0		0					0		0	0		0		0		0	0							0		0	0	
Distributed/lumped	Distributed	0	0	0		0	0		0				0	0	0		0		0	0	0			0	0	0			0	0	0			0
	Lumped				0			0		0		0				0		0				0	0					0					0	
Event/continuous	Event	0		0		0			0																									
	Continuous		0		0		0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Time steps	Second												0																					
	Minutes				0												0				0									0				
	Hourly				0			0							0			0				0	0	0		0		0	0		0			
	Daily		0		0					0	0	0		0		0				0					0							0	0	0
	Monthly													0																				
	Annually				0														0						0									

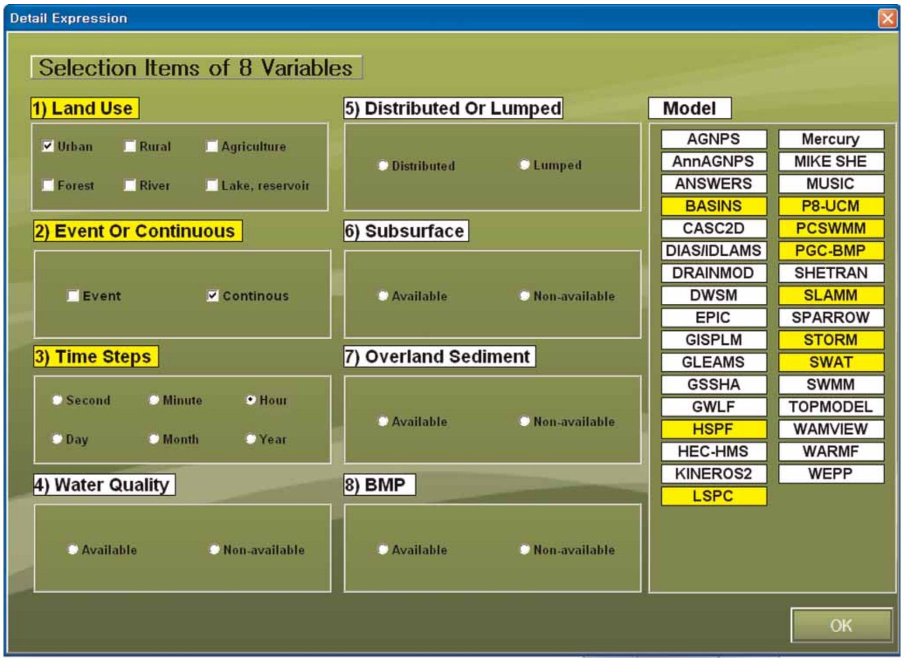

Figure 3 | Graphical user interface (GUI) for selection of user input attributes and sub-attributes.

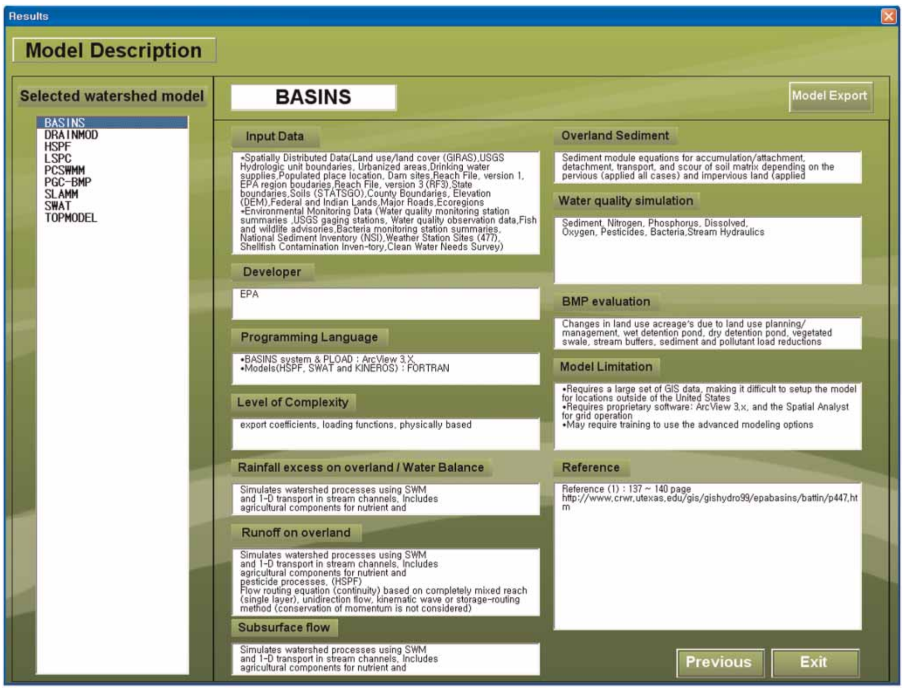

Figure 4 | Selected watershed model as shown in the result window.

to land type, distributed/lump, event/continuous and time steps. In addition, subsurface simulation, overland sedimentation, BMP and water quality simulation parameters are shown in Supplementary Information Tables S2–S5 (available online at http://www.iwaponline.com/wst/070/184.pdf).

SELECTION PROGRAM FOR AVAILABLE WATERSHED MODELS

SPAWM is the selection program to assist model users selecting pertinent watershed models which can predict water quantity and quality. This program is composed of two parts: (1) selection and (2) description part. In the selection part, eight factors could be selected based on watershed characteristics and user's needs. In addition, the only watershed models which are being intersection of sets are selected through SPAWM (Figure 3). In the description part, selected appropriate watershed models are presented and users can prepare input data and compare characteristics before building and running the selected watershed model (Figure 4). Using the capabilities of watershed model as can be seen in Table 3, the SPAWM is developed. Figure 3 shows the graphical user interface (GUI) of SPAWM. The eight attributes (1) land use, (2) event or continuous, (3) time steps, (4) water quality, (5) distributed or lumped, (6) subsurface, (7) overland sediment, and (8) BMP and their sub-attributes are shown with radio buttons for selection.

Attributes can be chosen separately or simultaneously. When an attribute is selected, the selected watershed models change to a yellow color in the model window. The 'land use' sub-attributes include urban, rural, agriculture, forests, rivers, and lakes or reservoirs. The attribute 'event' or 'continuous' can also be selected either individually or simultaneously. The same applies for all the other attributes.

After the selection is completed, the selected watershed model will be displayed in the results window. The displayed information includes input data, the developer, programming language, level of complexity, rainfall excess on overland/water balance, runoff on overland, subsurface flow, overland sediment, water quality simulation, BMP evaluation, model limitation, and references (linked to an external Excel file) as shown in Figure 4. The displayed information can also be exported as a text file. An example of the model selection based on SPAWM is shown in the Supplementary Information (available online at http://www.iwaponline.com/wst/070/184.pdf).

SUMMARY AND CONCLUSION

We developed the SPAWM to assist decision making in the selection process of appropriate watershed models. By evaluating thirty-three well known watershed models, we are able to form a watershed library to cover a wide range of possible scenarios. The watershed models evaluated include AGNPS, AnnAGNPS, ANSWERS, BASINS, CASC2D, IAS/IDLMAS, DRAINMOD, DWSM, GISPLM, GLEAMS, GSSHA, GWLF, HSPF, HEC-HMS, KINEROS2, LSPC, Mercury Loading Model, MIKE SHE, MUSIC, P8-UCM, PGC-BMP, SHETRAN, SLAMM, SPARROW, STORM, SWAT, SWMM, TOPMODEL, WAMView, WARMF, and WEPP. By classifying the watershed models in accordance to their attributes such as rainfall excess, overland sediment and BMP, the user can input the desired attributes and sub-attributes into SPAWM and the most appropriate watershed model will be selected from the library. This will enable the user to browse rapidly through the possible watershed models that may suit the particular watershed management requirements.

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