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Catchment Modelling Tools and Pathways Review

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PATHWAYS PROJECT

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UCD Centre for Water Resources Research

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1. INTRODUCTION TO CATCHMENT MANAGEMENT TOOLS

A catchment management tool (CMT) is a computer programme that helps a decision maker design or select appropriate options for managing water at catchment scale. Some tools may focus on water resources management, mainly relating to water quantities and distribution and others go further and include a focus on the management of water quality. Because of the importance of spatial variation in catchment information and behaviour, most CMTs are associated with a Geographical Information System (GIS) and because of the complexity of the processes involved in catchment behaviour most CMTs require the use of a catchment model. A survey of the international literature shows that the term "catchment management tool" covers a wide range of computer programmes with a wide range of capabilities. Most cover both water quality and quantity aspects of the catchments behaviour. However, in most the water quality aspects tend to be limited to a small number of contaminants.

This review is to inform decisions relating to a catchment management tool for the EPA funded Pathways research project and we have concentrated on (i) CMTs that address water quality management issues and (ii) CMTs for use by scientifically or technically trained people responsible for the design, implementation or management of measures for addressing the quality of natural waters. The review does not include formal decision support systems for use by a more general target group. Deliverable number 4 of the EPA funded WINCOMS project reviews a range of decision support systems addressing water quality issues and Deliverable number 6 examines in more detail a selection of those with most potential for use by all stakeholders. Here, in keeping with the major thrust of the Pathways project we concentrate on catchment management tools with a special focus on their ability to represent the various pathways taken by water as it moves through the hydrological cycle and the consequences for water quality.

The report has two main parts. In Section 2 we describe briefly the various components of a catchment management tool and then we focus on complete systems by describing the 15 systems which our survey identified as having some relevance for the Pathways project. This allows us draw some general conclusions about the current status of CMTs. Then in Section 3 we examine in more detail how the individual pathways are currently treated in catchment models. This is both to document existing practise in modelling individual pathways and also to identify the range of existing pathway modelling techniques available for transposition into a Pathways CMT.

2. CATCHMENT MODELLING AND DATA MANAGEMENT SYSTEMS

2.1. Introduction

A CMT usually contain a spatial and time series data management system, a catchment model and a specialised Graphical User Interface. The choice of catchment model must be determined by the range of issues and contaminants covered by the CMT and by the spatial and temporal scales at which detailed information is required by the decision maker. An inappropriate choice of catchment model and modelling approach can invalidate the output from the CMT. In this report we review the state of the art in relation to CMT's focussed on managing water quality and we also review the hydrological models used in all aspects of catchment management, including water resources management and flood forecasting.

The choice of catchment modelling approach will determine the data requirements. Data may be spatial varying (maps) or temporally varying (time-series) and both must be managed within the framework of the CMT. Other forms of data include parameter sets, constraint sets, and point information. All such data must be carefully managed and a GIS packaged linked to a formal database system (DBS) is generally used. The use of existing GIS and DBS systems may have the disadvantage of constraining flexibility in the design of the CMT, but has the distinct advantage of proven technology with easier communication in standard data formats with outside data sources.

2.2. GIS support and links

Geographic Information Systems (GIS) are an indispensable tool in hydrological modelling and nutrient management in agricultural catchments because they make use of the capabilities of modern, high-speed computers to store, manipulate, and display large amounts of environmental data in a spatial format. In most CMTs hydrological modelling is linked with GIS capabilities (Coroza et al., 1997).

2.2.1 Types of linkage

There are four ways to link GIS with catchment models (Nyerges (1992) cited in (Coroza et al., 1997)):

(i) Isolated coupling, in which the hydrological modeling and GIS systems reside on different hardware platforms, and data transfer is offline. This method is rarely used although isolated systems are the easiest to set up and require the least level of programming knowledge and experience. However, they are generally the least useful, because of the need to transfer data offline. An example of such a model is WATFLOOD/SPL9 (Crammer et al., 2001, Leon et al., 2002, Stadnyk et al 2005)

(ii) Loose coupling, with online data transfer between software components through data files using special linking programs, or through a common data store. Loose coupling usees the GIS as an aid in developing the input data files for the model. These preliminary input files can be modified in order to produce a complete input files in the format required by the model. Using this approach both the model and the GIS system are used without any modification (Nasr, 2004). An example of such a type is TOPMODEL. (Beven et al., 1995).

(iii)Tight-coupling, with the two systems communicating interactively with each other. A special interfacing program communicates between the GIS and the hydrological model and serves as a control program issuing commands both to the GIS and the model. Output from the GIS is converted into the proper input format for the model and then read into the model. Output from the model may likewise be converted to a GIS format and then displayed by the GIS. All of these operations are carried on under the control of the interface program (Nasr, 2004). Examples are ANSWERS and AGNPS.

(iv) Full integration, which does not require a linking program, but the GIS and models share a common data store and user-interface which come up as one software product. Typically, with this method the hydrological model is coded within the built-in programming or macro language of the GIS and has direct access to the facilities of the GIS. In a fully-integrated system, the model is embedded as a component in the host GIS application (Pullar and Springer, 2000) and therefore modelling is performed entirely with the GIS. Examples of catchment models fully-integrated within a GIS are SWAT, AVGWLF, and HSPF (MAPWINDOWS).

The level of system coupling between a model and a GIS has an impact on the reliability and ease of use of the system. Well integrated systems work as a coherent whole and still afford flexibility for modifying the modelling scenario (Pullar and Springer, 2000).

2.2.2 Most commonly used GIS platforms

A range of reliable GIS tools are widely available nowadays. Some are free e.g. GRASS, PCRaster, MapGuide, Mapwindow, and OpenMap while others are propriety/commercial packages and must be purchased or licensed, e.g. ArcGIS (ArcView and ArcInfo) and MapInfo.

2.2.3 Portability

Portability has five aspects

(i) Hardware: This is less an issue nowadays as desktop PCs and laptops possess sufficient resources and computing power to run complex problems. Multi-core processors open up the possibility of having the hydrological model and GIS run in parallel on separate CPU cores within the same PC, sharing common memory space.

(ii) Operating system: There are two widely used operating system groups, Windows and Unix (including Apple's operating system and Linux). Most general GIS tools can operate on windows-based PCs but there are still some that operate on a UNIX system, Table 1.

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Table 1 GIS platform availability

	Arc/Info	GRASS	MapInfo	MapViewer	WinGIS	MapWindow
Windows	Yes	No	Yes	Yes	Yes	Yes
Unix	Yes	Yes	No	No	No	No

(iii) File formats: Each GIS system has its own native file formats for spatial and other data. However, many systems have tools for importing data from other GIS systems so this is less of an issue now.

(iv) Programming language and support tools: Each modern GIS can be programmed to do complex tasks automatically. This is usually done with a unique macro language which must be leaned or with a built-in high-level language. Visual Basic is a common choice of many systems, but the programs for each are not necessarily interchangeable as the support subroutines (or tools) they call will be different in each different system.

(v) Degree of integration of GIS and hydrological model. Hydrological (catchment) modeling tools are frequently used with GIS systems. The highest degree of integration is when the hydrological model is written in the programming language of the GIS package. The alternative is to have the hydrological model as an external, stand-alone, package. In this case the GIS is effectively a pre- and post- processor for the hydrological model, but the latter can be compiled for used with any GIS system or platform.

2.3. System outputs

The outputs produced by existing catchment management tools include

(i) Time-series of catchment outflows. Typically daily or hourly but many models can have shorter or longer time-intervals. The appropriate intervals depend on catchment size and response time and on the purpose of the analysis. Annual averages or totals can be calculated from the daily or hourly values.

(ii) Time-series of pollutant concentrations. Typically calculated for the same time intervals as the discharge time-series but can be different.

(iii) Summary of annual water balance. A water balance calculation on a monthly or annual basis or over the entire data period is a very useful characterisation of the catchment and is a good check on data consistency

(iv) Summary of annual pollutant export. The total annual export of a given pollutant from a catchment or subcatchment is estimated and reported. For systems with dynamic models, the estimation is done from the concentration and discharge data at the modelling time-scale and aggregated to the annual scale. For systems with empirical export coefficient equations, the estimate is made at the annual time-scale.

(v) Pollutant critical source area maps. As export data is estimate at subcatchment level, the average export per unit area for each subcatchment can be calculated and a map can be produced colour coded to identify the subcatchments of high and low exports. The spatial resolution of this mapping depends on the number and size of the subcatchments and this is generally under the control of the user.

(vi) Actual evapotranspiration from each sub-catchment can be output as time-series or mapped.

(vii) Some CMTs generate their own meteorological inputs for use in simulating projected scenarios (e.g. climate change effects) or for Monte carlo simulation (e.g. for sensitivity analyses). Where this is done, the system can output the generated climate variables,

2.4. Most commonly encountered Management Systems

Here we identify and review the most commonly encountered catchment management systems. Our literature search yielded 15 systems for this review. Each review below starts with a short description of the purpose and origin of the system, then lists the input data required and outputs produced. The hardware and software required to run the system are specified.

2.4.1 BASINS

Description:

Better Assessment Science Integrating point and Nonpoint Sources (BASINS) is a system developed by the US EPA to meet the needs of local, state, and federal US agencies. It integrates a geographic information system (GIS), national watershed and meteorological data, and state-of-the-art environmental assessment and modelling tools into one package. Originally released in September 1996, BASINS addresses three objectives: (1) to facilitate examination of environmental information, (2) to provide an integrated watershed and modelling framework, and (3) to support analysis of point and nonpoint source management alternatives.

BASINS supports the development of total maximum daily loads (TMDLs), which are the main regulatory quantities used in the USA. Calculating these require a watershed-based approach that integrates both point and nonpoint sources. BASINS can simulate a variety of pollutants at multiple scales, using a range of modeling tools from the simple to the sophisticated.

BASINS can be used to suggest the cause(s) of contaminated surface waters from point and nonpoint-source pollution, wet weather combined sewer overflows (CSO), storm water management issues, and drinking water source protection. BASINS is also used in urban/rural landuse evaluations, animal feeding operations, and habitat management studies. It is also used in an educational setting, providing schools and educational institutions with a quick, free resource of GIS software and surface water data for the United States.

The heart of BASINS is its large suite of interrelated components for watershed and water quality analysis. These components are grouped into several categories:

1. Nationally derived environmental and GIS databases for the US

2. Assessment tools (TARGET, ASSESS, and DATA MINING) for evaluating water quality and point source loadings at a large or small scales;

3. Utilities including local data import and management of local water quality observation data

4. Two watershed delineation tools

5. Utilities for classifying, based on elevation (DEM), landuse, soils, and water quality data

6. BASINS has an in-stream water quality model (QUAL2E)

7. BASINS has a simplified GIS based nonpoint source annual loading model (PLOAD)

8. Two catchment models that include pollution loading and transport (HSPF and SWAT)

9. A postprocessor (GenScn) for model data and scenario generator to visualize, analyze, and compare results from HSPF and SWAT; and

10. Many mapping, graphing, and reporting formats to assist in using BASINS outputs in reports.

BASINS' databases and assessment tools are directly integrated within an ArcView GIS environment. The simulation models run in a Windows environment, using data input files generated in ArcView (Figure 1).

Data Requirements and System Outputs:

Inputs: DEM (shape files and grid datasets), landuse/ landcover data, soil type, weather data (location of weather stations and weather data), environmental background data, environmental monitoring data (water quality monitoring stations and observation data), and point sources/loadings data.

Outputs: Maps, graphs, and tables summarizing point and nonpoint pollution in catchment (flow, sediment load, nitrogen, phosphorus, bacteria, and pesticides.

HSPF: HSPF produces a time history of the runoff flow rate, sediment load, and nutrient and pesticide concentrations, along with a time history of water quantity and quality at any point in a catchment. Simulation results can be processed through a frequency and duration analysis routine that produces output compatible with conventional toxicological measures (e.g., 96-hour LC50).
SWAT: SWAT produces daily runoff flow rate, pollutant values at both catchment and sub-catchment levels.
QUAL2E: QUAL2E produces a table contains flows, velocities, travel time, depths, and cross-sectional areas along each reach and water quality constituent concentrations along a reach.

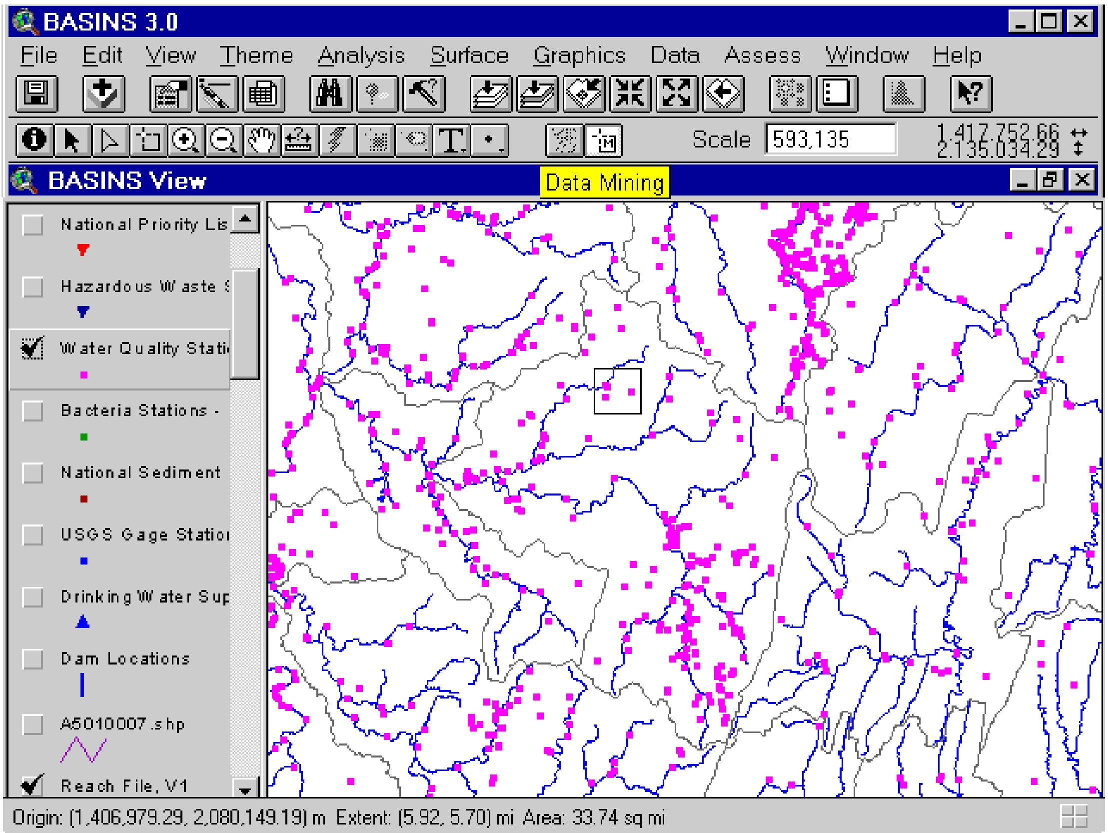

Figure 1 BASINS screen shot

<u>*Platform, Operating system, Hardware and software requirements:*</u>

Platform: PC
Operating System: Windows
BASINS can be installed and operated on a standalone, internet connected Windows compatible 32 bit personal computers equipped with the software, random access memory (RAM), virtual memory, and hard disk.
Software requirements: Microsoft Internet Explorer 5.01 or later.

GIS engine: ArcView 3.1, 3.2, or 3.3 (required); with the Spatial Analyst extension (preferred). BASINS 4.0 contains the installation program for an open source GIS program (MapWindow).

Homepage: http://www.epa.gov/OST/BASINS/
Source: Standards and Health Protection Division (4305T)
Office of Science and Technology, Office of Water, U.S. Environmental Protection Agency, 1200 Pennsylvania Avenue, NW, Washington, DC 20460

Cost & License: Free, no license required.
Availability: can be downloaded from the BASNS webpage.
Training: Lectures, data sets and exercises are available and workshops for BASINS can be arranged. See http://www.epa.gov/waterscience/basins/training.htm.

2.4.2 MIKEBASIN

Description:

MIKE BASIN is a general multi-purpose GIS-based modelling system for integrated river basin management and planning. It generates a mathematical representation of the river using a network configuration of the main rivers and their tributaries, the hydrology of the basin in space and time, existing as well as potential major infrastructure schemes and their various demands for water. It simulates natural inflows, multiple multi-purpose reservoir operation and water right allocation in river basins based on a prioritized water accounting procedure. It allows for conjunctive use of surface water and ground water. An extension to the basic module includes water quality simulation based on point and non-point sources.

In order to support the identification and assessment of policies and cost efficient strategies for meeting the legal and institutional accession requirements, a GIS-based Decision Support System (DSS) has been developed which

- Provides a national overview of pollution sources, river systems, water quality conditions, existing water supply and waste water treatment facilities, technical options for improvements and associated costs;
- Assesses water quality conditions as a consequence of applying different regulatory strategies and estimate the corresponding investments and operation & maintenance costs;
- Identifies least cost strategies for meeting specified effluent and/or water quality standards.
- Estimates economic and financial implications of accession, including effects on investment programmes, recurrent costs and financing options

Model Structure or Mathematical Basis:

1. MIKE BASIN is a deterministic, conceptual, distributed and continuous time modelling system

2. The model was developed for river basins with mixed land use accounting for water allocation simulation for agricultural and urban water supply. It performs a simple water accounting procedure for each node and between nodes taking into account possible routing mechanisms. It is applicable for river basins at any size ranging from small systems to large scale international river basins. It can incorporate several river basins so can simulate inter-basins transfer schemes.

3. The principal processes it represents are: rainfall- runoff, river flow processes (with or without routing) ground water (linear reservoir approach, complete water balances for reservoirs including rainfall/evaporation on lake surface), and water quality of runoff and river flow.

4. Point sources(e.g. water supplies with associated treatment plants) as well as non-point pollution can be modeled. Non-point pollution e.g. total nitrogen and phosphorus loads, can be specified by the user and can include their seasonal

variation. The Load Calculator is a part of the MIKE BASIN water quality module that allows easy integration of other GIS-based data for automatic calculation of loads. For example, if GIS data on agricultural landuse is available (by administrative district) and sewered population (by potentially different districts), then the Load Calculator will process them to identify the effective loads per catchments, possibly modulated by runoff (which is important for phosphorus modelling).
Water quality in reservoirs and groundwater is modelled as well, assuming perfect mixing.

Data Requirements:

The model requires time series data of catchment run-off (increments of naturalized flow) for each branch of the river/stream network, DEM (shape files and grid datasets), landuse/ landcover data, soil type, weather data (location of weather stations and weather data), environmental background data, environmental monitoring data (water quality monitoring stations and observation data), and point sources/loadings data.

Additional input files define reservoir characteristics and operation rules of each reservoir, meteorological time series, and data pertinent to water rights (water supply or irrigation) such as diversion requirements and other information describing return flows.

Outputs:

MIKE BASIN produces, at user specified time intervals, inflows to all nodes (shown on the GIS map), reservoir water levels/storage, abstractions including specification of shortages. The system also calculates concentrations and loads of ammonia, nitrate, oxygen, total phosphorus, E. coli, BOD, and any other user-defined substance (e.g., salinity). MIKE BASIN also produces monthly tables for each node/user including basic statistics. It can display with colours the conditions throughout the system at any point in time, and animate the conditions for a specified time period. The results can be displayed as maps in ArcGIS, HTML tables, animations, databases. They can be linked to Excel spreadsheets for further analysis or as input to specialist programmes written in Visual Basic or .Net

Platform, Operating system, Hardware and software requirements:

MIKE BASIN runs within ArcView utilizing a fully Windows integrated Graphic User Interface under Windows 95, 98 or Windows NT, XP. It requires a Pentium 90 MHz or more processor with a minimum of 32 MB RAM and 1GB hard disk.

Homepage:

http://www.dhigroup.com/Software/WaterResources/MIKEBASIN.aspx
http://www.crwr.utexas.edu/gis/gishyd98/dhi/mikebas/Mbasmain.htm
http://hydrologicmodels.tamu.edu/MikeBASIN.doc

Source:

DHI agent in Ireland:
Alan G. Hooper, CDM, 5^{th} Floor, O'Connell Bridge House, D'Olier Street, Dublin 2, Co. Dublin.
Tel.: 01 672 2700;
E-mail: hooperag@cdm.com

Cost & License: License required, for cost contact DHI agent

Technical Support and Training:

Software support centre (technical support):
E-mail: software@dhigroup.com
Tel: +45 4516 9333(Open 7.30-16.00 GMT)
Fax: +45 45 16 92 92
Training: http://www.dhigroup.com/Software/Training.aspx

2.4.3 Watershed Modelling System (WMS)

Description:

The Watershed Modeling System (WMS) is a comprehensive, modular, graphical modeling environment for all phases of watershed hydrology and hydraulics. WMS includes powerful tools to automate modeling processes such as automated basin delineation, geometric parameter calculations; GIS overlay computations (CN, rainfall depth, roughness coefficients, etc.), and cross-section extraction from terrain data. It thus provides the inputs required by a range of hydrologic modeling programs such as HEC-1, HEC-HMS, TR-20, TR-55, Rational Method, NFF, MODRAT, OC Rational, HSPF, XPSWMM, and EPA-SWMM. It also provides similar support for a range of hydraulic models including HEC-RAS, XPSWMM, EPA-SWMM, SMPDBK, and CE-QUAL-W2. Two-dimensional distributed hydrologic models (including channel hydraulics and groundwater interaction) can be created with GSSHA, developed by the US Army Corps of Engineers. Essentially, WMS is a pre- and post- processor for all of these models.

The WMS interface is separated into several modules; each containing tools for creating and manipulating model inputs and outputs from different data types. These are:

Map and GIS Modules: provide a suite of tools for defining watershed data in a GIS and then using the information to directly create and manage hydrologic and hydraulic models. Results of watershed and floodplain delineations can also be saved in the map module and converted to GIS data layers for export.

Terrain Data Module: to create, edit, and preprocess all digital terrain data, whether it is a TIN or DEM. In WMS, topographic data can be contoured, displayed in oblique view with mapped images and hidden surfaces removed, and several other display options that can be set to visualize and understand the land surface better.

Drainage Module: Automatic delineation of streams and watershed/sub-basin boundaries based on the land surface represented by the DEM or a TIN.

Hydrologic Modeling Module: Each hydrologic model supported by WMS has a defined graphical interface in this module (HEC-1, HEC-HMS, TR-20, TR-55, NFF, Rational Method, HSPF, MODRAT, OC Rational, XPSWMM, and EPA-SWMM). Through this interface, the model input parameters can be viewed and edited. Watershed models built using the Map or Drainage Modules are linked to a simple schematic (tree) representation in the Hydrologic Modeling Module.

River Modeling Module: This processes digital terrain and map data (TINs and coverages) to build the basic geometry necessary for a 1D hydraulic model, such as HEC-RAS, SMPDBK, XPSWMM, and EPA-SWMM.

Scatter Point Module: used to interpolate data from scattered points to grids or TINs. WMS supports several interpolation schemes including linear, natural neighbor, inverse distance weighted, and Clough-Tocher. Interpolation from 2D scattered data is used primarily for floodplain delineation in WMS.

2D Grid Module: used for surface visualization and for the development of distributed (2D) rainfall/runoff analytical models.

Data Requirements and System Outputs:

Data required by WMS include: Digital elevation models (DEMs or TINs), scanned maps, aerial photos, soil type and land use, discharge hydrographs and precipitation time-series.

WMS is compatible with many spatial data formats e.g. USGS DEMs, USGS NED data ArcGIS Raster (ASCII format), ESRI Shape files, DXF and DWG CAD files
TIFF, JPEG, and MrSID images.

Model Output

Depending on which module is run, the outputs can vary but may include: watershed and sub-basin delineations, flow paths on the entire terrain model, floodplain delineation and mapping, flood extents and flood depth maps, and storm drain networks.
The main outputs of the hydrologic Modeling Module are: times of concentration, rainfall depth mapping, and runoff coefficient calculations, calibrated parameters of detention basins (reservoirs), and calibrated flow parameters of culverts, weirs, and open channels.

Platform, Operating system, Hardware and software requirements:

Windows 2000/XP, 1.5MhZ processor, 512 MB RAM, 1024x768 Display, 300 MB disk space

Homepage: http://www.aquaveo.com/wms

Cost, License, & Availability:
See http://www.aquaveo.com/wms for pricing

Training:

http://www.aquaveo.com/training-courses

2.4.4 SOBEK

Description

SOBEK was developed jointly by Dutch public institutes and private consultants, mainly by Deltares and Delft Hydraulics. SOBEK is a general software package for the integrated simulation of water flows and water quality processes in rivers, estuaries, canals or sewer networks. It is a powerful instrument for flood forecasting, optimisation of drainage systems, control of irrigation systems, sewer overflow design, groundwater level control, simulation of river morphology, salt intrusion and surface water quality.

SOBEK is equipped with a very robust numerical scheme that handles drying and flooding and sub- and super-critical flows efficiently. It has a water quality process database and editor so the user can specify the water quality processes to be simulated. There is a flexible link to various GIS systems. SOBEK also allows for the integration of user-defined modules through the use of specific data exchange formats.

User Interface

SOBEK has a unique interface concept (Figure 2) where the same set of interface tools is used for all SOBEK modules. Examples of these interface tools are the Case Manager, the Case Analysis Tool and the GIS network editor NETTER.

SOBEK will link with

- The OpenGIS environment NETTER. This environment is free of charge. It allows for the import and export of a range of GIS formats. The NETTER layers provide an extremely fast data access while performing map based input data editing and post processing of results.

- A Map Front End approach which allows SOBEK components to be plugged into GIS environments such as ArcGIS.

SOBEK reads all standard GIS formats, and layered maps can be imported and all objects and their ID's can be used directly. SOBEK even allows the generation of a complete network schematisation on basis of a vector layer. It is also possible to define a SOBEK schematisation in a GIS environment and export it to SOBEK.

SOBEK Models

SOBEK can simulate fresh water management scenarios in River, Rural and Urban systems alike, Table 2. Each is done with a different module and data transfer between the modules is fully automatic and modules can be run in sequence or simultaneously to facilitate the physical interaction.

SOBEK-Rural

SOBEK-Rural is a tool for modelling irrigation systems, land drainage systems, natural streams in lowlands and hilly areas. Applications are typically related to optimizing agricultural production, flood control, irrigation, canal automation, reservoir operation, and water quality control. SOBEK-Rural can also answer questions about increased pollution loads in response to growing urbanisation.

The software calculates the flow in simple or complex channel networks, consisting of thousands of reaches, cross sections and structures. For more detail, the rainfall run-off process of urban areas and various types of unpaved areas can be modelled, taking into account land use, the unsaturated zone, groundwater, capillary rise and the interaction with water levels in open channels. For water quality and environmental problems the water quality module can simulate a wide range of scenarios.

SOBEK-River
SOBEK-River is designed for simple and complex river systems and estuaries. It simulates the water flows, the water quality and morphological changes in river systems, estuaries and other types of alluvial channel networks. The networks can be branched or looped. SOBEK-River can account for complex cross-sectional profiles consisting of various sub-sections.
The Windows-based interface makes it user-friendly and easy to use. Direct on-screen display of the river network gives you an overall view of your system.

Table 2 SOBEK modules and applications

Application / Module	Rural	Urban	River
Hydrodynamics			
1DFLOW	√	√	√
Overland flow (2D)	√	√	
Hydrology			
RR (rainfall runoff)	√	√	
Morphology			
1DMOR (+ sediment transport)			√
Water Quality			
1DWAQ	√		√
2DWAQ	√		
Emissions	√		
Real Time Control			
RTC simulation	√	√	

SOBEK-Urban
SOBEK-Urban models urban drainage systems consisting of sewers, open channels, storage tanks, reservoirs, control gates, pumps and weirs. It can be used for the design of new urban areas and the analysis and improvement of existing ones. The model can be used to investigate what measures will prevent drainage congestion, street flooding and water pollution from sewer overflows. The return period of street flooding and sewer

overflows can be analysed using long time series of rainfall data or storm events. The model helps to find out how the performance of the urban drainage system can be improved by a better operation of pumps gates and weirs.

SOBEK-Urban's graphic display superimposes the hydraulic components over a (GIS or aerial photo) map of the area to create a layered overview of the network (sewer pipes, manholes, canals, weirs and pumping stations). Animation options show the direction of flow and by varying the thickness and colours of network elements all input and computed parameters can be visualised.

Scenario Modelling

SOBEK can evaluate the effectiveness of measures taken to keep a system running at peak efficiency. Specifications for manual or automatic operation of pumps, sluice gates, weirs, storage tanks and other structures can be incorporated into a model, providing a realistic picture of how a system behaves in extreme scenarios (e.g. storms, high winds and pollution loads).

Inputs:

Area schematization (mesh and network, topography, cross-sections, characteristics of structures, open boundary locations), process selection, initial conditions, rainfall time series and any other inflows, initial water levels, time step, computational parameters, and output options.

Outputs:

Hydraulic outputs: floodplain inundation extentand depth, discharge, flow velocity and water depth

Water quality outputs: salinity, E.Coli, faecal and total, O_2, BOD, temperature, Organic C, N, P, and Si, inorganic P, ammonium, nitrate, silica, algae, and heavy metals can be displayed as maps, graphs, tables and animations to facilitate the analysis and dissemination of results.

Homepage:

http://delftsoftware.wldelft.nl/

Software and Hardware Requirements

Operating System: Windows 98/XP/ XP Prof/NT.
For normal applications SOBEK needs at least 100 Mb of free disk space and a Pentium II processor with 64 Mb memory. For optimal performance a Pentium III processor, 128 Mb memory, and 1 Gb of free disk space is recommended.

Computational cores, such as the 1D2D Hydrodynamic simulation engine, will soon also be supported on GNU/Linux distribution: Redhat Enterprise 4 release 3.

Availability, License, and Cost

Two license types are supported: single user and concurrent user floating network licenses. For license cost, please check web-site: http://delftsoftware.wldelft.nl/

Contact: Edward Melger, SOBEK Product Manager,
Phone: +31(0)88 335 8550
Fax.: +31(0)15 285 8582

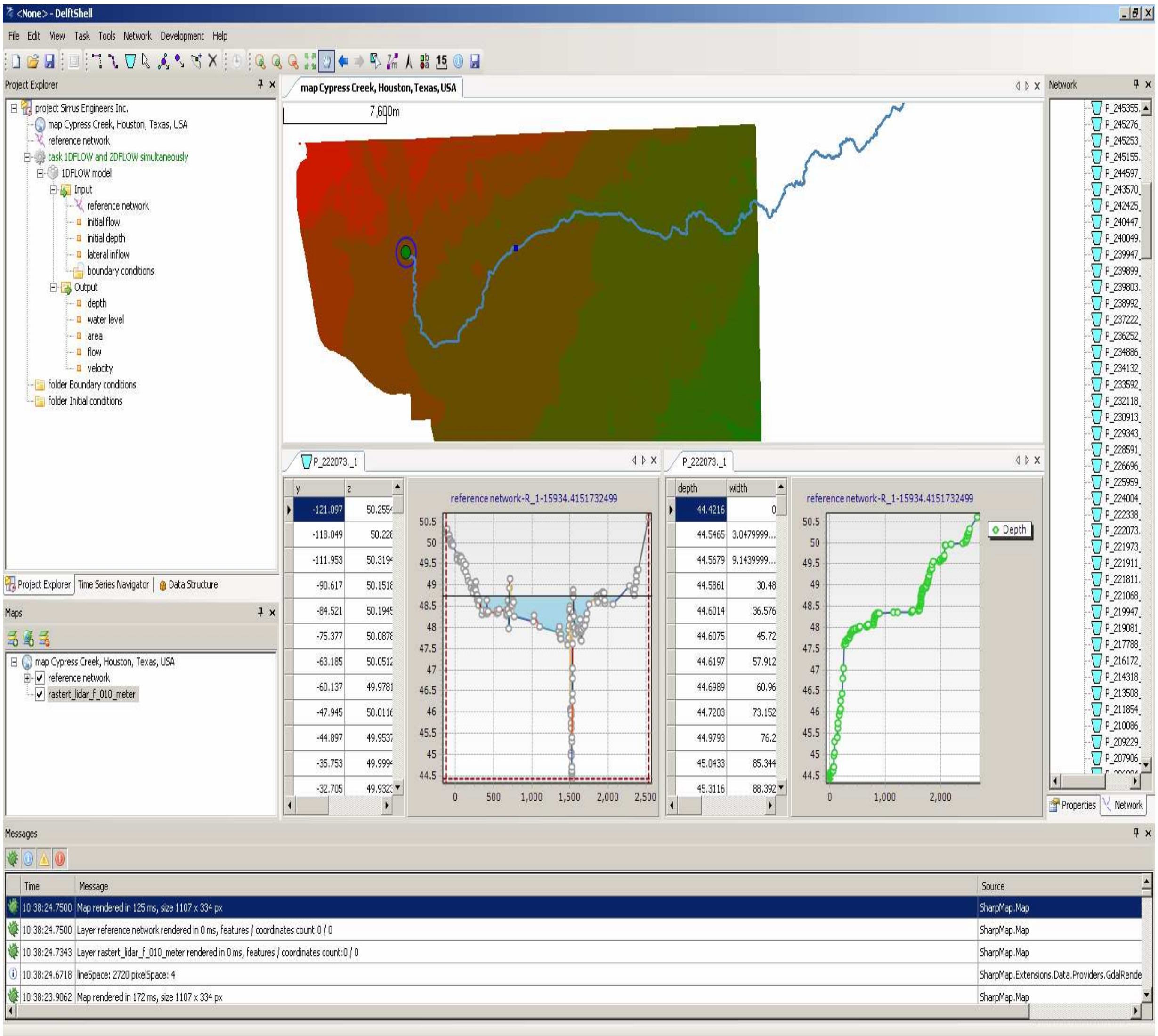

Figure 2 SOBEK graphical interface

2.4.5 MONERIS

The GIS-oriented model MONERIS (MOdelling Nutrient Emissions in RIver Systems) was developed at the Institute of Freshwater Ecology and Inland Fisheries, Leibniz, Germany. It is a multipurpose environmental model system with three main objectives:

- To identify source of nutrient emissions on a regional basis
- To analyze transport and retention of nutrients in river systems
- To provide a framework for examining management alternatives

Because many states and local agencies use a catchment-based approach to implementing the Water Framework Directive, the MONERIS system is configured to support environmental and ecological studies in a catchment context. The system is designed to be flexible and can support analysis at a variety of scales.

Seven contamination pathways can be simulated by the MONERIS model:

(i) point sources (discharges from municipal waste water treatment plants and direct industrial discharges)
(ii) inputs into surface waters via atmospheric deposition
(iii) inputs into surface waters via groundwater
(iv) inputs into surface waters via tile drainage
(v) inputs into surface waters via paved urban areas
(vi) inputs into surface waters by erosion
(vii) inputs into surface waters via surface runoff (only dissolved nutrients)

Input data Requirement and Model Outputs

Spatial input data (GIS data):
River network, land surface digital elevation model, land use classification data, digital soil map for physical-chemical soil parameters, hydrogeological map, depth of groundwater table (near and remote groundwater resources) within the river catchment area, meteorological input data, data on atmospheric deposition of nitrogen oxides and ammonium, and digital maps of the administrative areas (districts, regions, and countries) in the river basin which are required to derive population information and N-surplus.

Data for calculating point source emissions (WWTPs):
Discharge water loads, current treatment, current capacity of WWTP, volume of wastewater discharge (m^3/area), total load discharged into receiving waters (t/area), and plant capacity as inhabitant equivalents

Monitoring data for surface water:
The water quality database should contain fortnightly and monthly values of contaminant concentrations and daily or weekly discharge at various points starting from the source of the river downstream to the outlet. Typical nutrients include Ammonia (NH_4), Nitrite as Nitrogen (NO_2), Nitrate as Nitrogen (NO_3), Phosphates (PO_4), Total Phosphorus (TP). Temperature data is needed for nitrogen retention calculations.

Management and agricultural data:
Data on population, cultivation and livestock numbers for municipalities or districts are required.

Outputs

MONERIS produces estimates of annual loads through each of the defined points and diffuse pathways. It estimates nutrient retention and loss within the river system itself (i.e., the stream's self-purification processes). The final output is an estimate of annual nutrient load in the river at the outlet of the study catchment, which is equal to the emissions into the river via point and diffuse sources minus the estimated nutrient retention and loss within the river system. The programme can produce maps, tables, graphs of the waterbalance (flow), Emissions (both net and total). It can compare the results of various management scenarios

Hardware and software requirements

MONERIS is designed to be used with MS-EXCEL and can be operated on IBM compatible personal computers (PCs) with a 1.6GHz or better processor, 1 GB RAM, Operating system WINDOWS 2000, XP, ARC View 3.2 or ARC GIS 9.0, Spreadsheet software MS-Office EXCEL 2003 (this is an indispensable requirement since MONERIS 2.0 does not run with EXCEL 2000 or later versions).

Source

Contact: Horst Behrendt, Forchungsverbund Berlin e.V., Müggelseedamm 310, 12561 Berlin, Germany.
Phone: +493064181683
E-mail: behrendt@igb-berlin.de

Homepage: http://www.icpdr.org/icpdr-pages/item20080506172727.htm
The MONERIS user manual: can be downloaded from this homepage.

2.4.6 NELUP

Description

The NERC-ESRC Land-Use Programme (NELUP) was initiated in 1989 to investigate techniques for producing a decision-support system for land-use planning that incorporated the socio-economic mechanisms of land allocation constrained by our scientific understanding of the physical and ecological environments. Its main purpose is to provide quantitative economic and environmental comparisons of both present and alternative future scenarios that are relevant to land-use planners. The result of this multi-disciplinary research programme was the NELUP decision-support system (DSS) for analysing the implications and predicting the impact of agricultural land-use change at the river-basin scale (O’Callaghan, 1995).

NELUP uses a general systems framework for organizing the large amounts of information that are relevant to land-use decisions. The first level is that of empirical information which contains the descriptive data from which more sophisticated levels

may be constructed, ranging from physically based models, through biosystems to the individual and political levels. An holistic and structured approach is adopted for organizing information at the different levels and making it easily accessible to users in a decision support system. The level of the open systems of living organisms and ecosystems is where socio-economic demands impact on the environment and where ideas of sustainability and environmental carrying capacity have operational meaning for planners and managers (O'Callaghan, 1995).
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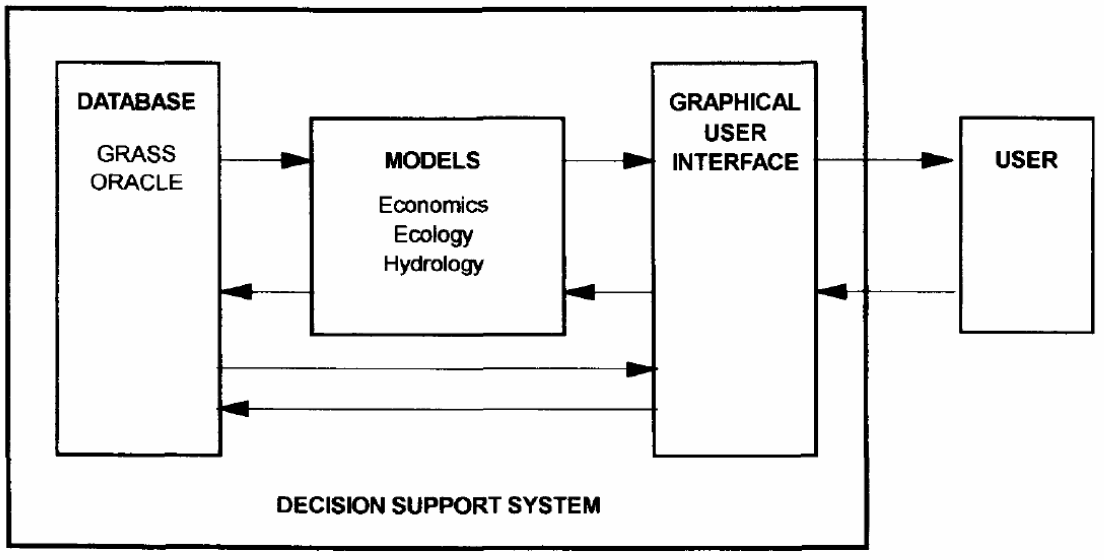

Figure 3 Structure of NELUP

Three sets of models (Figure 3) underpin the NELUP DSS, (i) agricultural economics, (ii) ecological and (iii) hydrological. These models are used to identify the characteristics of a region under its present land use and to evaluate how these characteristics will respond to specific land-use modifications. There are two routes by which a land use change may be imposed within the system. The first is an indirect route, whereby the economics models predict how land owners respond to economic policy shifts through changes in land use and land management. The second is a direct route, whereby specified areas of land cover are changed to a different type.

Agricultural economics
The agricultural-economics component consists of two linear-programming models, a catchment-level model and a farm-level model. The catchment-level model predicts the aggregated behaviour of a region by treating the area as a macro-farm. The advantage of this is that, within a single simulation, the model can account for the wide variation in agricultural activity that can exist across a region. Predicted land-use patterns can be disaggregated into a finer spatial-resolution by categorising the region according to its agricultural-production potential. The farm-level model works on a similar basis to the catchment-level model. However, it is used to investigate the potential response of a particular type of farm to changes in agricultural policy.

Ecology

Within the ecological component, specific models predict the distribution of various species within the landscape and the effects of environmental management on these distributions.

Hydrology
There are two modelling systems in the hydrological component. The NUARNO (ARNO) system uses a conceptual, spatially aggregated modelling approach to describe the movement of water and contaminants at the river-basin scale. The second system, SHETRAN uses a detailed physically based distributed modelling approach to provide more information about the hydrological system, at a much finer resolution. The two modelling systems are operated in a similar manner to the agricultural economics models, with NUARNO providing an overview of the catchment hydrology and SHETRAN providing a capability for analysing smaller-scale problems in much greater detail.

GIS-Based Decision Support System (DSS)
The GIS-Based DSS was designed to: (i) integrate models covering economics, ecology and hydrology that describe the changes in the spatial pattern of forestry and land use and the impacts of these changes; (ii) integrate nationally available data sets within a database which describe the biophysical and economic conditions within a river basin; and (iii) create an interactive, user-friendly interface to the database and models to allow exploration of future land use scenarios.

Hardware and Software Requirements

Grass –GIS, UNIX

Source:
Contact: Dr. Sarah Dunn, The Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen, AB15 8QH, Scotland, UK.
E-mail: s.dunn@macaulay.ac.uk
Phone: +44 (0) 1224 395000
Fax: +44 (0) 1224 395010

2.4.7 NL-CAT

Description:

In the Netherlands, the model STONE (Wolf et al., 2003) is used to assess the long term impact of nutrient management strategies and manure legislation on nitrate concentrations in groundwater and nutrient load of surface water systems on a national scale (Schoumans et al., 2004). This model consist of a fertilizer and manure distribution module (CLEAN or MAMBO), a hydrological model (SWAP) and a soil-water quality model (ANIMO). The model estimates nutrient losses from agricultural land and natural areas to surface waters. However processes and transport within surface waters are not modeled in STONE so an improved model, NL-CAT, (Nutrient Losses at catchment scale) was built (Schoumans et al., 2005) containing the two important STONE components SWAP and ANIMO in combination with a surface water quantity and a surface water quality module. The SWAP module (Kroes and Van Dam, 2003) is used to generate hydrological input to the ANIMO module (Groenendijk et al., 2005). ANIMO simulates the nutrient cycle in soil and the nutrient leaching to groundwater and surface waters. Surface water discharges are simulated by the SURFACE WATER module (Smit et al., 2009). Finally, simulation of surface water quality processes and retention within a (large) catchment is performed by the NUSWALITE module (Siderius et al., 2009). To quantify the amounts of P (and optionally N) added to the surface water system via surface erosion, the NL-CAT model was extended with a simple erosion module; P-USLE, based on the modified and Revised Universal Soil Loss Equations (Renard et al, 1997) and implemented in a GIS-environment.

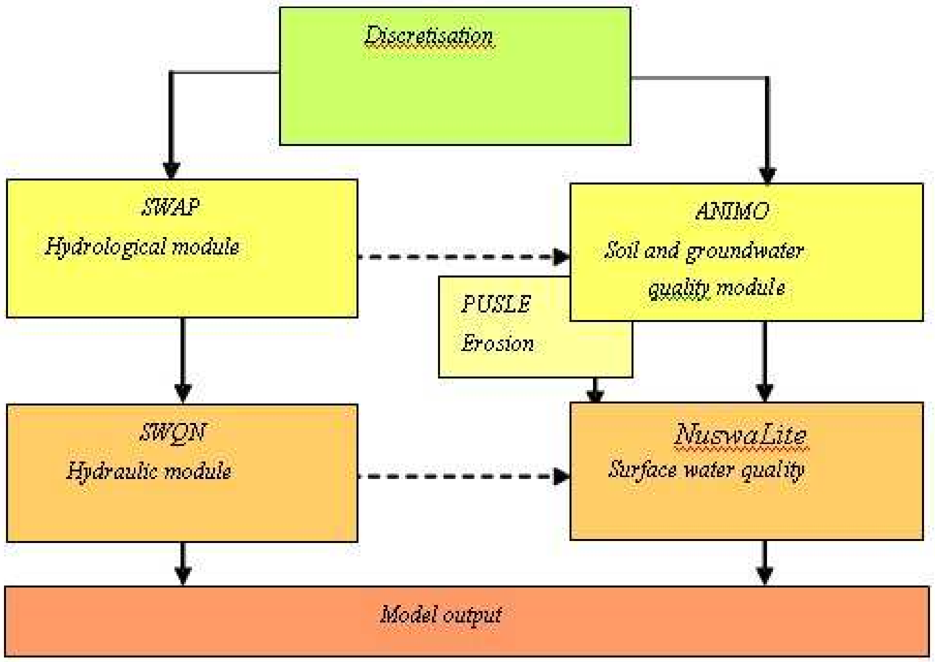

Figure 4 NL-CAT structure

Input:

Meteorological data: precipitation, evaporation, solar radiation, and sunshine hours.
DEM, Land use, soil type, cop distribution.
Groundwater levels, drainage, and boundary conditions (e.g. abstractions, recharge).
Nutrients amount of manure and chemical fertiliser spread on land.
For calibration: discharges at measurement stations, N- and P- concentrations at the measurement station, N- and P- loads at measurement stations.

Outputs

Discharge at measurement specified locations
N- and P- concentration at specified locations
N- and P- loads at specified locations

Source:

Contacts: Ir. P Groenendijk , Postbus 47, 6700AA, Wageningen, the Netherlands.
Phone 0317-486434
Fax 0317-424988

E-mail: Piet.Groenendijk@wur.nl

2.4.8 REALTA

Description

The Realta model identifies potential agricultural risk areas at a River Basin District level and quantifies phosphorus export rates from the River Basin District and its main subcatchments. It uses a GIS to investigate the relationship between a set of agricultural indicators and water pollution potential. Variations in both physical (land) characteristics and usage (management) practices are considered to influence the risk of phosphorus loss to surface waters.

The factors considered in evaluating the potential for loss and transport of phosphorus from agricultural systems are as follows:

(a) Runoff Risk to Surface Waters: The physical characteristics which influence the transport of phosphorus to surface waters: geology, soil type, slope and rainfall are combined in a runoff risk map.
(b) Land use.
(c) Soil Phosphorus Levels.
(d) Mineral Fertiliser Loading.
(e) Organic Fertiliser Loading (cattle, sheep).
(f) Organic Fertiliser Loading (Intensive Agricultural Enterprises – pigs, poultry).

Other factors that have a significant bearing on phosphorus loss from agriculture include farmyard condition and the management of land spreading activities. An equal bias for these factors is assumed across the River Basin District in the absence of quantitative information.
However it is considered that the organic loading data in part reflects this variation in that greater volumes of manure are generated, stored and disposed of in areas of higher stocking density.

Development of the Potential Agricultural Risk Map

A ranking scheme, similar to that suggested by (Magette, Hallissey et al. 2007), is developed whereby each of the phosphorus loss indicators is subdivided into zones of relative risk, each of which has a numerical value for scoring purposes. The relative importance between factors is also represented by a further scoring system or ‘weighting’. A ‘score’ or ‘rank’ for a given combination of factors affecting loss and transport of phosphorus is developed in two steps. In the first step, the weight of each factor is multiplied by the relative risk associated with the magnitude of each factor. Then all the products are summed up.

The resulting composite map establishes the range of potential agricultural risk areas across the River Basin District. The ranking scheme developed for all predominantly grassland catchments in Ireland is shown in Table 3.
The total scores used to derive the potential risk classes are shown in Table 4. At present landuse data is only used to distinguish between agricultural and non-agricultural areas. Non-agricultural areas are excluded from the analysis.

The potential agricultural risk map is updated once in every five years when agricultural statistics are made available from census data and/or national farm survey data.

Calibration of the Potential Agricultural Risk Map

The potential agricultural risk map is calibrated on an annual basis by the physical measurement of in-stream phosphorus loadings in selected agricultural areas. These physical measurement results are then extrapolated across each of the main subcatchments to enable the quantification of the annual phosphorus export rate from the River Basin Districts.

The application of the model therefore requires a limited programme of physical in-stream measurements in small agricultural areas each year to take account of annual variations in hydrological conditions, farm management practices, and the associated impacts on agricultural losses to water.

Boundary Conditions

The conceptual boundary of the model is the point at which the loss and transport of phosphorus is measured in-stream from predominantly agricultural areas (normally 10-30 km^2 in size).

Input requirements

The main model input parameters, ranked in order of their importance (highest to lowest) are as follows:

(i) Organic Fertiliser Loading; Land Use; Runoff Risk to Surface Waters.

(ii) Soil Phosphorus Levels

(iii) Mineral Fertiliser Loading

Validation Requirements:

Annual phosphorus export loading from the River Basin District and the main subcatchments, for a 2-3 year period; and annual quantification of all point source discharges within the River Basin District.

System Strengths

- The model has proven to work in Irish grassland catchments.
- Data requirements are available for most River Basin Districts.
- The model is relatively easy to use and is therefore cost effective.

System Weaknesses

- In-stream and lake retention is not included.
- The model has not been tested outside Ireland.
- Additional calibration data will be required for land uses and agricultural practices not found in Ireland.
- A limited programme of physical in-stream measurements is required each year.

Temporal and Spatial Resolution

Temporal resolution: The quantification of phosphorus export rates from the River Basin District can be updated annually.

Spatial resolution: Agricultural data of the highest resolution available for the River Basin District should be used to maximize the performance of the model. In Ireland, agricultural statistics available at a District Electoral Division level (approximately 10-15 km^2) have been successfully used in conjunction with CORINE land use data.

Source:

Contacts: Dr Alan Barr (Main Contact) or Ms Alison Murdock, Kirk McClure Morton, 74 Boucher Road, Belfast BT12 6RZ , Northern Ireland.
Phone +44 2890 667914
E-mail: alan.barr@kmm.co.uk (Alan Barr)
alison.murdock@kmm.co.uk (Alison Murdock)

Table 3 Phosphorus ranking scheme and risk classes for agricultural catchments

Phosphorus Ranking Scheme for Irish grassland catchments Factor	Factor Weighting	Risk Class	Score
Chemical Fertiliser Loading	12	1. (0-9 kg/ha) 2. (10-11 kg/ha) 3. (12-14 kg/ha) 4. (15-19 kg/ha) 5. (20+ kg/ha)	0.8 1.6 2.4 3.2 4.0
Organic Fertiliser Loading (cattle, sheep, poultry)	24	1. (0.0-1.0 LU/ha)* 2. (1.0-1.5 LU/ha) 3. (1.5-2.0 LU/ha) 4. (2.0 + LU/ha)	1.0 1.5 2.0 4.0
Organic Fertiliser Loading (piggeries)	24	1. (low potential) 2. (moderately low potential) 3. (moderately high potential) 4. (high potential)	0.8 1.6 3.6 4.0
Soil Phosphorus Levels	16	1. (0-5 mg/l) 2. (6-9 mg/l) 3. (10-14 mg/l) 4. (15+ mg/l)	1.0 2.0 3.0 4.0
Runoff Risk to Surface Waters	24	1. (very low risk) 2. (low risk) 3. (medium risk) 4. (high risk)	1.0 1.5 2.5 4.0

*Unit LU/ha is livestock units/hectare

Table 4 Total scores for derivation of potential risk classes

grassland catchments Total Score	Potential Risk Class
0	Non-agricultural areas
0 – 120	Index 1 Low Risk
120 - 200	Index 2 Medium Risk
200 – 280	Index 3 High Risk
>280	Index 4 Very High Risk

2.4.9 TRK System

Description

TRK is a tool developed in Sweden for nitrogen (N) and phosphorus (P) gross and net load calculations, retention and source apportionment. The TRK system supports calculations of concentration and area losses of diffuse sources (for N from arable land using the dynamic soil profile model SOILNDB), calculations of the water balance (using the distributed dynamic HBV model) and N transport and retention processes in water (using the HBV-N model). The results are presented in the GIS graphical interface, and source apportionment is carried out for each sub-basin as well as for whole river basins. Results from the system have been used for international reports on transport to the sea, the assessment of the reduction of the anthropogenic load on the sea and for guidance on effective measures to reduce the load on the sea at the national scale. The tool is applied in Nordic countries and Sweden.

The TRK system combines

1. Preparation of maps of areal distribution of different land-use categories and positioning of point sources using GIS;

2. Calculations of concentration and areal losses of diffuse sources (for N from arable land by using the dynamic soil profile model SOILNDB);

3. Calculations of the water balance (by using the distributed dynamic HBV model) and N transport and retention processes in water (by using the model HBV-N).

The results are presented in the GIS, and source apportionment is made for each sub-basin as well as for the whole river basins. The results from the system have been used for international reports on the transport to the sea, (e.g. for OSPAR) for the assessment of the reduction of anthropogenic load on the sea and for guidance on effective measures for reducing the load on the sea on a national scale.

Processes within the TRK system

N- leaching from arable land:
Generalized N root-zone leaching estimates for arable land are calculated using the SOILNDB modelling tool. SOILNDB is a management oriented modelling tool based on the one-dimensional SOIL-SOILN models describing N dynamics and losses in arable soils, a parameter database and parameter estimation algorithms. The method is based on calculating a number of standard N leaching rates (defined as the rate that nitrogen leaching would occur from the root zone for a specified year if the weather and harvest were normal) for a number of combinations of soils, crops and fertilization forms and regions (catchment, area etc.).

Catchment modelling of water discharge:
The HBV model is a conceptual, continuous, dynamic and distributed rainfall-runoff model. The catchment is divided into several coupled sub-basins and a daily water balance is calculated for each sub-basin using daily precipitation and temperature data from climate stations. It provides daily values of areal precipitation, snow accumulation or melt, soil moisture, groundwater level, and finally, runoff from every sub-basin, and routing through lakes and larger basins.

N transport and retention:
The HBV-N model simulates N transport and retention in groundwater, river and lake systems at the catchment scale. The N model is integrated into the HBV-model and has separate routines for daily simulations of inorganic and organic N. The soil leakage from different land-use types is mixed with discharge from rural households in the groundwater. Concentration variations in the local runoff, due to biological and chemical processes in e.g. open ditches and riparian zones, are described with simple functions mainly based on temperature, concentration and hydrology. The local N runoff is then mixed with contributions from upper sub-basins and lake water. In the river and lake routines, atmospheric deposition of Nitrogen on the water surface and the load from industry and treatment plants are included. N retention is calculated in rivers and, more importantly, in lakes. The inorganic N may be reduced due to denitrification, sedimentation and biological uptake, while organic N may increase due to biological production or decrease by sedimentation and mineralisation.

P-leaching from arable land:
P transport is based on water discharge simulated by HBV linked to empirical, multiple regression, models. Four parameters influence the P concentration from arable land, livestock density, P concentration in topsoil, duration of high water flow, and area.

Model input requirements:

SOILNDB:
Crops types
Harvest & crop management
Fertilization and manure details
Soil type (texture) and organic content
Atmospheric deposition rates & concentrations
Meteorological data (air temperature, precipitation, air humidity, solar radiation data, and wind speed)

HBV:
Digitalized subbasin boundaries and elevation maps
Land cover maps
Daily precipitation and temperature from climate stations
Average potential evapotranspiration
Lake rating curve and regulation regime for hydropower reservoirs
Observed time-series of water flow in the river
Validation data: Time-series of several years of daily or monthly water flow, groundwater levels, observations in rainfall and discharge, snow-cover, snow depths, and frozen-ground depth.

HBV-N (additional to the HBV-input data):
Soil type and crop distribution of the arable land
Soil leakage concentrations
Lake depths
Atmospheric N-deposition
Point-source N emissions
Rural households and person equivalents of N contribution
Observed time-series of N in the river
Validation data: Time-series of several years of grab-samples; $NO_{2\text{-}3}$, NH_4, Org.N, Tot.N in up-stream subbasins without lakes, at several sites along the river section, and at lake outlets.

TRK-P:
Livestock density
P concentration in topsoil
Runoff
Soil specific area

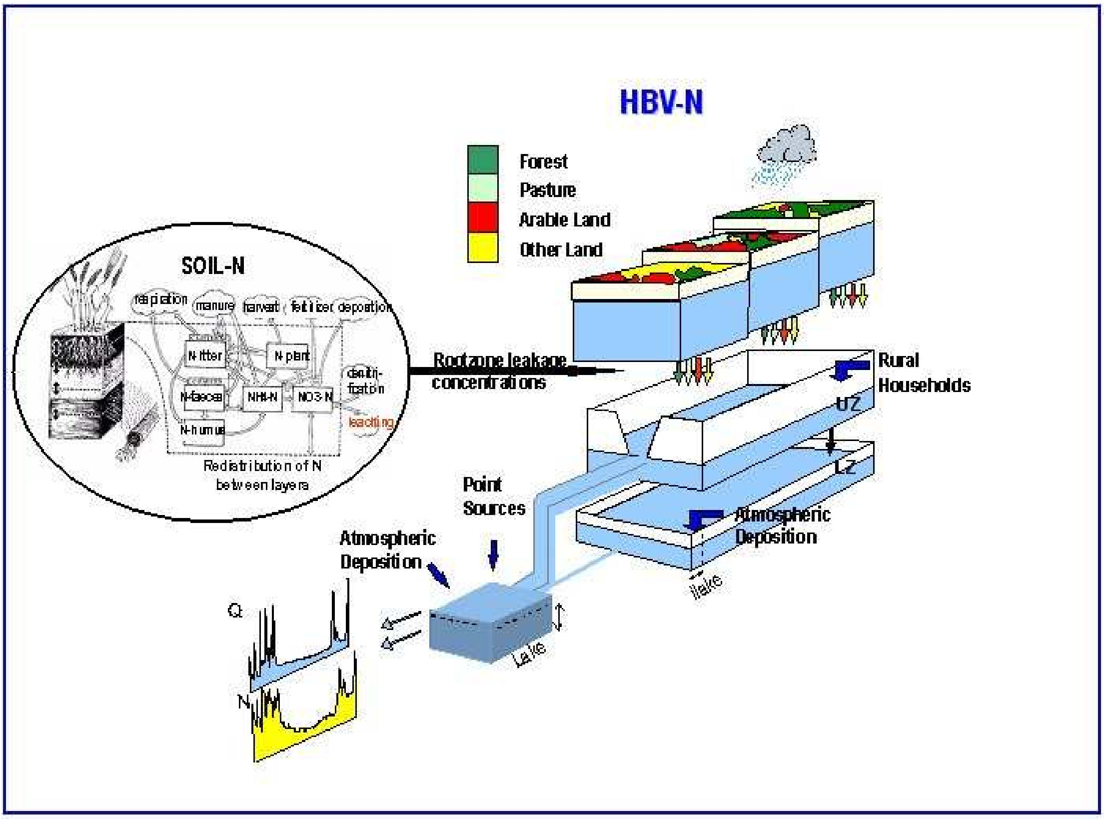

Figure 5 Pathways in the TRK (HBV-N) system

Model Advantages:
• Integrated catchment modelling
• Enables large-scale applications
• Process-based with scenario possibilities
• HBV and HBV-N includes an automatic calibration routine
• Validated against independent measurements

Model Limitations
• Model set-up may be time-consuming
• Simplified process descriptions involves uncertainties
• Internal variables that are unvalidated (involve uncertainties)

Temporal resolution
The method calculates normalized nutrient load for a specific year.
SOILNDB: The model runs with a daily time-step and results are aggregated to give annual standard arable root-zone N-leaching estimates.
HBV: The model runs with a daily time-step and results are aggregated to give annual normalized runoff coefficients.

HBV-N: The model runs with a daily time-step and results are aggregated to give annual normalized retention coefficients.

Spatial resolution
The catchment is subdivided into a number of sub-basins. The number of subbasins (and thereby spatial distribution) is chosen by the modeller for each application.

Source:

Main contact: Helene Ejhed, IVL Svenska Miljöinstitutet AB/ IVL Swedish Environmental Research Institute, Sweden helene.ejhed@ivl.se

Alternative contacts: Berit Arheimer, SMHI, 601 76 Norrköping, Sweden, berit.arheimer@smhi.se

Holger Johnsson, Dep. of Soil Sciences, SLU, Box 7072, 750 07 Uppsala, Sweden jonas.olsson@smhi.se

2.4.10 Water Evaluation And Planning System (WEAP)

Description:

WEAP is a user-friendly software for surface and groundwater resource simulations. It is based on water balance accounting principles and can be applied to urban and agricultural systems, a single watershed or complex transboundary river basin systems. WEAP is designed as a comparative analysis tool. A base case is developed, and then alternative scenarios are created and compared to this base case. Using the systems projections can be made to assess changes in water demand, supply, and pollution over a long-term planning horizon to develop adaptive management strategies. The model has built-in models for: rainfall runoff and infiltration, evapotranspiration, crop requirements and yields, surface water/groundwater interaction, and instream water quality. WEAP operates on the basic principle of a water balance and was developed at the US branch of the Stockholm Environment Institute, Boston, Massachusetts, USA.
The Stockholm Environment Institute provided primary support for the development of WEAP. The Hydrologic Engineering Center of the US Army Corps of Engineers funded significant enhancements. A number of agencies, including the UN, World Bank, USAID, US EPA, IWMI, Water Research Foundation (formerly AwwaRF) and the Global Infrastructure Fund of Japan have provided project support.

The main features of WEAP are:

(i) An intuitive GIS-based graphical interface to provide a simple, yet powerful, means for constructing, viewing, and modifying the model configuration. Elements can be overlain on a map built from Arcview and other standard GIS and graphic files and edited on-screen

(ii) Wizards, prompts, and error messages provide advice throughout the program.

(iii) What-if analysis of various policy scenarios and long-range planning studies. Adaptive agriculture practices such as changes in crop mix, crop water requirements, farm management strategies, canal linings, changes in reservoir operations, water conservation strategies, water use efficiency programs, changes in instream flow requirements, and implications of new infrastructure development.

(iv) WEAP was designed to produce outputs suitable for direct inclusion in reports. The user may customize reports as graphical, tabular or map-based output and select from a number of formatting options (e.g., metric or English units, years, absolute levels, percent shares, or growth rates). Specific report configurations can be saved as "favourites," to be retrived in the future.

Using WEAP generally involves the following steps:

Study definition: to establish the problem configuration and to set-up the time frame, spatial boundaries, and system components.
Current accounts: A snapshot of actual water demand, pollution loads, resources and supplies for the system are developed. This can be viewed as a calibration step in the development of an application.
Scenarios: A set of alternative assumptions about future impacts of policies, costs, and climate, for example, on water demand, supply, hydrology, and pollution can be explored.
Evaluation: The scenarios are evaluated with regard to water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables.

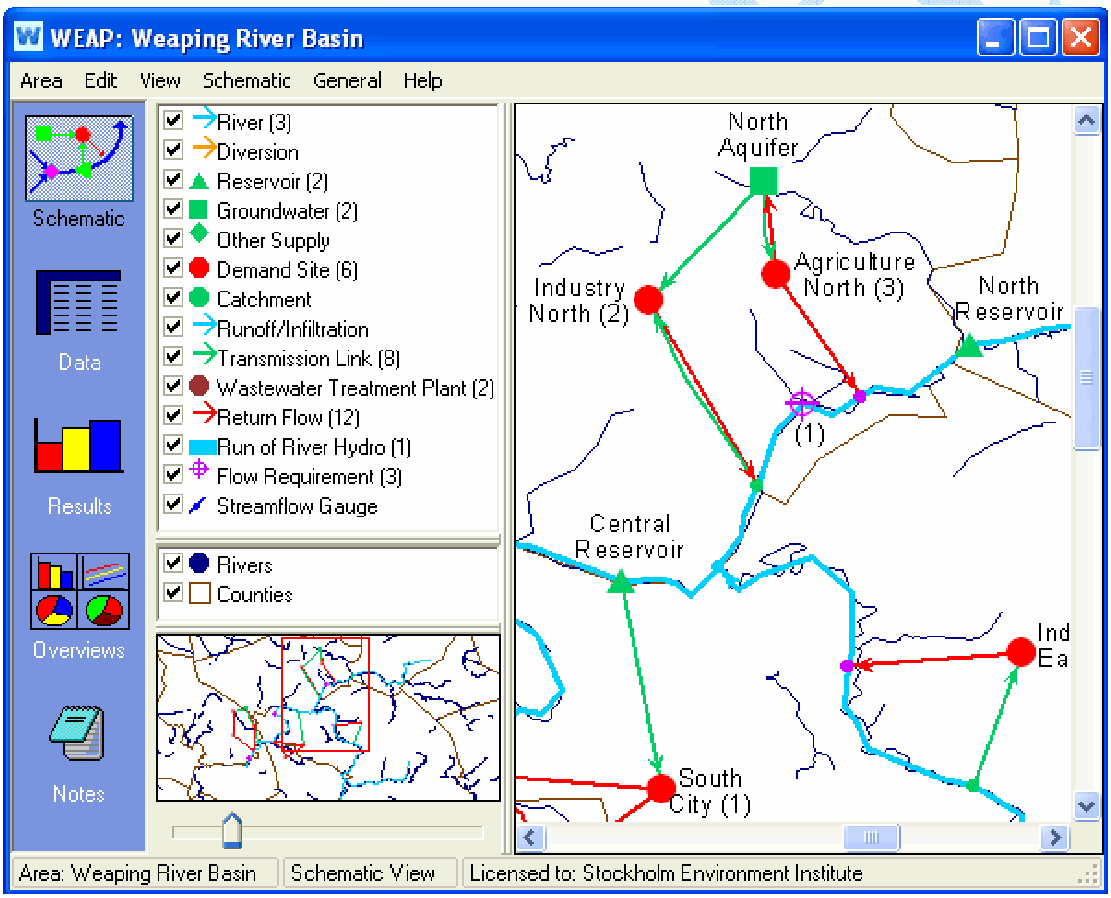

Figure 6 Graphical User Interface of the WEAP system

Inputs

- Configuration of the system (can use GIS layers for background) and component capacities and operating policies

- Water demand: Spatially explicit demographic, economic, crop water requirements, and current and future water demands and pollution generation.
- Economic data: Water use rates, capital costs and discount rate estimates.
- Water supply: Historical inflows at a monthly time-step and groundwater sources. Scenarios: Reservoir operating rule modifications, pollution changes and reduction goals, socioeconomic projections, water supply projections.

Key Outputs:

Mass balances, water diversions, sectoral water use, benefit/cost scenario comparisons, pollution generation, and pollution loads.
The outputs can be displayed as maps, tables, graphs, and charts.
The system also provides a dynamic links to spreadsheets and other models.

Sources:

Contact: Jack Sieber, Senior Software Scientist, Stockholm Environment Institute (SEI), In USA; SEITellus Institute, 11 Arlington St., Boston, MA 02116-3411 USA
Phone: +1.617.266.5400
E-mail: weap@tellus.com
Website: http://www.weap21.org/.
Documentation: WEAP21 User Guide; available online at http://www.weap21.org/index.asp?doc=08

Training:
3-day courses available at the Stockholm Environment Institute's U.S. Center, Boston, Massachusetts, USA.
http://www.weap21.org/index.asp?doc=06.
On-line tutorial available at http://www.weap21.org/.

Hardware and Software Requirements

200 MHz or faster Pentium class PC with Microsoft Windows 95 or later (a 400 MHz PC with Windows 98 or later is recommended).
A minimum of 32 MB of RAM and 50 MB of free hard disk space is also required (64 MB of RAM recommended).
Microsoft Internet Explorer version 4.0 is required for viewing WEAP's HTML Help. Monitor should be set to a minimum resolution of 800x600, but preferably even higher (e.g., 1024x768 or 1280x1024), to maximize the presentation of data and results.

Cost, License, & Availability:

Free for Non-profit, governmental or academic organization based in a developing country.
Academic license (except developing countries): $1000,
Commercial License: $ 3000.

2.4.11 Watershed Management Decision Support System (WAMADSS)

Description

The Centre for Agricultural, Resource and Environmental Systems (CARES) at University of Missouri-Columbia, U.S. developed a watershed management decision support system (WAMADSS) by integrating ArcInfo GIS with AGNPS, the Soil and Water Assessment Tool (SWAT) and the Cost and Return Estimator (CARE) model to aid in development of water quality management plans. The system can be used for evaluating the environmental and economic impacts of changing land use and/or management practices (LUMPs).

WAMADSS has three major components: a graphical user interface (GUI), a GIS, and a modelling system.

(i) **Graphical User Interface (GUI)**: composed of visual objects such as menus, buttons and input fields, the GUI provides an interactive interface for developing model inputs and entering parameters. It also provides access to the GIS and modelling system and allows the user to select LUMPs, parameter values and evaluation criteria.

(ii) **Geographic Information System (GIS):** The use of GIS minimizes the time required to describe the spatial detail of a watershed. The GIS, in this case ARC/INFO, is used to manage spatial and tabular database, generate model parameters and present water quality /economic results of baseline and alternative LUMAPs. The ARC Macro Language (AML) generates the GUI.

(iii) **Modelling System**:
Agricultural Non-Point Source Pollution Model (AGNPS) simulates erosion, sediment, runoff, and nutrient (nitrogen and phosphorus) transport from agricultural watersheds for individual storm events.
Soil and Water Assessment Tool (SWAT), which models continuous behaviour, is also integrated into the package. It is a continuous daily time-step model which simulates the impacts of alternative land use management practices on surface and ground water quality. The purpose of incorporating both AGNPS and SWAT in WAMADSS is to offer the user more options for evaluating the impacts of alternative LUMPs.
Cost and Return Estimator (CARE) calculates annualized net returns of a particular spatial configuration of LUMPs at a acre, field and watershed basis. The spatial input data needed to calculate annualized net returns include: set-aside requirement, total acres per field, planted acres per field (total acres times proportion planted), initial crop yields and cost of production per acre. Cost of production is estimated from crop yield, LUMP and average costs of farm labor, fertilizer, pesticides, fuel and machinery/equipment.

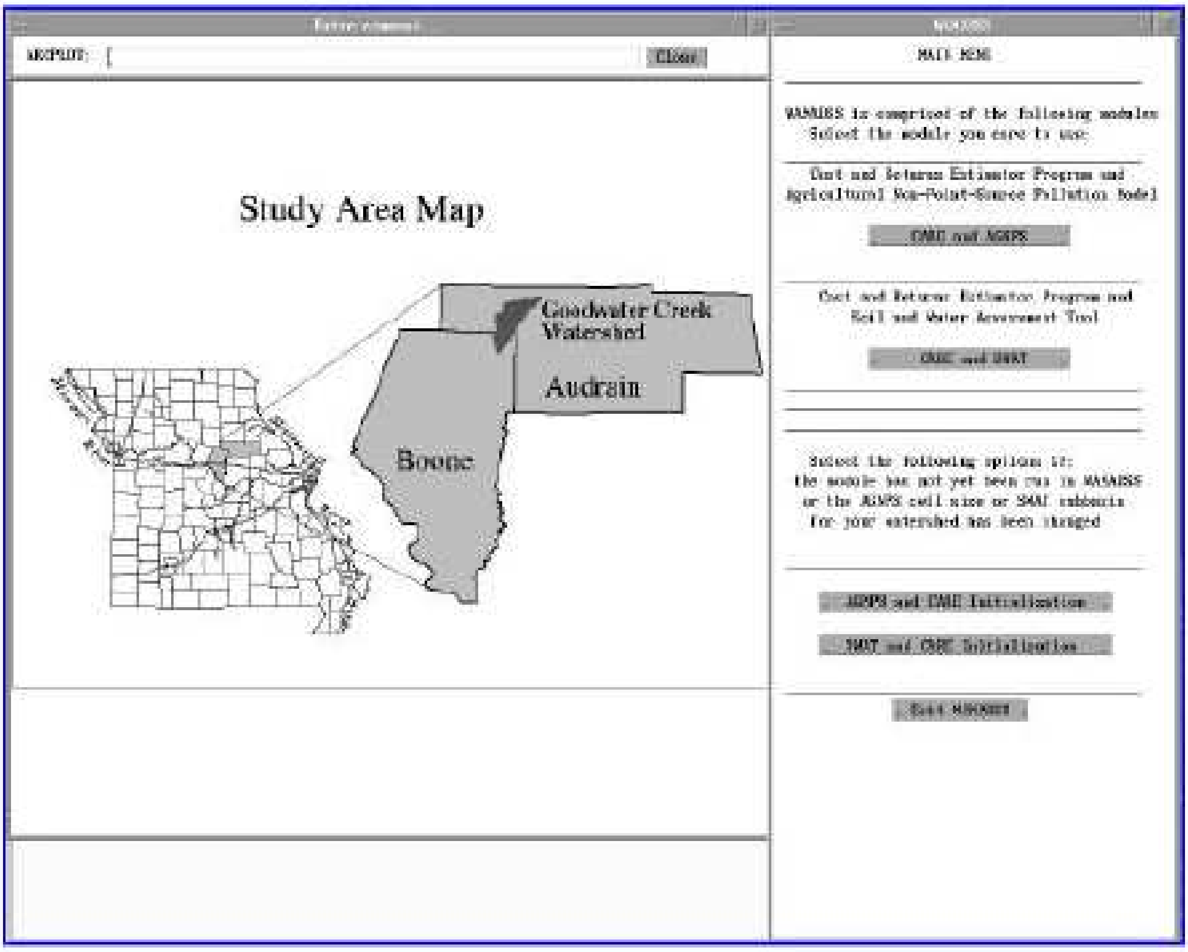

Figure 7 Graphical User Interface of the WAMADSS

Spatial Data Process

WAMADSS divides the watershed into grid cells with a specified data resolution using the watershed boundary map layer. The central points of all grid cells are extracted as point coverage in ArcInfo to represent the watershed. The point coverage is linked to other spatial data through the spatial location of those points, i.e. the coordinates of those points and other relational INFO files through their identification items. The digital elevation model (DEM) is created from the digital contour coverage using the same resolution. The slope and aspect coverage are generated from DEM and are then linked to each central point. Other spatial layers including soils, land use and hydrology are first rasterized using the same data resolution to identify the soil type, landuse categories and stream type in each cell. The rasterized grids are then vectorized so that soil, landuse and stream information can be linked to each central point. The resulting INFO file of the central point coverage contains all spatial information, such as the cell number, landuse category, soil type, stream type, aspect, and land slope.

2.4.12 Catchment Management Support System (CMSS)

Description

WinCMSS is a tool for catchment managers and planners to examine the impact of changes in land use and/or land management practices, on water quality in catchments (Davis and Farley (1997). In addition, it provides an instream nutrient assimilation component if net loads leaving the subcatchments are required. The system was designed to assist a decision maker engaged in policy development (Davis and Farley, 1997). The model was developed at CSIRO Land and Water, Canberra and it is owned by CSIRO and Land and Water Resources Research and Development Corporation (trading as Land and Water Australia).

WinCMSS is ideally suited to a "first cut" analysis of the major contributors of sediment or nutrients from a catchment. Since the model does not consider hydrology or any time-variant components, it is restricted to long-term average behaviour, i.e. average annual loads of pollutants (usually Total Phosphorus and Total Nitrogen). CMSS uses average annual loading rates (T/ha/yr) to describe nutrient generation. The rates are representative of "net delivery" (i.e. the delivery process is not explicitly represented) and the results are simply summed over an area. Both diffuse (i.e. areal) and point sources of nutrient generation are included when calculating total load. The strengths of CMSS lie in its simplicity and its ability to encapsulate a wide range of policy initiatives. Policy scenarios can be easily developed and compared.

Limitations
CMSS does not consider hydrology or any time-variant components so is restricted to long-term average behaviour. CMSS was designed for the typical strategic policy planning process and is not intended to be a substitute for detailed water quality models. It is a useful first-cut tool for any catchment water quality investigation. It comes with extensive supporting material to assist with catchment description and derivation of appropriate generation rates.

Data requirements

Most applications use published data for the loading rates from different land uses, modified for local conditions if suitable data exist. The process of collating the information on land uses, point sources and loading rates can be built into a wider process of stakeholder engagement and so CMSS can be a very useful tool for gaining a shared understanding about the basics of water quality in an area. Unless it is highly tuned to local data, CMSS is not appropriate for use in target setting or applications where accurate quantitative estimates are necessary.

For the model, the following data is needed:
(i) subcatchment map
(ii) land use map (where land uses are differentiated on their nutrient generating capacity)
(iii) nutrient generation rates for these land uses.

For assimilation and routing between subcatchments, the following is needed:
(i) a time of travel coefficient for each subcatchment
(ii) an assimilation coefficient for each subcatchment.

Once the basic data is loaded, WinCMSS predicts the average annual nutrient loads. Additional data can be supplied, e.g. slope, rainfall, which describes the characteristics of the catchments. Then, the power of WinCMSS is that practices and policies can be incorporated involving changes, either in land use or land management, to part of the studied catchment. Variations in model attributes can be used to representation the implementation of policies, either at the whole catchment or individually at sub-basin scales. When assigning practices and policies, the modeler must distinguish between land use and land management. Land use is what the land is actually used for, eg. dairy farming, and land management is how that land use is managed, eg. use of wastewater lagoons below dairy sheds. A distinction is also made between practices and policies. A management practice is an action carried out by a land owner or other person responsible for the land use. A management policy, however, is a statement of intent by a government or other organisation about how they intend to induce land owners to undertake a certain management practice.

References and training

Appendix A in Cuddy and Reed (2005) contains references for an extensive list of papers and documents that describe CMSS and various applications. Some of these are available from the WinCMSS Toolkit Product website.

Training is provided on an as-needs basis by contacting the Product Manager. The model can be obtained from http://www.toolkit.net.au/

System requirements

WinCMSS is programmed in Borland C for Microsoft Windows. It requires at least 16MB of RAM and 10MB of free disk space.

Source

Contact: Susan Cuddy, CSIRO Land and Water, Australia
Phone: (02) 6246 5705
fax (02) 6246 5845
E-mail: Susan.Cuddy@csiro.au

2.4.13 EveNFlow

Description

EveNFlow was developed at ADAS, U.K. as a robust modelling system for estimating inorganic nitrogen fluxes and concentrations in river waters, primarily originating from agricultural land, for any catchment within England and Wales. The system is intended to work in two modes: the national mapping of annual total nitrate losses at a spatial resolution of 1 km^2 and the simulation of daily river flow and nitrate concentrations at the mouths of river catchments that are between 100 and 2,000 km^2 in area.

EveNFlow is a semi-distributed model with five modular components:

Component 1: A soil nitrate model that simulates the soil crop interaction that controls the mass of nitrate present in the soil at the onset of winter drainage that is vulnerable to leaching. The model contains elements of the NITCAT (Lord, 1992), N-CYCLE (Scholefield *et al*., 1991) and MANNER (Chambers *et al*., 1999) field scale models of nitrogen cycling under arable grassland.

Component 2: A soil drainage model composed of elements from the MORECS Hough, M. and Jones, R.J.A. (1997) and IRRIGUIDE (Bailey & Spackman, 1996) evapotranspiration models.

Component 3: A leaching function that predicts the cumulative proportion of available nitrogen that is leached as a function of rainfall and soil water content. The model was derived from the SLIM and SACFARM models (Addiscott and Whitmore, 1991).

Component 4: A drainage routing model based upon a one-dimensional form of TOPMODEL (Beven *et al*, 1995). The model simulates the river hydrograph and mixes rapid and slow soil drainage derived from different depths in the soil profile. The model is parameterized from soil HOST class data (Boorman *et al*, 1995).

Component 5: This estimates nitrate retention in the rivers. Retention in aquifers or the vadose zone is currently not simulated, but can be by application of denitrification rate parameters from de Witt (2001) to the deepest soil water store in the routing model. The retention in the river is calculated on a daily basis using empirical relationships between discharge and channel geometry to estimate the proportion of nitrate removed by bed processes.

Input requirements

The system requires statistical data on land use, farming practices, climate and soil characteristics, collated at a spatial resolution of one square kilometre as a National Environment Database. The data required by each component is described below:
Component 1 (Soil Nitrate):
Crop types and yields, fertilizer and manure management, soil type and characteristics, grazed stocking density, mean climate data.

Component 2 (Soil Drainage):
Soil type and characteristics, daily weather data, crop type.

Component 3 (Soil Leaching):
HOST class, soil type, and characteristics.

Component 4 (Drainage routing):
Soil Host Class.

Component 5 (Nitrate Retention):
River network, river bed characteristics, and point source inputs.

For model validation:

- Observed river flow data time series;
- Observed nitrate concentrations in river.

Outputs

The model outputs daily flow, concentrations and loads, and so is able to capture system dynamics.

Model Advantages:

- Data required are typically widely available;
- In principle the model does not require calibration for application to new catchments;
- EveNFlow is a conceptual approach and is of relatively low to moderate complexity;
- The model components are modular and can be validated independently;
- The model includes snowmelt and in-river retention modules;
- The model operates on a daily time-step

Model Limitations:

- EveNFlow does not explicitly model the interaction between the root zone and groundwater.
- In EveNFlow, crop growth is not subject to nutrient limitation. The model does not simulatel weather related variation in crop yields and does not explicitly model net nitrogen mineralisation.

Spatial resolution

For EveNFlow the smallest unit is 1 km^2. In practice the catchment is subdivided into group response units (1-10 km^2) based upon topography, rainfall and HOST (Hydrology of Soil Types) classes.

Source:

Contact: Dr Steven. G. Anthony, ADAS Woodhorne, Wergs Road, Wolverhampton, WV6 8TQ, UK.

Phone: +44 (0)1902 693192
E-mail: Steve.Anthony@adas.co.uk

Or, Dr Martyn Silgram,
Phone: +44 (0)1902 693354
E-mail: Martyn.Silgram@adas.co.uk

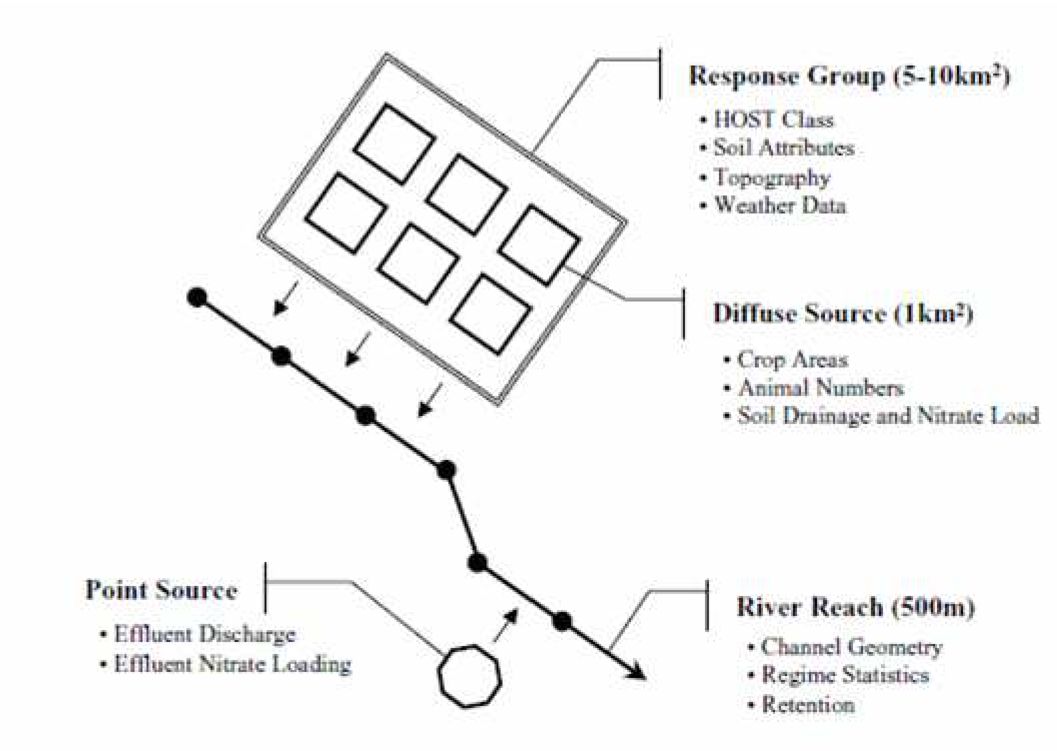

Figure 8 Data structures of EvenFlow

2.4.14 Total Catchment Management (TCM)-Manager

Description:

TCM-Manager, integrates both resource data storage facilities and hydrological and contaminant models into a single, user-friendly, interactive graphical interface to provide both advice on environmental impact of land-use change (expert system) as well as decision support. This method attempts to provide the planner/manager with simple environmental simulation software (Martens and DiBiase, 1996).

TCM-Manager has several practical characteristics intended for total catchment management:
(1) Provision of a natural resource inventory.
(2) Capable of large-scale impact assessment.
(3) Capable of long-term planning of multiple and complex land-use changes.
(4) Suitable for sensitivity analyses.
(5) Assessment of accumulated environmental impact.
(6) Determination of best management practices (BMPs).

Three modules are incorporated into the system architecture:

(1) Database management system: The database management system relies on the input of topographic and land-use information for a given region. This is manipulated to establish the fundamental site MAP. MAP information is contained in several layers including land-use, run-off coefficients, soils, and geology.

(2) Model base management system: The model base module incorporates all hydrological and contaminant modelling algorithms. These are primarily concerned with either simulations of storm events (STORM) or annual estimates (ANNUAL).

(3) Dialogue generation and management system: The dialogue generation and management system allows for selection of appropriate models and provides the frame-work for users to specify scenario queries and reporting formats.

Hardware and software requirements:

IBM PC computer or compatible with more than 8MB main memory
Windows 3.X, Windows 95, NT
C++ compiler

Source:
Contacts: Martens and Associates Pty Ltd., Locked Bag 12, Newton, MSC 2042, Australia.
Phone: +61-2-95195970,
Fax.: +61-2-95191535.
E-mail: ma@mpx.com.au

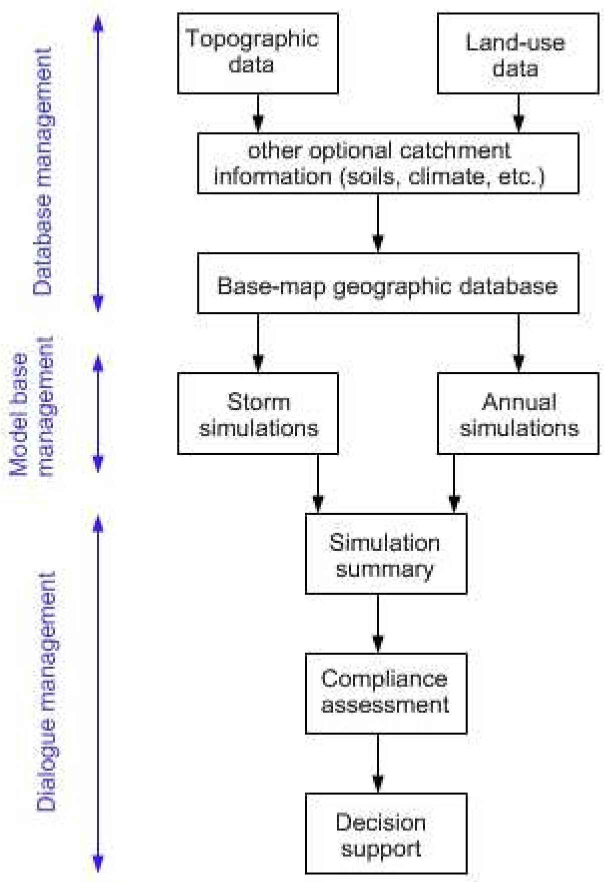

Figure 9 General conceptual architecture of TCM-Manager

2.4.15 Elbe-DSS

Description

The Elbe-DSS is a computer based system for integrated river basin management of the German part of the River Elbe basin. Simulation models are used to assess the performance of measures such as reforestation, changes of agricultural practices or the efficiency of wastewater treatment plants at achieving management targets. The MONERIS, see § 2.4.5 and GREAT-ER (Feijtel, Boeije et al. 1998; Price, Munday et al. 2009) systems are integrated into the Elbe-DSS (Berlekamp, Lautenbach et al. 2007) to assess nutrient and pollutant loads.

MONERIS calculates nutrient inputs from diffuse and point sources on a sub-catchment scale of about 1000 km^2. GREAT-ER is a tool for exposure assessment of point source emissions and considers fate in sewage treatment plants as well as degradation and transport of contaminants in rivers. Both models make long-term predictions, but their spatial scales of operation differ. GREAT-ER divides the whole river network into small segments that are linked through a routing algorithm. The segments are coupled to MONERIS using an accumulated flow length distribution. Linking the two models allows the simulation of both diffuse nutrient emissions (calculated from MONERIS) and point source emissions (from GREAT-ER) to the river network, where further degradation and transport processes are simulated.

Components of the DSS

(i) GIS-based user interface: which allows flexible easy-to-use access to pre- and user-defined scenarios.

(ii) Graphical User Interface: This is in addition to the GIS interface and it integrates a database management system (DBMS) and a knowledge-based toolbox.

(iii) Models (MONERIS and GREAT-ER): MONERIS calculates nutrient inputs of phosphorus and nitrogen into river basins. It simulates the average long-term loads of P- and N from point and non-point sources. It also calculates diffuse inputs caused by erosion, surface runoff, groundwater flow, tile drainage, atmospheric deposition and impervious urban areas for each of the sub-catchments.
GREAT-ER is an aquatic fate and exposure assessment model that calculates concentrations of hazardous substances released by point sources, e.g. sewage treatment plants. The model takes into account emissions from households and industrial inputs, degradation in sewer system and wastewater treatment plants depending on treatment efficiency.
GREAT-ER is able to assess uncertainty in its outputs by running Monte-Carlo simulations, but MONERIS is a deterministic model without the possibility of Monte-Carlo simulations.

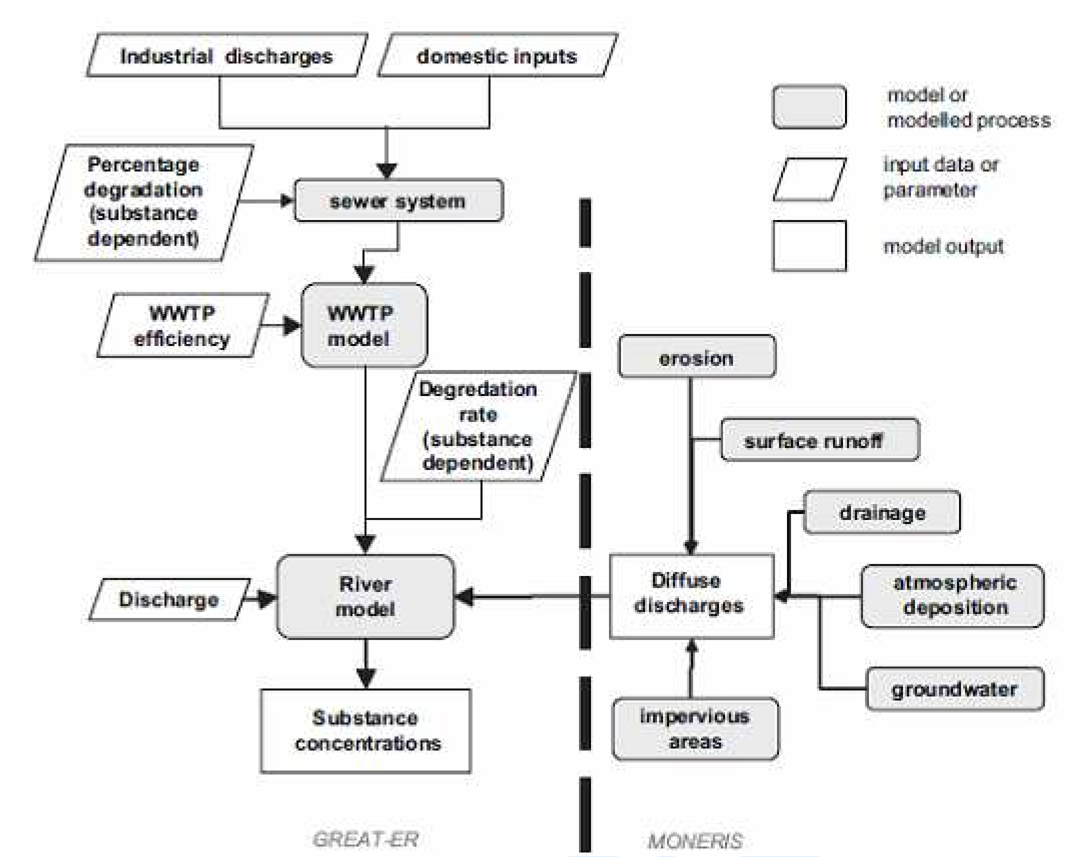

Figure 10 Integrating data and processes between GREAT-ER and MONERIS

Inputs

Input data required by MONERIS are landcover, soils, hydrogeology, catchment boundaries, elevation, municipal census data, river network, and population density. GREAT-ER needs information of discharge attribute, hydrological flow conditions and substance specific data. Discharge attributes are quantified as size and type of the discharge sites, namely connected population, industrial equivalents, mean wastewater flow and the type of wastewater treatment.

Mean and low flow values together with the mean flow velocity are necessary for each river reach. Substance related data can be classified into emission data, physico-chemical properties and more general parameters determining the fate behaviour, e.g. elimination rates, elimination efficiencies in the sewerage system and the sewage treatment plant.

Outputs

MONERIS: N and P loads (see § 2.4.5)

GREAT-ER's direct output is a set of pollutant concentrations at a set of points in a river network.

Hardware and Software Requirements

PC (2000 MHz or more, 1024 MB of
RAM, Windows NT/2000/XP)
Software required: Excel 97 or higher
Program languages: CCC, Python, Fortran77
Program size: 500 MB including data

Availability

Availability: CD from developer, free of charge

Contacts: Dr. Sebastian Kofalk, German Federal Institute
of Hydrology (BfG), Scharrenstr. 2-3, 10178, Berlin, Germany
Phone: +49 30 63986 436
Fax: +49 30 63986 438
E-mail: kofalk@bafg.de

2.4.16 Catchment models as management systems

Some catchment models can be applied to a study area to evaluate some land-use/nutrient management strategies and therefore such models can be classified as management tools. These models are capable of simulating nutrient loss from catchments, would generally be linked with a GIS tool, and would certainly have to be distributed in nature. A number of the catchment models already reviewed (see Appendix C) could strictly be classified as management systems. These are: SWAT, SWIM, INCA-N and INCA-P, APEX, WAFLOOD, ANSWERS, HSPF, and AVGWLF. However, these have not been included in this section as they generally require more expertise from the modeler and/or have other limitations.

2.5. Comparison and Evaluation of existing CMTs

Table 5 summarises the capabilities of the catchment management tools reviewed here. Table 6 lists some of their operating characteristics and Table 7 summarises their input data requirements. All except one (WMS) have some water quality modelling capabilities however, some are limited to sediment, N and P. Those that can simulate more contaminants than sediment, N and P are BASINS, MIKEBASIN and SOBEK. All three can simulate bacteria and other contaminants and could be candidates if an existing catchment management tools were being considered. All three come from organisations with extensive experience of hydraulic and water quality modelling. However, each has some individual disadvantages;

(i) BASINS was developed for use in the USA and is written to interface easily with USA data sources. However, it is possible to edit Irish data sources to comply with the input formats required by Basins ((Nasr, Bruen et al. 2007)). However, this procedure must be done individually for each catchment and might have to be redone each time a new version of BASINS is issued. Although not an ideal solution, an experienced GIS could be trained to perform this step for the program operator. In terms of integrating new pathways into the model, this would require modifying the FORTRAN source code. This procedure has been done in the UCD Centre for Water Resources Research for some of the models, e.g. SWAT and HSPF) but is difficult and requires a specialist hydrological modeller with computer programming experience..

(ii) MIKEBASIN is based on the MIKE SHE hydrological model. This is a distributed physically-based model and is one of the most detailed and complex models available. It is a commercial model so the source code is not normally made available to users to facilitate the incorporartion of additional pathways or modifications of existing pathways are not easily done by the user. Such improvements could be incorporated by the model developer in its upgrade cycle, but this would be subject to negotiation between model users and developer. Specific licences would be required for each user. The MIKE SHE approach (as implemented in SHETRAN) has been tested (and compared to two other hydrological models) in some Irish catchments for modelling phosphorus (EPA LS-2.2.2) and its performance was not the best of the models evaluated.

(iii)SOBEK is used in Holland and concentrates more on the process within channels with less focus on modelling processes within the catchment.

While any of these three models could contribute significantly to catchment management activities, none seem to have the flexibility to address the key focus of the Pathways project on identifying, quantifying and modelling the various pathways of water flow through a catchment and the water quality implications. In particular none can easily incorporate any new conceptualisations that may emerge from the project.

Table 5 Summary of CMTs : modeling capabilities

System	Critical Source Areas	Flow	Water Quality components	Hydraulic attributes (reservoirs, pumps, etc.)	Models Erosion/ Sediment transport/	Models	Suitability for assessing: land-use changes, nutrient management, water measures
BASINS	Can be displayed on GIS map	Yes	Nitrogen, Phosphorous Bacteria, Pesticides (L and C)	Reservoirs Lakes, Dams, Irrigation demand	yes	SWAT HSPF QUAL2E	All 3
MIKEBASIN	Can be displayed on GIS map	Yes	ammonia, nitrate, Total nitrogen oxygen, total phosphorus, E. coli, BOD, and a user-defined substance (e.g., salinity). (L and C)	Reservoirs Hydropower Irrigation demand Lakes	yes	MIKESHE EUROSEM	All 3
WMS	Can be displayed on GIS map	yes	No	Lakes, reservoirs, weirs, culverts	yes	hydrologic models (HEC-1, HEC-HMS, TR-20, TR-55, Rational Method, NFF, MODRAT, OC Rational, HSPF, XPSWMM, and EPA-SWMM.) Hydraulic models (HEC-RAS, XPSWMM, EPA-SWMM, SMPDBK) water quality CE-QUAL-W2.	Water use management
MONERIS	Can be displayed	yes	TN NO3	Retention in lakes	no	MONERIS	Not suitable to assess water measures

System	Critical Source Areas	Flow	Water Quality components	Hydraulic attributes (reservoirs, pumps, etc.)	Models Erosion/ Sediment transport/	Models	Suitability for assessing: land-use changes, nutrient management, water measures
	on GIS map		TP PO4-P (L and C)				
NELUP	Can be displayed (GRASS GIS)	yes	NO3. PO4-P (L and C)	Irrigation demand, dams, lakes	No	SHETRAN ARNO	
NL-CAT	GIS	yes	TN. NO3. NH4. TP.PO4-P (L and C)	Irrigation demand.	yes	SWQN, AMINO, NUSWALITE, SWAP	All 3
TRK system	no	yes	Dissolved organic N/P Total P DIN (dissolved inorganic nitrogen) Total N (L and C)	Dams, lakes, reservoirs, weirs	no	SOILNDB HBV HBV-N TRK-P	All 3 (TRK-N) But not TRK-P
TCM-Manager	no	yes	Total Nitrogen Total Phosphorous Suspended solids (L)	no	no	STORM, ANNUAL	Land use changes and nutrient management only
WAMADSS	Can be displayed on GIS map, or GUI	yes	TN TP (L and C)	Reservoirs Lakes, Dams, Irrigation demand	yes	AGNPS SWAT Cost and Return Estimator (CARE) model	Land use changes and nutrient management only

System	Critical Source Areas	Flow	Water Quality components	Hydraulic attributes (reservoirs, pumps, etc.)	Models Erosion/ Sediment transport/	Models	Suitability for assessing: land-use changes, nutrient management, water measures
CMSS		No	Total phosphorous Total Nitrogen (L)	No	no	No simulation	Land use changes and nutrient management only
SOBEK	yes	yes	CL, salinity, E.Coli, faecal and total, O_2, BOD, temperature, Org C, N, P, and Si, inorganic P, ammonium, nitrate, silica, algae, heavy metals. (L and C)	Operation of pumps, sluice gates, weirs, storage tanks	Only SOBEK-River	SOBEK-Rural SOBEK-Urban SOBEK-River	All 3
Realta	No (only risk areas at the RBD)	no	Soluble inorganic P And Total phosphorous (L)	No		No model	Not suitable at all
EveNFlow	no	yes	Nitrate (L and C)	no	no	Soil nitrate model Soil drainage model Drainage routing model	All 3
WEAP	yes	yes	In-stream WQ only	crop water needs, canal linings, reservoir operations; water conservation strategies; changes in instream flow requirements; new infrastructure	no	WEAP, QUAL2K MODFLOW	All 3

Table 6 Summary of CMTs : operating details

System	Models	Visualisation tool	Time step	Spatial Scale	Empirical/dynamic
BASINS	SWAT HSPF QUAL2E	GIS layers	Daily	Results can be given at field level	Semi-empirical, physically-based
MIKEBASIN	MIKESHE EUROSEM	GIS layers	Daily	Results can be given at field level	Physically-based models used
WMS	hydrologic models (HEC-1, HEC-HMS, TR-20, TR-55, Rational Method, NFF, MODRAT, OC Rational, HSPF, XPSWMM, and EPA-SWMM.) Hydraulic models (HEC-RAS, XPSWMM, EPA-SWMM, SMPDBK) water quality CE-QUAL-W2.	GIS layers	Daily	Results can be given at catchment level	Both empirical and semi-empirical models
MONERIS	MONERIS	GIS layers		Resolution is c. 10 km^2 or more, depending on the resolution of input GIS data layers. Model gives spatial information at sub-catchment level	Physically based
NELUP	SHETRAN ARNO	Own user-interface (maps, plots, etc.)	Daily	SHETRAN: 100m*100m	conceptual, physically-based
NL-CAT	SWQN, AMINO,	GIS	Daily	Model gives spatial	Simple physically-based models

System	Models	Visualisation tool	Time step	Spatial Scale	Empirical/dynamic
	NUSWALITE, SWAP			information at field level	
TRK system	SOILNDB HBV HBV-N TRK-P	GIS layers	Models run at a daily time step, but results are annual normalized coefficients	No limit mentioned Model gives spatial information at field level	Empirical models
TCM-Manager	STORM, ANNUAL	Graphs, plots, outputs to standard GIS packages	Either storm events or annual simulations	Lumped system	
WAMADSS	AGNPS SWAT Cost and Return Estimator (CARE) model	GIS layers, Own Graphical User interface	Daily	Model gives spatial information at farm- /field-level	Semi-empirical, physically-based models
CMSS	No simulation	Own user-interface	annual	Model gives spatial information at field scale	
SOBEK	SOBEK-Rural SOBEK-Urban SOBEK-River	OpenGIS, NETTER	Minutes (lab scale) to decades (morphology)	Grid resolution 1 - 50 m	
Realta	No model		annual Scale	reported success at catchments area of 10-15km^2 Model gives spatial information at sub-catchment level	Risk as phosphorus export rates
EveNFlow	Soil nitrate model Soil drainage model Drainage routing model	No GUI, graphs only	daily time-step	Resolution: 1 km^2 Model gives spatial information at sub-catchment level	
WEAP	WEAP, QUAL2K MODFLOW	GIS layers	Time-step can be between 1 day and 1 year	Catchment level (demands, point sources etc. at nodes)	

Table 7 Summary of CMTs : input data requirements

System	BASINS	MIKEBASIN	WMS	MONERIS	NELUP	NL-CAT	TRK	WEAP	TCM-Manag	WAMADSS	CMSS	SOBEK	Realta
Topography	R	R	R	N	R	R	R	R	R	R	R	R	R
River network	R	R	R	R	R	R	R	R	R	R	R	R	R
Overall catchment information on fertiliser, manure, point sources	R	R	N	N	R	O	R	O	R	R	R	R	R
Land cover map	R	R	R	N	R	R	R	R	R	R	R	R	R
Land Manage-ment Information	R	R	N	N	R	R	R	N	R	R	O	R	N
Soil texture map	R	R	R	R	R	R	R	R	R	R	N	R	R
Soil hydrogeological map	O	O	N	R	O	N	N	N	R	O	N	R	R
Water management information	R	O	N	R	O	R	N	R	N	O	R	R	N
Administrative census information on fertisier, manure, livestock, etc.	R	R	N	R	R	N	R	O	O	O	O	O	N
Point sources location map	R	R	O	R	N	R	R	R	R	R	O	R	R
Weather monitoring stations	R	R	R	R	R	R	R	R	R	R	N	R	N
Surface water monitoring map	R	R	O	R	R	N	R	R	O	R	N	R	R
Groundwater monitoring map	O	O	N	O	N	O	O	R	O	R	N	N	N

R -> Required
O -> Optional
N -> Not required

3. PATHWAYS IN CMTS: -CATCHMENT MODELLING REVIEW

3.1. Introduction

An extensive review of catchment models was undertaken to determine international practice in relation to (i) what hydrological pathways are modelled and (ii) how they are modelled. This will guide the selection of hydrological modelling approach in the development of a catchment management tool and may identify modelling weaknesses or gaps of particular relevance to the Pathways project. Models can be categorised in a variety of different ways. Here, to emphasis our interest in the modelling approach we divide models into (i) physically-based models which are substantially based on equations describing physical laws or relationships and (ii) conceptual models, substantially based on simplified conceptualisations of the important pathways or processes. For some models the difference is quite clear and they are easily classified. However, for others, the difference, e.g. between simplifying a physical relationship and developing a simple conceptual model are not as clear-cut.

3.2. Types of catchment models

Catchment models can be classified under a number of headings, depending on either their physical basis or spatial/temporal resolution. In terms of physical basis there are three generic types

(a) Physically-based models: In these the various hydrological processes are modelled using equations representing the physical laws operating, typically laws of conservation of mass, energy and momentum. Other laws, such as Darcy's, which together with mass conservation, gives Richard's equation are also included in this category.

(b) Conceptual models: In conceptual models, the equations representing the operation of each hydrological process are simplifications of reality, or analogues. For instance a catchment's response to heavy rainfall may be modelled by a series of linear reservoirs, even though a linear reservoir is not a natural occurrence. Also, the flows of water from high to low pressure areas, heat from high temperature to low temperature areas and electricity from areas of high (negative) potential to areas of low potential all are examples of Potential flows. Each obeys the same physical law so that onecan be used as an analogy fror the other.

(c) Empirical/Black box models: In black-box models, equations representing the models behaviour are fitted to measured data. They are typically empirical equations or "systems" modesl such as the unit hydrograph. The equations may be linear or nonlinear and very often are scale specific.

Some disagreement may arise in the classification of catchment models as "physically-based". A strict interpretation of the term would exclude models with any empirical relationship or where the form of the relationship has been derived from data rather than from basic physical principles. This strict interpretation is methodologically impractical as many relationships which are now regarded as physical principles were originally developed from observation and experiment (Darcy's Law is an example). Thus, where the author claims the model to be physically-based we have usually treated it as such, even if it may have one or more empirical or conceptual components.

3.3. Implementation Issues / language/ platform

Implementation issues are less of a constraint, with most programs able to execute on an Intel platform (i.e. a PC) with Windows NT, 2000 or XP. Some packages have implementation issues with Windows Vista. Main memory and external storage are relatively inexpensive and are not constraints. A small number of systems require a UNIX-based platform and/or the GRASS GIS package, but these tend to be the older programs.

3.4. Water Quality Issues suitability for WFD

Our choice of catchment management tools and hydrological models to review was informed primarily by the need to support the WFD with its focus on water quality. Systems or models focussed exclusively on flood forecasting or water quantity regulation and control were not included.

4. PATHWAYS IN PHYSICALLY-BASED MODELS

4.1. Evapotranspiration

Some models require potential evapotranspiration as an input time-series. This can be obtained directly from lysimeter measurements or indirectly by calculation from a number of meteorological measurements. Other models include this calculation within and so require the meteorological data as input time-series.

4.1.1 Energy and Mass balance methods

The computation can be based on some combination of energy balance and mass transfer considerations e.g. Penman, Penman-Monteith, and Priestley-Taylor methods.

Priestley-Taylor

The Priestley-Taylor equation (Priestley and Taylor 1972) is

$$PET_0 = \lambda \frac{s}{s+\gamma}(R_n - G)a$$

Equation 1

Where, λ is the latent heat of vapourisation (MJ/kg); Rs net solar radiation (MJ/m^2/d); G soil heat flux (MJ/m^2/d); s is the slope of the saturation vapour pressure temperature relationship; γ is the psychrometric constant and a is the Priestely-Taylor coefficient representing the fraction of water available for evapotranspiration.

Penman-Monteith

The Penman-Monteith equation is

$$PET_0 = R_s \frac{s}{s+\gamma}\left(\frac{\gamma u_2}{s+\gamma}\right)\left(\frac{r}{T+273}\right)$$

Equation 2

Where, T is air temperature (^{o}C); r is a resistance term and u_2 is wind speed (m/s) at 2 m above the ground.

4.1.2 Methods based on solar radiation and temperature

Some simpler methods are based on solar radiation and temperature e.g. Jensen-Haise and Hargreaves.

Jensen_Haise

The Jensen-Haise equation (Jensen and Haise 1963) is

$$PET_0 = \frac{CT\ (T - T_x) R_s}{\lambda}$$

Equation 3

Where PET_0 is potential evapotranspiration (mm/d); C_T a temperature coefficient; λ latent heat of vaporization (MJ/kg); R_s solar radiation (MJ/m^2/d); T mean temperature for a five day period (^{o}C); T_x is a baseline temperature.

Hargreaves

The Hargreaves equation (Hargreaves and Samani 1982) is

$$PET_0 = 0.0135(T + 17.78) R_s$$

Equation 4

Where, PET_0 is potential daily evapotranspiration (mm/day); T mean temperature (^{o}C) and R_s incident solar radiation expressed as mm (water)/ day

Note, if R_s is expressed as MJ/m^2/day then the equation becomes

$$PET_0 = 0.0135(T + 17.78)\,Rs\left(\frac{238.8}{595.5 - 0.55T}\right)$$

Equation 5

4.1.3 Air temperature and length of day

Some methods depend on the air temperature and length of day e.g. Blaney-Criddle and Hamon (1963).

Blaney-Criddle

The Blaney Criddle formula is

$$PET_0 = p\left(0.46T_{mean} + 8\right)$$

Equation 6

Where, ET_0 is a reference potential evapotranspiration, T_{mean} is a mean daily temperature and, *p* is the mean daily percentage of daylight hours.

Hamon

The Hamon (1963) equation is

$$PET_0 = \frac{29.8\,D\,e_a(T_a)}{T_a + 273.2}$$

Equation 7

Where:
PET_0 = Potential ET (mm/day); D = number of daylight hours (hrs); T_a = mean daily temperature (^{o}C); $e_a(T_a)$ = saturation vapor pressure (kPa) evaluated at the atmospheric temperature T_a.

4.1.4 Survey of use of Potential Evapotranspiration methods

The review of physically-based models shows that the Penman-Monteith method is the most popular evapotranspiration model, used in 15 of the models surveyed, even though it is the most demanding of the methods with regards to data requirements, Figure 1. The Priestley-Taylor (9 models) is also commonly used. Other common evapotranspiration models include: Ritchie, Hargreaves and Hamon. In eight models, potential evapotranspiration is a required input. In another six, event-based, models, evapotranspiration is neglected over the short period of simulation.

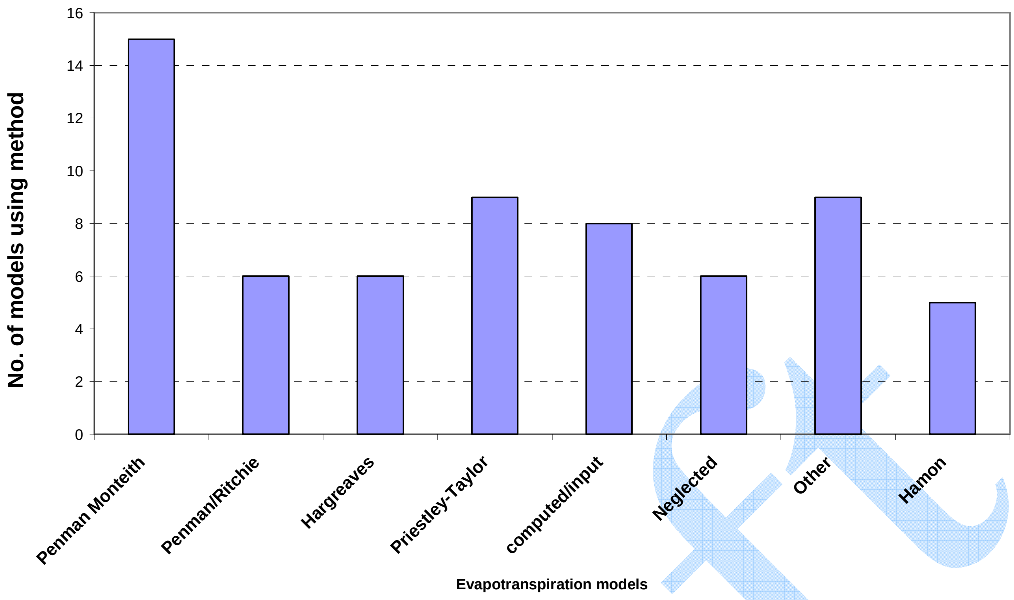

Figure 11 Usage of Potential Evapotranspiration estimation methods in physically based models.

4.2. Infiltration and surface runoff generation

There are a number of mechanisms by which surface runoff may be generated. For instance, the classical Hortonian (infiltration excess) surface runoff occurs whenever the precipitation rate exceeds the soil's rate of infiltration. At the beginning of a rainfall event (assuming the soil is initially dry), the infiltration rate is usually very high due to soil suction. However, this decreases as the soil becomes wetter. When the rainfall intensity is higher than the infiltration rate, surface depressions begin to fill and once all surface depressions have filled, surface runoff commences. In contrast, the Dunne mechanism (saturation excess) relates to runoff generated when the soil surface becomes saturated and cannot accept any infiltration and is associated with a rise in the local watertable.

Most runoff simulation first estimate infiltration and then assume any excess net precipitation becomes runoff. The infiltration calculation may be done using (i) physically based models (e.g.Green and Ampt (1911), Richards (1931) equations, Phillips (1957) equation and Smith and Parlange (1978)), (ii) conceptual models (e.g. Nash 1957) or (iii) empirical relations (e.g. Horton (1933), Holtan (1961), and Soil Conservation Service (1972)). However, an alternative approach is to estimate runoff, e.g. using the Soil Conservation Service's runoff curve number approach and then assume the excess net precipitation becomes infiltration.

4.2.1 Green & Ampt Method

The Green & Ampt equation was originally developed to estimate infiltration in cases where excess water is available at the surface at all times (Green and Ampt, 1911). The method assumes that the soil profile is homogenous and that antecedent moisture is uniformly distributed in the profile. As water infiltrates into the soil, a wetting front is generated and moves downwards. The model assumes the soil above the wetting front is completely saturated and there is a sharp break in moisture content at the wetting front, Figure 12.

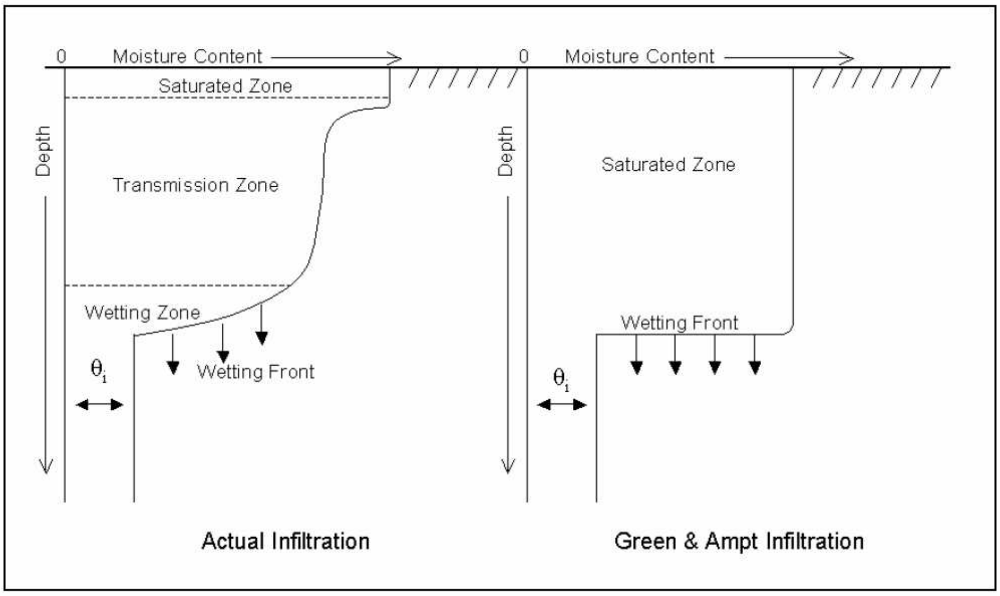

Figure 12 Green & Ampt infiltration method (Neitsch, et al. 2005)

Originally intended for use in event-based modelling, the method was extended to allow multiple successive wetting fronts for use in continuous simulation models, see (Chu and Mariño 2005).

4.2.2 SCS- Curve Number Method (1972)

The SCS-curve number runoff equation is an empirical model that computes the runoff volume for a rainfall event as

$$Q = \frac{(P - I_a)^2}{P - I_a + S}$$

Equation 8

Where, Q is the total runoff volume, P is the precipitation, I_a is an initial abstraction accounting for surface storage, interception and infiltration prior to runoff, and S is a retention parameter. This varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content. It is estimated as a function of a curve number CN which varies non-linearly with the moisture content of the soil. The curve number drops as the soil approaches the wilting point and increases to near 100 as the soil approaches saturation.

4.2.3 Richards Equation

The Richards equation represents the movement of a liquid in a porous material (Richards 1931). It combines the equations of mass conservation with Darcy's law. The equation in two dimensions is

$$C(h)\frac{\partial h}{\partial t}=\frac{\partial}{\partial z}\left(K_x(h)\bullet\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial z}\left(K_z(h)\bullet\frac{\partial h}{\partial z}\right)-\frac{\partial K_z(h)}{\partial z}-S(h)$$

Equation 9

Where *h* is the pressure head, $K_x(h)$ is the lateral hydraulic conductivity, $K_z(h)$ is the vertical hydraulic conductivity, *z* is the distance from the surface, *x* is the horizontal distance, *t* is the time, *C(h)* is the differential water capacity, and *S(h)* represents the volume of water taken up by roots from a unit volume of soil in unit time.

Although Richards equation adequately represents the physics of water movement in unsaturated soil, its solution in two-dimensions is computationally demanding both in terms of mere CPU time and numerical stability (Koivusalo et al., 2002). Therefore while some complex hydrological models retain the full version of the Richards equation (e.g. MIKE SHE, SHETRAN), most tend to simplify the model into a quasi two-dimensional solution. In the quasi-two-dimensional model, the modelling domain is split into vertical columns, and in each column the soil water movement is solved according to a one-dimensional approximation to the Richards equation. A piece-wise linear version can be used in Monte Carlo simulations (Bruen 1995)

4.2.4 Review of use of infiltration methods

A review of infiltration calculation methods for the physically-based models have revealed that the most common models of infiltration and runoff generation are: the Green and Ampt (1911) equation, Richards (1931) equation, and the SCS- curve number method, Figure 13. Other methods used were Smith and Parlange (1978), Holtan's formula, Horton's equation, Overton, and Phillips equation. While the SCS method may be appropriate for catchment models used for flood modelling, methods that take account of some of the controls on infiltration are more appropriate for general use models.

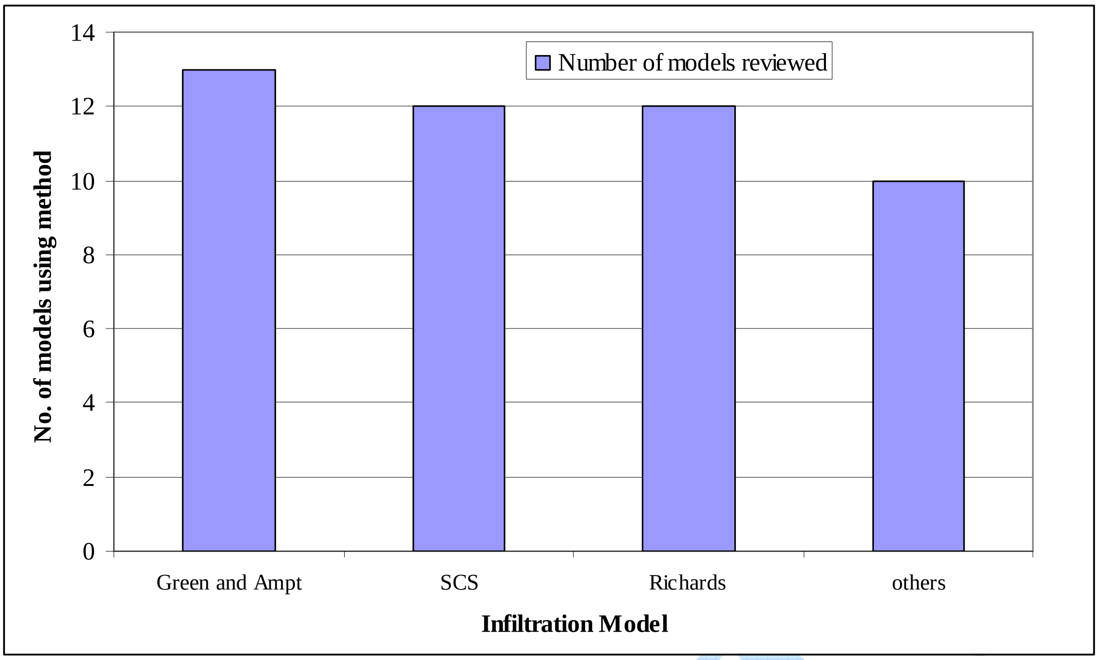

Figure 13 Usage of infiltration estimation methods in physically based models.

4.3. Runoff Routing (physically based models)

Once the rainfall input is divided between infiltration and runoff, the latter must be conveyed to the catchment outlet. Modelling component that do this can range from 'simple' unit hydrographs (Sherman, 1932) to more complex formulations such as the kinematic or diffusive wave equations (Ponce and Simons, 1977, Ponce, 1990 and Singh, 1994), or the complete Saint-Venant (Saint-Venant 1871) equations (Chahinian et al., 2005).

4.3.1 St. Venant Equations

The St. Venant Equations (also called the shallow water equations) are a set of partial differential equations that describe the continuity and dynamic equations of free-surface water in the x- and y-directions. These were derived by depth-integrating the full three-dimensional Navier-Stokes equations.

The basic formulation of unsteady one-dimensional flow in open channels is due to (Saint-Venant 1871). He wrote the continuity equation as

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0$$

Equation 10

where, Q(x,t) is the discharge and A(x,t) the area of flow. The momentum equation can be written in terms of discharge, Q, and cross-sectional area A, i.e. in the 2-dimensional state space form, as

$$\frac{1}{B}\frac{\partial A}{\partial x} + \frac{1}{gA}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + \frac{1}{gA}\frac{\partial Q}{\partial t} = S_0 - \frac{n^2}{A^2 R^{4/3}}|Q|Q$$

Equation 11

where, $B = \frac{\partial A}{\partial z}$ is the top-width of the water surface and z is its elevation.

Equation 10 and Equation 11 or their equivalents, together with appropriate boundary and initial conditions, are the basic equations for both direct flow routing.

4.3.2 Diffusive Wave approximation

The diffusive wave equation is a simplification of the St. Venant equation assuming that the acceleration and inertia forces are neglected (Chanson, 2004), i.e.

$$\frac{1}{B}\frac{\partial A}{\partial x} = S_0 - \frac{n^2}{A^2 R^{4/3}}|Q|Q$$

Equation 12

4.3.3 Kinematic Approximation

The kinematic wave equation is also a simplification of the St. Venant equation assuming that the acceleration and inertia forces in Equation 11 are neglected and the free surface is assumed to be parallel to the bottom (Chanson, 2004). These assumptions reduce the resulting equation to a simple form that can be analytically solved, i.e. either Equation 11 or Equation 12 is replaced by

$$0 = S_0 - \frac{n^2}{A^2 R^{4/3}}|Q|Q$$

Equation 13

This simplicity makes the kinematic wave model the most preferred hydraulic routing method.

4.3.4 Time lag

The time lag factor, commonly referred to as the route and lag method, generally uses the time of concentration (the time required by a drop of water to flow from the remotest area in the catchment to reach the outlet) concept to compute the proportion of runoff that reaches the catchment outlet at a given time.

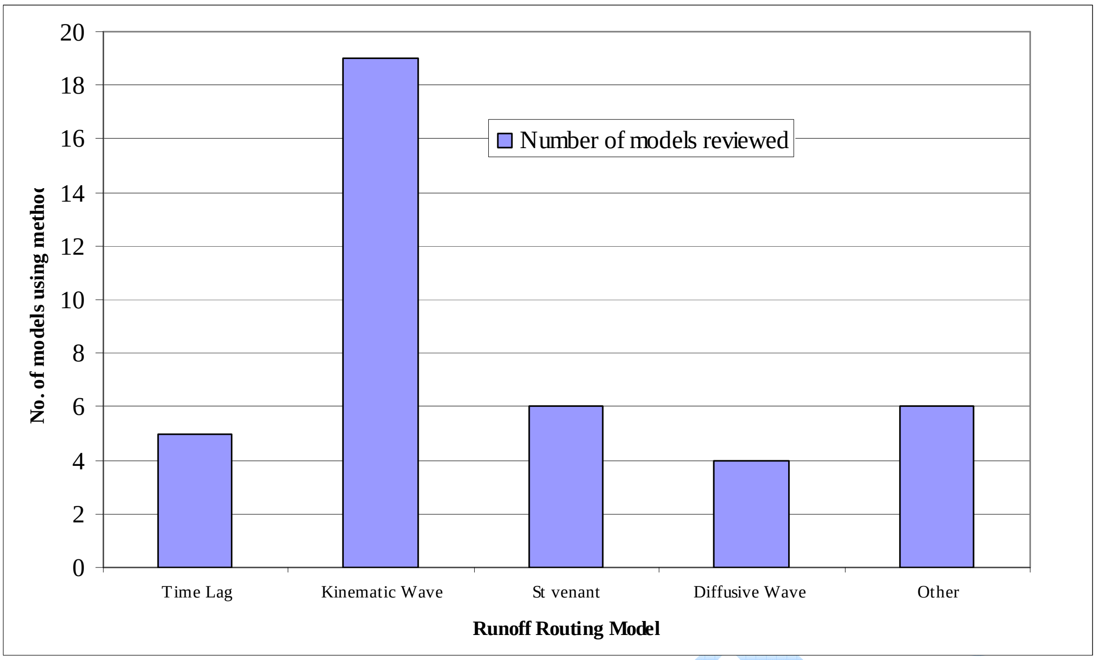

Figure 14 Usage of runoff routing methods in physically based models.

The majority (19) of the models reviewed used the kinematic wave approximation of the St. Venant equation for routing runoff over the catchment surface, Figure 14. Only 5 of the models reviewed used a time lag factor, 6 solved the 2D St. Venant equations, while 4 models applied the diffusive wave approximation of the St. Venant equations. Other runoff routing models were: the multi-flow direction method (Quinn et al., 1991), USDA-SCS synthetic unit hydrograph, and the variable storage coefficient flood routing method (Williams, 1975).

4.4. Unsaturated Soil Water

Once all abstractions are determined, soil moisture accounting is made, which requires an estimate of surface and subsurface flows. This requires an application of the water budget equation. If the portion of the precipitation infiltrating into the soil is estimated, the status of soil moisture is assessed, which is needed to determine the catchment wetness and transform potential evapotranspiration into actual evapotranspiration (Singh and Frevert, 2002)

The unsaturated soil is conceptualised as a single soil layer by most physically-based models. A small number of models divide the soil into a thin upper layer (20mm thickness) or tillage layer which contributes to fast runoff and a soil moisture zone which holds most of the moisture capacity. The water budget equation accounts for the quantification of moisture in the soil layer while a number of models were used to track the movement of moisture in the soil. Examples of these are the Richards equation and the Brooks-Corey equation for the estimation of percolation.

4.5. Groundwater

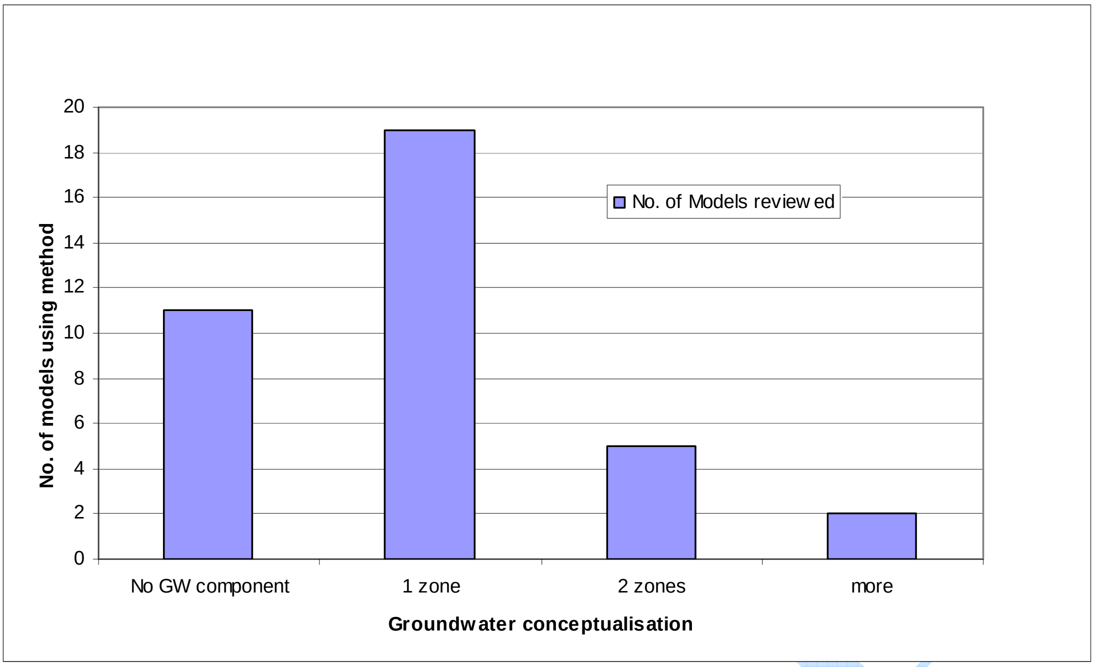

Figure 15 Usage of groundwater conceptualizations in physically based models

The review of the conceptualisation of the saturated soil has shown that most models use one store or layer to represent groundwater, Figure 15. A small number of models have two stores: shallow GW and Deep Groundwater stores. The shallow Groundwater store usually contributes to runoff through baseflow and to the deep store by percolation. The water that percolates into the deep groundwater store is considered to be lost from the system, i.e. does not take any further part in the simulation.

In some models, the groundwater zone can be subdivided into a number of layers/sub-zone where a mass-balance is carried out separately for each layer. Other models neglect groundwater altogether.
The flow of moisture in the groundwater zone is mainly simulated using either Darcy's Law or Richards equation. Most saturated groundwater components receive water the unsaturated soils above and they can contribute to the runoff volume through baseflow. A few models implement additional pathways e.g. exchange of flow with stream, lake-groundwater interactions, well pumping, and well-injection.

4.6. Channel Routing

A review of the methods of channel routing in physically-based models has revealed that similar to the runoff routing, the kinematic wave approximation of the St. Venant Equations was the most preferred option, Figure 16. The Saint Venant equations were also common. The review indicates a slight preference in favour of the Muskingum routing method in comparison to variable storage method and the diffusive wave model. In some models the channel routing process is neglected.

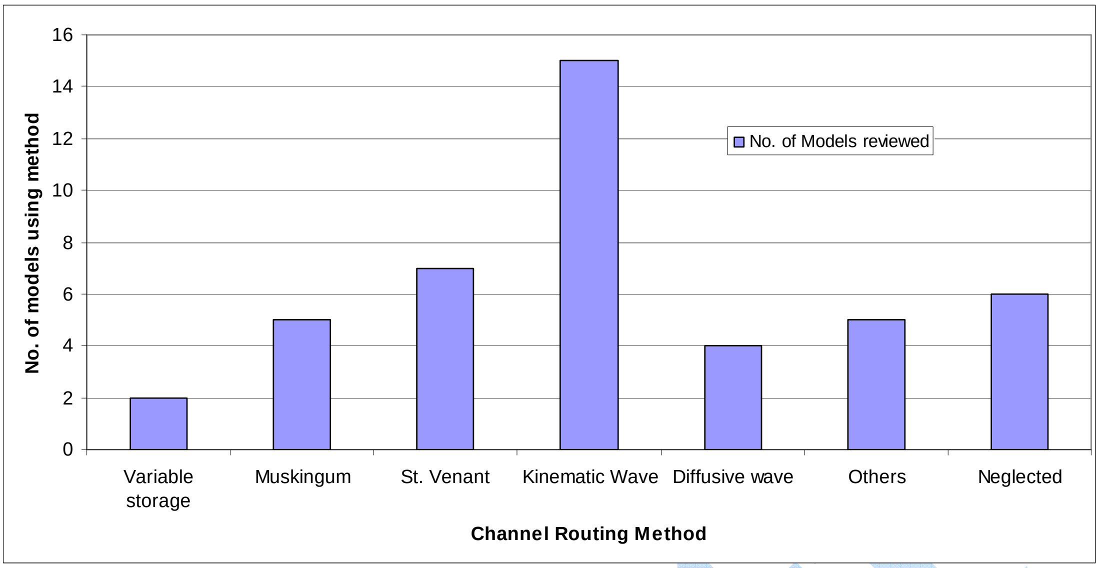

Figure 16 Usage of Channel routing methods in physically based models

5. PATHWAYS IN CONCEPTUAL MODELS

5.1. Infiltration and Runoff Production

The review of physically-based models identified three widely used methods of calculation infiltration and runoff; Green and Ampt infiltration method, Richards' equation, and the SCS method. In contrast, conceptual models make use of a wider variety of methods for the quantification of surface runoff. A small number of models apply the SCS method (HEC-1, SCS-CN Based model, HEC-HMS, SYN-HYD, and ULTRA). A number of models estimate runoff as an infiltration excess by applying common infiltration formulae. For example, HYSIM and SLURP use Philips infiltration equation, HEC-1 and HEC-HMS use Green and Ampt, and ARC/EGMO uses Holtan's formula. Some models apply an initial loss-continuing loss rate infiltration model or user-specified time-varying losses or some other empirical relationships (e.g. WBNM2000, IHACRES, HBV, and SYMHID). TOPMODEL and TOPCAT models combine factors representing the topography of the catchment with a negative exponential law linking the transmissivity of the soil with the distance of the saturated zone below the ground surface.

Some models use the contributing area concept (e.g. PRMS and LBRM). HYRROM, SMAR and CLS apply a linear function with a parameter that controls the proportion of rainfall which enters the soil moisture store.

5.2. Runoff Routing

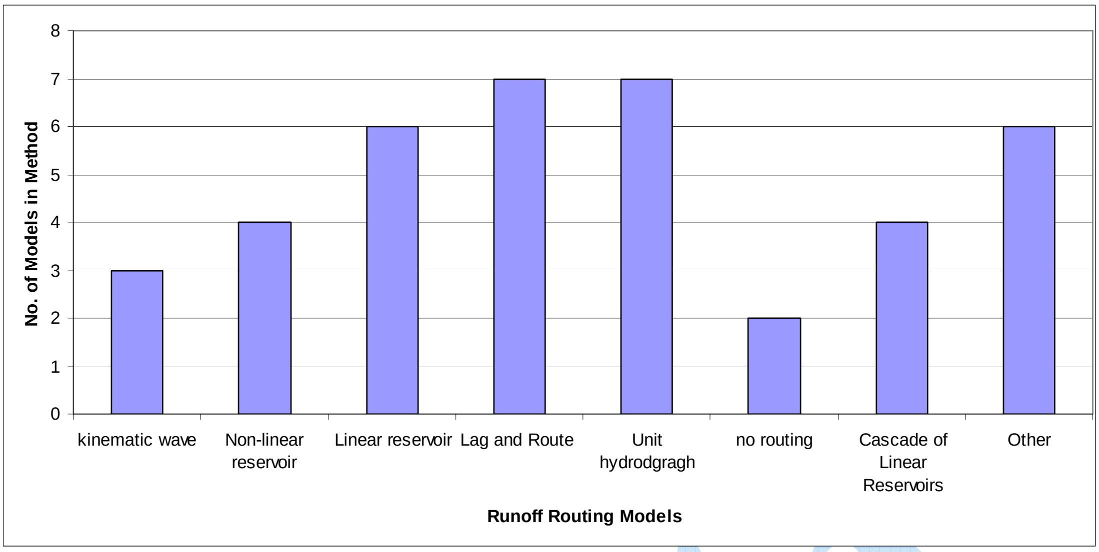

Figure 17 Runoff routing methods in conceptual models

A review of conceptual models has demonstrated a wide range of methods used for runoff routing, Figure 17. The Unit hydrograph method, Linear reservoir and the lag time methods were more commonly used. Other methods included: Nash model or Cascade of linear reservoirs, non-linear reservoir, and the kinematic wave equation.

5.3. Evapotranspiration

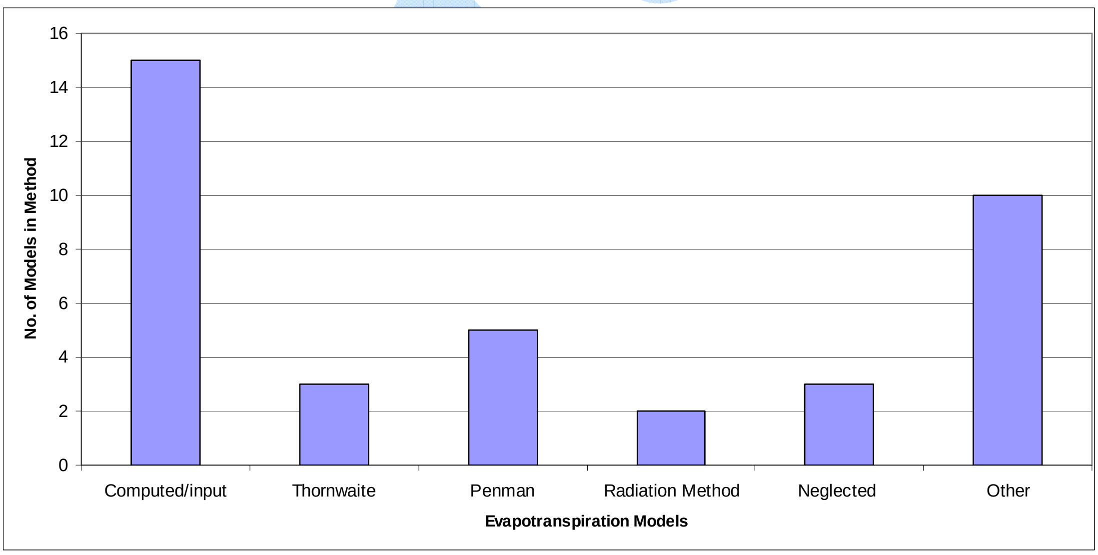

Figure 18 Evapotranspiration estimation in conceptual models

Almost half of the conceptual models examined do not estimate evapotranspiration directly, but do so from a record of potential evapotranspiration which is a required input for these models, Figure 18. The record of potential evapotranspiration may be measured by a lysimeter at a meteorological station or it can be computed from pan evaporation data and other meteorological variables.

Some conceptual models apply physically-based evapotranspiration formulae e.g. the Penman and Penman-Moneith equations. Some empirical models of potential evapotranspiration are also used: e.g. Thorntwaite and Jensen-Haise models. The process is completely neglected in a few of the event-based models (SCS-CN Based Model, SYN-HYD, and ULTRA).

5.4. Unsaturated Soil Water

<u>Figure 19 Representation of unsaturated zone in conceptual models</u>

The unsaturated soil water is conceptualised as a single store in more than half of the conceptual models reviewed. Most of the other models divide the unsaturated zone into an upper and lower soil zone. The upper/surface soil zone usually acts as the active soil moisture store from which some surface runoff and most of the evapotranspiration demand are drawn. It also feeds the lower unsaturated zone. The subsurface/ lower zone acts as a temporary store which feeds the groundwater store by deep percolation to, and in 14 models it also contributes to interflow.

A small number of models conceptualise the unsaturated soil zone as more than 2 layers. For instance, the SMAR model divides the soil moisture storage into layers of 25mm moisture storage capacity each (except for the bottom layer). Also the ARC/EGMO model provides the option of using a multi-layer model for the unsaturated and when chosen, the water movement is modelled using the Richards equation.The stores in the models are either treated linearly or non-linearly. 17 models use the linear reservoir concept while 12 models use non-linear reservoir relationships. A few models (e.g. SCS-CN Based Model, SYN-HYD, and ULTRA) do not model the unsaturated zone explicitly.

Certainly all soil stores account for evapotranspiration, and surface runoff. Deep percolation is included in all models that incorporate a saturated soil zone. However, interflow/subsurface flow is accounted for in only 14 models (less than half of the models in the review).

5.5. Groundwater

Figure 20 Representation of groundwater in conceptual models

The vast majority of the models reviewed conceptualise groundwater as a single store that contributes baseflow to the stream/channel, Figure 20. Only three of the models reviewed (the UBC model, HYSIM, and ARC/EGMO) separate the groundwater into two stores (a shallow/upper store and a deep/permanent groundwater store). Some models neglect the saturated zone altogether (e.g. SCS-CN Based Model, WASMOD, and WBNM2000). Six models provide two subsurface responses (a baseflow response and a slow groundwater flow response).

The stores in the models are either treated linearly (see § 5.6.1 below) or non-linearly (see § 5.6.3 below). Seventeen models use the linear reservoir concept while 9 models have non-linear reservoirs.

5.6. Channel Routing

5.6.1 Linear Reservoir

A linear reservoir is a simple conceptual system in which the output is linearly proportional to a storage amount, Figure 21.

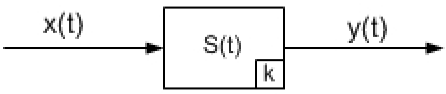

Figure 21 Linear Reservoir

It has a single input time series, *x(t)*, a single output time series, *y(t)* and one parameter, *k*, related by the equations:

$$\frac{dS}{dt} = x(t) - y(t)$$

Equation 14

$$y(t) = \frac{1}{k} S(t)$$

Equation 15

When used in hydrological modeling, *x(t)* and *y(t)* are water flows and *S(t)* is the amount of water in the reservoir. The parameter, *k*, has the dimension of time and is the lag time of the model. The response of a linear reservoir can be represented by an exponential unit hydrograph.

5.6.2 Cascade of linear reservoirs

A cascade of linear reservoir is a sequence of n reservoirs where the output from the first reservoir is the input to the second; the output from the second is the input to the third and so on, Figure 22. Each reservoir has a single parameter (its lag time) and the lag time of the entire cascade is the sum of the individual lag times. This conceptual model is quite effective at modeling small catchment response to rainfall.

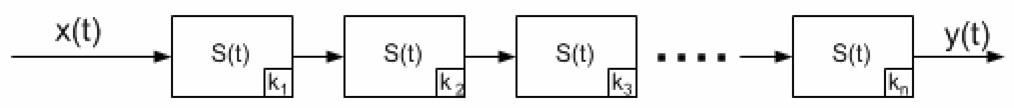

Figure 22 Cascade of reservoirs

5.6.3 Non-linear Reservoir

In a nonlinear reservoir, the conservation Equation 14 remains unaltered, but a non-linear relationship is assumed between the output and the amount of water in the reservoir. While any relationship can be used, a power relationship is typical i.e. Equation 15 becomes

$$y(t) = \frac{1}{k} S^{n}(t)$$

Equation 16

5.6.4 Muskingum method

The Muskingum method is commonly used for simulating reaches of rivers. In it, the storage of water in the reach is assumed to be linearly related to both the inflows and outflows, i.e. instead of Equation 15 or Equation 16, we have

$$S(t) = \frac{1}{k}\left[\alpha x(t) + (1-\alpha)y(t)\right]$$

Equation 17

Where, the additional parameter, α, can vary between 0 and 1, but is rarely above 0.5.

5.6.5 Modified Puls method

The Puls method not a new conceptualization, but is a general technique for routing inflows through a reservoir, channel reach or any storage relationship with outflow. It could be considered an implementation of non-parametric nonlinear storage routing.

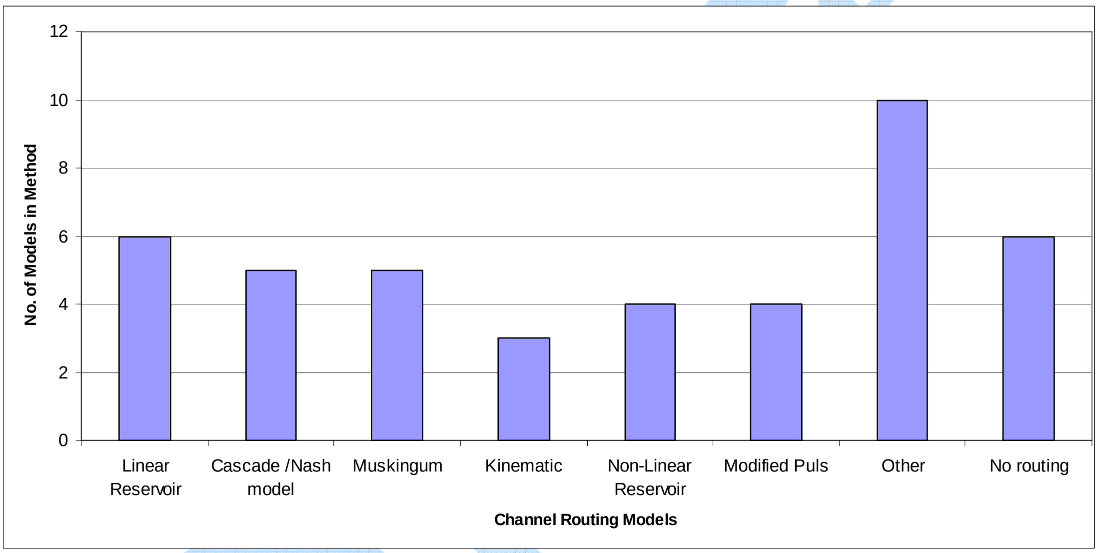

Figure 23 Channel routing methods in conceptual models

The wide range of applied models for the representation of channel routing shows that there is no preference for a specific approach, Figure 23. The methods used include: the linear reservoir concept (single reservoirs, and cascade of reservoirs), non-linear reservoirs, Muskingum, kinematic approximation, and the Modified Puls method. A number of models apply a budget concept at the end of the catchment and therefore do not route the flow down a stream.

6. DISCUSSION OF PATHWAYS

Infiltration and Runoff Generation

The review on physically-based models has shown that the most common approach for quantifying runoff volume is infiltration excess (26 out of 38 models). The most popular methods for infiltration were Green & Ampt method and the Richards equation. In a large number of models, runoff volume was computed using the empirical SCS method.

Runoff generation as infiltration excess was also a common approach in conceptual models (18 out of 33 models). However the review on methods on the quantification of runoff volume in conceptual models has revealed a wide spectrum of methods, the majority of which are empirical and unique.

Runoff Routing

Runoff routing in the reviewed physically-based models relied heavily on St. Venant equations and its approximations, the most popular method being the kinematic wave approximation of St. Venant equation.

In contrast, the choice of runoff routing method in the conceptual models reviewed showed no strong preference for the kinematic wave method. Simple methods e.g. the lag and route method and the unit hydrograph were popular. A wider range of routing models were available and were used by conceptual models in comparison to the physically-based models.

Evapotranspiration

The review on physically-based models has shown that Penman-Monteith is the most commonly used for the quantification of evapotranspiration water. A wide range of models is also noticed.

A large number of conceptual models (15) receive evapotranspiration as a model input (usually measured). The process is neglected in a small number of models but similar to physically-based models a wide range of models is applied.

Soil Water

The unsaturated water zone can be conceptualised as a single, or multi –store zones.

In physically-based models, the single store representation is the most popular. A small number of models use a two-store concept.

Similar to physically-based models, the single unsaturated zone concept is popular in the conceptual models reviewed. However, more conceptual models compared to physically-based models use the two-store concept.

A number of models were able to track the flow in the unsaturated zone in physically-based models e.g. using Brooks-Corey and the Richards equation. In conceptual models, unsaturated zones were simulated using either linear or non-linear relationships.

Groundwater

The review of the conceptualisation of the saturated soil has shown that most models (physically-based and conceptual) use one store or layer to represent groundwater. A small number of models have two stores: shallow GW and Deep Groundwater stores.

Channel Routing

The review has revealed that the kinematic wave model (or the St. Venant equations and its approximations) was the most preferred method in physically-based models. A wide spectrum of channel routing methods was used in conceptual models with no particular preference for a specific method.

7. CMT PERFORMANCE ISSUES

1.1 Ease of use (learning curve)

All CMT systems reviewed here were intended for use by a user with some knowledge and expertise in the scientific or technical areas involved. None were intended for use by the general public. Some require an experienced modeller, but others do not. The use of standard GUI components and a GIS platform (used now by many technical users) facilitates learning.

1.2 Calibration

While many parameters in a CMT have some physical connection and may be estimated indirectly from appropriate data, ideally a CMT will allow at least some of its parameters to be calibrated if sufficient suitable data is available. While it adds another layer of complexity to the tool, it increases its ability to simulate specific catchments.

1.3 Validation

Validation generally requires a calibrated (or otherwise fitted) model to be run with data not used in the calibration and its simulation compared with corresponding measured data. Such "Split sample" techniques are essential to develop confidence in the model, particularly for more complex models with many parameters, where over-parameterisation may lead to the curse of equifinality (Beven 2006).

1.4 Uncertainty analyses

Inceasingly, decision makers are asking, not just for simulations of various management scenarios, but also some information on the uncertainty of the simulation results. This information can inform the choice of a course of action (management scenarios or environmental policies etc.). Modern CMTs can undertake a sensitivity analysis, typically via a Monte Carlo simulation.

1.5 Sensitivity analyses

A related topic is how sensitive the model outputs are to variations in parameter values or input time-series. Many tools address this via the "brute force" method of simulation, although there are some analytical techniques available.

1.6 Expansion

The properties and capabilities of any given CMT represents a particular set of trade-offs between scope/complexity and ease of use/reliability taken by its authors at a particular point in time. For other applications and in other times, further capabilities may be required and a CMT should be able to accommodate such expansion.

8. CONCLUSIONS

The work on producing catchment management tools are been underway for some time and some of the tools identified date from as early as 1989. Some of the management problems and model conceptualisations have not changed very much since then but there is a stronger emphasis on water quality and more concern about a wider range of contaminants now than in the early days. What has changed substantially is the computing power available, the use of GIS and Graphical Windows as supporting technologies. The latter, has facilitated the wider practical use of these tools.

This review of existing CMTs identified three systems (BASINS, MIKEBASIN and SOBEK) which would be candidates if a CMT had to be deployed immediately in Ireland without taking on board any of the scientific results of the Pathways project. The hydrological models underpinning two of these (HSPF (in BASINS)and SHETRAN – similar to MIKE-SHE) have been tested for phosphorus simulation in three small Irish catchments as part of an EPA-funded research project (Nasr, Bruen et al. 2007). HSPF performed better than SHETRAN for these catchments. However none are ideal as all three have various practical disadvantages. In particular, all three have a rigid catchment model structure (although some have multiple models) and lack the flexibility to easily include any new scientific information or conceptualisation that may be generated by this project. Effectively the same modelling structure is used for all parts of the catchment, with spatial variation represented by parameter variation only and not variation in model structure (no existing CMT does this at present). They also have rigid graphical user interfaces which cannot be tailored to match any specific requirements that may emerge from the Pathways end-user workshops. Thus a CMT with a more flexible and accessible modelling structure is required if the results of current research are to be easily incorporated into catchment management.

The review of pathways modelling indicated a very broad range of modelling techniques used for each of the major surface and near-surface pathways. However, there is less variation and flexibility in modelling groundwater pathways, which is a major focus of the Pathways project. This historic focus on surface and near-surface processes is due to many models' origin in flood or water resources applications.

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APPENDIX A: LIST OF CATCHMENT MODELS EXAMINED.

(with reasons for exclusion if not reviewed here)

Model acronym	Full name	Comment
AGNPS	Agricultural Nonpoint Source Pollution Model	Reviewed
APEX	Agricultural Policy/Environmental eXtender	Reviewed
ANSWERS	(Areal Nonpoint Source Watershed Environment Response Simulation	Reviewed
ARC/EGMO		Reviewed
ARNO /NUARNO		Reviewed
CASC2D		Reviewed
CEQUEAU		Reviewed
CHDM	Catchment Hydrology Distributed Model	Reviewed
CLS	Constrained Linear System Model	Reviewed
CREAMS	Chemicals, Runoff, and Erosion from Agricultural Management Systems	Not reviewed: incorporated in SWAT
DHSVM	Distributed Hydrology Soil Vegetation Model	Reviewed
DWSM	Dynamic Watershed Simulation Model	Reviewed
EPIC	Erosion-Productivity Impact Calculator	Reviewed
EUROSEM	European Soil Erosion Model	Reviewed
GBHM	Geomorphology-based hydrological model	Reviewed
GLEAMS	Groundwater Loading Effects of Agricultural Management Systems	Not reviewed: incorporated in SWAT
GLUE	Generalized Likelihood Uncertainty Estimation	Not reviewed: numerical method in TOPMODEL

Model acronym	Full name	Comment
GWLF/AVGWLF	Generalized Watershed loadings Function	Reviewed
HBV	Hydrologiska Byråns Vattenbalansavdelning	Reviewed
HEC-1	The Hydrologic Engineering Center (HEC), U.S. Army of Corps of Engineers	Reviewed
HEC-HMS	Hydrologic Engineering Center (HEC) – Hydrological Modelling System	Reviewed
HMS	Hydrological Modelling System	Reviewed
HSPF	Hydrologic Simulation Program-Fortran	Reviewed
HYDROTEL		Reviewed
HYMOD	Hydrologic MODel	Reviewed
HYRROM	Hydrological Rainfall Runoff Model	Reviewed
HYSIM	Hydrologic Simulation Model	Reviewed
IHACRES	Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data	Reviewed
INCA	Integrated Nitrogen in. CAtchments model	Reviewed
IHDM	Institute of Hydrology Distributed Model	Reviewed
IHM	integrated Hydrologic Model	Not reviewed: combination of HSPF and MODFLOW
InHM	Integrated Hydrology Model	Reviewed
ISBA-MODCOU		Reviewed
IWFM	Integrated Water Flow Model	Reviewed
KINEROS	kinematic runoff and erosion model	Reviewed
LASCAM	Large-Scale Catchment Model	Reviewed
LBRM	Large Basin runoff model	Reviewed
LISEM	Limburg Soil Erosion Model	Reviewed
MIKE-SHE		Reviewed
NWSRFS	National Weather Service River Forecast System	Not reviewed: Weather-River

Model acronym	Full name	Comment
		Forecasting system
NAM	Nedbor Afstromning Modele	Reviewed
OPUS		Reviewed
PARCHED-THIRST		Reviewed
PDM	Probability Distributed Model	Reviewed
PRMS	Precipitation-Runoff Modeling System	Reviewed
PRZM/PRZM3	Pesticide Root Zone Model	Reviewed
PSRM	Penn State Runoff Model	Reviewed
RORB		Reviewed
SAMS2000	Stochastic Analysis, Modelling, and Simulation	Not reviewed: Stochastic model
SCS-CN		Reviewed
SEFM	Stochastic Event flood modelling	Not reviewed: Stochastic model
SHETRAN		Not reviewed: River water quality model
SIMCAT		Reviewed
SIMHYD		Reviewed
SIRG	Numerical Model of Surface Runoff, Infiltration, River Discharge, and Groundwater Flow	Reviewed
SLURP	Semi-distributed Land Use-based Runoff Processes	Reviewed
SMAR		Reviewed
SMDR	Soil Moisture Distribution and Routing	Reviewed
SRM	Snowmelt Runoff model	Not reviewed: no pathways in model
SSARR	Streamflow Synthesis and Reservoir Regulation	Reviewed
STORM		Not reviewed: urban model
SWAT	Soil Water and Assessment Tool	Reviewed
SWIM	Soil and Water Integrated Model	Reviewed
SWMM	Storm Water Management Model	Reviewed
SWRRB	Simulator for Water Resources in Rural Basins	Not reviewed: incorporated in SWAT

Model acronym	Full name	Comment
SYNHYD		Reviewed
Tank		Reviewed
Thales C		Reviewed
TOPCAT		Reviewed
TOPKAPI		Reviewed
TOPMODEL		Reviewed
TOPOG		Reviewed
TREX	Two-Dimensional Runoff Erosion and Export	Reviewed
UBC	University of British Colombia Watershed Model	Reviewed
ULTRA	unitgraph lumped technical review and analysis model	Reviewed
URBS	Urban Runoff Branching Structure	Not reviewed: Urban Model
UTM-TOX	Unified Transport Model for Toxic Materials	Not reviewed: obsolete
VIC	Variable Infiltration Capacity	Reviewed
WaSIM-ETH		Reviewed
WASMOD	water and snow balance modeling system	Reviewed
WATEM		Not reviewed: erosion and Tillage model – no proper representation of flow pathways
WATFLOOD/SPL9		Reviewed
WBNM2000	Watershed Bounded Network Model	Reviewed
WEPP	Water Erosion Prediction Project	Reviewed
WISTOO		Reviewed
Xinanjiang		Reviewed

APPENDIX B : BRIEF DESCRIPTION OF CATCHMENT MODELS

ISBA-MODCOU

ISBA-MODCOU is a coupled model between the MODCOU macro-scale hydrological model and the ISBA land surface scheme.

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Distributed, physically-based, continuous-simulation Hydrological Unit: square grid cells.
Origin (development and maintenance)	MODCOU developed at Ecole des Mines de Paris/CIG, UMR CNRS Sisyphe Fontainebleau, France ISBA developed at Météo-France/CNRM, Tououse, France
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** **Operating System:** **Open source:** **Computer Language:** **GIS-based:** **Visualisation facilities:**
Pathways and processes modelled	Surface runoff, infiltration, evapotranspiration, soil water storage, groundwater and river/aquifer exchange.
Inputs (data requirements)	Daily precipitation, potential evapotranspiration
Outputs	Flow at outlet and stream flow.
Calibration Method	
Parameters	
Water quality constituents	None
Case Studies / Publications	Caballero, Y., Voirin-Morel, S., Habets, F., Noilhan, J., LeMoigne, P., Lehenaff, A., and Boone, A. (2007). Hydrological sensitivity of the Adour-Garonne river basin to climate change. Water Resources Research, Vol. 43, No. 7, W07448.

	Habets, F., LeMoigne, P., and Noilhan, J. (2004). On the utility of operational precipitation forecasts to served as input for streamflow forecasting. Journal of Hydrology, Vol. 293, No. 1-4, pp. 270-288
Assumptions/Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: P.Etchevers/ F. Habets/ J. Noilhan/ and S.Voirin Météo-France/CNRM, Toulouse, France E.Ledoux /C. Golaz Ecole des Mines de Paris/CIG UMR CNRS Sisyphe, Fontainebleau, France

CLS Model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Lumped, conceptual, continuous-simulation
Origin (development and maintenance)	Developed by E. Todini and L. Ciarapica. Department of Earth and Geo-Environmental Sciences, University of Bologna, Bologna, Italy
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open source:** Yes **Computer Language:** FORTRAN **GIS-based:** No **Visualisation facilities:** No graphical user interface
Pathways and processes modelled	Evapotranspiration, soil moisture, groundwater, runoff generation, runoff routing, and channel routing
Inputs (data requirements)	Rainfall and potential evapotranspiration
Outputs	Surface and subsurface runoff
Calibration Method	2nd order gradient method (automatic calibration)
Parameters	
Water quality constituents	None

Case Studies / Publications	Datta, B. and Lettenmaier, D. P. (1985). A nonlinear time-variant constrained model for rainfall-runoff, Journal of Hydrology, Vol.77, No. 1-4, pp. 1-18. Selvalingam, S. and Sally, M.H. (1981). Modeling Of A Small Catchment In Central Java Through Cls Model. USDA, Agricultural Research (Southern Region), pp. 134-135. Todini, E. (1978). Using A Desk-Top Computer For An On-Line Flood Warning System. IBM Journal of Research and Development, v 22, n 5, pp. 464-471.
Versions	SCLS (CLS + soil moisture accounting model of the Xinanjiang model)
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	**How to obtain Model:** contact Prof. E. Todini, Department of Earth and Geo-Environmental Sciences, University of Bologna, Via Zamboni, 67 40127 Bologna Italy Phone: +39-051-2094537 ezio.todini@unibo.it **Documentation:** Not available in the public domain but it can be obtained from Professor Todini. Cost: free of charge

Probability Distributed Model (PDM)

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Lumped, conceptual, continuous-simulation
Origin (development and maintenance)	Centre for Ecology and Hydrology, Wallingford, U.K.

Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open source:** No **Computer Language:** FORTRAN **GIS-based:** No **Visualisation facilities:** model has a graphical user interface
Pathways and processes modelled	Evaporation, surface runoff, infiltration, percolation (groundwater recharge), and groundwater flow.
Inputs (data requirements)	Rainfall and potential evapotranspiration
Outputs	Surface runoff and groundwater flow
Calibration Method	Model calibration by automatic optimisation and by interactive visualisation.
Parameters	Model has 18 parameters (See Table 1 in Moore (2007).
Water quality constituents	None
Case Studies / Publications	Cabus, P. (2008) River flow prediction through rainfall-runoff modelling with a probability-distributed model (PDM) in Flanders, Belgium. Agricultural Water Management, Vol. 95, No. 7, pp. 859-868. Moore, R.J. and Bell, V.A. (2002). Incorporation of groundwater losses and well level data in rainfall runoff models illustrated using the PDM. Hydrology and Earth System Sciences, 6(1), 25-38. Moore, R.J. (2007). The PDM rainfall-runoff model. Hydrology and Earth System Sciences, 11(1), 483-499.
Assumptions and Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: Robert J. Moore Head, Hydrological Modellling & Forecasting Group Centre for Ecology & Hydrology Crowmarsh Gifford Wallingford Oxfordshire OX10 8BB United Kingdom

	Tel: +44(0)1491 692262 Fax: +44(0)1491 692424 email: rm@ceh.ac.uk Cost: £2000 (ex VAT) per PC installation for commercial use. Discount available for academic use

TOPCAT-NP

TOPCAT is a simple hydrological model (simplification of the model TOPMODEL) that provides time series modelling of flow and of nitrate, phosphates and phosphorus.

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	lumped conceptual hydrological model, event-based
Origin (development and maintenance)	Developed by P.F. Quinn, C.J.M. Hewett and N.D.K. Dayawansa at the university of Newcastle Upon Tyne, U.K.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows, DOS **Open source:** **Computer Language:** FORTRAN **GIS-based:** no **Visualisation facilities:** no GUI, results displayed as graphs
Pathways and processes modelled	Surface runoff, subsurface flow, Channel routing, infiltration and saturation excess runoff, interception, evapotranspiration, baseflow, nitrogen and phosphorus.
Inputs (data requirements)	Rainfall, observed runoff hydrograph, potential evapotranspiration
Outputs	Runoff hydrograph, baseflow
Calibration Method	Automatic also uncertainty analysis routine Generalised Likelihood Uncertainty Estimation (GLUE).
Parameters	Parameters are intended to be physically interpretable and their number is kept to a minimum. Critical

	parameters: saturated zone parameter, the saturated transmissivity values, and the root zone parameter and in large catchments a channel routing velocity.
Water quality constituents	Nutrients: Nitrogen and Phosphorus
Case Studies / Publications	Quinn, P.F., Hewett, C.J.M., and Dayawansa, N.D.K. (2008). TOPCAT-NP: A minimum information requirement model for simulation of flow and nutrient transport from agricultural systems. Hydrological Processes, Vol. 22, No. 14, pp. 2565-2580 Quinn, P., Gallart, F., Llatron, J., and Russell, K. (1998). Nesting localized patch models and data within catchment models and data. IAHS-AISH Publication, No. 248, pp. 275-281. Hewett, C. J.M., Quinn, P. F., Heathwaite, A. L., Doyle, A., Burke, S., Whitehead, P. G., and Lerner, D. N. (2009). A multi-scale framework for strategic management of diffuse pollution. Environmental Modelling and Software, Vol. 24, No. 1, pp. 74-85.
TOPCAT and TOPMODEL	TOPCAT is a simplification of the model TOPMODEL (Quinn and Beven 1993, Beven et al. 1995) and as such, uses identical soil moisture stores and subsurface flow equations. TOPCAT does not, however use a topographic distribution function and thus does not allow the representation of topographically controlled variable source areas. The model TOPCAT also contains an extra baseflow/dry weather flow component and two overland flow components that are caused by intense agricultural management practices.
Versions	TOPCAT-N, TOPCAT-P.
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	How to obtain Model: Contact: Dr. P.F. Quinn, School of Civil Engineering and Geosciences, Newcastle University, Newcastle Upon Tyne NE1 7RU, UK. E-mail: P.F.Quinn@ncl.ac.uk Cost: Free of charge

Pesticide Root Zone Model (PRZM) and PRZM3

Model Type (lumped or distributed), event-based or continuous	one-dimensional, finite-difference model that accounts for pesticide and nitrogen fate in the crop root zone. Physically based, continuous-simulation
Origin (development and maintenance)	Developed by the EPA Athens laboratory (Carsel et al., 1984) for modelling the fate of pesticides within the crop root zone, and subsequent leaching to groundwater
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open source:** yes **Computer Language:** FORTRAN **GIS-based:** no **Visualisation facilities:** no GUI, results are displayed as graphs
Pathways	Pesticide and nitrogen fate in the crop root zone and the unsaturated zone, infiltration, evapotranspiration, percolation, and runoff. chemical uptake by plants, surface runoff, erosion, decay, volatilization, foliar washoff, advection, dispersion, and retardation.
Inputs (data requirements)	Rainfall, pan evaporation, solar radiation, temperature, and wind speed, pesticide loading
Outputs	Runoff, sediment yield, nitrogen and pesticide loads.
Calibration Method	Model incorporates Monte Carlo simulation.
Parameters	Physically-based parameters that can either be measured or obtained from literature. In absence of values, they can be calibrated. A Monte-Carlo simulation module is incorporated. It reads special data for parameters to be varied (e.g., distribution types and moments) and output variables to be observed, generates random numbers, correlates them and performs transformations, exchanges these generated values for PRZM-3 parameters, performs statistical analysis on the output variables, and writes out statistical summaries for the output variables.
Water quality constituents	Chemicals, pesticides, and nitrogen
Case Studies / Publications	Ma, Q.L., Wauchope, R.D., Hook, J.E., Johnson, A.W., Truman, C.C., Dowler, C.C., Gascho, G.J., Davis, J.G., Sumner, H.R., and Chandler, L.D. (1998).GLEAMS, Opus and PRZM-2 model predicted versus measured runoff from a coastal plain loamy sand. Transactions of the American Society of Agricultural Engineers, v 41, n 1, pp. 77-88. Young, D. F., and Carleton, J. N. (2006).Implementation of a probabilistic curve number method in the PRZM

	runoff model. Environmental Modelling and Software, v 21, n 8, pp. 1172-1179. Zacharias, S., and Heatwole, C.D. (1994). Evaluation of GLEAMS and PRZM for predicting pesticide leaching under field conditions. Transactions of the American Society of Agricultural Engineers, v 37, n 2, pp. 439-451. Banton, O., and Villeneuve, J.-P. (1989). Evaluation of groundwater vulnerability to pesticides: A comparison between the pesticide DRASTIC index and the PRZM leaching quantities. Journal of Contaminant Hydrology, v 4, n 3, pp. 285-296. Smith, M.C., Bottcher, A.B., Campbell, K.L. and Thomas, D.L. (1991). Field testing and comparison of the PRZM and GLEAMS models. Transactions of the American Society of Agricultural Engineers 34 3, pp. 838–847.
Versions	PRZM3- links two models PRZM and VADOFT in order to predict pesticide transport and transformation down through the crop root and unsaturated zone. PRZM releases: 3.12.3 (2006), 3.12.2(2005), 3.12.1 (2003), 3.12beta(1998), 2.3 (1996), 2.00 (1994), 1.02 (1993), 1.00(1992)
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Technical Support, Contact CEAM at: Phone: 706-355-8400 Fax: 706-355-8104 E-mail: ceam@epamail.epa.gov Mail: Center for Exposure Assessment Modeling (CEAM) National Exposure Research Laboratory - Ecosystems Research Division U.S. Environmental Protection Agency (U.S. EPA) 960 College Station Road Athens, Georgia 30605-2700 PRZM3 model system with documentation is available for microcomputer (DOS) systems, and can be downloadable from: http://www.epa.gov/ceampubl/gwater/przm3/przm3123.html

	Cost: Free of charge

VIC

Variable Infiltration Capacity Model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	semi-distributed grid-based hydrological model, conceptual hydrological unit: irregular cells (horizontal), layers (vertical)
Origin (development and maintenance)	Originally developed by Xu Liang at the University of Washington
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Unix, Linux, DOS, Windows **Open source:** yes **Computer Language**: C **GIS-based:** yes, ARC/INFO **Visualisation facilities:** GIS
Pathways and processes modelled	Runoff, evapotranspiration, infiltration, percolation, baseflow.
Inputs (data requirements)	Rainfall, sub-daily air temperature, maximum and minimum daily temperature, atmospheric vapour pressure, wind speed, shortwave radiation
Outputs	Baseflow, runoff, total evaporation, and moisture content of soil layers.
Calibration Method	random autostart simplex method and the Genetic optimization
Parameters	Sensitivity analysis: Lohmann et al. (1998); Xie and Yuan (2006)
Water quality constituents	None
Case Studies / Publications	Linde, A., Aerts, J., Dolman, H., and Hurkmans, R. (2007). Comparing model performance of the HBV and VIC models in the Rhine basin. IAHS-AISH Publication: Quantification and Reduction of Predictive Uncertainty for Sustainable Water Resources Management, No. 313, pp. 278-285. Lohmann, D., Raschke E., Nijssen, B., and Letternmaier, D.P. (1998). Regional scale hydrology: I. Formulation

	of the VIC-2L model coupled to a routing model. Hydrological Sciences Journal, Vol. 43, No. 1, pp. 131-141. Chen, J., and Wu, Y. (2008). Exploring hydrological process features of the East River (Dongjiang) basin in South China using VIC and SWAT. IAHS-AISH Publication: Hydrological Sciences for Managing Water Resources in the Asian Developing World, No. 319, pp. 116-123. Lohmann, D. , Raschke, E., Nijssen, B., and Letternmaier, D.P. (1998). Regional scale hydrology: II. Application of the VIC-2L model to the Weser River, Germany. Hydrological Sciences Journal, Vol. 43, No. 1, pp. 143-158. Xie, Z., and Yuan, F. (2006). A parameter estimation scheme of the land surface model VIC using the MOPEX databases. IAHS-AISH Publication, No. 307, pp. 169-179. Xie, Z., Liu, Q., and Su, F. (2004). An application of the VIC-3L land surface model with the new surface runoff model in simulating streamflow for the Yellow River basin. IAHS-AISH Publication, No. 289, pp. 241-248.
Assumptions and Limitations	
Versions	VIC-2L, VIC-3L
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contacts: Dennis P. Lettenmaier Department of Civil and Environmental Engineering ,University of Washington 202D Wilson Ceramic Lab, Box 352700 University of Washington Seattle, WA 98195-2700 ph 206-543-2532 fx 206-616-6274 dennisl@u.washington.edu Or vicadmin@hydro.washington.edu Documentation: http://www.hydro.washington.edu/Lettenmaier/Models/VIC/VIChome.html

Lohmann, D., Raschke, E., Nijssen, B., and Letternmaier, D.P.(1998). Regional scale hydrology: II. Application of the VIC-2L model to the Weser River, Germany. Hydrological Sciences Journal, Vol. 43, No. 1, pp. 143-158.

ULTRA

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	lumped conceptual, event-based
Origin (development and maintenance)	Developed by J.F. Sabourin at Paul Wisner and Associates Inc., based on concepts developed by Dr. Paul Wisner and Messrs. J. P'Ng, A. Lam, and D. Jobin at the University of Ottawa.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open source:** **Computer Language**: BASIC **GIS-based:** No **Visualisation facilities:** No
Pathways and processes modelled	unit hydrograph and rainfall losses
Inputs (data requirements)	Rainfall
Outputs	Tabular and graphical displays of the hydrograph and hyetograph are available.
Calibration Method	Manual
Parameters	Two parameters define the shape of the unit hydrograph, two parameters define the shape of the unit hydrograph
Water quality constituents	No
Case Studies / Publications	ULTRA's sub-models are based on algorithms developed in the PC Interhymo (Otthymo 89) model. The Otthymo 89 model has been applied with success throughout Canada as well as in basins in Switzerland, Italy, Spain, Portugal, Cameroon, and the United States of America. It has been applied by over 50 Canadian organizations and is a recommended model in several Canadian guidelines for flood control and storm water management.
Assumptions/Limitations	
Versions	

How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	How to obtain model: from the HOMS National Reference Centre for Canada **Contact:** Mr K. David Harvey Atmospheric Environment Service, Environment Canada La Salle Academy, 373 Sussex Dr., Room E-122 Ottawa, Ontario K1A OH3 Tel: +(613) 992 28 74 Fax: +(613) 992 42 88 Email: Dave.Harvey@ec.gc.ca **Cost:** Free of Charge

SYNHYD

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Conceptual, lumped-parameter, event-based
Origin (development and maintenance)	Developed by Gert Aron at the Pennsylvania State University, U.S.A
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** DOS **Open source:** **Computer Language:** GWBASIC **GIS-based:** No **Visualisation facilities:** No
Pathways and processes modelled	Surface runoff and losses.
Inputs (data requirements)	Rainfall, subarea dimensions, travel times

Outputs	Runoff hydrographs
Calibration Method	Manual
Parameters	Rainfall, travel times, curve numbers
Water quality constituents	None
Case Studies / Publications	Seliga, T. A., G. Aron, K. Aydin, and E. White, 1992. Storm Runoff Simulation Using Radar Rainfall Rates and a Unit Hydrograph Model (SYN-HYD) Applied to GREVE Watershed. In: Am. Meteor. Soc., 25th mt. Conf. on Radar Hydrology, pp. 587-590.
Assumptions/Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	To obtain model contact: Gert Aron, Professor Emeritus of Civil Engineering, Department of Civil and Environmental Engineering, Pennsylvania State University Sackett Building E-mail: gxa4@psu.edu

Large Basin Runoff Model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Conceptual, lumped-parameter, continuous-simulation
Origin (development and maintenance)	Developed by Dr. Thomas E. Croley II and Timothy S. Hunter, Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration (NOAA).
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** MS-DOS, Windows **Open source:** Yes **Computer Language:** FORTRAN 95

	GIS-based: No **Visualisation facilities:** a simple windows-based application, no visualisation tool for outputs.
Pathways and processes modelled	Surface runoff, evapotranspiration, infiltration, interflow, groundwater flow, and percolation.
Inputs (data requirements)	Daily precipitation, temperature, solar radiation, observed outflow (for model calibration);
Outputs	Surface runoff, interflow and groundwater flow.
Calibration Method	Model is calibrated by applying a systematic search of the parameter space to minimize the root-mean-squared-error between observed and simulated outflow. This procedure in implemented in FORTRAN 95.
Parameters	Model has 9 empirical parameters. A calibration example in which the possible values and ranges of the 9 parameters is presented in Crowley (2002).
Water quality constituents	no
Case Studies / Publications	Croley, T. E., II (1987). Great Lakes Large Basin Runoff Model. ASCE, pp. 14-19. Croley, T. E., II, He, C., and Lee, D. H. (2005). Distributed-parameter large basin runoff model. II. Application Journal of Hydrologic Engineering, Vol. 10, No. 3, pp. 182-191. He, C., and Croley, T. E., II (2007). Application of a distributed large basin runoff model in the Great Lakes basin. Control Engineering Practice: Special Section on Modelling and Control for Participatory Planning and Managing Water Systems, Vol. 15, No. 8, pp. 1001-1011. Croley, T. E., II, and He, C. (2006). Watershed surface and subsurface spatial intraflows model. Journal of Hydrologic Engineering, Vol. 11, No. 1, pp. 12-20. Watkins Jr., D. W., Li, H., Thiemann, K. A., Adams III, T. E. (2003). Radar Rainfall Estimates for Great Lakes Hydrologic Models. World Water and Environmental Resources Congress, pp. 1449-1458.
Assumptions and Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contacts: Dr. Thomas E. Croley II (tom.croley@noaa.gov) Timothy S. Hunter (tim.hunter@noaa.gov) U.S. Department of Commerce

	National Oceanic and Atmospheric Administration Office of Atmospheric Research / Environmental Research Laboratories Great Lakes Environmental Research Laboratory 4840 S. State Rd Ann Arbor, MI 48105 Model, source codes, and all examples are available to download from: http://www.glerl.noaa.gov/wr/LBRMFiles.html

Crowley, T.E. II (2002). Large Basin Runoff Model. Chapter 17 in Mathematical Models of Large Watershed Hydrology. Singh, V.P. and Frevert, D.K. eds. Water Resources Publications, Colorado, USA, pp. 717-770.

WASMOD

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Conceptual, lumped, continuous-simulation
Origin (development and maintenance)	Developed at the Department of Earch Sciences, Uppsala University, Sweden
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open source:** **Computer Language:** FORTRAN **GIS-based:** No **Visualisation facilities:** plots, no GUI
Pathways and processes modelled	Snowfall and snow melting, rainfall, evapotranspiration, soil moisture accounting, fast flow (surface runoff) and slow flow (Baseflow)
Inputs (data requirements)	Monthly precipitation, potential evapotranspiration, temperature, and humidity Monthly runoff (calibration)
Outputs	Flow (surface runoff, and baseflow) , soil moisture index, actual evapotranspiration

Calibration Method	Automatic optimization. A detailed example of model calibration is presented in Xu (2002).
Parameters	Model has 3-6 parameters depending on the availability of input data and climate of study region. For sensitivity analysis, see Xu (2001). Model Sensitivity: Sensitive to precipitation data error, not so sensitive to potential evapotranspiration data error
Water quality constituents	None
Case Studies / Publications	Widén-Nilsson, E., Halldin, S., and Xu, C.-Y. (2007). Global water-balance modelling with WASMOD-M: Parameter estimation and regionalisation. Journal of Hydrology, Vol. 340, No. 1-2, pp. 105-118. Gong, L., Widén-Nilsson, E., Halldin, S., and Xu, C.-Y. (2009). Large-scale runoff routing with an aggregated network-response function. Journal of Hydrology, Vol. 368, No. 1-4, pp. 237-250. Engeland, K., Xu, C.-Y., and Gottschalk, L. (2005). Assessing uncertainties in a conceptual water balance model using Bayesian methodology. Hydrological Sciences Journal, Vol. 50, No. 1, pp. 45-63. Müller, F., Schrautzer, J., Reiche, E.-W., and Rinker, A. (2006).Ecosystem based indicators in retrogressive successions of an agricultural landscape. Ecological Indicators: Theoretical Fundamentals of Consistent Applications in Environmental Management, Vol. 6, No. 1, pp. 63-82.
Assumptions/Limitations	
Versions	WASMOD-M, NOPEX-6
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: Prof. Chong-yu Xu, Department of Geosciences, Hydrology, University of Oslo Sem Saelands vei 1 P O Box 1047 Blindern N-0316 Oslo Norway Tel: + 0047-22-855825 Fax: + 0047-22-854215 Email: chongyu.xu@geo.uio.no

	Cost:

Xu, C-Y, 2001. Statistical analysis of a conceptual water balance model, methodology and case study, Water Resources Management 15: 75-92.
Xu,C. -Y., 2002. WASMOD – the Water and Snow Balance Modelling System. Chapter 17 in Mathematical Models of Small Watershed Hydrology and Applications. Singh, V.P. and Frevert, D. K. eds, Water Resources Publications, Colorado, USA, pp. 555-590.

The UBC model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Conceptual, continuous-simulation, lumped
Origin (development and maintenance)	Developed by M.C. Quick and A. Pipes at the department of Civil Engineering, University of British Colombia, Vancouver, Canada.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC, IBM **Operating System:** MS-DOS **Open source:** **Computer Language:** **GIS-based:** No **Visualisation facilities:** own GUI
Pathways and processes modelled	The model simulates evapotranspiration, infiltration, interflow, percolation, runoff, baseflow and deeper groundwater flow.
Inputs (data requirements)	Temperature, snowfall and rainfall, observed flow (for model calibration)
Outputs	Surface runoff, Interflow, quick response baseflow, and deep groundwater response
Calibration Method	Semi-automatic calibration routine
Parameters	Model is designed so that many parameters of the model do not require calibration. Other optimizable parameters are given default values to provide a good basis for the start of calibration. Parameter ranges (available in the User Manual)
Water quality constituents	no
Case Studies / Publications	Micovic, Z., and Quick, M. C. (1999). Regional flow estimation using a hydrologic model. Proceedings, Annual

	Conference - Canadian Society for Civil Engineering, v 2, pp. 369-379, 14th Hydrotechnical Specialty Conference. Hudson, R.O. and M.C. Quick. (1997). A component based water chemistry simulator for small subalpine watersheds. Canadian Water Resources Journal 22(3):299–325. Whitfield, P.H., Reynolds, C.J. and Cannon, A.J. (2002). Modelling streamflows in present and future climates—examples from Georgia Basin, British Columbia. Canadian Water Resources Journal 27(4):427–456.
Assumptions and Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: Prof. M.C. Quick Department of Civil Engineering, University of British Colombia, Vancouver 8, B.C. , Canada Tel: 604 224-8895 [Home] E-mail: mquick@civil.ubc.ca /mcquick@telus.net Cost: The model is available at nominal cost which covers preparations of model disks, manual, input and output files. Requests should be made to Prof. M.C. Quick.

HYMOD

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Conceptual, lumped, continuous simulation
Origin (development and maintenance)	Developed at the University of Arizona
Platform (PC?), Operating System, Open source?, GIS-based (what	**Platform:** PC **Operating System:** Windows

GIS?), Computer Language, Visualisation facilities	**Open source: yes** **Computer Language:** Matlab **GIS-based:** No **Visualisation facilities:** No
Pathways and processes modelled	Pathways and processes lumped in 3 quick response storages and one slow response storage.
Inputs (data requirements)	Rainfall, temperature, observed outflow (for model calibration)
Outputs	Runoff discharge
Calibration Method	Manual (original version of model), single-objective SCEM-UA and the multi-objective MOSCEM-UA algorithms developed at the University of Amsterdam were used for the optimization of the parameters of the HYMOD model (Bos and de Vreng, 2006)
Parameters	5 parameters require optimization: the maximum storage capacity in the catchment, the degree of spatial variability of the soil moisture capacity within the catchment, the factor distributing the flow between the two series of reservoirs, and the residence time of the linear quick and slow reservoirs.
Water quality constituents	None
Case Studies / Publications	Moradkhani, H., Sorooshian, S., Gupta, H. V., and Houser, P. R. (2005). Dual state-parameter estimation of hydrological models using ensemble Kalman filter. Advances in Water Resources, Vol. 28, No. 2, pp. 135-147. D.P. Boyle, H.V. Gupta, S. Sorooshian, V. Koren, Z. Zhang and M. Smith, Toward improved streamflow forecast: value of semidistributed modeling, *Water Resources Research* **37** (11) (2001), pp. 2749–2759.
Assumptions/Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Prof. Hoshin V. Gupta, University of Arizona, john w harshbarger 314, PO BOX 210011 Arizona, USA Tel: 520-626-9712 Email: hoshin.gupta@hwr.arizona.edu

	Cost: Free of charge

Bos, A. and de Vreng, A. (2006). Parameter optimization of the HYMOD model using SCEM-UA and MOSCEM-UA. M.Sc. Thesis, University of Amsterdam. http://student.science.uva.nl/~devreng/files/Parameter%20optimization%20of%20the%20HYMOD%20model%20using%20SCEM-UA%20and%20MOSCEM-UA.pdf.

PSRM (Penn-State Runoff Model)

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Distributed, semi-continuous (up to 8 consecutive storm events). Hydrological Unit: subareas
Origin (development and maintenance)	Developed by Gert Aron, David L. Lakatos, and Elizabeth L. White at the Pennsylvania State University, U.S.A.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** IBM-compatible PCs **Operating System:** DOS **Open source:** **Computer Language:** GW-BASIC **GIS-based:** no **Visualisation facilities:** no Graphical user interface
Pathways and processes modelled	Infiltration, runoff, and channel routing
Inputs (data requirements)	Catchment data, Rainfall, observed flow hydrograph (for model calibration)
Outputs	Outflow hydrograph (Runoff discharge)
Calibration Method	Manual
Parameters	The curve number CN, initial abstraction factor, weighting factor of Muskingum method, and Manning's n. For sensitive parameters , see Kibler and Aron (1978).
Water quality constituents	None in original model, PSRM-QUAL: total suspended solids, trace metals, nutrients, chemical oxygen demand (COD) and biological oxygen demand (BOD)
Case Studies / Publications	Aron, G., David, J. V., Lakatos, F. , and Blair, D. (1979). Penn State Urban Runoff Model To Pinpoint Flood

	Peak Source Location. Journal of the American Water Resources Association, Vol. 15, No. 5, pp. 1250-1264. Tsihrintzis, V. A. and Sidan, C. B. (2008). ILLUDAS and PSRM-QUAL predictive ability in small urban areas and comparison with other models. Hydrological Processes, Vol. 22, No. 17, pp. 3321-3336. Lakatos, D. F. (1981). Planning Storm Runoff Control Impoundments Using The Penn State Runoff Model. Water Science and Technology, Vol. 2, pp. 995-1000. Shamsi, U.M. (1996). Storm-water management implementation through modelling and GIS. Journal of Water Resources Planning and Management - ASCE, Vol.122, No. 2, pp. 114-127.
Assumptions and Limitations	
Versions	KU-Penn State Runoff Model, PSRM-QUAL,
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	To obtain model contact: Gert Aron, Professor Emeritus of Civil Engineering, Department of Civil and Environmental Engineering, Pennsylvania State University Sackett Building E-mail: gxa4@psu.edu Cost:

Kibler, D. F., Aron, G. (1978). Effects Of Parameter Sensitivity And Model Structure In Urban Runoff Simulation. Ky Univ Off Res Eng Serv Bull UKY BU116, pp. 81-89.

WBNM2000

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	conceptual, event-based, distributed, parametric model. Hydrological unit : catchment divided into subareas, depending on stream channel network.

Origin (development and maintenance)	Developed by M.J. Boyd, E.H. Rigby, and R. VanDrie at the Faculty of Engineering, University of Wollongong, Australia
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** DOS **Open source:** yes **Computer Language:** FORTRAN 77/90, PASCAL for graphics **GIS-based:** No **Visualisation facilities:** WBNM graphical user interface
Pathways and processes modelled	Model computes the flood generated on natural and urban catchments.
Inputs (data requirements)	Rainfall
Outputs	Runoff
Calibration Method	Manual
Parameters	A very few number of lag parameters
Water quality constituents	None
Case Studies / Publications	Boyd, M. J. , Rigby, E. H. and VanDrie, R. (1996). WBNM - a computer software package for flood hydrograph studies. Environmental Software, Vol. 11, No. 1-3, Modelling and Simulation Theme: Regional Development and Environmental Change, pp. 167-172. Adams, A. (1991). Application and comparison of RORB, WBNM and RAFTS runoff routing models. National Conference Publication - Institution of Engineers, Australia: Challenges for Sustainable Development, Vol. 2, No. 91, pt 22, pp. 485-491. Venugopal, K., Gopalakrishnan, T.V., and Sakthivadivel, R. (1983). Watershed Bounded Network Model (WBNM) For Runoff Prediction Of Large Basins. Nordic Hydrology, Vol. 14, No. 4, pp. 229-238. Boyd, M.J., Rigby, E.H., and VanDrie, R. (2000). WBNM2000 - Computer software for flood studies on natural and urban catchments. , Hydraulic engineering Software VIII, Water Studies, Vol. 7, pp. 37-46.
Assumptions/Limitations	
Versions	

How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: Professor Michael Boyd, Faculty of Engineering, University of Wollongong, Australia 2522. Tel: +61 2 4221 3054 Fax: +61 2 4221 3238 Email: michael_boyd@uow.edu.au Web URL: http://www.edu.au/eng/staff/boyd.html Cost: free of charge

PARCHED-THIRST

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Process-based and semi-distribtuted by subcatchments lumped into hydrological response units, continuous-simulation Hydrological unit : Hydrological response units
Origin (development and maintenance)	Deeveloped by Damion Young and John Gowing, University of Newcastle upon Tyne
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open source:** no **Computer Language:** compiled Visual Basic, FORTRAN 77(PARCHED only) **GIS-based:** No **Visualisation facilities:** a simple, but limited interface written in Visual Basic, also model has a decision support system
Pathways and processes modelled	Model is developed to simulate the main processes in a Rainwater Harvesting System. The main modules are:

	Climate Generator, Infiltration/Runoff Model, Soil-Water Model, and Crop Growth Model. The hydrological pathways in the model are: evapotranspiration, infiltration, soil water, rainfall, and runoff.
Inputs (data requirements)	Daily rainfall, maximum and minimum temperature, wind speed, humidity, and solar radiation.
Outputs	Runoff, generated climate variables (rainfall, temperature, wind speed, humidity, and solar radiation)
Calibration Method	Physical parameters require field measurements and estimation by pedotransfer functions. In principle no calibration required.
Parameters	Soil physical parameters, topography, crop parameters, climate parameters. Layout of the rainwater harvesting system. Two levels of parameters: level to be easily changed by the (novice) user and the advanced level, normally default and only to be changed by experts Sensitivity: Very high sensitivity to the soil water retention parameters
Water quality constituents	None
Case Studies / Publications	Young, M. D. B. , Gowing, J. W. , Wyseure, G. C. L. , and Hatibun, N. (2002). Parched-Thirst: development and validation of a process-based model of rainwater harvesting. Agricultural water management , Vol. 55, No. 2, pp. 121-140. Case studies (see Wyseure et al. 2002)
Assumptions/Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Mark Damion Bede Young Department of Agricultural and Environmental Science King George VI Building University of Newcastle upon Tyne, NE1 7RU, UK Phone: 0191 222 6942 Fax: 0191 222 5228

	email: m.d.b.young@ncl.ac.uk Homepage: http://www.staff.ncl.ac.uk/m.d.b.young/index.html How to obtain Model and documentation: contact M.Young, also visit http://www.agr.kuleuven.ac.be/vakken/IC03_IC04/runoffirri/PTHdbV22.pdf (documentation) http://www.biw.kuleuven.be/VAKKEN/IC03_IC04/runoffirri/PTModel_download.aspx (model) Cost: free of charge

Wyseure, G. C. L., Gowing, J. W., and Young, M. D. B. (2002). PARCHED-THIRST: an agrohydrological model for planning rainwater harvesting systems in semi-arid areas. Mathematical models of small watershed hydrology and applications. Singh, V. P., and Frevert, D. (eds). Water Resources Publications, Colorado, U.S.A., pp. 301-334

SIRG

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Semi-Physically-based, distributed, continuous-simulation hydrological model. Hydrological Unit:sub-basins
Origin (development and maintenance)	Developed at the Department of Civil Engineering, Ajou University, South Korea.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open source:** **Computer Language:** **GIS-based:** No **Visualisation facilities:** no GUI, data and outputs displayed as graphs.
Pathways and processes modelled	Rainfall-runoff, infiltration, sub-surface flow, river discharge, and groundwater flow.
Inputs (data requirements)	Rainfall, water depths, and current velocities of river flow and groundwater elevations during the period of rainy

	season. Observed hydrograph and groundwater elevations for model calibration
Outputs	Discharge hydrograph and groundwater level.
Calibration Method	Manual
Parameters	Model has approximately 15 parameters the majority of which are empirical.
Water quality constituents	No.
Case Studies / Publications	Application to a watershed area of Yang-yang Namdae-chun located in the north-eastern coast of Korea (Yoo, 2002).
Assumptions/Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: Prof. Dong Hoon Yoo, Department of Civil Engineering, Ajou University, Suwon, 442-749, South Korea dhy@hydroprogram.com

Yoo, D.H. (2002). Numerical Model of Surface Runoff, Infiltration, River Discharge, and Groundwater Flow-SIRG, Chapter 6 in Mathematical Models of Small Watershed Hydrology and Applications. Singh,V.P. and Frevert,D.K. eds. Water Resources Publications, Colorado, U.S,A. , pp. 167-182.

Thales Model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	simple distributed parameter, physically-based, continuous simulation Hydrological unit: TAPES-C model divides the catchment into elements using the “stream-tube” approach. (See Grayson et al. 1995).
Origin (development and maintenance)	Developed by G.Blöschl (Australian National University), R.B. Grayson (University of Melbourne) and I.D. Moore (Australian National University).
Platform (PC?), Operating System, Open source?, GIS-based (what	**Platform:** PC **Operating System:** Windows

GIS?), Computer Language, Visualisation facilities	**Open source:** **Computer Language:** **GIS-based:** no **Visualisation facilities:** no GUI, data and outputs displayed as graphs.
Pathways and processes modelled	Infiltration, surface runoff, channel routing, Groundwater flow, and rill flow (modelled as channel flow)
Inputs (data requirements)	Rainfall, observed runoff hydrograph
Outputs	Runoff, baseflow
Calibration Method	
Parameters	Input parameters: water content at field capacity, drainable porosity, effective hydraulic conductivity of the soil profile, coefficient and exponent of the flow area-discharge relationship (given, for example, by Manning's equation or the Darcy-Weisbach equation) as well as the infiltration parameters.
Water quality constituents	No.
Case Studies / Publications	Adams, R., Western, A., Anderson, B., and Seed, A. (2008). Investigating spatial and temporal variability in runoff and sediment generation using a physically-based model, Thales. Australian Journal of Water Resources, v 12, n 3, pp. 233-243. Western, A. W., Grayson, R. B., and Green, T. R. (1999). The Tarrawarra project: high resolution spatial measurement, modelling and analysis of soil moisture and hydrological response. Hydrological Processes, v 13, n 5, pp. 633-652. Grayson, R. B., I. D. Moore, and T. A. McMahon (1992), Physically Based Hydrologic Modeling 1. A Terrain-Based Model for Investigative Purposes, Water Resour. Res., 28(10), 2639–2658.
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	How to obtain Model and documentation, Contact: Prof. Rodger Grayson CRC for Catchment Hydrology and Centre for Environmental Applied Hydrology

	Department of Civil and Environmental Engineering University of Melbourne Victoria, 3010, Australia Phone: (61 3) 9905 1969 / 0417 054 660 Fax: (61 3) 9905 5033 E-mail: rodger@civenv.unimelb.edu.au Cost:

Grayson, R.B., Blöschl ,G., and Moore, I.D. (1995). Distributed parameter hydrologic modelling using vector elevation data: THALES and TAPES-C, Chapter 19 in Computer Models of Watershed Hydrology. Singh,V.P. ed., Water Resources Publications, Colorado, U.S.A., pp. 669-696.

Tank Model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Lumped, conceptual, continuous-simulation
Origin (development and maintenance)	Developed by M. Sugawara, Mianai Karasuyama, Tokyo, Japan
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open Source:** **GIS-Based:** No **Computer Language:** FORTRAN **Visualisation Facilities:** no Graphical user inerface
Pathways and processes modelled	Model composed of four tanks laid vertically in series. Tanks have bottom (except the last tank) and side outlets. The outputs from the side outlets are the calculated runoffs. Output from Top tank=surface runoff, second tank = intermediate runoff, third tank= sub-base runoff, and fourth tank= baseflow.

Inputs (data requirements)	Rainfall, observed discharge (for model calibration)
Outputs	Computed runoff volumes.
Calibration Method	Automatic Calibration by hilltop climbing method (see Sugawara, 1979 and Sugawara 1995)
Parameters	7 empirical runoff-infiltration coefficients, coefficients of the position of side outlets: 4 coefficients, parameters of soil moisture structure: 4 parameters. Methodology and approach for calibrating these parameters and coefficients are detailed in Sugawara (1995).
Water quality constituents	None
Case Studies / Publications	Ramli, M., Ohnishi, Y., and Nishiyama, S.(2007). Coupled tank model and flow model for slope seepage flow analysis. Geotechnical Engineering, Vol. 38, No. 2, pp. 51-56. Paik, K., Kim, J. H., Kim, H. S., and Lee, D. R. (2005). A conceptual rainfall-runoff model considering seasonal variation. Hydrological Processes, Vol. 19, No. 19, pp. 3837-3850.
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	How to obtain Model: Contact Dr. M. Sugawara 6-13-30 Mianai Karasuyama Setagaya – Ku Tokyo 157, Japan. Documentation: Contact Author. Also see Sugawara (1995).

Sugawara, M. (1979). Automatic calibration of the tank model. Hydro. Sci. Bull. No. 24, pp. 375–388

Sugawara, M. (1995). Tank Model, Chapter 6 in Computer Models of Watershed Hydrology. Singh,V.P. ed., Water Resources Puiblications, Colorado, U.S.A., pp. 165-214.

<u>OPUS</u>

Model Type (lumped or distributed),	Distributed, continuous, physically-based, hydrological model.

event-based or continuous, Hydrological unit	Hydrological Unit: Finite difference cell.
Origin (development and maintenance)	Developed by Roger E. Smith, United States Department of Agriculture, Agricultural Research Service
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** DOS **Open source:** **Computer Language:** FORTRAN **GIS-based:** No **Visualisation facilities**: Opus-GUI (Beta version)
Pathways and processes modelled	Infiltration, interaction of surface water and soil water, runoff, non-point source pollution, erosion, growth of plants, development of cover, water use, uptake of nutrients, cycling of soil nitrogen, phosphorus, and carbon, and transport of adsorbed pesticides and nutrients.
Inputs (data requirements)	Rainfall, maximum and minimum daily temperature, solar radiation, concentration of chemicals in soil, and observed runoff. Parameters must be input to describe the soil hydraulics, the basic soil organic matter, the field slope and size, the soil erodibility characteristics, depth and spacing of any drains, vegetation growth parameters, and other basic information.
Outputs	The model produces a variety of output files, in part depending on the simulation options chosen. The simulation of residue and soil nitrogen cycles, pesticide transport, and erosion processes are optional. There is a main output file giving summaries of water balance on a daily, monthly, and annual basis, plus optional output files for water and chemical distributions in the soil profile, for hydrologic detail, and for daily plant status. Main outputs: Discharge, concentration of chemicals in runoff water.
Calibration Method	
Parameters	Parameters must be input to describe the soil hydraulics, the basic soil organic matter, the field slope and size, the soil erodibility characteristics, depth and spacing of any drains, vegetation growth parameters, and other basic information. Five parameters describe the hydraulic and water retention characteristics of a soil layer: saturated hydraulic conductivity, saturated water content, residual water content, air entry pressure, and a pore size distribution index. Sensitive parameters: see chapter 4 in Zacharias, 1998.

Water quality constituents	Nitrogen, phosphorous, carbon, pesticides. Ten pesticides can be considered simultaneously
Case Studies / Publications	Ma, Q.L., Wauchope, R.D., Hook, J.E., Johnson, A.W., Truman, C.C., Dowler, C.C., Gascho, G.J., Davis, J.G., Sumner, H.R., and Chandler, L.D.(1998). GLEAMS, Opus and PRZM-2 model predicted versus measured runoff from coastal plain loamy sand. Transactions of the American Society of Agricultural Engineers, Vol. 41, No. 1, pp. 77-88. Fontes, J. C., Pereira, L. S., and Smith, R. E. (2004). Runoff and erosion in volcanic soils of Azores: simulation with OPUS. CATENA, Vol. 56, No. 1-3, Volcanic Soil Resources: Occurrence, Development and Properties, pp. 199-212. Bormann, H. , Diekkruger, B. , and Hauschild, M. (1999). Impacts of landscape management on the hydrological behaviour of small agricultural catchments. Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere, Vol. 24, No. 4, pp. 291-296. Moberly, C., Workman, S. R., Warner, R. C. (2001). Calibration and Evaluation of a Hydrologic Model for Loose-Dump Mine Spoil. International Journal of Mining, Reclamation and Environment, Vol. 15, No. 3, pp. 147-162.
Assumptions and Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: Roger E. Smith United States Department of Agriculture Agricultural Research Service, Water Management Research Unit Room S-320 2150 CENTRE AVE BLDG D, STE 320 FORT COLLINS, CO, 80526 USA

	Phone: (970) 492-7430 Fax: (970) 492-7408 email: roger.smith@ars.usda.gov How to obtain Model: contact the author for a copy of the model and documentation sroger@engr.colostate.edu Cost: Free of charge

Zacharias,S. (1998). Modeling Spatial Variability of Field-Scale Solute Transport in the Vadose Zone. PhD Dissertation, Virginia Tech, U.S.A. http://scholar.lib.vt.edu/theses/available/etd-9898-142438/unrestricted/chap4.pdf

HYDROTEL Model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Physically-based, spatially distributed model, continuous-simulation. Hydrological Unit: relatively homogeous hydrological unit (RHHU).
Origin (development and maintenance)	Developed at the INRS-ETE (Institut National de la Recherche Scientifique, Eau, Terre et Environnement), Canada.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open source:** **Computer Language:** C++ **GIS-based:** No **Visualisation facilities:** Physitel (a graphical pre-processes for Hydrotel), Hydrotel GUI.
Pathways and processes modelled	Evapotranspiration, infiltration, vertical water budget, surface and sub-surface runoff, and river routing.
Inputs (data requirements)	Precipitation, temperature,(albedo, solar radiation, humidity of the air and wind if Penman Montieth model used).
Outputs	Runoff discharge and baseflow
Calibration Method	Shuffled complex evolution used for calibration.

Parameters	Parameters that are typically calibrated: - Evapotranspiration coefficient (a multiplicative parameter which boosts or reduces PET) - Depth of each of the three layers of soil. - Recession coefficient for the third layer. - Manning's n (roughness coefficient) for overland runoff routing There are other parameters that are either measurable or can be obtained from literature.
Water quality constituents	None
Case Studies / Publications	Fortin, J.P., Turcotte, R., Massicotte, S., Moussa, R., Fitzback, J., and Vellaeneuve, J.P. (2001). Distributed watershed model compatible with remote sensing and GIS data. II: Application to Chaudiere watershed. Journal of Hydrologic Engineering, Vol. 6, No. 2, pp. 100-108. Fortin, J.P. , Turcotte, R., Massicotte, S., Moussa, R., Fitzback, J., and Villeneuve, J.P. (2001). Distributed watershed model compatible with remote sensing and GIS data. I: Description of model. Journal of Hydrologic Engineering, Vol. 6, No. 2, pp. 91-99. Fortin, V., Chahinian, N., Montanari, A., Moretti, G., and Moussa, R. (2006). Distributed hydrological modelling with lumped inputs. IAHS-AISH Publication, No. 307, pp. 135-148. Fortin, J.P., Moussa, R., Bocquillon, C. et Villeneuve, J.P. (1995) . "Hydrotel, un modèle hydrologique distribué pouvant bénéficier des données fournies par la télédétection et les systèmes d'information géographique". Revue des Sciences de l'eau, 8, 97-124.
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: Prof. Jean-Pierre Fortin, INRS-ETE (Institut National de la Recherche Scientifique, Eau, Terre et Environnement, Canada jean-pierre_fortin@ete.inrs.ca

	Documentation: http://hydrotel.codeplex.com/Wiki/View.aspx?title=Documentation (in French). Homepage: http://www.ete.inrs.ca/activites/modeles/hydrotel/en/accueil.htm Cost:

InHM (Integrated Hydrology Model)

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Physically-based, distributed, three-dimensional Hydrological Unit: control volume finite element
Origin (development and maintenance)	The Integrated Hydrology Model, is the product of research that begun at the University of Waterloo in 1993 and continued at Stanford University in 1998.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows, Linux/Unix **Open source:** yes **Computer Language:** Fortran 95 **GIS-based:** No **Visualisation facilities:** not available
Pathways and processes modelled	Overland flow, subsurface flow, infiltration, baseflow, percolation, and channel flow, evapotranspiration.
Inputs (data requirements)	Rainfall, solar radiation, daily maximum and minimum temperatures, vapour pressure, observed flow for model calibration.
Outputs	Surface runoff, stream flow, subsurface flow.
Calibration Method	manual
Parameters	Physically-based parameters: Porous Media Parameters, Surface Water Parameters, numerical(mathematical) parameters (explained in model website Inhm.org)
Water quality constituents	Solutes, and sediments (Ran et al, 2007).

Case Studies / Publications	Rapid simulated hydrologic response within the variably saturated near surface Ebel, Brian A.1; Loague, Keith1 Source: Hydrological Processes, v 22, n 3, p 464-471, January 30, 2008 A hypothetical reality of Tarrawarra-like hydrologic response Mirus, Benjamin B.1; Loague, Keith1; VanderKwaak, Joel E.2; Kampf, Stephanie K.3; Burges, Stephen J.4 Source: Hydrological Processes, v 23, n 7, p 1093-1103, March 30, 2009 A high-resolution integrated hydrology-hydrodynamic model of the Barataria Basin system Inoue, Masamichi1, 2; Park, Dongho2; Justic, Dubravko1, 3; Wiseman Jr., William J.4 Source: Environmental Modelling and Software, v 23, n 9, p 1122-1132, September 2008 Physics-based continuous simulation of long-term near-surface hydrologic response for the Coos Bay experimental catchment Ebel, Brian A.1, 5; Loague, Keith1, 5; Montgomery, David R.2, 6; Dietrich, William E.3, 4 Source: Water Resources Research, v 44, n 7, July 2008
Assumptions/Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contacts: Joel E. VanderKwaak joel@integratedhydrology.com or Keith Loague Professor, Department of Geological & Environmental Sciences Stanford University, Stanford, California CA 94305-2115, USA. E-mail: keith@pangea.stanford.edu Homepage: http://inhm.org/ Model and Documentation: can be downloaded from http://inhm.org/

Ran, Q., Heppner, C.S., VanderKwaak,J.E., and Loague,K. (2007). Further testing of the integrated hydrology model (InHM): multiple-species sediment transport. Hydrological Processes, Vol. 21, pp. 1522-1531.

CHDM

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	A physically-based event-based semi-distributed model.
Origin (development and maintenance)	Developed by Prof. Vicente L. Lopes, at the Department of Biology, Texas State University - San Marcos.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** **Operating System:** **Open source:** **Computer Language:** **GIS-based:** **Visualisation facilities:**
Pathways and processes modelled	represents the processes of interception, depression storage, infiltration-excess overland flow, channel flow and non-equilibrium sediment transport.
Inputs (data requirements)	
Outputs	
Calibration Method	
Parameters	
Water quality constituents	sediments
Case Studies / Publications	Lopes, V. L.(1995).CHDM - Catchment Hydrology Distributed Model. Watershed Management Symposium - Proceedings, pp. 144-154. De Aragão, R., Srinivasan, V.S., Suzuki, K., Kadota, A., Oguro, M., Sakata, Y. (2005). Evaluation of a

	physically-based model to simulate the runoff and erosion processes in a semiarid region of Brazil. IAHS-AISH Publication, n 292, pp. 85-93.
Assumptions/Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: Prof. Vicente L. Lopes Department of Biology 601 University Drive Texas State University San Marcos, Texas 78666 USA Phone: (512)245-6709 Fax: (512)245-7919 Email: vlopes@txstate.edu How to obtain Model: Documentation: Cost:

EUROSEM

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Physically-based, distributed event-based model Hydrological Unit: homogenous units or elements
Origin (development and maintenance)	The European Soil Erosion Model (EUROSEM) is a joint effort of many European scientists. The work has involved more than 40 scientists from ten European Community countries, two other European countries and collaboration with the USDA Agricultural Engineering Research Service, Fort Collins, Colorado, USA.
Platform (PC?), Operating System, Open source?, GIS-based (what	**Platform:** PC **Operating System**: Windows 95, 98, NT4, 2000

GIS?), Computer Language, Visualisation facilities	**Open source:** Yes **Computer Language:** FORTRAN **GIS-based:** no **Visualisation facilities:** No graphical user interface
Pathways and processes modelled	Interception, depression storage, detachment of soil particles by raindrop impact and by runoff, sediment deposition, runoff
Inputs (data requirements)	Rainfall, observed hydrograph, topographic and hydraulic characteristics, information about the soil.
Outputs	Runoff depth, runoff volume, sediment concentration and total sediment removed.
Calibration Method	Manual
Parameters	It is quite important to calibrate the runoff hydrology before attempting to calibrate the sediment transport parameters. List of parameters are available in Table 3.1 in Morgan et al. (1998). For sensitive parameters see Veihe and Quinton (2000)
Water quality constituents	Sediments
Case Studies / Publications	Veihe, A. , Rey, J., Quinton, J.N., Strauss, P., Sancho, F.M., and Somarriba, M.(2001). Modelling of event-based soil erosion in Costa Rica, Nicaragua and Mexico: Evaluation of the EUROSEM model. Catena, v 44, n 3, pp. 187-203. Folly, A., Quinton, J.N., and Smith, R.E. (1999). Evaluation of the EUROSEM model using data from the Catsop watershed, the Netherlands. Catena, v 37, n 3-4, pp. 507-519. Modelling increased soil cohesion due to roots with EUROSEM De Baets, S., Torri, D., Poesen, J., Salvador, M.P., and Meersmans, J. (2008). Earth Surface Processes and Landforms, v 33, n 13, pp. 1948-1963. Soil erosion modelling with EUROSEM at Embori and Mukogodo catchments, Kenya Mati, B.M. , Morgan, R.P.C., and Quinton, J.N. (2006). Earth Surface Processes and Landforms, v 31, n 5, pp. 579-588. The European soil erosion model (EUROSEM): a dynamic approach for predicting sediment transport from fields

	and small catchments Morgan, R.P.C. , Quinton, J.N., Smith, R.E., Govers, G., Poesen, J.W.A., Auerswald, K., Chisci, G., Torri, D., and Styczen, M.E. (1998). Earth Surface Processes and Landforms, v 23, n 6, pp. 527-544.
Assumptions/Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: J.N. Quinton, Water Management Group, Cranfield University, Silsoe Bedford MK45 4DT U.K. Tel: (0)1525-863294 Fax: (0)1525-863300 Email: J.Quinton@cranfield.ac.uk How to obtain model and documentation: download from http://www.es.lancs.ac.uk/people/johnq/EUROSEM%20download.html EUROSEM homepage: http://www.es.lancs.ac.uk/people/johnq/EUROSEM.html Cost: Free of charge

Veihe, A. and Quinton, J. (2000). Sensitivity analysis of EUROSEM using Monte Carlo simulation I: Hydrological, soil and vegetation parameters Source: Hydrological Processes, v 14, n 5, pp. 915-926.

Morgan, R.P.C, Quinton, J.N., Smith, R.E., Govers, G., Poesen, J.W.A., Auerswald, K., Chisci, G., Torri, D., Styczen, M.E., and Folly, A.J.V. (1998). The European soil erosion model (EUROSEM): documentation and user guide. Silsoe College, Cranfield University.

Soil Moisture Distribution and Routing Model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	SMDR is a fully spatially distributed , physically-based model Hydrological Unit: element/cell on which geological, topographical and soil hydrodynamic properties are assumed homogeneous/uniform.
Origin (development and maintenance)	Developed at the Soil and Water Laboratory, Biological and Environmental Engineering Dept., Cornell University
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** SOLARIS, PC **Operating System:** LINUX, Windows **Open source:** Yes **Computer Language:** **GIS-based:** yes GRASS GIS **Visualisation facilities:** GRASS GIS, GUI in Python (for Windows)
Pathways and processes modelled	Evapotranspiration, runoff, lateral runoff, runoff routing, and infiltration.
Inputs (data requirements)	Precipitation Maximum, minimum and mean temperatures Observed streamflow data
Outputs	A number of digital maps are created at each time step: water storages (by cell and by layer), saturation degrees (by cell and by layer), and transferred volumes (infiltration, interflow, surface runoff, evapotranspiration, percolation, precipitation). ASCII files: Evapotranspiration, Comparison between observed and simulated Streamflows, Percolation, Surface runoff, Simulated streamflow, and Water storage.
Calibration Method	
Parameters	
Water quality constituents	No
Case Studies / Publications	Frankenberger, J. R., Brooks, E. S., Walter, M. T., Walter, M. F., and Steenhuis, T. S.(1999).A GIS-based variable source area hydrology model. Hydrological Processes, v 13, n 6, pp. 805-822.

	Narayanan, R., Frankenberger, J. R., and Jenkinson, B. J. (2000).Predicting Water Table Variations in a Forested Hillslope. ASAE Annual International Meeting, Technical Papers: Engineering Solutions for a New Century, v 2, pp. 1931-1948. Frankenberger, J. R., and Walter, M. F. (1997). Evaluation of diversions using a variable source area hydrologic model American Society of Agricultural Engineers, v 2. Brooks, E. S., Boll, J., and McDaniel, P. (2007). A.Distributed and integrated response of a geographic information system-based hydrologic model in the eastern Palouse region, Idaho. Hydrological Processes, v 21, n 1, pp. 110-122.
Assumptions/Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contacts: Todd Walter Biological and Environmental Engineering Cornell University Ithaca, NY 14853-5701 office: (607) 255-2488 lab: (607) 255-2463 Email: mtw5@cornell.edu Homepage: http://soilandwater.bee.cornell.edu/research/smdr/index.html Documentation: http://soilandwater.bee.cornell.edu/research/smdr/maindescription.html#download How to obtain Model: download from http://soilandwater.bee.cornell.edu/research/smdr/download.html Cost: Free of charge

<u>Institute of Hydrology Distributed Model (IHDM)</u>

Model Type (lumped or distributed),	Physically-based, distributed model, continuous simulations

event-based or continuous, Hydrological unit	Hydrological Unit: Finite Elements
Origin (development and maintenance)	Developed at the U.K. Institute of Hydrology.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** IBM-compatible PC **Operating System:** Windows **Open source:** **Computer Language:** FORTRAN **GIS-based:** No **Visualisation facilities:** no GUI
Pathways and processes modelled	Precipitation, interception, snowmelt, infiltration, evapotranspiration, saturated and unsaturated flow.
Inputs (data requirements)	Geometric description of the catchment, rainfall data, solar radiation, humidity of the air and wind and material hydraulic properties, observed flow for model calibration,
Outputs	Estimates of flow, water contents, and pressure potentials at user-specified locations in the catchment.
Calibration Method	Manual calibration. See Rogers et al. (1985) and Calver (1988)
Parameters	Some are physically-based and obtained from field measurements, some are optimizable. See Rogers et al. (1985), Calver (1988), and Binley and Beven(1991).
Water quality constituents	none
Case Studies / Publications	Beven, K. and Binley, A. (1992). Future of distributed models: Model calibration and uncertainty prediction. Hydrological Processes, Vol. 6, No. 3, pp. 279-298. Wood, W.L. and Calver, A. (1992). Initial conditions for hillslope hydrology modelling. Journal of Hydrology, Vol. 130, No. 1-4, pp. 379-397. Calver, A. and Wood, W.L (1989). On the discretization and cost-effectiveness of a finite element solution for hillslope subsurface flow. Journal of Hydrology, Vol. 110, No. 1-2, pp. 165-179. Wood, W. L. (1996). A note on how to avoid spurious oscillation in the finite-element solution of the unsaturated flow equation. Journal of Hydrology, Vol. 176, No. 1-4, pp. 205-218.

	Binley, A.M. and Beven,K.J. (1991). Changing Responses in Hydrology: Assessing the Uncertainty in Physically Based Model Predictions. Water Resources Research, Vol. 27, No. 6, pp. 1253-1261.
Assumptions/Limitations	
Versions	IHDM4, IHDM3
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: A. Calver, Centre for Ecology and Hydrology (CEH) Wallingford, Wallingford, Oxfordshire OX10 8BB email: anc@ceh.ac.uk Tel: +44 (0)1491 838800 (switchboard) Fax: +44 (0)1491 692424

Rogers, C.C.M., Beven, K.J., Morris, E.M. and Anderson, M.G. (1985). Sensitivity analysis, calibration and predictive uncertainty of the institute of hydrology distributed model. Journal of Hydrology, Vol.81, pp. 179–191.

Calver, A. (1988). Calibration, sensitivity and validation of a physically-based rainfall-runoff model. Journal of Hydrology, Vol. 103, No. 1-2, pp. 103-115.

IWFM

Integrated Water Flow Model formerly known as IGSM2 (Integrated Groundwater and Surface water Model 2nd generation).

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Physically-based, distributed, continuous simulation Hydrological Unit: elements (finite element method)
Origin (development and maintenance)	Developed by the State of California Department of Water Resources, formerly known as IGSM2 (Integrated Groundwater and Surface water Model 2nd generation)
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language,	**Platform:** PC **Operating System:** Windows **Open source:** Yes

Visualisation facilities	**Computer Language:** Fortran 77 and Fortran 95. **GIS-based:** no **Visualisation facilities:** no GUI, results can be plotted as graphs.
Pathways and processes modelled	The model simulates groundwater heads in a multi-layer aquifer system, stream flows, lakes (open water bodies), direct runoff of precipitation, return flow from irrigation water, infiltration, evapotranspiration, vertical moisture movement in the root zone and the unsaturated zone that lies between the root zone and the saturated groundwater system. The interaction between the aquifer, streams and lakes as well as land subsidence, tile drainage, subsurface irrigation and the runoff from small watersheds adjacent to model domain are also modelled by IWFM.
Inputs (data requirements)	Main inputs: Precipitation, information about wells (location, elevations of bottom and top perforations), stream inflow data, monthly evapotranspiration data, observed outflow, initial aquifer head values.
Outputs	Virtual Crop Characteristics, Element Face Flow Output File, Boundary Flux Output File, Tile Drain Hydrograph Output, Stream Flow Hydrograph Output File, Groundwater Level Hydrograph Output, Groundwater Level Output at Every Node, Layer Vertical Flow Output File.
Calibration Method	Model can be used in conjugation with the automatic calibration programme PEST (Paramater ESTimation program).
Parameters	A full account of model parameters is given in Dogrul (2007)
Water quality constituents	no
Case Studies / Publications	Dogrul, E. C., Brush, C. F., and Kadir, T. N. (2006). Integrated Water Flow Model (IWFM), A Tool For Numerically Simulating Linked Groundwater, Surface Water And Land-Surface Hydrologic Processes. American Geophysical Union, Fall Meeting 2006, abstract #H41D-0434 The model was applied in a number of catchments and basins in California.
Assumptions/Limitations	
Versions	V3.0, V3.01
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	How to obtain model: Model executables and source code can be downloaded from http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/IWFMv3_01/index_v3_01.cfm Documentation: Theoretical and user manual can be also downloaded from

	http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/IWFMv3_01/index_v3_01.cfm Cost: Free of charge

Dorgul, E. (2007). Integrated Water Flow Model (IWFM V3.0). User's Manual. Hydrology Development Unit Modeling Support Branch, Bay-Delta Office, Department of Water Resources, California, USA.

HEC-HMS

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	continuous, distributed parameter, conceptual Hydrological unit: Hydrologic elements are connected in a dendritic network. Available elements are: subbasin, reach, junction, reservoir, diversion, source, and sink.
Origin (development and maintenance)	Developed at the Hydrologic Engineering Center , U.S. Army Corps of Engineers
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Sun Solaris 2.5, Windows95/98/NT/XP/Vista, Linux **Open source:** No **Computer Language:** Java, but some modules still written in FORTRAN **GIS-based:** yes the HEC-GeoHMS version **Visualisation facilities:** own GUI
Pathways and processes modelled	Snowmelt , precipitation, Infiltration, runoff, evapotranspiration, Interception, Detention Storage, overland flow, groundwater flow, and channel Flow.
Inputs (data requirements)	The minimum required input is precipitation data and parameters required by the selected computation methods. Optionally, observed flow data and stage-flow curves may be included.
Outputs	Surface runoff
Calibration Method	The program includes a versatile optimization facility that may be employed when observed flow data are available. Goodness-of-fit is estimated by either percent error in peak flow, sum of absolute residuals, sum of squared residuals, or peak-weighted root mean square error. The search algorithm is either a uni-variant or

	downhill simplex method. See Cunderlik and Simonovic (2004).
Parameters	Sensitive parameters: imperviousness, curve number and base flow recession factor (Al-Abed et al., 2005). Kenbl et al. (2005) and McColl and Aggett (2007) found the curve number (CN) and initial abstraction (Ia) to be the most sensitive parameters. Also see Cunderlik and Simonovic (2004).
Water quality constituents	No
Case Studies / Publications	Cydzik, K., and Hogue, T. S. (2009). Modeling postfire response and recovery using the hydrologic engineering center hydrologic modeling system (HEC-HMS). Journal of the American Water Resources Association, v 45, n 3, pp. 702-714. Chu, X., and Steinman, A. (2009). Event and continuous hydrologic modeling with HEC-HMS. Journal of Irrigation and Drainage Engineering, v 135, n 1, pp. 119-124. Anderson, M.L., Chen, Z.-Q., Kavvas, M.L., and Feldman, A. (2002). Coupling HEC-HMS with atmospheric models for prediction of watershed runoff. Journal of Hydrologic Engineering, v 7, n 4, pp. 312-318. Yusop, Z., Chan, C.H., and Katimon, A. (2007). Runoff characteristics and application of HEC-HMS for modelling stormflow hydrograph in an oil palm catchment. Water Science and Technology, v 56, n 8, pp. 41-48. Gaytán, R., De Anda, J., Nelson, J. (2008). Computation of changes in the run-off regimen of the Lake Santa Ana watershed (Zacatecas, Mexico). Lakes and Reservoirs: Research and Management, v 13, n 2, pp. 155-167.
Assumptions/Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contacts: William Scharffenberg, Research Division, Hydrologic Engineering Center, U.S. Army Corps of Engineers 609 Second Street, Davis, CA 95616 Tel: (530) 756-1104

	Fax: (530) 756-8250 Model Website: http://www.hec.usace.army.mil Documentation and model: downloadable from the HEC-HMS website

Al-Abed, N., Abdulla, F. and Abu Khyarah, A. (2005). GIS-hydrological models for managing water resources in the Zarqa River basin. Environmental Geology. Vol. 47, NO. 3, pp.405-411.
McColl, C. and Aggett, G. (2007). Land-use forecasting and hydrologic model integration for improved land-use decision support, Journal of Environmental Management, Vol. 84, No. 4, pp. 494-512.
Cunderlik, J.M. and Simonovic, S.P. (2004). Calibration, validation, and sensitivity analysis of the HEC-HMS hydrological model. CFCAS project: Assessment of Water Resources Risk and Vulnerability to changing climate conditions. Project Report IV. http://www.eng.uwo.ca/research/iclr/fids/publications/cfcas-climate/reports/Report%20IV.pdf.

HMS

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	a physically-based, continuous-simulation, distributed-parameter model system developed to simulate the hydrologic response of large river basins. It comprises pre-processcing, post-preocesscing, and four modules, which are Soil Hydrologic Model (SHM), Terrestrial Hydrologic Model (THM), Ground-water Hydrologic Model (GHM), and Channel Ground-water Interaction (CGI). Hydrological unit: finite difference grid
Origin (development and maintenance)	Developed by Dr. Zhongbo Yu, Earth System Science Center, The Pennsylvania State University
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** Sun workstation, PC **Operating System:** Windows, Unix **Open source:** **Computer Language:** C and FORTRAN **GIS-based:** no but can be linked to GIS (see Yu et al., 2001)

	Visualisation facilities: no GUI
Pathways and processes modelled	vertical soil moisture flow, evapotranspiration (ET), infiltration, overland flow, channel flow, and ground-water flow.
Inputs (data requirements)	Precipitation, temperature (max. and min), wind speed, solar radiation.
Outputs	streamflow, surface runoff, ground-water baseflow, and water levels in wells.
Calibration Method	Based on the indirect approach by using a process like Latin Hypercube sampling to cover the range of adjustable variables systematically. Calibration targets can be: streamflow, surface runoff, ground-water baseflow, and water levels in wells. See Yu. and Schwartz (1999).
Parameters	Numerous. Physical parameters can be obtained from measurements/records, some require calibration.
Water quality constituents	No
Case Studies / Publications	Yu, Z., Barron, E.J., Yarnal, B., Lakhtakia, M.N., White, R.A., Pollard, D., and Miller, D.A. (2002).Evaluation of basin-scale hydrologic response to a multi-storm simulation. Journal of Hydrology, v 257, n 1-4, pp. 212-225. Olivera, F. (2001).Extracting hydrologic information from spatial data for HMS modelling. Journal of Hydrologic Engineering, v 6, n 6, pp. 524-531. Yu, Z. (2000). Assessing the response of subgrid hydrologic processes to atmospheric forcing with a hydrologic model system. Global and Planetary Change, v 25, n 1-2, pp. 1-17. Yu, Z., Lakhtakia, M.N., Yarnal, B., White, R.A., Miller, D.A., Frakes, B., Barron, E.J., Duffy, C., and Schwartz, F.W. (1999).Simulating the river-basin response to atmospheric forcing by linking a mesoscale meteorological model and hydrologic model system. Journal of Hydrology, v 218, n 1-2, pp. 72-91. Frakes, B. and Yu, Z. (1999). An evaluation of two hydrologic models for climate change scenarios. Journal of the American Water Resources Association, v 35, n 6, pp. 1351-1363. Yu, Z., Carlson, T.N., Barron, E.J., and Schwartz, F.W. (2001). On evaluating the spatial-temporal variation of soil moisture in the Susquehanna River Basin. Water Resources Research, v 37, n 5, pp. 1313-1326.
Assumptions/Limitations	

Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: Dr. Zhongbo Yu Earth System Science Center The Pennsylvania State University University Park, PA 16802 phone: (814) 865-1781; fax: (814) 865-3191; email: yu@essc.psu.edu Homepage: http://hydro.nevada.edu/hms/hms.html Cost:

Yu, Z. and Schwartz F. W. (1999). Automated calibration applied to watershed-scale flow simulations. Hydrological processes, Vol. 13, No.2, pp. 191-209.
Yu, Z., Guo, Y., Voortman, J. , White, R., and Miller, D. A. (2001). Journal of American Water Resources Association, vol. 37, 957-971.

SCS-CN Based Model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Deterministic Model, event-based, lumped
Origin (development and maintenance)	Developed by Dr. Vijay P. Singh at Texas A & M University, U.S.A. and Dr. Surendra Kumar Mishra, Indian Institute of Technology, India.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open Source:** **GIS-Based:** No **Computer Language:** **Visualisation Facilities:** no graphical interface, results can be plotted as graphs
Pathways and processes modelled	Infiltration and surface runoff
Inputs (data requirements)	Rainfall hyetograph, antecedent precipitation amount, infiltration data, geomorphological characteristics of the watershed, soil-vegetation-land use complex.

Outputs	Infiltration and runoff volumes, Infiltration rates and runoff hydrographs
Calibration Method	Optimization by Marquardt least square approach
Parameters	Potential maximum retention, initial abstraction coefficient, infiltration rate, and storage routing coefficient Model sensitivity: Model is sensitive to variation of parameters values on small agricultural watershed but insensitive to urban watersheds.
Water quality constituents	None
Case Studies / Publications	Reshmidevi, T.V. , Jana, R., and Eldho, T.I. (2008). Geospatial estimation of soil moisture in rain-fed paddy fields using SCS-CN-based model. Agricultural Water Management, v 95, n 4, pp. 447-457. Mishra, S.K. , Jain, M.K., and Singh, V.P. (2004). Evaluation of the SCS-CN-based model incorporating antecedent moisture. Water Resources Management, v 18, n 6, pp. 567-589. Tyagi, J.V., Mishra, S.K., Singh, R., and Singh, V.P. (2008). SCS-CN based time-distributed sediment yield model. Journal of Hydrology, v 352, n 3-4, pp. 388-403. Jain, M.K., Mishra, S.K., and Singh, V.P. (2006). Evaluation of AMC-dependent SCS-CN-based models using watershed characteristics; Source: Water Resources Management, v 20, n 4, pp. 531-552. Singh, P.K., Bhunya, P.K., Mishra, S.K.,and Chaube, U.C.(2008). A sediment graph model based on SCS-CN method. Journal of Hydrology, v 349, n 1-2, pp. 244-255. Mishra, S. K., Kumar, S. R., and Singh, V. P. (1999). Calibration and validation of a general infiltration model. Hydrological Processes, v 13, n 11, pp. 1691-1718.
Versions	

How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contacts: 1. Dr. Vijay P. Singh, Professor of Biological and Agricultural Engineering, Department of Biological and Agricultural Engineering, Texas A and M University, Scoates Hall, 2117 TAMU, College Station, Texas 77843-2117, U.S.A. Email: vsingh@tamu.edu 2. Dr. Surendra Kumar Mishra, Department of Water Resources Development and Management, Indian Institute of Technology, Roorkee-247 667, Uttarakhand, India. E-mail: skm61fwt@iitr.ernet.in Documentation: No manual for the model. Theoretical details and applications of the model can be found in Mishra and Singh (2002).

Mishra, S.K. and Singh,V.p. (2002). SCS-CN-Based Hydrologic Simulation Package. Chapter 13 in Mathematical Models of Small Watershed Hydrology and Applications. Singh,V.P. nad Frevert,D.K. eds., Water Resources Publications, Colorado, U.S., pp. 391-464.

CEQUEAU Model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Water-balance type conceptual model with distributed parameters, continuous-simulation. Hydrological Unit: 'partial squares'
Origin (development and maintenance)	Developed at the INRS-ETE (Institut National de la Recherche Scientifique, Eau, Terre et Environnement), Canada.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open source:** No **Computer Language:** **GIS-based:** No **Visualisation facilities:** CEQUEAU interface
Pathways and processes modelled	Rainfall, snow melt, evapo-transpiration, infiltration, Runoff, interflow, baseflow, and channel routing

Inputs (data requirements)	maximum air temperature (°C) minimum air temperature (°C) precipitation (mm) observed streamflow for the calibration period
Outputs	Steam flows at any points of the watershed and estimated data on the watershed (daily rain, mean daily temperature, snow accumulation on the soil, mean daily snowmelt, daily evaporation, water level in the SOIL reservoir, water level in the WATER TABLE reservoir).
Calibration Method	adjustment of the parameters of the model is done by trials and errors or by optimization using BOTM technique based on M.J.D. Powell's method (1964).
Parameters	Table 13.3, page 557 in Morin (2002) produces a list of 28 parameters that can be optimized. The optimization algorithm BOTM allows the simultaneous optimization of 21 parameters.
Water quality constituents	Yes (The model contains a module that allows simulation of the water quality of a river).
Case Studies / Publications	Ayadi, M. and Bargaoui, Z .(1998). Modelling of flow of the Miliane River using the CEQUEAU model. Hydrological Sciences Journal/Journal des Sciences Hydrologiques ,vol. 43, no. 5, pp. 741-758. Fortin, J.P. , Proulx, H. , and Bellon, A. (1987). Utilisation des donnees d'un radar meteorologique pour la simulation des ecoulements en riviere a l'aide d'un modele hydrologique matriciel, Journal of Hydrology, Volume 90, Issues 3-4, pp. 327-350. Pinheiro, A. and Caussade, B. (1994) Model to describe the fate of agricultural pollutants Proceedings - National Conference on Hydraulic Engineering, n pt 1, pp. 170-174. Boukchina, R., Lagace, R., and Morin, G.(1995). Modelling nitrate output from agricultural watersheds using a hydrological model. Water Quality Research Journal of Canada, v 30, n 2, pp. 247-263.
Versions	V2.0, V4.0
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Technical Contact: Guy Morin Institut National de la Recherche Scientifique Eau, Terre et Environnement

	2800, rue Einstein, C.P. 7500 Sainte-Foy (Québec) Canada G1V 4C7 Guy_Morin@inrs-ete.uquebec.ca Tél : (418) 654-2547 Télécopie : (418) 654-2600 Model Homepage: http://www.ete.inrs.ca/activites/modeles/cequeau/aindex.html A demo version of CEQUEAU V4.0 is available for download.

Powell, M.J.D. (1964). An efficient method for finding the minimum of a function of several variables without calculating derivatives. Computer J. 7, 155-162.

Morin, G. (2002). CEQUEAU Hydrological Model, Chapter 13 in ‘Mathematical Models of Large Watershed Hydrology’. Singh,V.P. and Frevert,D.K. eds., Water Resources Publications, Colorado, USA, pp. 507-576.

ARC/EGMO

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Conceptual, semi-distributed, 3D-catchment model, multilayer Hydrological unit: hydrotope (a unit which behaves hydrologically uniform and unique)
Origin (development and maintenance)	Developed at the Bureau of Applied Hydrology, Germany
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows, Unix **Open source:** No **Computer Language:** C language **GIS-based:** yes ARCInfo or ARCView **Visualisation facilities:** ARCInfo or ARCView
Pathways and processes modelled	Evapotranspiration, infiltration, snow melt, begetation model, surface and subsurface flow routing, and baseflow.

Inputs (data requirements)	time series of precipitation, air temperature, air humidity, global radiation or sun duration, wind velocity
Outputs	Time series (stream flow (discharge), water budget components, carbon and nitrogen budget components, vegetation variables, results of the climate regionalization, etc.); imported easily into GIS (e.g. ArcView, ArcGIS) or into table calculation programs (EXCEL, ACCESS etc.)
Calibration Method	Calibration only necessary for some parameters of the lateral flows domain (subsurface storage and flow etc.). Many parameters are physically-based and hence measurable or obtained from maps/records.
Parameters	very sensitive against precipitation, global radiation and air temperature but also against the site characteristics (e.g. vegetation parameter)
Water quality constituents	nutrients
Case Studies / Publications	Müller-Wohlfeil, D.-I. , Bürger, G. and Lahmer, W. (2000). Response of a River Catchment to Climatic Change: Application of Expanded Downscaling to Northern Germany. Climatic Change Vo.47, No. 1-2, pp. 61–89. Klöcking, B., Haberlandt, U. (2002). Impact of land use changes on water dynamics--a case study in temperate meso and macroscale river basins, Physics and Chemistry of the Earth, Parts A/B/C, Vol. 27, No. 9-10, pp. 619-629. Becker, A. and Braun, P. (1999). Disaggregation, aggregation and spatial scaling in hydrological modelling, Journal of Hydrology, Vol. 217, No. 3-4, pp. 239-252. Haberlandt, U., Klöcking, B., Krysanova, V., and Becker, A. (2001). Regionalisation of the base flow index from dynamically simulated flow components - A case study in the Elbe River Basin. Journal of Hydrology, v 248, n 1-4, pp. 35-53.

	Haberlandt, U. , Krysanova, V., Klöcking, B., Becker, A., and Bárdossy, A. (2001). Development of a metamodel for large-scale assessment of water and nutrient fluxes - First components and initial tests for the Elbe River basin. IAHS-AISH Publication, n 268, pp. 263-269, Regional Management of Water Resources.
Assumptions/Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: Büro für Angewandte Hydrologie (BAH) Köberlesteig 6 13156 Berlin webmaster@bah-berlin.de www.bah-berlin.de Documentation: www.arcegmo.de (in German) Cost: commercial licence fees applies, free for universities and research institutions. Training available

Soil and Water Integrated Model (SWIM)

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	continuous-time spatially distributed river basin model, simulating hydrology, vegetation, erosion and nutrients. Hydrological unit: Hydrological Response Unit (HRU) or hydrotope. A hydrotope is a set of disconnected units in the sub-basin, which have a unique land use and soil type and can be assumed to behave in a hydrologically uniform way within the sub-basin.
Origin (development and maintenance)	SWIM was developed in the Potsdam Institute for Climate Impact Research, Germany on the basis of two other models: SWAT (Arnold et al., 1993 & 1994) and MATSALU (Krysanova et al., 1989). The SWAT model was developed in the Blackland Research Center (USDA ARS, Temple, Texas) while the The MATSALU model developed in Estonia on the basis of CREAMS has the similar structure as SWAT.

Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** UNIX uses the Geo Information System GRASS , LINUX, and Windows **Open Source:** yes **GIS-Based:** GRASS **Computer Language:** C (SWIM/GRASS interface) , FORTRAN (SWIM code) **Visualisation Facilities:** GRASS GIS interface
Pathways and processes modelled	Hydrological processes: precipitation, surface runoff, snow melt, evapotranspiration, infiltration, subsurface runoff, and streamflow routing. The water balance for the shallow aquifer includes groundwater recharge, capillary rise to the soil profile, lateral flow, and percolation to the deep aquifer.
Inputs (data requirements)	daily precipitation, average, minimum and maximum air temperature, solar radiation, rainfall intensity parameters river runoff in the basin outlet, river cross-sections or mean river width and depth in subbasin outlets, hydraulic structure (for regulated rivers) amount of N and P applied per hectare
Outputs	Vertical and lateral water flows, plant biomass and crop yields, nitrogen- and phosphorus concentrations, sediment transport at daily, monthly or annual time steps and as GIS layers.
Calibration Method	manual
Parameters	Many parameters. Sensitive parameters are tested and shown in Chapter 4 of SWIM Manual (Krysanova etal. 2000).
Water quality constituents	Nutrients (N and P) and sediments.
Case Studies / Publications	Hattermann, F. F. , Wattenbach, M, Krysanova, V., and Wechsung, F. (2005). Runoff simulations on the macroscale with the ecohydrological model SWIM in the Elbe catchment - Validation and uncertainty analysis. Hydrological Processes, v 19, n 3, special Issue: SWAT 2000 Development and Applications, pp. 693-714. Krysanova V., Meiner, A., Roosaare, J., Vasilyev, A. 1989. Simulation modelling of the coastal waters pollution from agricultural watershed. *Ecoogical. Modelling* 49, 7-29.

	Krysanova, V., Hattermann, F., and Wechsung, F. (2005). Development of the ecohydrological model SWIM for regional impact studies and vulnerability assessment. Hydrological Processes, v 19, n 3, special Issue: SWAT 2000 Development and Applications, pp.763-783. Gaze, S. R. , Simmonds, L. P. , Brouwer, J. , and Bouma, J. (1997). Measurement of surface redistribution of rainfall and modelling its effect on water balance calculations for a millet field on sandy soil in Niger, Journal of Hydrology, Vol. 188-189, pp. 267-284. Wattenbach, M., Hattermann, F., Weng, R., Wechsung, F., Krysanova, V., and Badeck, F. (2005). A simplified approach to implement forest eco-hydrological properties in regional hydrological modelling. Ecological Modelling, v 187, n 1 SPEC. ISS., pp. 40-59.
Versions	SWIM-CN (carbon cycle included).
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: Valentina Krysanova Potsdam Institute for Climate Impact Research P.O.Box 601203, Telegrafenberg 14412 Potsdam, Germany phone: +49-(0)331-288-2515 fax: +49-(0)331-288-2600 e-mail: valen@pik-potsdam.de How to obtain Model: For code and documentation please contact Fred Hattermann at hattermann@pik-potsdam.de.

Krysanova V., Wechsung, F., Arnold, J., Srinivasan, R., and Williams, J. (2000). SWIM (Soil and Water Integrated Model) User Manual, V SWIM- 8 . Potsdam Institute for Climate Impact Research, Potsdam, Germany.

INCA
Integrated Catchment Model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	The INCA model is a semi-distributed, deterministic, dynamic nitrogen model which simulates and predicts nitrogen transport and processes within catchments.
Origin (development and maintenance)	The INCA model was developed at the Aquatic Environments Research Centre (AERC) of the University of Reading, U.K.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** IBM Compatible PC with MSDOS **Operating System:** Windows **Open source:** No **Computer Language:** C++ **GIS-based:** yes, GIS-INCA interface **Visualisation facilities:** output graphics and statistics package
Pathways and processes modelled	Surface runoff, infiltration, evapotranspiration, soil moisture accounting, groundwater flow, nitrogen and phosphorous processes.
Inputs (data requirements)	Daily rainfall, soil moisture deficit, temperature and solar radiation, observed instream data at whatever frequency is available, fertiliser inputs (either annual averages or daily time series).
Outputs	• Daily time series of flows, and water quality outputs, eg. nitrate-nitrogen and ammonium-nitrogen concentrations, at selected sites along the river; • profiles of flow or water quality along the river at selected times; • cumulative frequency distributions of flow and water quality at selected sites; • table of statistics for all sites; • Daily and annual water quality loads for all land uses and all processes. • 3D pictorial representations of flow and water quality
Calibration Method	Manual (calibration procedure recommended by the authors is described in chapter 7 of the user guide (Butterfield, et al.).
Parameters	A detailed account of the parameters in INCA as well as a table showing the range of values of parameters are given in Chapters 5 and 8 of the INCA-N user guide (Butterfield, et al.). Granlund et al (2004) provides values of calibrated parameters of the INCA model.
Water quality constituents	N, P Sediments , Macrophytes, epiphytes and phytoplankton

Case Studies / Publications	Ranzinia, M., Forti, M. C., Whitehead, P. G., Arcovaa, F. C. S., de Ciccoa, V. and Wade, A. J. (2007) Integrated Nitrogen CAtchment model (INCA) applied to a tropical catchment on the Atlantic Forest, São Paulo, Brazil Hydrology and Earth Systems Science Journal, 11, 614-622. Wade, A. J., Butterfield, D., Griffiths, T. and Whitehead, P. G. (2007) Eutrophication control in river systems: an application of INCA-P to the River Lugg Hydrology and Earth Systems Sciences, 11, 584-600. Wade, A. J., Butterfield, D. and Whitehead, P. G. (2006) Towards an improved understanding of the nitrate dynamics in lowland, permeable river-systems: applications of INCA-N Journal of Hydrology, 330, 185-203. Wade, A. J., Neal, C. N., Whitehead, P. G. and Flynn, N. (2005) Modelling nitrogen fluxes from the land surface to the coastal zone in European systems: a perspective of the INCA project Journal of Hydrology, 304, 413-429. Whitehead, P. G., Hill, T. J. and Neal, C. N. (2004) Impacts of forestry on nitrogen in upland and lowland catchments: a comparison of the River Severn at Plynlimon in Mid Wales and the Bedford Ouse in south-east England using the INCA model Hydrology and Earth Systems Science, 8, 533-544.
Assumptions and Limitations	Knowledge of initial soil conditions, cannot differentiate between algal species
Versions	INCA-N, INCA-P, INCA-Chalk, INCA-C, and INCA-Sed
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Cost: Free of charge for evaluation purposes. To obtain Model contact: Prof. Paul Whitehead Aquatic Environments Research Centre, Department of Geography, University of Reading, Reading, RG6 6AB, UK. Tel: +44 (0)118 931 8740

	Fax: +44 (0)118 975 5865 E-mail: aerc@reading.ac.uk

Butterfield, D., Wade, A.J. and Whitehead, P.G.(?). INCA-N v1.7 User Guide
Granlund, K., Rankinen, K. and Lepistö, a. (2004). Testing the INCA model in a small agricultural catchment in southern Finland. Hydrology and Earth System Sciences, 8(4), 717-728.

The Xinanjiang Model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Conceptual, continuous simulation, quasi-distributed Hydrological unit: sub-basins
Origin (development and maintenance)	Developed in 1973, published in 1980 (Zhao et al, 1980)
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open source:** Yes **Computer Language:** FORTRAN **GIS-based:** No **Visualisation facilities:** None
Pathways and processes modelled	Runoff, interflow, baseflow, evapotranspiration, and runoff routing
Inputs (data requirements)	Rainfall and measured pan evaporation.
Outputs	Discharge and actual evapotranspiration
Calibration Method	Manual, automatic calibration (GLOBE package). See Yunian (2000)
Parameters	There are 17 parameters in total (15 of which pertain to the sub-basin). The output is more sensitive to 7 parameters (Zhao nad Liu, 1995).
Water quality constituents	No
Case Studies / Publications	Li, H., Zhang, Y., Chiew, F., Xu, S. (2009). Predicting runoff in ungauged catchments by using Xinanjiang model with MODIS leaf area index, Journal of Hydrology, Volume 370, Issues 1-4, Pages 155-162

	Cheng, C.-T., Zhao, M.-Y., Chau, K.W. , Wu, X.-Y. (2006). Using genetic algorithm and TOPSIS for Xinanjiang model calibration with a single procedure, Journal of Hydrology, Volume 316, Issues 1-4, Pages 129-140 Liu,J., Chen, X., Zhang, J., Flury, M. (2009). Coupling the Xinanjiang model to a kinematic flow model based on digital drainage networks for flood forecasting. Hydrological Processes, Vol.23, No. 9, pp. 1337-1348.
Assumptions and Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: Prof. Guo Shenglia Wuhan University China Email: slguo@whu..edu.cn Cost: Free of charge

Zhao,R.J., Zhuang,Y.-L., Fang,L.-R., Liu,X.-R., and Zhang,Q.-S.(1980). The Xinanjiang Model, Hydrological Forecasting Proceedings Oxford Symposium, IAHS 129,pp. 351-356.

Yunian, L. (2000). Automatic Calibration of the Xinanjiang Model for the Upper Reach of the Huaihe River. Master of Science Thesis, IHE Delft.

Zhao,R.J., and Liu, X.R. (1995) The Xinanjiang Model. Chapter 7 in Computer Models of Watershed Hydrology, Singh,V.P. editor, Water Resources Publications, Colorado, USA.

ARNO /NUARNO

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Semi-distributed conceptual model Hydrological unit: sub-units over which the processes are lumped

Origin (development and maintenance)	Developed by E. Todini and L. Ciarapica, Department of Earth and Geo-Environmental Sciences, University of Bologna, Bologna, Italy
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open source:** No **Computer Language:** FORTRAN **GIS-based:** No **Visualisation facilities:** no graphical user interface, graphs only
Pathways and processes modelled	The processes represented in the model are: soil moisture balance, drainage, percolation, groundwater, evapotranspiration, overland runoff routing, and stream routing.
Inputs (data requirements)	Continuous record of precipitation and temperature, average temperature
Outputs	Runoff and baseflow
Calibration Method	Manual
Parameters	Only soil component parameters (6 parameters) require accurate calibration using historical data. Other parameters do not require calibration and can be directly evaluated on the basis of geo-morphological, soil and land use maps
Water quality constituents	None
Case Studies / Publications	Abdulla, F. A., Lettenmaier, D. P. and Liang, Xu (1999). "Estimation of the ARNO model baseflow parameters using daily streamflow data." Journal of Hydrology 222(1-4): 37-54. Mellor, D., Sheffield, J. ,O'Connell, P.E. and Metcalfe, A.V. (2000). "A stochastic space-time rainfall forecasting system for real time flow forecasting II: Application of SHETRAN and ARNO rainfall runoff models to the Brue catchment " Hydrology and Earth System Sciences 4(4): 617-626. Todini, E. (1996). The ARNO rainfall--runoff model, Journal of Hydrology, Volume 175, Issues 1-4, pp. 339-382
Assumptions/Limitations	Limitations: Not all the ARNO model parameters can be directly estimated or derived from maps, which is the major model limitation when wishing to use the model on ungauged catchments.
Versions	

How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contacts: E. Todini, Department of Earth and Geo-Environmental Sciences, University of Bologna, Piazza di Porta S. Donato, 1 Bologna Tel: +39 051 20 9 4537 Email: todini@geomin.unibo.it Cost: free of charge for academic use

TOPKAPI

TOPographic Kinematic Approximation and Integration model.

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Physically-based distributed hydrological catchment model, also has a lumped model version. Modelling unit: square cells over which the model equations are integrated.
Origin (development and maintenance)	Developed by E. Todini and L. Ciarapica. Department of Earth and Geo-Environmental Sciences, University of Bologna, Bologna, Italy
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open Source:** No **Computer Language:** FORTRAN **GIS based?:** Yes **Visualisation facilities:** own Visual interface, GIS
Pathways and processes modelled	It relates the components of flow to soil moisture within the catchment. It considers surface runoff as being generated by (1) saturation from above (Hortonian), (2) saturation from below (Dunne) or (3) return flow, in which subsurface flow is forced to the surface by topographic influences., e.g. in areas of subsurface flow convergence or concave slope profiles.
Inputs (data requirements)	Precipitation, soil temperature, potential evapotranspiration
Outputs	Discharge, Water level, spatially distributed information
Calibration Method	Parameter by optimization method
Parameters	Its parameters are physically based, the parameter set is large enough to represent adequately the phenomena but

	not too large to become overparametrized and difficult to calibrate.
Water quality constituents	None
Case Studies / Publications	Liu, Z., M.V.L. Martina and E. Todini, Flood forecasting using a fully distributed model: application of the TOPKAPI model to the Upper Xixian Catchment, Hydrology and Earth Systems Sciences **9** (4) (2005), pp. 347–364 Ciarapica, L. and Todini, E. (2002). Hydrological Processes, v 16, n 2, pp. 207-229.TOPKAPI: A model for the representation of the rainfall-runoff process at different scales Liu, Z.-Y., Tan, B.-Q., Tao, X., Xie, Z.-H. (2008). Application of a distributed hydrologic model to flood forecasting in catchments of different conditions. Journal of Hydrologic Engineering, v 13, n 5, Methodologies in Hydrologic Modeling, pp. 378-384. Implementation of the TOPKAPI model in South Africa: Initial results from the Liebenbergsvlei catchment Vischel, T., Pegram, G., Sinclair, S., Parak, M. (2008). Water SA, v 34, n 3, pp. 331-342.
Assumptions and Limitations	TOPKAPI is based on the following assumptions: (1) At spatial scales larger than one hundred meters, it is convenient to assume that the total amount of precipitation reaching the catchment infiltrate into the soil, untill the soil becomes saturated. (2) Subsurface flow is an essential component of a flood wave. It is significant in terms of volume of water and also because it tends to saturate downstream areas close to the channels. (3) The dynamics of horizontal flow, both surface and subsurface, depend "statistically" on the distribution of the slopes and not much on their actual position within the catchment. (4) At the catchment scale, all the major components of the flow (drainage, evapotranspiration, infiltration etc.) can be related to the total soil moisture content of the soil.
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	**How to obtain Model:** contact Prof. E. Todini, Department of Earth and Geo-Environmental Sciences, University of Bologna, Via Zamboni, 67 40127 Bologna Italy Phone: +39-051-2094537

	ezio.todini@unibo.it **Documentation:** Not available in the public domain but it can be obtained from Professor Todini. Cost: free of charge for academic use

GBHM

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Physically-based distributed, continuous-simulation hydrological model. Hydrological unit: hillslope element.
Origin (development and maintenance)	Developed at the Institute of Industrial Science, University of Tokyo.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open source:** **Computer Language:** **GIS-based:** yes ARC/INFO **Visualisation facilities:** GIS ARC/INFO
Pathways and processes modelled	Interception, infiltration, evapotranspiration, surface runoff, saturated and unsaturated flow, and channel routing.
Inputs (data requirements)	Daily potential evaporation, hourly precipitation and air temperature
Outputs	River discharge at selected points, soil moisture, and actual evaporation
Calibration Method	
Parameters	Topographical parameters (hillslope length, angle, and elevation) estimated from DEM; soil water parameters estimated from field. The anisotropy ratio of soil hydraulic conductivity, r_a, is not measurable, which needs to be calibrated. All other parameters are physically-based and therefore should be obtained from measurements.

	Hourly (or higher temporal resolution) hydrological responses are sensitive to the DEM resolution and the threshold area that used to extract the river network. The DEM resolution is suggested to be finer than 1-km; the threshold area is suggested to be less than 1-km^2.
Water quality constituents	None.
Case Studies / Publications	Jijun Xu, Dawen Yang, Yonghong Yi, Zhidong Lei, Jin Chen, Wenjun Yang, Spatial and temporal variation of runoff in the Yangtze River basin during the past 40 years, Quaternary International, Volume 186, Issue 1, Larger Asian rivers and their interactions with estuaries and coasts, 1 August 2008, Pages 32-42. Wang, L., T. Koike, K. Yang, T. J. Jackson, R. Bindlish, and D. Yang (2009), Development of a distributed biosphere hydrological model and its evaluation with the Southern Great Plains Experiments (SGP97 and SGP99), *J. Geophys. Res.*, 114, D08107, doi:10.1029/2008JD010800. Application to the Seki River Basin in Japan and comparison with MIKE SHE and TOPMODEL (Yang et al. 2002). Application to a large tropical catchment in Thailand (Yang et al. 2002).
Assumptions/Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contacts: Dr. Dawen Yang Institute of Industrial Science, University of Tokyo 4-6-1, Komaba, Meguro-ku, Tokyo, 153-8505, JAPAN Tel: +81-3-5452-6381 Fax: +81-3-5452-6383 E-mail: yang@rainbow.iis.u-tokyo.ac.jp Documentation: Not available. How to obtain Model: contact Dr. Dawen Yang

Yang,D., Oki,T, Herath, S., Musiake, K. (2002). A Geomorphogy-Based Hydrological Model and its applications. Chapter 9 in Mathematical Models of Small Watershed Hydrology and Applications. Singh,V.P. and Frevert,D.K. eds, pp. 259-300.

WISTOO Model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Distributed, continuous-simulation, physically-based. Hydrological unit: raster square elements/cells.
Origin (development and maintenance)	Model was developed at Cracow University of Technology in cooperation with Warsaw University of Technology, Poland.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open source:** **Computer Language:** **GIS-based:** Yes (can take GIS data) **Visualisation facilities:** own Graphical User Interface
Pathways and processes modelled	The model simulates interception, evapotranspiration, infiltration, surface and subsurface flow, groundwater, baseflow, and channel flow.
Inputs (data requirements)	Precipitation, air temperature, relative humidity, wind velocity, and solar radiation.
Outputs	Surface runoff, interflow, and baseflow
Calibration Method	None of the parameters used in the model is optimized (Ozga-Zielinska, M., 2002). Fitting of simulated hydrographs to observed ones is done by soil parameter correction.
Parameters	state of the terrain and land-use (ex. resistance coefficient – roughness, coverage height, permeability, coverage retention etc.), soil and sub-soil type: porosity coefficient, maximal soil conductivity, soil depth. Physically-based parameters, mainly calculated from digital thematic layers Model output hydrograph is sensitive to cell size. Cell size should be equal to mean river bed width.

Water quality constituents	No
Case Studies / Publications	Example of WISTOO model application for Lososina River Watershed (Ozga-Zielinska et al., 2002)
Assumptions and Limitations	• High level of detail in spatial data • Model structure focuses on mountainous watersheds (but it can also be applied for hilly watersheds)
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: Dr Wieslaw Gadek Cracow University of Technology Institute of Water Engineering and Water Management 31-155 Krakow ul. Warszawska 24 Poland wieslaw.gadek@iigw.pl Documentation: Entire documentation is available at Cracow University of Technology.

M. Ozga-Zielinska, W. Gadek, K. Ksiazynski, E. Nachlik, and R. Szczepanek (2002). MATHEMATICAL MODEL OF RAINFALL-RUNOFF TRANSFORMATION-WISTOO, chapter 19 in Mathematical Models of Large Watershed Hydrology. Edt by Vijay P. Singh and Donald K. Frevert, Water Resources Publications, Colorado, USA.

SWMM model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	physically based distributed rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas but also simulates non-urban (rural areas). Hydrological Unit: subcatchments and river segments.
Origin (development and maintenance)	SWMM was first developed in 1971 by the U.S. Environmental Protection Agency and has undergone several major upgrades since then. The recent version SWMM 5 was pursued under a Cooperative Research and Development Agreement between the Water Supply and Water Resources Division of the U.S. Environmental Protection Agency and the consulting engineering firm of Camp Dresser & McKee Inc.
Platform (PC?), Operating System, Open source?, GIS-based (what	**Platform:** PC **Operating System:** Windows

GIS?), Computer Language, Visualisation facilities	**Open source:** Yes (except XP-SWMM) **Computer Language:** C **GIS-based:** No **Visualisation facilities:** own GUI (SWMM 5), also XP-SWMM is coupled with EXPERT GUI. MIKE-SWMM
Pathways and processes modelled	The model simulates: time-varying rainfall, evaporation of standing surface water, snow accumulation and melting, rainfall interception from depression storage, infiltration of rainfall into unsaturated soil layers, percolation of infiltrated water into groundwater layers, interflow between groundwater and the drainage system, and nonlinear reservoir routing of overland flow.
Inputs (data requirements)	Precipitation, Temperature, wind speed, and evaporation.
Outputs	hydrographs and pollutographs at any desired location in the drainage system.
Calibration Method	Manual, coupled with some calibration routines (Wan and James, 2002), Barco et al. 2008
Parameters	Detailed in the SWMM user Manual (Rossman, 2009)
Water quality constituents	yes
Case Studies / Publications	Peterson, E.W. and Wicks, C. M. (2006). Assessing the importance of conduit geometry and physical parameters in karst systems using the storm water management model (SWMM). Journal of Hydrology, v 329, n 1-2, pp. 294-305. Cho, J.H. and Seo, H.J. (2007). Parameter optimization of SWMM for runoff quantity and quality calculation in a eutrophic lake watershed using a genetic algorithm. Water Science and Technology: Water Supply, v 7, n 5-6, pp. 35-41. Liong, S.-Y., Chan, W. T., and Shreeram, J. (1995). Peak-flow forecasting with genetic algorithm and SWMM. Journal of Hydraulic Engineering - ASCE, v 121, n 8, pp. 613-617. Wu, Y., Jiang, Y., Yuan, D., Li, L.(2008). Modeling hydrological responses of karst spring to storm events: Example of the Shuifang spring (Jinfo Mt., Chongqing, China). Environmental Geology, v 55, n 7, pp. 1545-1553
Assumptions and Limitations	• URBAN areas oriented (but not exclusively) • Simulates process in small basins

	• Time step not flexible (1 hr)
Versions	XP-SWMM (not a public domain model), SWMM 5.0, SWMM 5.0.015
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	How to obtain Model: The model, user manual, and graphical user interface can be downloaded from http://www.epa.gov/ednnrmrl/models/swmm/ Technical Support: There is no formal support offered for EPA SWMM. A SWMM Users Listserve, established by the University of Guelph, allows subscribers to ask questions and exchange information. To subscribe, send an email message to listserv@listserv.uoguelph.ca. Cost: Free of charge GUI US$ 500-5000

Rossman, L.A. (2009). Storm Water Management Model, User's Manual, Version 5.0. National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, OH 45268. EPA/600/R-05/040.

Wan, B. and James, W. (2002). SWMM calibration using genetic algorithms. Global Solutions for Urban Drainage, pp. 1-14.

Barco, J., Wong, K. M., and Strenstrom, M. K. (2008). Automatic calibration of the U.S. EPA SWMM model for a large urban catchment Journal of Hydraulic Engineering, v 134, n 4, pp. 466-474.

Erosion Productivity Impact Calculator EPIC

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Continuous simulation mechanistic model that can be used to determine the effect of management strategies on agricultural production and soil and water resources, lumped
Origin (development and maintenance)	Was developed at Texas Agricultural Experiment Station (TAES) Blackland Research Center, Temple, Texas, U.S.

Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC IBM, Macintosh, or Sun **Operating System:** DOS, UNIX, Windows **Open source:** No **Computer Language:** FORTRAN version 5125 **GIS-based:** Spatial-EPIC is a GIS-based application for EPIC, GRASS GIS, GEPIC (GIS-based tool for EPIC) **Visualisation facilities:** Spatial-EPIC, WinEPIC
Pathways and processes modelled	The model simulates weather, surface runoff, baseflow, percolation, evapotranspiration, lateral subsurface flow and snow melt. Water Erosion; Wind Erosion; N & P loss in runoff, nitrogen leaching; Organic N & P transport by sediment; N & P mineralization, immobilization and uptake; Denitrification; Mineral P cycling; N fixation; Pesticide fate and transport; Soil temperature Crop growth and yield for over 80 crops; Crop rotations; Tillage, Plant Environment control (drainage, irrigation, fertilization, furrow diking, liming); Economic accounting; Waste management(feed yards dairies with or without lagoons).
Inputs (data requirements)	Precipitation, temperature (monthly means) optional; solar radiation, wind speed, relative humidity
Outputs	Runoff, sediment load, nitrogen and phosphorous loads
Calibration Method	Manual
Parameters	Most sensitive parameters: sand, silt, coarse fragment contents, and curve number (SCS method) (Bhuyan et a;. 2002)
Water quality constituents	Nutrients (nitrogen and phosphorus), sediments
Case Studies / Publications	Edwards D. R. , Benson V. W., Williams J. R., Daniel T. C., Lemunyon J., and Gilbert R. G. (1994) Use of the EPIC model to predict runoff transport of surface-applied inorganic fertilizer and poultry manure constituents. Transactions of the ASAE, vol. 37, no2, pp. 403-409. Vadas, P. A. , Krogstad, T., and Sharpley, A. N. (2006).Modeling Phosphorus Transfer between Labile and Nonlabile Soil Pools: Updating the EPIC Model. Soil Science Society of America Journal, v 70, n 3, p 736-743. Pierson, S.T., Cabrera, M.L., Evanylo, G.K., Schroeder, P.D., Radcliffe, D.E., Kuykendall, H.A., Benson, V.W., Williams, J.R., Hoveland, C.S., and McCann, M.A. (2001). Phosphorus losses from grasslands fertilized with

	broiler litter: EPIC simulations, Journal of Environmental Quality, v 30, n 5, pp. 1790-1795. Hauser, V. L., Gimon, D. M., Bonta, J. V., Howell, T. A., Malone, R. W., and Williams, J.R. (2005). Models for hydrologic design of evapotranspiration landfill covers. Environmental Science and Technology, v 39, n 18, pp. 7226-7233. Chung, S.W., Gassman, P.W., Kramer, L.A., Williams, J.R., and Gu, R.(1999). Validation of EPIC for two watersheds in southwest Iowa Journal of Environmental Quality, v 28, n 3, pp. 971-979.
Assumptions and Limitations	Limitations • Cannot represent watershed subsurface flow. • Does not simulate sediment routing in detail. • No mention of how the model deals with tile drains.
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contacts: Dr. Jimmy Williams Texas A&M University – TAES Blackland Research and Extension Center 720 E. Blackland Road Temple, TX 76502 Tel.- (254) 774-6124 Email – williams@brc.tamus.edu Avery Meinardus Texas A&M University – TAES Blackland Research and Extension Center 720 E. Blackland Road Temple, TX 76502 Tel. (254) 774-6110 Email – meinardu@brc.tamus.edu or epic@brc.tamus.edu Website: http://epicapex.brc.tamus.edu/

	Training: To schedule a training session (minimum of 5 participants) if one is not currently available, please contact: Evelyn Steglich, Texas A&M University – TAES Blackland Research and Extension Center (254) 774-6127 Email – esteglich@brc.tamus.edu Cost: Free of charge

Bhuyan,S.J., Kalita, P. K., Janssen, K. A., and Barnes, P. L. (2002). Soil loss predictions with three erosion simulation models, Environmental Modelling & Software, Vol.17, Issue 2, pp 135-144

APEX

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Continuous simulation mechanistic model, distributed in nature. Hydrological Unit: subcatchments/subareas homogeneous in terms of weather, soil, landuse, and management practices.
Origin (development and maintenance)	Was developed at Texas Agricultural Experiment Station (TAES) Blackland Research Center, Temple, Texas, U.S. The Agricultural Policy EXtender (APEX) model was developed in the 1990s to facilitate multiple subarea scenarios and/or manure management strategies, such as automatic land application of liquid manure from waste storage ponds, which cannot be simulated in EPIC. In addition to the EPIC functions, APEX has components for routing water, sediment, nutrients, and pesticides across complex landscapes and channel systems to the watershed outlet.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC IBM, Macintosh, or Sun **Operating System:** DOS, UNIX, Windows **Open source:** No **Computer Language:** Fortran **GIS-based:** yes, ArcGIS (WinAPEX-GIS and SWAPP **Visualisation facilities:** WinAPEX (Version 0604), WinAPEX-GIS (version 0806), SWAT-APEX (SWAPP)

Pathways and processes modelled	The model simulates weather and snow melt, surface runoff, baseflow, percolation, evapotranspiration, lateral subsurface flow, routing of water, sediment, nutrients, and pesticides across complex landscapes and channel systems to the watershed outlet. Water Erosion; Wind Erosion; N & P loss in runoff, nitrogen leaching; Organic N & P transport by sediment; N & P mineralization, immobilization and uptake; Denitrification; Mineral P cycling; N fixation; Pesticide fate and transport; Soil temperature Crop growth and yield; Crop rotations; Tillage, Plant Environment control (drainage, irrigation, fertilization, furrow diking, liming); Economic accounting; Waste management (feed yards dairies with or without lagoons).
Inputs (data requirements)	Daily Precipitation, maximum and minimum temperature , and solar radiation (wind speed, relative humidity If Penman equation is to be used). Wind speed also if dust erosion is simulated.
Outputs	Weather, hydrology, erosion, nutrients, pesticides, crop production, soil properties. By sub-area, routing reach and total watershed. Option S: daily, monthly, annual; user selects outputs
Calibration Method	Manual
Parameters	Sensitivity analysis (Wang et al., 2006)
Water quality constituents	N and P cycles: mineral, organic (NO3, NH3, active & stable organic N; labile P, active and stable mineral and organic P, uptake, mineralization- immobilization nitrification, denitrification, N fixation, volatilization GLEAMS pesticide component. Wash off of plants, decay in soil & on foliage, leaching runoff and sediment transport
Case Studies / Publications	Wang, E., Xin, C., Williams, J. R., Xu, C. (2006). Predicting soil erosion for alternative land uses. Journal of Environmental Quality, v 35, n 2, pp. 459-467. Borah, D. K., Yagow, G., Saleh, A., Barnes, P. L., Rosenthal, W., Krug, E. C., and Hauck, L. M. (2006). Sediment and nutrient modeling for TMDL development and implementation. Transactions of the ASABE, v 49, n 4, pp. 967-986. Test of APEX for nine forested watersheds in East Texas Wang, X. ,Saleh, A., McBroom, M.W., Williams, J.R., and Yin, L. (2007). Journal of Environmental Quality, v

	36, n 4, pp. 983-995
Assumptions and Limitations	
Versions	4220, 5140, 7045, 8190(1999) , 1310(2003), 2110(2006), 0604(2008), 0806.
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: J.R Williams , USDA-ARS, 808 E Blackland Road, Temple, TX 76503 Tel +1 817 770 6508 Fax +1 817 770 6561 Model : Model executables for version0604 can be downloaded from http://epicapex.brc.tamus.edu/downloads/model-executables.aspx Documents (theoretical and user manual) can be downloaded from: http://epicapex.brc.tamus.edu/downloads/user-manuals.aspx Website: http://epicapex.brc.tamus.edu/ Cost: Free of charge

Wang, X., Potter, S.R., Williams, J.R., Atwood, J.D., and Pitts, T.(2006). Sensitivity analysis of APEX for national assessment. Transactions of the ASABE, v 49, n 3, pp. 679-688.

HYSIM

HYSIM is a **Hy**drological **Si**mulation **M**odel which uses rainfall and potential evapotranspiration data to simulate river flow

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Continuous, conceptual, semi-distributed Hydrological Unit: subareas

Origin (development and maintenance)	Developed by Ron Manley, Water Resources Associates
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open source:** no **Computer Language:** Visual Basic **GIS-based:** no **Visualisation facilities:** has own GUI
Pathways and processes modelled	It simulates interception storage, runoff from impermeable areas, overland flow, interflow from the upper and lower and soil horizons, rapid and slow response from groundwater and the hydraulics of flow in river channels.
Inputs (data requirements)	Precipitation. This is given as catchment areal average. ii) Potential evapotranspiration rate. Estimates based on an empirical relationship. ii) Potential melt rate. This can be based on the degree day method or a more complex one. iv) Sewage flow/direct abstractions. The net figure for these is used. v) Groundwater abstractions.
Outputs	Outflow discharge, recharge to groundwater, evapotranspiration.
Calibration Method	An optimization scheme based on the Rosenbrook method. There is a choice of three objective functions, depending on whether high flows, low flows or overall accuracy is most important
Parameters	The model has around 25 parameters. Calibration in HYSIM uses an automatic search algorithm for the most sensitive parameters. The other parameters can be set by hydrograph analysis or by measured physical characteristics of the catchment
Water quality constituents	no
Case Studies / Publications	Mountain N.C. and Jones J.A.A.(2006). Reconstructing extreme flows using an airflow index-based stochastic weather generator and a hydrological simulation model. CATENA, Volume 66, Issues 1-2, pp.120-134. Pilling, C. and Jones, J. A. A. (1999). High resolution climate change scenarios: implications for British runoff, Hydrological Processes, Vol. 13, Issue 17, pp. 2877 – 2895. Charlton, R., Fealy, R., Moore, S., Sweeney, J., and Murphy, C. (2006). Assessing the impact of climate change

	on water supply and flood hazard in Ireland using statistical downscaling and hydrological modelling techniques. Climatic Change, v 74, n 4, pp. 475-491. Manley, R. E. (1978). Calibration Of Hydrological Model Using Optimization Technique. ASCE J Hydraul Div, v 104, n 2, pp. 189-202.
Assumptions and Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contacts: Ron Manley Water Resources Associates Email: rm04@watres.com Cost: Free of charge How to obtain model: both model and user manual can be downloaded from: http://www.watres.com/software/soft-hysim.html Training available: Yes, see http://www.watres.com/training/tr-HYSIM.htm

DHSVM

Distributed Hydrology Soil Vegetation Model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Distributed physically-based continuous-simulation model Hydrological/Modelling unit: computational grid cells.
Origin (development and maintenance)	originally developed in the early 1990s by Mark Wigmosta while at the University of Washington (Wigmosta et al. 1994). Since then the model code has been further developed by a wide cast of characters at the University of Washington, Pacific Northwest National Laboratory, and the University of British Columbia.
Platform (PC?), Operating System, Open source?, GIS-based (what	**Platform:** PC, SUN workstations, and HP workstations. **Operating System:** Windows, UNIX, LINUX

GIS?), Computer Language, Visualisation facilities	**Open source**: yes **Computer Language:** ANSI-C **GIS-based:** yes ARC/INFO **Visualisation facilities:** GIS interface
Pathways and processes modelled	Evapotranspiration, snowpack accumulation and melt, interception, unsaturated moisture movement, saturated subsurface flow, surface overland flow, and channel flow and sediment transport
Inputs (data requirements)	Air temperature, Wind speed, humidity, incoming shortwave radiation and incoming longwave radiation ,precipitation, observed runoff, and sediment load
Outputs	Runoff, evapotranspiration, channel flow, and sediment yield.
Calibration Method	Manual, see Storck et al. (1998).
Parameters	Physically-based parameters that can be either measurable or obtained from literature. A small number can be calibrated.
Water quality constituents	No, only sediments.
Case Studies / Publications	Storck, P., Bowling, L., Wetherbee, P., and Lettenmaier, D. (1998). Application of a GIS-based distributed hydrology model for prediction of forest harvest effects on peak stream flow in the Pacific Northwest. Hydrological Processes, Vol. 12, No.6, pp. 889-904. Doten, C. O., Bowling, L.C., Lanini, J. S., Maurer, E. P., and Lettenmaier, D. P. (2006). A spatially distributed model for the dynamic prediction of sediment erosion and transport in mountainous forested watersheds Water Resources Research, v 42, W04417, doi:10.1029/2004WR003829. Cuo, L., Giambelluca, T. W., Ziegler, A. D., and Nullet, M., A. (2006). Use of the distributed hydrology soil vegetation model to study road effects on hydrological processes in Pang Khum Experimental Watershed, northern Thailand. Forest Ecology and Management, v 224, n 1-2, pp. 81-94, March 15, Catchment Processes in Southeast Asia Cuo, L., Lettenmaier, D. P., Alberti, M., Richey, J. E. (2009). Effects of a century of land cover and climate change on the hydrology of the Puget Sound basin. Hydrological Processes, v 23, n 6, pp. 907-933.

	VanShaar, J. R., Haddeland, I., Lettenmaier, D. P. (2002). Effects of land-cover changes on the hydrological response of interior Columbia River basin forested catchments. Hydrological Processes, v 16, n 13, pp. 2499-2520.
Assumptions and Limitations	
Versions	DHSVM 2.0.1, DHSVM 3.0_r1, DHSVM 3.0
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	How to obtain model: http://www.hydro.washington.edu/Lettenmaier/Models/DHSVM/code.shtml Contact: dhsvm-users group (http://www.hydro.washington.edu/Lettenmaier/Models/DHSVM/contact.shtml) dhsvm@hydro.washington.edu Technical Support: no technical support is available other than the DHSVM web page, unless specific arrangements have been made.

SIMHYD

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	lumped conceptual daily rainfall-runoff model
Origin (development and maintenance)	SIMHYD is a simplified version of the daily conceptual rainfall-runoff model, HYDROLOG, that was developed in 1972 and the more recent MODHYDROLOG. SIMHYD is one of the rainfall-runoff models in RRL (Rainfall-Runoff Library) which was developed by the CRC for Catchment Hydrology's Predicting Catchment Behaviour Research Program. The SIMHYD code was written by Dr. Francis Chiew (The University of Melbourne, Australia).
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open Source:** No **GIS-based:** No **Computer language:**

	Visualisation facilities: own friendly interface
Pathways and processes modelled	The model calculates: Interception, runoff, infiltration , evapotranspiration, interflow, recharge, and baseflow.
Inputs (data requirements)	daily precipitation and potential evapotranspiration
Outputs	Runoff which consists of (impervious runoff, infiltration excess runoff, interflow and Baseflow).
Calibration Method	When using the RRL, the following automatic calibration methods are available: Uniform random sampling, Pattern search, Multi start pattern search, Rosenbrock search, Rosenbrock multi-start search, Genetic algorithm, and the Shuffled Complex Evolution (SCE-UA).
Parameters	7 model parameters only.
Water quality constituents	no
Case Studies / Publications	Jones, R. N., Chiew, F. H.S., Boughton, W. C., and Zhang, L. (2006). Estimating the sensitivity of mean annual runoff to climate change using selected hydrological models. Advances in Water Resources, v 29, n 10, pp. 1419-1429. Wang, G., Zhang, J., and He, R. (2007). Comparison of hydrological models in the middle reach of the Yellow River. IAHS-AISH Publication, n 311, pp. 158-163, Methodology in Hydrology. Development of a coupled pathogen-hydrologic catchment model Haydon, S., and Deletic, A. (2006). Journal of Hydrology, v 328, n 3-4, pp. 467-480. Integration and application of the Rainfall Runoff Library Kim, S., Vertessy, R.A., Perraud, J.-M., and Sung, Y. (2005). Water Science and Technology, v 52, n 9, pp. 275-282. Siriwardena, L., Finlayson, B.L., and McMahon, T.A. (2006). The impact of land use change on catchment hydrology in large catchments: The Comet River, Central Queensland, Australia. Journal of Hydrology, v 326, n 1-4, pp. 199-214
Versions	

How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	How to obtain model and documentation: SIMHYD is one of the rainfall-runoff models in RRL (Rainfall-Runoff Library), a software product in the Catchment Modelling Toolkit (www.toolkit.net.au/rrl). Cost: Free of charge Contact: Dr. Francis Chiew, Cooperative Research Centre for Catchment Hydrology, Department of Civil and Environmental Engineering, University of Melbourne, Parkville 3010, Victoria, Autralia. f.chiew@civen.unimelb.edu.au

Simple Lumped Reservoir Parametric Model SLURP

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	is a continuous simulation, conceptual distributed (originally lumped) hydrological model in which the parameters are related to land cover (vegetation type) Hydrological unit : The model divides the watershed into hydrologically-consistent sub-units known as aggregated simulation areas (ASA). An ASA is not a homogeneous area but is a grouping of smaller areas with known properties.
Origin (development and maintenance)	Developed by Dr. Geoff W. Kite at the National Hydrology Research Institute, Saskatchewan Canada.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open source:** no **Computer Language:** FORTRAN 90 **GIS-based:** no but can be used. **Visualisation facilities:** own GRU interface
Pathways and processes modelled	The model routes precipitation through the appropriate processes and generates outputs (evaporation, transpiration and runoff) and changes in storage (canopy interception, snowpack and soil moisture). Runoffs are accumulated from each land cover within an ASA using a time/contributing area relationship for each land cover

	and the combined runoff is converted to streamflow and routed between each ASA.
Inputs (data requirements)	Inputs include daily time series of precipitation, temperature, hours of bright sunshine and dew point temperature
Outputs	The SLURP model produces two types of output: i) point data such as streamflow at different locations in the basin, and ii) spatially distributed data such as basin-wide evaporation, transpiration, or net runoff
Calibration Method	manual
Parameters	The most important parameters are: the saturated conductivity, precipitation multiplication factor, rain/snow division factor, and the snowmelt rate (Kite, 1995).
Water quality constituents	no
Case Studies / Publications	Jain, S.K., N. Kumar, T. Ahmed and G.W. Kite, 1998. SLURP model and GIS for estimation of runoff in a part of Satluj catchment, India. Hydrological Sciences Journal, 43(6), 875-884. Barr AG, Kite GW, Granger R, Smith C (1997) Evaluating three evapotranspiration methods in SLURP macroscale hydrological model. Hydrological Processes, v 11, n 13, p 1685-1705. Effects of reduced land cover detail on hydrological model response Armstrong, Robert N.; Martz, Lawrence W. Source: Hydrological Processes, v 22, n 14, p 2395-2409, July 1, 2008 The temporal transferability of calibrated parameters of a hydrological model Apaydin, Halit; Anli, Alper S.; Ozturk, Ahmet Source: Ecological Modelling, v 195, n 3-4, p 307-317, June 15, 2006 Large-scale distributed watershed modelling for reservoir operations in cold boreal regions St. Laurent, M.E.; Valeo, C. Source: Canadian Journal of Civil Engineering, v 34, n 4, p 525-538, April 2007
Assumptions and Limitations	
Versions	

How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: Dr. Geoff W. Kite National Hydrology Research Institute 11 Innovation Blvd Saskatoon Saskatchewan Canada S7N 3H5 phone (306) 975-5687 fax (306) 975-5143 geoff.kite@ec.gc.ca kiteg@nhrisv.nhrc.sk.ec.gc.ca cost: contact Dr. Geoff W. Kite

Kite, G. (1995). The SLURP model in Computer models of Watershed Hydrology. Edited by Singh,V.P. Water Resources Publication, Colorado, USA.

<u>SSARR</u>

The Streamflow Synthesis and Reservoir Regulation Model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Semi-distributed, continuous simulation, conceptual.
Origin (development and maintenance)	Developed by the US Army Corps of Engineers, North Pacific, 1972.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC, RISC-processor workstations **Operating System:** Dos, Unix **Open source:** yes **Computer Language:** Fortran **GIS-based:** No

	Visualisation facilities: GUI (AUTOREG for RISC workstations)
Pathways and processes modelled	The model simulates rainfall-runoff, interception, evapotranspiration, soil moisture accouting, baseflow infiltration, and routing of runoff into the stream system.
Inputs (data requirements)	Precipitation and temperature
Outputs	Surface runoff, subsurface flow, and baseflow.
Calibration Method	Has an automatic calibration feature.
Parameters	Sensitive parameters (see Kang,1978).
Water quality constituents	no
Case Studies / Publications	COMPARISON OF TWO DAILY STREAMFLOW SIMULATION MODELS OF AN ALPINE WATERSHED. Brendecke, Charles M.1; Laiho, Douglas R.1; Holden, Dyan C.1 Source: Journal of Hydrology, v 77, n 1-4, p 171-186, 1985 Interactive calibration for the SSARR watershed model Rockwood, D.M.; Kuehl, D.W. Source: Proceedings of The Western Snow Conference, p 273, 1993 STREAMFLOW MODELING OF UPPER INDUS RIVER CATCHMENTS. Selvalingam, S.; Masood, A. Source: Water Resources Bulletin, v 14, n 4, p 827-841, 1978. COMPARISON OF DETERMINISTIC MATHEMATICAL WATERSHED MODELS. Perrier, E.R.; Ford, W.B. Source: Paper - American Society of Agricultural Engineers, 1977 Climate change impacts in the Elbow River Watershed Valeo, C.; Xiang, Z.; Bouchart, F.J.-C.; Yeung, P.; Ryan, M.C. Source: Canadian Water Resources Journal, v 32, n 4, p 285-302, Winter 2007
Assumptions and Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to	How to obtain model and documentation: http://www.nwd-wc.usace.army.mil/report/ssarr.htm Cost: Free of charge.

use (?) / training available	Contact: D. D. Speers Hydrologic Engineering Branch, Water Management Division, U.S. Army of Engineers, North Pacific Division, Portland District, P.O. Box 2870, Portland, OR 97208-2870, USA.

Sensitivity of the Parameters of the SSARR Model. Kang, Narut Source: Journal of Hydraulic Research, v 16, n 1, p 1-25, 1978

SMAR

Soil Moisutre Accounting and Routing Model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Lumped, conceptual, continuous simulation model
Origin (development and maintenance)	SMAR Model is a development of the 'Layers' conceptual rainfall-runoff model introduced by O'Connell et al. (1970), its water balance component having been proposed in 1969 by Nash and Sutcliffe (Clarke, p.307, 1994). The SMAR/layers model has been further modified by Khan, (1986) and Liang (1992).
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform: PC** **Operating System: Windows** **Open source: yes** **Computer Language: FORTRAN** **GIS-based: No** **Visualisation facilities:** only as part of the Rainfall Runoff Library (RRL) or the Galway package.
Pathways and processes modelled	Evaporation and evapotranspiration, infiltration, percolation, interflow, baseflow and surface runoff
Inputs (data requirements)	Pan evaporation, rainfall, and observed runoff hydrograph (for model calibration)
Outputs	Surface runoff, interflow, quick and slow groundwater flow.
Calibration Method	Automatic (genetic algorithm, Simplex method), within the RRL (Uniform Random Search, Pattern Search, Multi Start Pattern Search, Rosenbrock Method, Multi Start Rosenbrock search, genetic algorithm).
Parameters	Around 6 parameters.
Water quality constituents	No

Case Studies / Publications	M.A. Fazal, M. Imaizumi, S. Ishida, T. Kawachi, T. Tsuchihara, Estimating groundwater recharge using the SMAR conceptual model calibrated by genetic algorithm, Journal of Hydrology, Volume 303, Issues 1-4, 1 March 2005, Pages 56-78 Ahmed Nasr, Michael Bruen, Development of neuro-fuzzy models to account for temporal and spatial variations in a lumped rainfall-runoff model, Journal of Hydrology, Volume 349, Issues 3-4, 1 February 2008, Pages 277-290 Assessing the performance of eight real-time updating models and procedures for the Brosna River Goswami, M.1; O'Connor, Kieran M.1; Bhattarai, K.P.1; Shamseldin, A.Y.2 Source: Hydrology and Earth System Sciences, v 9, n 4, p 394-411, 2005, Advances in Flood Forecasting Rainfall-runoff modelling of Bua River basin, Malawi Mkhandi, S.H.1; Kumambala, P.G.2 Source: IAHS-AISH Publication, n 308, p 239-243, 2006
Versions	SMARY (Tan and O'Connor, 1996), SMARG (Goswami et al. , 2002)
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Cost: Free of Charge How to obtain: Can be obtained from: Department of Engineering Hydrology, University College Galway, Galway, Ireland. Documentation: journal articles and M.Sc. Theses at the Department of Engineering Hydrology, University college Galway, Ireland.

B. Q. Tan, K. M. O'Connor, Application of an empirical infiltration equation in the SMAR conceptual model, Journal of Hydrology, Volume 185, Issues 1-4, 1 November 1996, Pages 275-295.
O'Connell, P.E., J.E. Nash, and J.P. Farrell, River Flow forecasting through conceptual models. Part 2. The Brosna catchment at Ferbane, Journal of Hydrology., 10: 317-329,
1970.
Clarke, R.T., Statistical Modelling in Hydrology, John Wiley and Sons, 1994.
Khan, H., 1986. Conceptual modelling of rainfall-runoff system. In: M.Eng. Thesis, Department of Engineering Hydrology, University College Galway.

Liang, G.C., 1992. A note on the revised SMAR model. In: Memorandum to the River Flow Forecasting Workshop Group, Department of Engineering Hydrology, University College Galway (unpublished).

Goswami, M., O'Connor, K.M., Shamseldin A.Y., 2002. Structures & performances of five rainfall–runoff models for continuous river-flow simulation. In: Proc. 1st Biennial Meeting of Int. Env. Modeling and Software Soc., Lugano, Switzerland, vol. 1, pp. 476–481.

TREX

Two-dimensional Runoff, Erosion, and Export model

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Physically-based, distributed-parameter, raster (square-grid), two-dimensional watershed model. Hydrological unit: finite difference square grid/cells.
Origin (development and maintenance)	Developed by Velleux, M., England, J., and Julien, P. in Colorado State University. The model was based on CASC2D but expanded and enhanced to support flood modeling and chemical transport features based on the WASP/IPX model
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows, linux, Unix **Open source:** yes **Computer Language:** C and follows ANSI C99 conventions. **GIS-based?:** No **Visualisation facilities:** No GUI.
Pathways and processes modelled	TREX has three components: hydrology (rainfall and interception, infiltration and transmission loss, storage, overland and channel flow), sediment transport, and chemical transport and fate.
Inputs (data requirements)	Precipitation data, meteorological variables for continuous simulations (temperature, relative humidity, wind speed, solar radiation)
Outputs	Runoff flow, sediment flow, and chemical loads at the outlet, summary files and time-series of flow, sediments and chemicals.
Calibration Method	Manual.
Parameters	Key parameters of the hydrological model include hydraulic conductivity (Kh), and surface roughness

	(Manning n). Key parameters of the sediment transport model include grain size, erosion threshold (e.g., critical shear stress), soil erosivity (K), land cover factor (C), porosity, and grain size distribution. Key parameters include the distribution (partition) coefficient (Kd) and the initial distribution of chemicals in soil and sediment. See Velleux et al. (2008) and Velleux et al. (2006) for sensitive parameters.
Water quality constituents	Sediments and chemicals (dissolved or particulate form)
Case Studies / Publications	Two-dimensional simulations of extreme floods on a large watershed England Jr., John F.; Velleux, Mark L.; Julien, Pierre Y. Source: Journal of Hydrology, v 347, n 1-2, p 229-241, December 15, 2007 TREX: Spatially distributed model to assess watershed contaminant transport and fate Velleux, Mark L.; England Jr., John F.; Julien, Pierre Y. Source: Science of the Total Environment, v 404, n 1, p 113-128, October 1, 2008 Mark L. Velleux,*† Pierre Y. Julien,† Rosalia Rojas-Sanchez,† William H. Clements,‡ and John F. England, Jr.§ Simulation of Metals Transport and Toxicity at a Mine-Impacted Watershed: California Gulch, Colorado *Environ. Sci. Technol.*, **2006**, *40* (22), pp 6996–7004
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Cost: Free of charge Contacts: Mark Velleux,HydroQual, Inc., 1200 MacArthur Boulevard Mahwah, NJ 07430 email: mvelleux@hydroqual.com John England Bureau of Reclamation Flood Hydrology and Meteorology Group, 86-68250, TSC Bldg. 67, Denver Federal Center Denver, CO 80225

	email: jengland@do.usbr.gov Pierre Julien Department of Civil Engineering Colorado State University Fort Collins, CO 80523 email:pierre@engr.colostate.edu How to obtain model and Documentation: http://www.engr.colostate.edu/~pierre/ce_old/Projects/TREX%20Web%20Pages/TREX-Overview.html

LASCAM

LASCAM has been developed with the aim of predicting the impact of land use and climatic changes on the daily trends of stream flow and water quality.

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Complex conceptual model (within subcatchment), continuous simulation, distributed model, semi-physically based Hydrological unit: subcatchment aggregated via stream networks.
Origin (development and maintenance)	Developed at the Centre for Water Research, University of western Australia by M. Sivapalan, N.R. Viney, and C. Zammit
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System: windows ,** Linux and Mac **Open source:** no **Computer Language:** Fortran 95 **GIS-based:** no **Visualisation facilities:** own GUI
Pathways and processes modelled	The model simulates surface and subsurface runoff, groundwater, evapotranspiration, and streamflow routing
Inputs (data requirements)	Daily rainfall, annual pan evaporation, measured streamflow and water quality data.
Outputs	Surface and subsurface runoff, actual evaporation, recharge to the permanent groundwater table, baseflow, and

	estimates of soil water storage.
Calibration Method	Calibrations scheme based on the Shuffled Complex Evolution algorithm.
Parameters	The hydrological and water quality model has 87 parameters, which describe each of the 13 potential flux paths. Of these, 30 define the water balance, 5 define the salt balance, 6 define the sediment balance and 29 define the nutrient balance (11 for the phosphorus model and 18 for the nitrogen model). A further 7 parameters define the initial storage values and 10 define the disaggregation of the initial average stores to each subcatchment. While some parameters are physically meaningful and even measurable or can be estimated from literature values, most of the parameters are conceptual and can only be quantified by calibration against streamflow or stream nutrient load data.
Water quality constituents	Sediments, nutrients, salt
Case Studies / Publications	Modelling the effects of land-use modifications to control nutrient loads from an agricultural catchment in Western Australia Zammit, C.; Sivapalan, M.; Kelsey, P.; Viney, N.R. Source: Ecological Modelling, v 187, n 1 SPEC. ISS., p 60-70, September 10, 2005 A conceptual model of sediment transport: Application to the Avon River Basin in Western Australia Viney, Neil R.; Sivapalan, Murugesu Source: Hydrological Processes, v 13, n 5, p 727-743, April 15, 1999 Modelling catchment processes in the Swan-Avon river basin Viney, Neil R.; Sivapalan, Murugesu Source: Hydrological Processes, v 15, n 13, p 2671-2685, September 2001 Modeling of surface runoff in Xitiaoxi catchment, China. Xu, Ligang; Zhang, Qi; Li, Hengpeng; Viney, Neil R.; Xu, Jintao; Liu, Jia Source: Water Resources Management, v 21, n 8, p 1313-1323, August 2007
Limitations	The smallest unit sis sub-catchment and therefore it does resolve this subcatchement unit into smaller units and therefore cannot be used to predict the hydrological responses within these sub-units. The smallest temporal scale is one day. Large number of parameters.
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use	To obtain model and documentation, contact: Centre for Water Research, University of western Australia

(?) / training available	M023 , 35 Stirling Highway Crawley 6009 Australia CWR Melbourne Office Suite 1, Level 3 470 Collins St Melbourne Vic 3000 Phone +61 3 9629 9035 Centre Manager Ph: +61 8 6488 2409 Fax: +61 8 6488 3053 Email: info@cwr.uwa.edu.au Cost: free of charge Documentation: see Sivapalan et al. (2002)

Sivapalan,M., Viney,N.R., and Zammit, C. (2002). LASCAM: Large Scale Catchment Model in Mathematical Models of Large Watershed Hydrology, etd. Singh,V.P. and Frevert,D.K. Water Resources Publications,LLC.

MIKE SHE

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Physically Based, distributed, continuous simulation, integrated hydrologic modeling system Hydrological unit: rectangular grid/cell
Origin (development and maintenance)	MIKE SHE is a developed based on the SHE modelling concept developed by a European constortium of three organisations: the Institute of Hydrology (UK), the French consulting firm SOGREAH and the Danish Hydraulic Institute (DHI).

Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System: Windows** NT, 95 and 98, XP Professional, Vista Business **Open source: No** **Computer Language:** Fortran **GIS-based?:** Yes, Arcview GIS **Visualisation facilities:** GIS, interactive GUI with pre- and post-processing capabilities, MIKE SHE 2-D graphical Editor
Pathways and processes modelled	It simulates water flow (precipitation, evapotranspiration, interception, infiltration (unsaturated zone flow), overland flow, channel flow, and groundwater flow), water quality and sediment transport.
Inputs (data requirements)	Climate data (daily precipitation, daily mean temperature, potential evapotranspiration) Stream flow data (water stages and flows) Ground water data (groundwater stages, groundwater extractions) Soils data (saturated hydraulic conductivity, soil-moisture retention curves) Land use data (Land use and cropping pattern, leaf-area-index and root depth) Watershed characteristics
Outputs	actual evapotranspiration stages and flows in the river system recharge to the saturated zone and moisture contents in the unsaturated zone stages and flows in the saturated zone (groundwater model) exchange flows between rivers and aquifers, rivers and drained areas, rivers and overland flow.
Calibration Method	Manual
Parameters	Being physically based MIKE SHE adopts input data that are measured in field. Some model calibration is however always required. The most important calibration parameters are hydraulic conductivity of the aquifer, manning number in rivers, saturated/unsaturated hydraulic conductivity for the unsaturated zone model. As for pure groundwater models MIKE SHE are highly sensitive to the hydraulic properties of the aquifer system. In surface water dominated regimes it may however be the surface water features (Mannings M, cross-sectional geometry) that becomes the most important for the model calibration (Mannings M, channel geometry). Also see (Xevi et al., 1997)

Water quality constituents	Conservation solutes, chemical transformation equations may be added to facilitate modelling non-conservative solutes.
Case Studies / Publications	Application of the coupled MIKE SHE/MIKE 11 modelling system to a lowland wet grassland in southeast England Thompson, J.R.; Srenson, H. Refstrup; Gavin, H.; Refsgaard, A. Source: Journal of Hydrology, v 293, n 1-4, p 151-179, June 2004 Distributed hydrological modelling in California semi-arid shrublands: MIKE SHE model calibration and uncertainty estimation McMichael, Christine E.; Hope, Allen S.; Loaiciga, Hugo A. Source: Journal of Hydrology, v 317, n 3-4, p 307-324, Febrary 20, 2006 Assessing the impacts of land use changes on watershed hydrology using MIKE SHE Im, Sangjun; Kim, Hyeonjun; Kim, Chulgyum; Jang, Cheolhee Source: Environmental Geology, v 57, n 1, p 231-239, March 2009 Effect of grid size on effective parameters and model performance of the MIKE-SHE code Vzquez, R.F.; Feyen, L.; Feyen, J.; Refsgaard, J.C. Source: Hydrological Processes, v 16, n 2, p 355-372, Febrary 15, 2002
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contacts: DHI agent in Ireland: Alan G. Hooper, CDM, 87/89 Morehampton Road 1st Floor , Donnybrook , Dublin 4, IRELAND Telephone: +353-1-663-2900 Facsimile: +353-1-663-2888 E-mail: hooperag@cdm.com Software support centre (technical support): E-mail: software@dhigroup.com Tel: +45 4516 9333(Open 7.30-16.00 GMT) Fax: +45 45 16 92 92

	Cost: contact DHI agent in Ireland Training: http://www.dhigroup.com/Software/Training.aspx

Xevi,E., Christiaens, K., Espino, A., Sewnandan, W., Mallants, D., Sørensen, H. and Feyen, J. (1997) Calibration, Validation and Sensitivity Analysis of the MIKE-SHE Model Using the Neuenkirchen Catchment as Case Study. Water Resources Management,Vol. 11, No. 3, pp. 219 – 242.

Dynamic Watershed Simulation Model (DWSM)

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	The DWSM is a physically based, event-based, distributed, and unsteady rainfall-runoff, soil/sediment erosion-transport, and agrochemical mixing-transport model. Hydrological unit: subwatersheds, specifically, into one-dimensional overland elements, channel segments, and reservoir units. An overland element is represented as a rectangular area with the same area as in the field, width equal to the adjacent (receiving) channel length.
Origin (development and maintenance)	Developed by the Illinois State Water Survey , U.S.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** PC-DOS or Windows **Open source:** upon request **Computer Language:** FORTRAN **GIS-based:** No **Visualisation facilities:** None
Pathways and processes modelled	Simulates interception, infiltration, detention storage, and evaporation losses and routes the excess rainfall over overland surface and part of the infiltrated water through overland subsurface, and route the combined flow through channel segments, and through reservoir units, if any, from single or a consecutive series of rainfall events.
Inputs (data requirements)	Physical data representing the watershed, initial moisture, soil and agricultural chemicals and meteorological data representing the rainfall events

Outputs	Summary of total rainfall at each rain gage, watershed outflow volume, peak flow, and time to the peak flow. Summaries of areas, rainfall and rainfall excess depths, runoff volumes, and unit-width peak-flows in overland planes. Summaries of drainage areas, runoff volumes, peak flows and times to the peak flows for the channels and reservoirs. Time series of areal average rainfall intensity, watershed outflow, and outflows of selected channels and/or reservoirs at each time step, which can be used to develop hyetograph and hydrographs.
Calibration Method	Manual
Parameters	Sensitive to runoff curve number, saturated hydraulic conductivity, Manning's roughness coefficient, flow detachment coefficient, chemical partition coefficient, chemical mixing parameter, sediment particle size distribution, and rainfall intensities and their temporal distributions Calibration parameters include runoff curve number or saturated hydrological conductivity, Manning's roughness coefficient, flow detachment coefficient, chemical partition coefficient, and chemical mixing parameter
Water quality constituents	Nutrients, sediments, and pecticides.
Case Studies / Publications	Storm event flow and sediment simulations in agricultural watersheds using DWSM Borah, D.K.; Bera, M.; Xia, R. Source: Transactions of the American Society of Agricultural Engineers, v 47, n 5, p 1539-1559, September/October 2004 Storm event and continuous hydrologic modeling for comprehensive and efficient watershed simulations Borah, Deva K.; Arnold, Jeffrey G.; Bera, Maitreyee; Krug, Edward C.; Liang, Xin-Zhong Source: Journal of Hydrologic Engineering, v 12, n 6, p 605-616, November/December 2007 Watershed-scale hydrologic and nonpoint-source pollution models: Review of applications Borah, D.K.; Bera, M. Source: Transactions of the American Society of Agricultural Engineers, v 47, n 3, p 789-803, May/June 2004 Hydrologic and water quality model for tile drained watersheds in Illinois Borah, D.K.1, 2; Xia, R.1, 2; Bera, M.1, 2 Source: 2000 ASAE Annual International Meeting, Technical Papers: Engineering Solutions for a New Century, v 2, p 2461-2479, 2000, 2000 ASAE Annual International Meeting, Technical Papers: Engineering Solutions for a New Century

	Conference: 2000 ASAE Annual International Meeting, Technical Papers: Engineering Solutions for a New Century, July 09,2000 - July 12,2000 Publisher: American Society of Agricultural and Biological Engineers
Model Limitations	Only used to simulate single event Only for agricultural watersheds One-dimensional channel simulation (no ecological processes)
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Cost: Free of charge Contacts: Dr. Deva K. Borah, Woolpert, Inc., 415 Port Centre Parkway, Suite 101, Portsmouth, VA 23704-4924, Tel: 757-398-6858, Fax: 757-399-6869, Email: deva.borah@woolpert.com Cost: free of charge Contact the authors for documentation and model

LISEM

LImburg Soil Erosion Model simulates the hydrology and sediment transport during and immediately after a single rainfall event in a small catchment.

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	a single-event physically-based hydrological and soil erosion model for drainage basins. The LISEM model is one of the first examples of a physically based model that is completely incorporated in a raster Geographical Information System. Hydrological unit: grid cells
Origin (development and maintenance)	Dr. Ad P.J. De Roo, Mr. C.G. Wesseling, Dr. V.G. Jetten (Utrecht Universitfy (Physical Geography)). Mr. C.J. Ritsema (Staring Centre, Wageningen), the Netherlands
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open source:** No **Computer Language:** C++

	GIS-based: yes PCRaster **Visualisation facilities:** PCRaster
Pathways and processes modelled	Processes incorporated in the model are rainfall, interception, surface storage in micro-depressions, infiltration, vertical movement of water in the soil, overland flow, channel flow, detachment by rainfall and throughfall, detachment by overland flow, and transport capacity of the flow.
Inputs (data requirements)	Rainfall data
Outputs	• a text-file with totals (total rainfall, total discharge, peak discharge, total soil loss etc.); • a ASCII data file which can be used to plot hydrographs and sedigraphs. • Pc-Raster maps of soil erosion and deposition, as caused by the event; PcRaster maps of overland flow at desired time intervals during the event.
Calibration Method	manual
Parameters	Sensitive parameters (Roo et al., 1996)
Water quality constituents	Sediments, nutrients (nitrogen and phosphorus in solution and in suspension)
Case Studies / Publications	Evaluation of the LISEM soil erosion model in two catchments in the East African Highlands Hessel, Rudi; van den Bosch, Rik; Vigiak, Olga Source: Earth Surface Processes and Landforms, v 31, n 4, p 469-486, April 15, 2006 Suitability of transport equations in modelling soil erosion for a small Loess Plateau catchment Hessel, Rudi; Jetten, Victor Source: Engineering Geology, v 91, n 1, p 56-71, April 23, 2007 Effects of spatially structured vegetation patterns on hillslope erosion in a semiarid Mediterranean environment: A simulation study. Boer, Matthias; Puigdefábregas, Juan. Earth Surface Processes and Landforms, v 30, n 2, p 149-167, February 2005 Erosion models: Quality of spatial predictions. Jetten, Victor; Govers, Gerard; Hessel, Rudi. Hydrological Processes, v 17, n 5, p 887-900, April 15, 2003
Assumptions and Limitations	
Versions	1.53, 1.54, 1.55, 1.61, 1.63(2), 2.01, 2.02, 2.03, 2.12, 2.13, 2.154, 2.155, 2.156, 2.157, 2.158, 2.159 to 2.34 (VJ

	050704), 2.35 (VJ 050811), 2.36-2.391 (VJ 071005), 2.391-2.40 (VJ 170806), 2.5.0 (VJ 080217), 2.5.1-2.5.3 (VJ 080620), 3.0
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: Dr Ad P.J. De Roo Department of Physical Geography, Utrecht University, P.O. Box 80115, 3508 TC Utrecht, The Netherlands Tel:+31 30 253 5773 Fax: +31 30 254 0604 Email: a.deroo@frw.ruu.nl Model homepage: http://www.itc.nl/lisem/ Model and documentation: http://www.itc.nl/lisem/

LISEM: a single-event, physically based hydrological and soil erosion model for drainage basins. II: sensitivity analysis, validation and application
De Roo, A.P.J.; Offermans, R.J.E.; Cremers, N.H.D.T. Source: Hydrological Processes, v 10, n 8, p 1119-1126, 1996

CASC2D (CASC2D-SED)

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	CASC2D is a fully-unsteady, physically-based, distributed-parameter, raster (square-grid), two-dimensional, infiltration-excess (Hortonian) hydrologic model for simulating the hydrologic response of watersheds subject to an input rainfall field Hydrological unit: finite difference square grids.
Origin (development and maintenance)	CASC2D development was initiated in 1989 at the U.S. Army Research Office (ARO) funded Center for Excellence in Geosciences at Colorado State University. The original version of CASC2D has been significantly enhanced under funding from ARO and the U.S. Army Corps of Engineers Waterways Experiment Station (USACEWES). The upland erosion and channel sediment transport module was added by Johnson (1997) at Colorado State University and was called CASC2D-SED.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows, Unix **Open source:** Yes **Computer Language:** C **GIS-based?:** Yes, GRASS GIS, ARC/INFO

	Visualisation facilities: GRASS GIS, WMS 7
Pathways and processes modelled	Major components of the model include: continuous soil-moisture accounting, rainfall, interception, infiltration, surface and channel runoff routing, soil erosion and sediment transport.
Inputs (data requirements)	Precipitation data, meteorological variables for continuous simulations (temperature, relative humidity, wind speed, solar radiation)
Outputs	Runoff flow and sediment flow at the outlet, summary files and time-series of flow and sediments.
Calibration Method	The Shuffled Complex Evolution (SCE) automated calibration procedure (Duan et al. 1992) was successfully employed by Senarath et al. (2000) to calibrate CASC2D in continuous simulations. Published tables of parameter values (e.g. soil infiltration and overland roughness parameters) usually provide good initial values. GIS can be used to describe the spatial distribution of parameters using land-use/land-cover and soil textural classifications.
Parameters	Model has around 20 parameters. The most sensitive parameters are: overland flow Manning roughness coefficient, channel flow Manning roughness coefficient, soil saturated hydraulic conductivity; overland flow retention depth; and plant canopy resistance. The model is quite sensitive to errors in rainfall rate.
Water quality constituents	No, only sediment transport
Case Studies / Publications	M. Marsik and P. Waylen, An application of the distributed hydrologic model CASC2D to a tropical montane watershed, Journal of Hydrology **330** (2006), pp. 481–495 Billy E. Johnson, Pierre Y Julien, Darcy K Molnar, Chester C. Watson, THE TWO-DIMENSIONAL UPLAND EROSION MODEL CASC2D-SED,2000, Vol.36, No. 1, Journal of the American Water Resources Association, pp. 31-42
Versions	CASC2D-SED, CASC-2D
How to obtain Model (contacts, documentation), Cost, Easy to	Contact: Prof. P.Y. Julien Department of Civil Engineering

use (?) / training available	Colorado State University Fort Collins CO 80523-1372 Phone (970) 491-8450 Fax (970) 491-7008 pierre@engr.colostate.edu *Cost: Free of charge* How to obtain model and Documentation: http://www.engr.colostate.edu/~pierre/ce_old/Projects/CASC2D-SED%20Web%20site%20082506/CASC2D-SED-Home.htm Documentation exists for CASC2D Version 1.18 (Ogden 1998), which includes model details related to: hydrologic simulations, continuous formulation, and overland/channel erosion, sediment transport, and deposition.

Ogden, F.L., 1998, CASC2D Version 1.18 Reference Manual, Dept. of Civil & Environmental Engineering, U-37, University of Connecticut, Storrs, CT 06269, 106 pp.

Duan, Q., S. Sorooshian and V. Gupta, 1992, Effective and efficient global optimization for conceptual rainfall-runoff models, *Water Resour. Res*., 28(4): 1015-1031.

Senarath, S.U.S., F.L. Ogden, C.W. Downer, and H. O. Sharif, 2000, On the Calibration and Verification of Distributed, Physically-Based, Continouous, Hortonian Hydrologic Models, *Water Resources Research*, 36(6):1495-1510.

WaSIM-ETH

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Deterministic, physically based, fully distributed, continuous, modular and highly adaptable hydrological model Hydrological unit: cells/square grid.
Origin (development and maintenance)	Developed at the Swiss Federal Institute of Technology, Zurich
Platform (PC?), Operating System, Open source?, GIS-based (what	**Platform:** PC **Operating System:** Windows/Linux

GIS?), Computer Language, Visualisation facilities	**Open source:** No **Computer Language:** C++ **GIS-based:** No **Visualisation facilities:** Graphlines a GUI for WASIM-ETH, ShowGRID
Pathways and processes modelled	Interception, infiltration, evapotranspiration, surface runoff, soil water accounting, and groundwater flow,
Inputs (data requirements)	precipitation , temperature, wind speed, vapour pressure, and radiation
Outputs	Runoff, sediment yield, tracers load
Calibration Method	Manual
Parameters	A very large number of physically-based and free (can be calibrated) parameters. Free parameters~95. For sensitivity analysis of the most important parameters, see chapter 3.6 of WASIM-ETH manual (Schulla and Jasper, 2007).
Water quality constituents	sediments, and tracers (although chemical or bio-chemical processes like retardation and denitrification or multi phase flow are not taken into account.)
Case Studies / Publications	Krause, S., J. Jacobs, A. Bronstert (2007). Modelling the impacts of land-use and drainage density on the water balance of a lowland–floodplain landscape in northeast Germany. Ecol. Modelling 200(3-4): 475-492 Cullmann, J., V. Mishra, R. Peters (2006) Flow analysis with WaSiM-ETH model parameter sensitivity at different scales. Adv. Geosci. 9: 73-77 Krause, S., A. Bronstert (2006) The impact of groundwater-surface water interactions on the water balance of a mesoscale lowland river catchment in northeastern Germany. Hydrol. Proc. 21(2): 169-184 Kunstmann, H., J. Krause, S. Mayr (2006) Inverse distributed hydrological modelling of Alpine catchments. Hydrol. Earth Syst. Sci. 10: 395-412 Kunstmann, H., A. Heckl, A. Rimmer (2006) Physically based distributed hydrological modelling of the Upper Jordan catchment and investigation of effective model equations. Adv. Geosci. 9: 123-130 Lindenschmidt, K.-E., G. Ollesch, M. Rode (2004)

	Physically-based hydrological modelling for non-point dissolved phosphorus transport in small and medium-sized river basins. Hydrol. Sci. J. 49(3): 495-510
Assumptions and Limitations	
Versions	WaSIM-Topmodel, WaSIM-Richards
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Cost: Free of charge Contacts: Dr. Karsten Jasper, Postweg 11 CH 8143 Stallikon Tel.: +41 (0)44 700 26 14 E-mail: k.jasper @ wasim.ch Or Dr. Jörg Schulla Regensdorferstrasse 162 CH 8049 Zürich Tel.: +41 (0)44 341 84 30 E-mail: j.schulla @ wasim.ch Website: http://www.wasim.ch/en/index.html

Schulla,J. and Jasper, K. (2007). WASIM-ETH Model Description . Technical report, pp. 181.

HBV

Model Type (lumped or distributed), event-based or continuous	Semi-distributed conceptual model that is based on the theory of linear reservoirs. Hydrological units: sub-basins as primary hydrological units

Origin (development and maintenance)	Developed by Sweden's Meteorological and Hydrological Institute in the early 70´s to assist hydropower operations (Bergström 1976) by providing hydrological forecasts.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** DOS , Windows-95, NT or unix **Open source:** No **Computer Language:** There are several implemented versions, most of which in Fortran, the newest in C++. **GIS-based:** No **Visualisation facilities:** own GUI (IHMS 5)
Pathways and processes modelled	The model simulates: surface runoff, evapotranspiration, snow melting, soil moisture accounting, infiltration, and transmission losses
Inputs (data requirements)	§ Precipitation records (on daily or shorter timestep) § Air temperature records (if snow is present) § Monthly estimates of evapotranspiration § Runoff record for calibration
Outputs	Catchment discharge, usually daily values
Calibration Method	Automatic calibration technique has been developed (Harlin,1991)
Parameters	A range of parameters are included, a few measured, but many simply given a value by assumption. Usually between 10 and 15 are optimized by calibration. Sensitivity analysis: Lindström and Harlin, 1992; Harlin and Kung, 1992; Seibert, 1997; Lidén and Harlin, 2000
Water quality constituents	Nitrogen and phosphorus (HBV-NP)
Case Studies / Publications	Kobold, M. and Brilly, M (2006). The use of HBV model for flash flood forecasting . Natural Hazards and Earth System Science 6(3): 407-417. Bruland, O. and Killingtveit, A. (2002). "An energy balance based HBV-model with application to an Arctic watershed on Svalbard, Spitsbergen " Nordic Hydrology 33(2-3): 123-144. Tisseuil, Clément Wade, A., Tudesque, L.and Lek, S. (2008). "Modeling the stream water nitrate dynamics in a 60,000-km2 European catchment, the garonne, southwest France " Journal of Environmental Quality 37(6): 2155-2169.

	Sorman A. Arda, Sensoy, A. , Tekeli A. , Sorman, A., and Akyürek, Z. (2009). "Modelling and forecasting snowmelt runoff process using the HBV model in the eastern part of Turkey." Hydrological Processes 23(7): 1031-1040. Götzinger, J. and Bárdossy, A. (2007). "Comparison of four regionalisation methods for a distributed hydrological model." Journal of Hydrology 333(2-4): 374-384.
Versions	HBV, HBV-N, HBV-NP, HBV-96, PULSE
Limitations	Crude classification of land use (forest, lake, etc.) within a subbasin
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Cost: The model is free for research purpose. For commercial use a licence may be bought from SMHI. Training: Courses are organised regularly at SMHI. Contacts: Prof Sten Bergstrom Sweden's Meteorological and Hydrological Institute Box 923, S-60176 Norrkoping, Sweden.

Harlin, J. (1991). Development of a process oriented calibration scheme for the HBV hydrological Model. Nordic Hydrology, Vol. 22, No. 1, pp.13 -36.

<u>WATFLOOD/SPL9</u>

WATFLOOD is an integrated set of computer programs to forecast flood flows for watershed having response times ranging from one hour to several weeks. Continuous simulation can be carried out by chaining up to 100 events. SPL is the hydrological modeling component in WATFLOOD.

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	The model SPL9 is a physically-based, distributed simulation model of the hydrologic budget of a watershed. Hydrological unit: Group response units and grid cells.
Origin (development and maintenance)	Developed by N. Kouwen, Department of Civil Engineering, University of Waterloo, Ontario, Canada
Platform (PC?), Operating System, Open source?, GIS-based (what	**Platform:** PC, SUN Solaris, SGI and Linux systems **Operating System:** DOS, Unix

GIS?), Computer Language, Visualisation facilities	**Open source:** No **Computer Language:** FORTRAN95 **GIS-based:** no but can use GIS for data management **Visualisation facilities:** Green Kenue (formerly EnSim Hydrologic)
Pathways and processes modelled	The processes modeled include interception, infiltration, evaporation, snow accumulation and ablation, interflow, recharge, baseflow, and overland and channel routing.
Inputs (data requirements)	Rainfall, temperature and solar radiation.
Outputs	Total discharge.
Calibration Method	Hooke and Jeeves (1961) automatic pattern search optimization algorithm taken from Monro (1971). The program can be run to automatically determine which combination of parameters best fit measured conditions.
Parameters	Soil permeability, overland flow roughness, channel roughness, depression storage, and an upper zone depletion factor.
Water quality constituents	Not in original model (sediments, nutrients (P and N) Leon et al. 2000, pathogens (Dorner et al. 2006)
Case Studies / Publications	Kouwen, N., (1988). "WATFLOOD: A Micro-Computer based Flood Forecasting System based on Real-Time Weather Radar," Canadian Water Resources Journal, 13(1), pp.62-77. Pietroniro, A., Prowse, T.D., Hamlin, L., Kouwen, N. and Soulis, E.D. (1996). Application of a grouped response unit hydrologic model to a northern wetland region, International Journal of Hydrologic Processes, 10, pp. 1245-1261. Shaw, D. A., Martz, L. W., and Pietroniro, A. (2005) A methodology for preserving channel flow networks and connectivity patterns in large-scale distributed hydrological models. Hydrological Processes, Vol. 19, No.1. pp. 149-168. Bingeman, A.K, Kouwen, N. and Soulis, E. D. (2006). Validation of the hydrological processes in a hydrological model. Journal of Hydrologic Engineering, ASCE. 11 (5), pp.451-463. Dibike, Y.B. and Coulibaly, P. (2007). Validation of hydrological models for climate scenario simulation: the

	case of Saguenay watershed in Quebec. Hydrological Processes, Vol. 21, No. 23, pp. 3123-3135.
Assumptions and Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: N. Kouwen, Department of Civil Engineering, University of Waterloo, Email: kouwen@uwaterloo.ca or by phone at (519) 888-4567 X33309 Or Frank Seglenieks e-mail at frseglen@uwaterloo.ca or by phone at (519) 888-4567 X36112. Software executables can be downloaded from: http://www.civil.uwaterloo.ca/watflood/index.htm Cost: Free of charge Technical support: email N. Kouwen or Frank Seglenieks

Leon, L. F. , Soulis, E. D. , Kouwen, N. , Farquhar, G. J. (2001). Nonpoint source pollution: a distributed water quality modeling approach, Water Research, Volume 35, Issue 4, pp. 997-1007.

Dorner, S. M., Anderson, W.B., Slawson, R. M., Kouwen, N., and Huck, P.M. (2006). Hydrologic Modeling of Pathogen Fate and Transport. Environmental Science & Technology, Vol. 40, No. 15, pp. 4746-4753.

TOPOG

TOPOG is a terrain analysis-based hydrologic modelling.

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Deterministic, distributed-parameter hydrologic modelling package which uses topographical information. Hydrological unit: element
Origin (development and maintenance)	It has been developed jointly by CSIRO Land and Water and the Cooperative Research Centre for Catchment Hydrology, Australia
Platform (PC?), Operating System,	**Platform:** PC

Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Operating System:** Windows, UNIX (The full TOPOG package will only run on UNIX workstations) **Open source:** Yes **Computer Language:** FOTRAN and C **Visualisation facilities:** The screen graphics routines and user interface are written in X-WINDOWS and MOTIF. **GIS-based?:** No
Pathways and processes modelled	TOPOG describes how water moves through landscapes; over the land surface, into the soil, through the soil and groundwater and back to the atmosphere via evaporation. The model: (a) describe the topographic attributes of complex three dimensional landscapes (b) predict the spatial distribution of steady state waterlogging, erosion hazard and landslide risk indices (c) simulate the transient hydrologic behaviour of catchments, and how this is affected by changing catchment vegetation (d) model the growth of vegetation and how this impacts on the water balance (e) model solute movement through the soil (f) model sediment movement over the soil surface
Inputs (data requirements)	Total daily rainfall, mean daily vapour pressure deficit, daily maximum and minimum temperature, total solar radiation.
Outputs	Runoff hydrograph, estimates of solute and sediment yield.
Calibration Method	Manual
Parameters	Davis et al. (1999), Carluer and De Marsily (2004)
Water quality constituents	Conservative solute movement and sediment transport
Assumptions and Limitations	It is intended for application to small catchments (up to 10 km2, and generally smaller than 1 km2). The primary strength of TOPOG is that it is based on a sophisticated digital terrain analysis model, which accurately describes the topographic attributes of three-dimensional landscapes.
Case Studies / Publications	Silberstein, R. (2006). Hydrological models are so good, do we still need data? Environmental Modelling & Software, Vol. 21, No. 9, pp. 1340 – 1352. Carluer, N. and De Marsily, G (2004). Assessment and modelling of the influence of man-made networks on the

	hydrology of a small watershed: implications for fast flow components, water quality and landscape management. Journal of Hydrology, Vol 285, Issues 1-4, pp. 76-95 J. Schellekens, (2000). The interception and runoff generating processes in the Bisley catchment, Luquillo experimental forest, Puerto Rico. Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere, Vol 25, Issues 7-8, pp. 659-664 DAVIS, S.H., VERTESSY, R.A. AND SILBERSTEIN, R.P. (1999): The sensitivity of a catchment model to soil hydraulic properties obtained by using different measurement techniques. Hydrol. Process. 13: 677-688 VERTESSY, R.A. AND ELSENBEER, H. (1999): Distributed modeling of stormflow generation in an Amazonian rain forest catchment: Effects of model parameterization. Water Resources Research, Vol. 35, No. 7 2173 - 2187 ZHU, T.X., BAND, L.E. AND VERTESSY, R.A. (1999): Continuous modelling of intermittent stormflows on a semi-arid agricultural catchment. J. Hydrology 226: 11-29 ZHANG, L., DAWES, W.R., HATTON, T.J. HUME, I.H., O'CONNELL, M.G., MITCHELL, D.C., MILTHORP, P.L. AND YEE, M. (1999): Estimating episodic recharge under different crop/pasture rotations in the Mallee region. Part 1. Experiments and model calibration. Agricultural Water Management 42:219-235
Versions	TOPOG_Dynamic
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	TOPOG is available as a "restricted product" from the eWater CRC Catchment Modelling Toolkit(http://www.toolkit.net.au/). You will need to register as a Toolkit user and then email Richard Silberstein(Richard.Silberstein@csiro.au) or Joel Rahman (Joel.Rahman@csiro.au) for access to the code. **Cost:** Free of charge

	Technical support: currently, no technical support can be provided on installing or using TOPOG. **Training:** Check for upcoming workshops and online tutorials. UNIX Tutorials at http://www.per.clw.csiro.au/topog/workshops/tutorials/ **More Info:** Check TOPOG website (http://www.per.clw.csiro.au/topog/)

Water Erosion Prediction Project (WEPP)

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	is a process-based, distributed parameter, continuous simulation, erosion prediction model Hydrological unit: hillslope profiles
Origin (development and maintenance)	USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, IN
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows 95/98/NT/2000/XP/Vista **Open source:** No **Computer Language:** ANSI FORTRAN 77 **GIS-based:** no but some studies integrated it with GIS and ARCView use with WEPP is available on the website for evaluation **Visualisation facilities:** own interface, FS WEPP, GeoWEPP (with ARC GIS9.0)
Pathways and processes modelled	The WEPP model includes components for weather generation, frozen soils, snow accumulation and melt, irrigation, infiltration, overland flow hydraulics, water balance, plant growth, residue decomposition, soil disturbance by tillage, consolidation, and erosion and deposition.
Inputs (data requirements)	Rainfall
Outputs	Runoff Volume, sediment yield, and soil loss
Calibration Method	Manual
Parameters	Hillslope length, Manning's coefficients, and channel slope were found to be key parameters in the prediction of

	watershed sediment yields. Erodibility and critical shear stress were found to be important for events where channel scour was active, and the results were sensitive to the hydraulic conductivity for events with small runoff and small sediment contributions from hillslopes (Baffaut et al, 1997;Zhang,X.C.,2004; Pandey et al. 2008)
Water quality constituents	Sediments only
Case Studies / Publications	Dun, S., Wu, J., Elliot, W., Robichaud ,P., Flanagan, D., Frankenberger, J., Brown, R., and Xu, A. (2009). "Adapting the Water Erosion Prediction Project (WEPP) model for forest applications." Journal of Hydrology 366(1-4): 46-54. Pandey, A., Chowdary, V., Mal, B. and Billib,M. (2008). "Runoff and sediment yield modeling from a small agricultural watershed in India using the WEPP model." Journal of Hydrology 348(3-4): 305-319. Pieri, L., Bittelli, M., Wu, J., Dun, S, Flanagan, D., Pisa, P., Ventura, F., Salvatorelli, F.(2007). "Using the Water Erosion Prediction Project (WEPP) model to simulate field-observed runoff and erosion in the Apennines mountain range, Italy." Journal of Hydrology 336(1-2): 84-97. Raclot, D. and Albergel , J. (2006). "Runoff and water erosion modelling using WEPP on a Mediterranean cultivated catchment." Physics and Chemistry of the Earth, Parts A/B/C 31(17): 1038-1047.
Limitations	- Hillslope profile applications compute interrill and rill erosion and deposition along selected landscape profiles, while watershed applications also estimate channel erosion and deposition, and deposition in impoundments. The procedures do not consider classical gully erosion. - Model application is limited to areas where the hydrology is dominated by Hortonian overland flow.
Versions	2002.700, 2004.700, 2006.5, 2008.907 (latest version)
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	How to obtain Model: can be downloaded from http://topsoil.nserl.purdue.edu/nserlweb/weppmain/data/download2.htm Cost: Free of charge Software page: http://topsoil.nserl.purdue.edu/nserlweb/weppmain/ Documentation: http://topsoil.nserl.purdue.edu/nserlweb/weppmain/docs/readme.htm

Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS2000)

Model Type (lumped or distributed), event-based or continuous	It is a physically-based deterministic continuous, distributed parameter model (ANSWERS is an event-based simulation model) Hydrological Unit: The model divides the area simulated into a uniform grid of square (1 hectare or smaller), within which all properties (surface and subsurface soil properties, vegetation, surface condition, crop management, and climate) are assumed homogeneous.
Origin (development and maintenance)	Developed at the Agricultural Engineering Department of Purdue University (Beasley and Huggins, 1981)
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	Platform: PC and Sun workstation Operating System: Unix, Windows Open source: Yes Computer Language: FORTRAN77 GIS-based: GRASS-GIS, ArcView Visualisation facilities: GRASS-GIS, ArcView, Questions
Pathways and processes modelled	The model simulates interception; surface retention/detention; infiltration; percolation; sediment detachment and transport of mixed particle size classes in rills, interrill areas, and channels; crop growth; plant uptake of nutrients; N and P dynamics in the soil; nitrate leaching; and losses of nitrate, ammonium, total Kjeldahl nitrogen, and P in surface runoff as affected by soil, nutrient, cover and hydrologic conditions
Assumptions and Limitations	Limitations: • The sediment detachment sub-model is empirical and out of date. • Predictions of ammonium loss in surface runoff have been poor. This sub-model needs to be updated. • Current procedures for simulating fertilizer placement are cumbersome and need to be automated. • The currently distributed version of the model does not simulate interflow and groundwater contributions to baseflow. The model is therefore inappropriate for use in watersheds where baseflow is significant. The groundwater version of the model recently developed by Bouraoui et al. (1997) may overcome this limitation.

	• The model does not currently simulate nutrient cycles and fate in receiving waters. This limits the use of the model to small upland watersheds. • The model does not simulate snow pack and melt and is thus unsuitable for use in areas with significant winter snow accumulation and snowmelt.
Inputs (data requirements)	Rainfall
Outputs	Runoff volume, sediment yield, nitrogen and phosphorus,
Calibration Method	Manual
Parameters	Parameters are generally physically-based and calibration is not required. The most sensitive parameters for the major outputs include: Runoff volume: silt and clay content, solar radiation. Sediment yield: clay content Nitrate in runoff: clay content Dissolved: sensitive runoff volume parameters Sediment-bound TKN: clay content, soil N level, active organic N Sediment-bound P: initial labile P, clay and silt content Dissolved P: initial labile P, clay and silt content
Water quality constituents	Sediments, N (nitrate, ammonium, total Kjeldahl nitrogen) and P
Case Studies / Publications	Connolly, R. D., D. M. Silburn, et al. (1997). "Distributed parameter hydrology model (ANSWERS) applied to a range of catchment scales using rainfall simulator data. III. Application to a spatially complex catchment." Journal of Hydrology 193(1-4): 183-203. Ahmadi, S. H., S. Amin, et al. (2006). "Simulating Watershed Outlet Sediment Concentration using the ANSWERS Model by applying Two Sediment Transport Capacity Equations." Biosystems Engineering 94(4): 615-626. Bouraoui, F. and. Dillaha, T. (2000). "ANSWERS-2000: Non-Point-Source Nutrient Planning Model." ASCE Journal of Environmental Engineering 126(11), pp.1045-1055. Bouraoui, F. and. Dillaha, T. (1996). "ANSWERS-2000: Runoff and Sediment Transport Model." ASCE Journal

	of Environmental Engineering 122(6), pp.493 - 502.
Versions	ANSWERS, ANSWERS-2000
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Cost: Free of charge Model documentation: user manual only for the event-based version. How to obtain Model: Model can be downloaded from website: http://www.bse.vt.edu/ANSWERS/Download.php Model documentation and user support is very limited. Contacts: Prof. Theo Dillaha Professor of Biological Systems Engineering Virginia Tech, Blacksburg, VA 24061-0303, Phone: 540-231-6813, Fax: 540-231-3199, E-mail: dillaha@vt.edu Training available: No Website: http://www.bse.vt.edu/ANSWERS/index.php

Precipitation-Runoff Modeling System (PRMS)

Model Type (lumped or distributed), event-based or continuous Hydrological Unit	PRMS is a modular-design, deterministic, distributed-parameter Hydrological Unit: A watershed is divided into subunits based on such basin characteristics as slope, aspect, elevation, vegetation type, soil type, land use, and precipitation distribution. Two levels of partitioning are available. The first divides the basin into homogeneous response units (HRU) based on the basin characteristics. Water and energy balances are computed daily for each HRU. The sum of the responses of all HRU's, weighted on a unit-area basis, produces the daily system response and streamflow for a basin. A second level of partitioning is available for storm hydrograph simulation. The watershed is conceptualized as a series of interconnected flow planes and channel segments.

Origin (development and maintenance)	Model was developed by the: US Geological Survey.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating system:** UNIX, DOS **Computer Language:** Fortran 77 **Open source:** Yes (for UNIX only) **GIS-based:** No (but ARCINFO and SPANS are linked (see Flűgel and Lűllwitz (1993).) **Visualisation facilities:** GIS (PRMS developed into the Modular Modelling System Leavesley et al. (1996))
Pathways and processes modelled	models the impacts of precipitation (interception, soil-moisture accounting, evapotranspiration, surface runoff, subsurface flow, and groundwater), channel routing, climate(snow component), and land use on streamflow, sediment yields and groundwater recharge.
Inputs (data requirements)	For daily streamflow computations, a minimum of daily precipitation and daily maximum and minimum air temperature are required. For snowmelt computations, daily short-wave solar radiation data are recommended. For areas without snowmelt, daily pan evaporation data can be substituted for temperature data. For storm hydrograph and sediment computations, short time-interval precipitation, streamflow, and sediment data are needed. Physical descriptive data on the topography, soils, and vegetation are input for each watershed subunit. The spatial and temporal variation of precipitation, temperature and solar radiation are also needed
Outputs	The observed (if available) and predicted mean daily discharge for the basin is output in tabular form. Annual and monthly summaries of precipitation, interception, potential and actual evapotranspiration, and inflows and outflows of the ground water and subsurface reservoirs are available. A summary table of observed and predicted peak flows and runoff volumes for each storm period is output in tabular form.
Calibration Method	Parameter-optimization (Rozenbrock technique and Gauss- Newton technique) and sensitivity analysis capabilities are provided.
Parameters	Physically-based and can be spatially- or temporally-distributed. For sensitive parameters (see Jeton, and Smith, 1993).
Water quality constituents	No, only sediment transport.
Case Studies / Publications	Mazi, K. , Koussis, A. D. , Restrepo, P. J. , and Koutsoyiannis, D. (2004). A groundwater-based, objective-heuristic parameter optimisation method for a precipitation-runoff model and its application to a semi-arid basin, Journal of Hydrology, Volume 290, Issues 3-4, pp. 243-258

	Bongartz, K. (2003).Applying different spatial distribution and modelling concepts in three nested mesoscale catchments of Germany, Physics and Chemistry of the Earth, Parts A/B/C, Volume 28, Issues 33-36, Recent Development in River Basin Research and Management, pp. 1343-1349. Brendecke, C. M. , Laiho, D. R. , and Holden, D. C. (1985). Comparison of two daily streamflow simulation models of an alpine watershed, Journal of Hydrology, Volume 77, Issues 1-4, pp. 171-186. Legesse, D., Vallet-Coulomb, C., Gasse, F. (2003). Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia, Journal of Hydrology, Volume 275, Issues 1-2, pp. 67-85.
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Operation and Distribution: U.S. Geological Survey Hydrologic Analysis Software Support Program 437 National Center Reston, VA 20192 h2osoft@usgs.gov Cost: Free of charge http://water.usgs.gov/software/prms.html

Jeton, A. and Smith, J. (1993). Development of Watershed Models for two Sierra Nevada Basins using a Geographic Information System, Journal of the American Water Resources Association, Vol. 29, No. 6, pp. 923 – 932.

Flűgel, W. and Lűllwitz, Th. (1993). Using a distributed hydrologic model with the aid of GIS for comparative hydrological modelling of micro- and meso-scale catchments in the USA and in Germany, Macro-scale Modelling of the Hydrosphere, IAHS Publication No. 214.

Leavesley, G.H., Markstrom, S. L., Brewer, M. S. and Viger, R. J. (1996). The modular modeling system (MMS) — The physical process modeling component of a database-centered decision support system for water and power management. Water, Air, & Soil Pollution. Vol.90, No. 1-2, pp.303-311.

SHETRAN

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	SHETRAN is a three-dimensional, coupled surface/subsurface, physically-based, spatially-distributed, finite-difference model for coupled water flow, multifraction sediment transport and multiple, reactive solute transport in river basins. **Hydrological unit:** a regular rectangular grid with typical dimensions of a few hundreds of meters (200-300m). The equations are solved with an explicit finite difference method.
Origin (development and maintenance)	The SHETRAN system was developed by the Water Resources Systems Research Laboratory (WRSRL), is based on the SHE (Systeme Hydrologique Europeen), and was developed by international collaboration between the Danish Hydraulic Institute, the British Institute of Hydrology and SOGREAH in France.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows **Open Source:** No. **GIS-Based?:** No **Computer Language:** FORTRAN90 **Visualisation facilities:** SHEGRAPH graphics package
Pathways and processes modelled	Each of the major elements of the hydrologic cycle is modelled separately. Interception by the Rutter accounting method, evapotranspiration by the Penman Monteith method, flow in unsaturated soil by a one-dimensional Richards' equation, saturated, groundwater, flow by the Boussinesq equation and snowmelt by an energy-budget approach. It modells overland flow as a two-dimensional diffusie wave and Manning's resistance law.
Inputs (data requirements)	Time series of rainfall, net radiation, air temperature, humidity and wind speed,
Outputs	Main outputs: Runoff hydrograph and sediment yield.

Calibration Method	Manual
Parameters	Large number of physically-based parameters. See Bathurst (1986).
Water quality constituents	Soil erosion and multifraction transport on ground surface and in stream channels Multiple, reactive solute transport on ground surface and in stream channels and subsurface Nitrogen (Birkinshaw and Ewen ,2000). Phosphorus (Nasr et al, 2005)
Case Studies / Publications	Nasr, A., Bruen, M., Jordan, P., Moles, R., Kiely, G. and Byrne, P. (2007) A comparison of SWAT, HSPF and SHETRAN/GOPC for modelling phosphorus export from three catchments in Ireland. Water Research, 41, pp.1065-1073. Ewen, J., O'Donnell, G., Burton, A. and O'Connell, P.E. (2007) Errors and uncertainty in physically-based rainfall-runoff modelling of catchment change effects. Journal of Hydrology, 330, pp. 641-650. Birkinshaw, S.J. (2008) Physically-based modelling of double-peak discharge responses at Slapton Wood catchment. Hydrological Processes, 22, pp. 1419-1430. Bathurst J. C., Ewen J., Parkin G., O'Connell P. E. and Cooper, J. D. (2004) Validation of catchment models for predicting land-use and climate change impacts. 3. Blind validation for internal and outlet responses Journal of Hydrology, 287, pp.74-94.
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contact: Professor P.E. O'Connell Professor of Water Resources Engineering Department of Civil Engineering University of Newcastle Newcastle upon Tyne NE1 7RU, UK (44) (0) 191 222 6319 p.e.o'connell@ncl.ac.uk

	Website: http://www.ceg.ncl.ac.uk/shetran/ Cost: Software fees and license applied Training Available: No.

Bathurst, J.C., 1986. Sensitivity analysis of the System Hydrologique European for an upland catchment. Journal of Hydrology 87, 103-123.
Birkinshaw, S.J., and Ewen, J., (2000). Nitrogen transformation component for SHETRAN catchment nitrate transport modelling. Journal of Hydrology 230, pp.1-17.
Nasr, A, Taskinen, A, and Bruen, M (2005) Developing an independent, generic, phosphorus modelling component for use with grid-oriented, physically based distributed catchment models. Water Science and Technology, Vol. 51, no. 3-4, pp.135-142.

HSPF

A comprehensive package for simulation of catchment hydrologic and associated water quality processes on pervious and impervious land surface, in the soil profile, and in streams and well-mixed impoundments.

Model Type (lumped or distributed), event-based or continuous Hydrological unit	Quasi physically-based, semi-distributed, continuous. Hydrological unit: Pervious/Impervious land segment.
Origin (development and maintenance)	The origin of HSPF was that of the Stanford Catchment Model (SWM) (Crawford and Linsley, 1966) which was re-written using the FORTRAN programming language. Then numerous modifications and code enhancements have assisted in the development of the Hydrological Simulation Program – FORTRAN (HSPF). In addition, HSPF model system integrates other EPA existing models which include the Agriculture Runoff Management Model (ARM), the Non Point Source (NPS) Model, and the Hydrocomp Simulation Program (HSP).
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating Systems:** Unix, DOS **Computer Language:** FORTRAN 77. **Open source?:** Yes **GIS?:** YES, ARCView **Visualisation Facilities:** WMS 7.0 (Watershed Modelling System), BASINS, ARCview, EXPERT system
Pathways and processes modelled	HSPF uses continuous rainfall and other meteorologic records to compute streamflow hydrographs and pollutographs. HSPF simulates interception soil moisture, surface runoff, interflow, base flow, snowpack depth

	and water content, snowmelt, evapotranspiration, and ground-water recharge. It also simulates sediment detachment and transport, sediment routing by particle size, channel routing and reservoir routing.
Inputs (data requirements)	Data needs for HSPF are extensive. HSPF is a continuous simulation program and requires continuous data to drive the simulations. As a minimum, continuous rainfall records are required to drive the runoff model and additional records of evapotranspiration, temperature, and solar intensity are desirable. A large number of model parameters can also be specified although default values are provided where reasonable values are available.
Outputs	HSPF produces a time history of the runoff flow rate, sediment load, and nutrient and pesticide concentrations, along with a time history of water quantity and quality at any point in a catchment. Simulation results can be processed through a frequency and duration analysis routine that produces output compatible with conventional toxicological measures (e.g., 96-hour LC50).
Calibration Method	Manual, PEST (Parameter Estimation Tool) in WinHSPF
Parameters	A very large number of physically-based parameters (USEPA, 2000).
Water quality constituents	pH, temperature, dissolved oxygen, biochemical oxygen demand (BOD), ammonia, nitrite, nitrate, organic nitrogen, orthophosphate, organic phosphorus, phytoplankton, zooplankton, pesticides, conservatives, fecal coliforms.
Case Studies / Publications	Cho, J. , Barone, V.A. and Mostaghimi, S. (2009). Simulation of land use impacts on groundwater levels and streamflow in a Virginia watershed, Agricultural Water Management, Vol. 96, Issue 1, pp. 1-11 Hunter, H. M. and Walton, R. S. (2008). Land-use effects on fluxes of suspended sediment, nitrogen and phosphorus from a river catchment of the Great Barrier Reef, Australia, Journal of Hydrology, Vol. 356, Issues 1-2, pp.131-146. Ribarova, I. , Ninov, P. , and Cooper, D. (2008). Modeling nutrient pollution during a first flood event using HSPF software: Iskar River case study, Bulgaria. Ecological Modelling, Vol. 211, Issues 1-2, pp 241-246 Xu, Z. , Godrej, A. N. and Grizzard, T. J. (2007). The hydrological calibration and validation of a complexly-linked watershed-reservoir model for the Occoquan watershed, Virginia, Journal of Hydrology, Vol. 345, Issues 3-4, pp. 167-183

	Johnson, M. S. , Coon, W.F. , Mehta, V. K., Steenhuis, T. S., Brooks, E. S. and Boll, J. (2003). Application of two hydrologic models with different runoff mechanisms to a hillslope dominated watershed in the northeastern US: a comparison of HSPF and SMR, Journal of Hydrology, Vol. 284, Issues 1-4, pp. 57-76.
Assumptions and Limitations	HSPF assumes that the "Stanford Watershed Model" hydrologic model is appropriate for the area being modeled. Further, the instream model assumes the receiving water body model is well-mixed with width and depth and is thus limited to well-mixed rivers and reservoirs. Application of this methodology generally requires a team effort because of its comprehensive nature.
Versions	HSPF11, HSPF12.1, WinHSPF
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contacts: U.S. Geological Survey, Hydrologic Analysis Software Support Program 437 National Center, Reston, VA 20192 h2osoft@usgs.gov Model available: Official versions of U.S. Geological Survey water-resources analysis software are available for electronic retrieval at: http://water.usgs.gov/software/and via anonymous File Transfer Protocol (FTP) Cost: Free of charge

USEPA, (2000). BASINS Technical Note 6: Estimating hydrologic and hydraulic parameters for HSPF. EPA-823-R-00-012, United States Environmental Protection Agency, Office of Water (4305), USA.

TOPMODEL

TOPMODEL is a collection of modules to predict the relative amount and spatial distribution of subsurface, infiltration excess, and saturation excess overland flow based on surface topography and soil properties.

Model Type (lumped or distributed), event-based or continuous Hydrological Unit	semi-distributed, variable contributing area conceptual model Hydrological Unit: storage elements divided based on a topographic index.

Origin (development and maintenance)	TOPMODEL (a TOPography based hydrological MODEL) was developed by Prof. K. Beven of Lancaster University, UK.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platforms: PC** **Operating system:** Windows, DOS **GIS?:** TOPMODEL is integrated in GRASS GIS version 5 **Computer Language:** FORTRAN 77 **Open Source:** yes **Visualisation Facilities:** PV Wave, Water Information System (WIM) of HR Wallingford.
Pathways	Surface runoff is computed based on variable saturated areas, subsurface flow using a simple exponential function of water content in the saturated zone. Channel routing and infiltration excess overland flow are considered in the model. The structure of the model with regard to interception and root zone storage compartments is variable, allowing much flexibility to simulated different systems. Time steps should be in the range of an hour to represent surface runoff peaks. The length of the simulation period depends on the availability of precipitation and evapotranspiration input data. The spatial component requires a high quality DEM (digital elevation model) without sinks.
Inputs (data requirements)	Rainfall, observed runoff hydrograph, potential evapotranspiration
Outputs	Runoff hydrograph, baseflow
Calibration Method	Automatic also uncertainty analysis routine Generalised Likelihood Uncertainty Estimation (GLUE).
Parameters	Parameters are intended to be physically interpretable and their number is kept to a minimum. Critical parameters: saturated zone parameter, the saturated transmissivity values, and the root zone parameter and in large catchments a channel routing velocity.
Water quality constituents	No
Assumptions and Limitations	• Precipitation is considered uniform over the catchment. • All precipitation infiltrates unless the soil is saturated at a particular location. • Total runoff is composed of both surface runoff and sub-surface flows • Surface runoff is calculated by considering the extent of saturated contributing areas on the basis of a topographic index curve. • Soil moisture is depelted by evapotranspiration, by subsurface flow and by percolation. • The permeability of the upper soil layers is very large and decays exponentially with depth.

	• Downslope movement of water in the saturated zone is driven by gravty and is a function of local topography. • There is no downslope movement of water in the capilliary fringe of the unsaturated zone. • Sub-surface flows are calculated by integrating over space a steady-state equation for flow in saturated porous media (i.e. a groundwater flow equation)
Case Studies / Publications	Hydrological Processes Volume 11 Issue 9, pages 1069 – 1355 (1997), TOPMODEL special Issue. Campling,P., Gobin, A., Beven,K. and Feyen,J. (2002). Rainfall-runoff modelling of a humid tropical catchment: the TOPMODEL approach. Hydrological Processes, Volume 16, pp. 231- 253. Le Lay, M., Saulnier, G.-M, Galle, S., Seguis, L., Me´tadier M. and Peugeot, C. (2008). Model representation of the Sudanian hydrological processes: Application on the Donga catchment (Benin). Journal of Hydrology, 363, pp. 32 – 41. Xiong, L. and Guo S. (2004). Effects of the catchment runoff coefficient on the performance of TOPMODEL in rainfall-runoff modelling. Hydrological Processes, Volume 18, pp. 1823 – 1836.
Versions	TOPMODEL 95.02, STOPMODEL
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	**Contacts:** TOPMODEL is available from Prof. Keith Beven, Centre for Research in Environmental Systems and Statistics, Institute of Environmental and Natural Sciences, Lancaster University, Lancaster LA1 4YQ, UK, e-mail: K.beven@lancaster.ac.uk **Cost**: The model use is free for teaching and research purposes. Any other application should be negotiated with the author.

NAM

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	is a deterministic conceptual lumped hydrological model

Origin (development and maintenance)	Developed by Nielsen and Hansen of the Institute of Hydrology and Hydraulic Engineering, at the Technical University of Denmark. The NAM rainfall runoff is a module of DHI's MIKE 11 modelling suite
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform: PC** **Operating System:** Windows **Open Source**: NO **Computer Language:** FORTRAN **GIS-based:** MIKE 11 GIS, ArcGIS (linked through Temporal Analyst a MIKE software) **Visualisation Facilities:** MIKE 11 GIS, MIKE View
Pathways and processes modelled	uses a conceptual representation of the hydrological cycle and produces a time series of catchment runoff and subsurface contributions to stream flow. The simulated catchment runoff is split conceptually into three components: what the model terms surface runoff (overland flow), interflow and baseflow. The definition of the model's baseflow component is groundwater flow beneath the groundwater table that interacts with the surface water system. NAM model which simulates rainfall-runoff processes on a catchment scale by continually accounting for water content in four inter-related storage zones. These storages are snow storage, surface storage, a lower or root zone storage and groundwater storage. The amount of water that recharges the groundwater storage depends on the soil moisture content in the root zone. The groundwater flow is estimated using a linear storage-discharge relationship.
Inputs (data requirements)	The basic requirements for the model are meteorological data (time series of rainfall and evapotranspiration, temperature, and radiation), stream flow data and the definition of physical catchment parameters
Outputs	The output of the model is tabular data (water balance, net rainfall, potential/actual evapotranspiration and groundwater recharge), and time series data of all discharge components and storage components.
Calibration Method	Automatic calibration based on the Shuffled Complex Evolution (SCE) (ptimisation of several objective functions simultaneously) , See Madsen(2000)
Parameters	There are nine catchment parameters (seven surface water and two groundwater parameters) that can be adjusted according to physical and mathematical constraints in NAM, see Madsen(2000) for the description and possible range of values of these parameters.
Water quality constituents	No
Case Studies / Publications	Lǿrup,J., Refsgaard, J., and Mazvimavi, D. (1998) Assessing the effect of land use change on catchment runoff

	by combined use of statistical tests and hydrological modelling: case study from Zimbabwe. Journal of Hydrology , Vol. 205, pp. 147-163. Ilias, A., Hatzispiroglou, J., Baltas, E., and Anastasiadou-Partheniou, E. (2005), ‘Application of the NAM Model to the Ali-Efenti Basin’. Wessex Institute of Technology Conference: RIVER BASIN MANAGEMENT, Bologna, Italy, 6-8 September, 2005. Madsen, H. (2000). Automatic calibration of a conceptual rainfall-runoff model using multiple objectives. J. Hydrol. 235, pp. 276–288.
Assumptions and Limitations	
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	To obtain Model: Contact DHI Agent: CDM, 87/89 Morehampton Road 1st Floor Donnybrook , Dublin 4, IRELAND Att: Alan G. Hooper Telephone: +353-1-663-2900 Facsimile: +353-1-663-2888 E-mail: hooperag@cdm.com Training available. Visit: http://www.dhigroup.com/Software/Training.aspx Cost: contact DHI for license

Madsen, H. (2000). Automatic calibration of a conceptual rainfall-runoff model using multiple objectives. J. Hydrol. 235, pp. 276–288.

<u>RORB</u>

RORB is a runoff and streamflow routing program used to calculate hydrographs from rainfall and other channel inputs in both rural and urban catchments.

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	semi-distributed, conceptual, event-based hydrologic simulation model Hydrological unit: catchment division into sub-areas (5 – 15). The sub-division is on watershed line so that hydrographs calculated at the downstream boundaries of sub-areas include all of the contributing area upstream.
Origin (development and maintenance)	The RORB runoff routing software was developed within the Water Group of the Department of Civil Engineering by Eric Laurenson and Russell Mein. The latest version (RORB Version 6, 2008) is the result of a collaboration between Monash University (Russell Mein) and Sinclair Knight Merz (Rory Nathan), with support from the Melbourne Water Corporation.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows 95 and above, DOS **Computer Language:** FORTRAN95 **GIS based:** YES see reference below (Coroza et al, 1997) **Visualisation Facilities:** Graphical Editor, Winteracter Graphical User Interface
Pathways and processes modelled	It subtracts losses from rainfall to produce rainfall-excess and routes this through catchment storage to produce the hydrograph. It can also be used to design retarding basins and to route floods through channel networks.
Inputs (data requirements)	Can consist of rainfall on a catchment area or direct inflow to the channel system.
Outputs	Principal output: Runoff hydrographs at any node of the model and/or channel outflows to effluent streams. Other possible outputs: hyetographs of rainfall and rainfall-excess, formatted listings of the data.
Calibration Method	Manual
Parameters	Physically based. Therefore for ungauged catchments thus information from derived regional relationships can be used for estimation of parameter values.
Water quality constituents	none
Case Studies / Publications	Segond, M.-L., Wheater, H. S. , Onof, C. (2007). The significance of spatial rainfall representation for flood runoff estimation: A numerical evaluation based on the Lee catchment, UK. Journal of Hydrology, Volume 347, Issues 1-2, pp.116-131. Selvalingam, S. Liong, S. Y. , and Manoharan, P. C. (1987). Use of RORB and SWMM models to an urban

	catchment in Singapore, Advances in Water Resources, Volume 10, Issue 2, pp. 78-86. Coroza, O., Evans, D., and Bishop, I. (1997). Enhancing runoff modeling with GIS, Landscape and Urban Planning, Volume 38, Issues 1-2, pp. 13-23. Kuczera, G. (1990). Estimation of runoff-routing model parameters using incompatible storm data, Journal of Hydrology, Volume 114, Issues 1-2, pp. 47-60. Sun, X. , Mein, R. G., Keenan, T. D., and Elliott, J. F. (2000). Flood estimation using radar and raingauge data, Journal of Hydrology, Volume 239, Issues 1-4, pp. 4-18.
Versions	V1 (1975), V2 (1978), V3 (1981), V4 (1987), V5 (2005), V6 (2008).
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Cost: Free of charge How to obtain Model: RORB6 (http://civil.eng.monash.edu.au/expertise/water/rorb/obtain), or http://www.skmconsulting.com/Markets/environmental/resource_management/RORB+Download.htm Training: RORB workshops (taking place in Australia 2 -3 times a year) Enquiries: RORB@eng.monash.edu.au

HEC-1

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	Single storm event, lumped, conceptual parameter model Hydrological unit: Basin represented as an interconnected system of hydrologic and hydraulic components (subbasins).
Origin (development and maintenance)	Developed by the Hydrologic Engineering Centre (HEC), an organization within the Institute for Water Resources, US Army Corps of Engineers in Davis, California (1968)
Platform (PC?), Operating System,	**Platform:** PC

Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Open Source:** no **Computer Language:** ANSI standard FORTRAN77 **Visualisation Facilities:** HECDSS, Watershed Modelling System (WMS)7.0 **GIS based?:** Linked with ARC INFO
Pathways and processes modelled	These processes are separated into precipitation, interception/infiltration, transformation of precipitation excess to subbasin outflow, addition of baseflow, flood hydrograph routing, and reservoir routing
Inputs (data requirements)	precipitation hyetograph, observed hydrograph, solar radiation, temperature, wind
Outputs	Discharge
Calibration Method	Automated parameter estimation using the unit gradient search method (Zakermoshfegh et al., 2008)
Parameters	See Zakermoshfegh et al., 2008. Also section 4 in HEC(1998).
Water quality constituents	No
Case Studies / Publications	Smemoe, C. M. Nelson, E. J. and Zhao, B. (2004). Spatial averaging of land use and soil properties to develop the physically-based Green and Ampt parameters for HEC-1. Environmental Modelling & Software, Vol. 19, Issue 6, pp. 525-535. Muzik,I. (2002). First-order analysis of the climate change effect on flood frequencies in a subalpine watershed by means of a hydrological rainfall-runoff model. Journal of Hydrology, Vol. 267, Issues 1-2, pp. 65-73. Duru, J.O., and Hjelmfelt, A. T. (1994). Investigating prediction capability of HEC-1 and KINEROS kinematic wave runoff models. Journal of Hydrology, Vol. 157, Issues 1-4, pp. 87-103. Smith, D. P. and Bedient, P. B. (1981). Preliminary model of an urban floodplain under changing land use, Journal of Hydrology, Vol. 51, Issues 1-4, pp. 179-185. Maskey, S., Guinot, V., and Price, R. K. (2004). Treatment of precipitation uncertainty in rainfall-runoff modelling: a fuzzy set approach. Advances in Water Resources, Vol. 27, Issue 9, pp. 889-898.
Limitations and Assumptions	Limitations: • Simulations are limited to a single storm due to the fact that provision is not made for soil moisture recovery during periods of no precipitation.

	• The model results are in terms of discharge and not stage, although stages can be printed out by the program based on a user specified rating curve. • Streamflow routings are performed by hydrologic routing methods and do not reflect the full St. Venant equations which are required for very flat river slopes. • Reservoir routings are based on the modified Puls techniques which are not appropriate where reservoir gates are operated to reduce flooding at downstream locations.
Versions	Version 1 (1968), Version 2.0 (1973), Version 3.0 (1981), Version 4.0 (1991), Version 4.0.1E (1991), HEC-HMS
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	How to obtain Model: Cost: Free of charge Technical Support: Is not provided to nom-Corps users. Documentation: Available from website (http://www.hec.usace.army.mil/software/legacysoftware/hec1/hec1-documentation.htm). Lecture DVDs available to order (http://www.hec.usace.army.mil/training/dvd_catalog.html)

Zakermoshfegh, M., Neyshabouri ,S.A., and Lucas, C. (2008). Automatic Calibration of Lumped Conceptual Rainfall-Runoff Model Using Particle Swarm Optimization. Journal of Applied Sciences, Vol. 8 , No. 20, pp. 3703-3708.

Hydrologic Engineering Center (HEC), 1998. HEC-1 Flood Hydrograph Package V4.1, User's Manual US Army Corps of Engineers
609 Second Street, Davis, CA 95616, USA.

Agricultural Nonpoint Source Pollution Model (AGNPS)

Model Type (lumped or distributed), event-based or continuous	Distributed model (catchment divided into cells) Can simulate both single events and continuous periods. (was event-based up to mid 1990's) Hydrological Unit: AGNPS considers the catchment to be divided into square cells
Origin (development and maintenance)	Jointly developed and maintained by the USDA - Agricultural Research Service (ARS) and the Natural Resources Conservation Service, U.S. The model is comprised of several modules enabling users to develop appropriate input parameters for evaluations of best management practices using simulations for their watershed system.
Platform (PC?), Operating System,	**Platforms:** Windows, DOS

Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Operating System:** MS-DOS, UNIX(Solaris 2.5) **GIS:** AGNPS Arcview (V4.00) interface, Grass GIS **Computer Language:** standard FORTRAN 77, BORLAND C **Visualisation facilities:** ARCView and GRASS GIS **Source code available?:** YES
Pathways	Surface runoff (SCS Curve method), stream routing (no transmission losses)
Inputs (data requirements)	Daily precipitation, maximum and minimum temperature, dew point temperature, sky cover, and wind speed, and pollutant loads
Outputs	hydrology, with estimates of both runoff volume and peak runoff rate; (2) sediment, with estimates of upland erosion, channel erosion, and sediment yield; and nutrients (both sediment attached and dissolved), with estimates of pollution loadings to receiving cells.
Calibration Method	Automated runoff calibration feature
Parameters	Sensitive factors and parameters (sensitivity analysis by Liu et al (2008)): rainfall quantity, SCS-CN curve number, Energy intensity, manning's coefficient, soil erodibility, cropping factor, practice factor, fertilizer application, fertilizer available, land shape, and slope length.
Water quality constituents	Soluble and attached nutrients (nitrogen, phosphorus, & organic carbon) and any number of pesticides. Sediment yield by particle size class and source are calculated.
Versions	AnnAGNPS is the pollutant loading modeling module designed for risk and cost/benefit analyses. AnnAGNPS is the next generation AGNPS 5.0 model developed by USDA. Old single-event versions: AGNPS 4.03 & 5.00
Application (Case studies)	Liu, J., Zhang, L., Zhang, Y., Hong, H., Deng, H. (2008). Validation of an agricultural non-point source (AGNPS) pollution model for a catchment in the Jiulong River watershed, China. Journal of Environmental Sciences, v 20, n 5, pp. 599-606. Jaepil, C., Seuqwoo, P., Sanqium, I. (2008).Evaluation of Agricultural Nonpoint Source (AGNPS) model for small watersheds in Korea applying irregular cell delineation. Agricultural Water Management, v 95, n 4, pp. 400-408. Bhuyan,S., Koeliker, J., Marzen,L., Harrington,J.(2003). An integrated approach for water quality assessment of

	a Kansas watershed. Environmental Modelling and Software, v 18, n 5, pp. 473-484.
How to obtain Model (contacts, documentation), Cost, / training available	Contacts: Ron Bingner, Lead ARS Scientist, Project Manager, Ron.Bingner@ars.usda.gov Fred Theurer, Lead NRCS Scientist & Programmer, Co-Project Manager, Fred.Theurer@verizon.net Homepage: http://www.ars.usda.gov/Research/docs.htm?docid=5199 Cost: Free of charge To obtain Model: register online and contact Ron Bingner or Fred Theurer http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/Tools_Models/agnps/ Training : http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/Tools_Models/agnps/training.html

Soil Water and Assessment Tool (SWAT)

Model Type (lumped or distributed), event-based or continuous	Semi-empirical, continuous model- has a daily time step. Fully distributed. Hydrological modelling unit: hydrologic response units
Origin (development and maintenance)	The Soil and Water Assessment Tool (SWAT) model is a physically-based, distributed catchment model developed by Dr. Jeff Arnold for the USDA agricultural Research Service (ARS) to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Windows, DOS **Source code available?:** Yes **Computer Language:** FOTRAN 90 **GIS-based?:** ArcGIS 9.1**,** ArcGIS 9.2

	Visualisation facilities: ArcSWAT, AVSWAT, MPSWAT, and VIZSWAT
Pathways and processes modelled	Surface runoff, percolation, Evapotranspiration, transmission losses, pond and reservoir storage, irrigation, shallow and deep groundwater flow, reach routing, nutrient and pesticide loading, water transfer.
Inputs (data requirements)	Geographical data (DEM, soil map, landuse map), weather data (rainfall, evaporation, relative humidity, temperature, solar radiation and wind speed), pollutant inputs (land application of nutrients and pesticides).
Outputs	Daily flow, pollutant loads
Calibration Method	Both manual and automated calibration
Parameters	K. Eckhardt, J. G. Arnold (2001). Automatic calibration of a distributed catchment model. Journal of Hydrology, Volume 251, Issues 1-2, pp. 103-109. Spruill, C.A., S.R. Workman, and J.L. Taraba (2000). Simulation of daily and monthly stream discharge from small watersheds using the SWAT model . Transactions of the ASAE, Vol. 43(6), pp. 1431-1439. Vandenberghe V., A. van Griensven and W. Bauwens (2001). Sensitivity analysis and calibration of the parameters of ESWAT: Application to the river Dender . Water Science and Technology, Vol.43(7), pp. 295-301. Eckhardt, K., L. Breuer, and H.-G. Frede (2003). Parameter uncertainty and the significance of simulated land use change effects. Journal of Hydrology. Vol. 273(1-4), pp. 164-176.
Water quality constituents	Nitrogen, Phosphorus, pesticides, bacteria, and sediments
Case Studies / Publications	Comprehensive list of about 500 article in SWAT website https://www.card.iastate.edu/swat_articles/, some examples are: Arnold, J.G., Allen, P.M., Bernhardt, G., 1993. A comprehensive surface-groundwater flow model. *J. Hydrology*, 142, 47-69. Arnold, J.G., Williams, J.R., Srinivasan, R., King, K.W., Griggs, R.H., 1994. *SWAT, Soil and Water Assessment Tool*. USDA, Agriculture Research Service, Temple, TX 76502.
Versions	SWAT98.1, SWAT99.2, SWAT2000 and SWAT2005, ESWAT, SWAT-G,

How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contacts: Jeff Arnold&Hydraulic Engineer ARS-Temple& jgarnold@spa.ars.usda.gov Nancy Sammons&Computer Specialist ARS-Temple& nsammons@spa.ars.usda.gov Raghavan Srinivasan & Agricultural Engineer TAES-Temple& r-srinivasan@tamu.edu Mauro DiLuzio & Research Associate TAES-Temple& diluzio@brc.tamus.edu Cost: Free of charge except for VIZSWAT To obtain Model: SWAT Web site http://www.brc.tamus.edu/swat/ SWAT Documentation: http://www.brc.tamus.edu/swat/doc.html SWAT User's Group: http://groups.google.com/group/swatuser Training: available (see SWAT website http://www.brc.tamus.edu/swat/edu.html)

IHACRES

IHACRES stands for Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data.

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	lumped hybrid conceptual-metric model as it uses a conceptual module to estimate the effective rainfall and a transfer function module to convert effective rainfall into streamflow.
Origin (development and maintenance)	The model is the result of collaboration between the Institute of Hydrology, Wallingford, UK and the Australian National University, Canberra
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System:** Microsoft Windows, Mac OS X **GIS:** No **Visualisation tool:** incorporated in model (3D visualisation, charts and graphs) **Open Source:** Yes

	Computer Language: Java
Pathways and processes modelled	The core of the model consists of a non-linear loss module that converts rainfall into effective rainfall, and a linear routing module that converts effective rainfall into streamflow.
Inputs (data requirements)	Time series of observed rainfall, temperature or evapotranspiration, and observed streamflow
Outputs	(i) A time series of modelled streamflow is produced, along with multiple statistics which describe the characteristics of each series (ii) modelled catchment wetness index time series (iii) unit hydrographs (iv) hydrograph separation (in many cases) into dominant quick and slow flow components; and (v) indicative uncertainties associated with the unit hydrograph parameters.
Calibration Method	In the PC-IHACRES version of the model, the parameter optimization methodology uses an instrumental variable technique to identify the unit hydrograph parameters. The parameters of the non-linear storage are selected by a semi-automatic search of the parameter space.
Parameters	9 parameters.
Water quality constituents	No
Case Studies / Publications	Croke, B.F.W. and A.J. Jakeman (2004), "A Catchment Moisture Deficit module for the IHACRES rainfall-runoff model", Environmental Modelling and Software, vol 19, pp 1-5. Dye P.J. and B. F. W. Croke (2003), "Evaluation of streamflow predictions by the IHACRES rainfall-runoff model in two South African catchments", Environmental Modelling and Software, vol 18, pp 705-712. Croke, B.F.W., Andrews, F., Jakeman, A.J., Cuddy, S.M. and Luddy, A. (2006) IHACRES Classic Plus: A redesign of the IHACRES rainfall-runoff model? Environmental Modelling and Software, 21, pp. 426-427. McIntyre, N. and Al-Qurashi,A. Performance of ten rainfall–runoff models applied to an arid catchment in Oman. Environmental Modelling & Software 24 (2009) 726–738.

	Carcano, E., Bartolini, P., Muselli, M., and Piroddi, L. (2008) Jordan recurrent neural network versus IHACRES in modelling daily streamflows. Journal of Hydrology 362, pp.291– 307.
Assumptions and Limitations	
Versions	V1, V1.1, V1.2, Version 2.0.1, Version 2.1.0, Version 2.1.1, Version 2.1.2
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	To obtain Model: Catchment Modelling Toolkit website http://www.toolkit.net.au/Tools/IHACRES/license Cost: Free of Charge Contacts: Integrated Catchment Assessment and Management Centre http://icam.anu.edu.au/ School of Resources, Environment and Society Building 48A Linneaus Way The Australian National University Training workshops are available on demand. Contact the Product Manager for details or see www.toolkit.net.au/training. Ease of use: For operational and research uses, a sound working knowledge of hydrology is required. As an educational tool for exploring the performance and response characteristics of rainfall-runoff models, some knowledge of computer modelling is desirable

Hydrological Rainfall Runoff Model (HYRROM)

Model Type (lumped or distributed), event-based or continuous	HYRROM is a lumped, conceptual rainfall runoff model
Origin (development and maintenance)	Developed at Centre for Ecology and Hydrology(formerly Institute of Hydrology), Wallingford.
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** IBM compatible personal computers **Operating System:** MS-DOS **Visual Facilities:** Output is in the form of colour screen graphics which can be copied to a plotter or graphics printer if required. **Open Source:** No

	GIS-based?: No **Computer Language:** FORTRAN
Pathways and processes modelled	The model uses the concept of stores to keep account of the passage of water through a catchment. hydraulic state of the catchment. These stores can fill or empty during a simulation, and provide a contribution to runoff which varies with the volume of water they contain. Four stores are used: a surface routing store, an interception store, a soil store and a groundwater store.
Inputs (data requirements)	For calibration, the model requires a sequence of catchment average rainfall and river flow records. Either daily or monthly records can be used. Evaporation data must also be provided, preferably on a daily or monthly basis. However, if these are not available, annual data, or synthesized values, may also be used.
Outputs	Time series of flow
Calibration Method	Manual and Automatic optimization procedure (the Rosenbrock method)
Parameters	It has a total of 9 parameters which determine the behaviour of the flows and of the stores
Water quality constituents	No
Case Studies / Publications	The model has been used successfully on a wide range of hydrological studies, both in the United Kingdom and abroad. Davidson, J., Savic, D., Walters, G. (2003). Symbolic and numerical regression: experiments and applications Journal of Information Sciences , 150, pp. 95–117 Wilcock,D. and Wilcock,F. (1995). Modelling the hydrological impacts of channelization on streamflow characteristics in a Northern Ireland catchment. IAHS-AISH Publication, n231, Modelling and Management of Sustainable Basin-Scale Water Resources Systems.
Versions	
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Contacts: Helen A Houghton-Carr Acting Head of Water Resources Group Hydrological Risks and Resources Section Centre for Ecology and Hydrology (formerly Institute of Hydrology) Maclean Building, Crowmarsh Gifford

	Wallingford, Oxfordshire OX10 8BB United Kingdom Tel: +44 (0)1491 692332 Telefax:: +44 (0)1491 692238 Email: homs@ceh.ac.uk Cost: A charge applies Availability: It is now obsolete. It is a DOS program installed from floppy disks (dated 1991) with archaic graphics drivers which mean that the DOS user screen is corrupted and difficult to use. The model is no longer supported. Documentation: The software is accompanied by a comprehensive user manual in English. Ease of use: The program has been designed to be easy to use, with no requirements to understand the computer operating system or the structure of the data files. Output is in the form of colour screen graphics which can be copied to a plotter or graphics printer if required.

KINEROS2

The kinematic runoff and erosion model (KINEROS)

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	event oriented, physically based, distributed model describing the processes of interception, infiltration, surface runoff and erosion from small agricultural and urban watersheds Hydrological unit: Overland flow elements
Origin (development and maintenance)	USDA-Agricultural Research Service, TUSCON, Arizona
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** The source code has been successfully compiled and run on MS DOS and Windows PCs, as well as Sun, Silicon Graphics and Digital (VMS) workstations. **Operating System:** DOS based PC with x86DX or pentium processor **Open Source:** YES **Computer Language:** FORTRAN 77 **GIS-based:** GIS Grass Interface, ArcView

	Visualisation Facilities: can use own GUI, Automated Geospatial Watershed Assessment (AGWA) tool
Pathways and processes modelled	A rainfall record describing the rainfall rate pattern is used to simulate the runoff over a catchment of rather arbitrary complexity. The catchment is described by an abstraction into a tree-like network sequence of surfaces and channels. The infiltration algorithm will handle a two-layer soil profile and incorporates a new method, based on soil physics, to redistribute soil water during rainfall interruptions. Runoff is routed with an implicit finite difference solution of the kinematic wave equation. Erosion is simulated as a simple transport process operating with erosive detachment from splash and hydraulic sources, in equilibrium with settling based on particle fall velocity. The model allows pipe flow and pond elements as well as infiltrating surfaces, and includes a partially paved element to use in urban area simulation.
Inputs (data requirements)	Parameters must be input to describe the network, the characteristics of each element, and the rainfall.
Outputs	For any element, KINEROS2 can list runoff rate, interpolated rainfall rate and sediment discharge rate by particle class at each time, as well as a water volume and sediment mass balance summary.
Calibration Method	Manual, AGWA provides an interface to adjust the most sensitive KINEROS parameters by a common multiplier. Parameters for either plane or channel elements can be increased or decreased uniformly using this interface.
Parameters	The number and type of parameters required varies, depending on the type of element and the number of processes represented. For example, a simple impervious plane requires only length, width, slope and Manning n or Chezy C. At the other end of the spectrum, an eroding, infiltrating plane with a two-layer soil, represented by five particle size classes, with spatially variable saturated conductivity, subsurface rock and intercepting vegetation will require a total of 18 parameters. Of course, parameter values do not necessarily vary between elements, and neighboring elements often differ only in length, width and slope.
Water quality constituents	No only sediments
Case Studies / Publications	Kalin, L., Govindaraju, R., Hantush,M.(2003) Effect of geomorphologic resolution on modeling of runoff hydrograph and sedimentograph over small watersheds, Journal of Hydrology, Vol 276, Issues 1-4, pp. 89-111. J.Obiukwu Duru, Allen T. Hjelmfelt Jr. (1994). Investigating prediction capability of HEC-1 and KINEROS kinematic wave runoff models, Journal of Hydrology, Vol157, Issues 1-4, pp 87-103.

	Miller, S., Semmens, D., Goodrich, D., Hernandez, M., Miller, R., Kepner, W., Guertin, D.(2007) The Automated Geospatial Watershed Assessment tool, Environmental Modelling & Software, Vol 22, Issue 3, Special section: Advanced Technology for Environmental Modelling, pp. 365-377
Assumptions and Limitations	KINEROS2 is a process-based runoff model that simulates the production of excess rainfall and its conversion to surface runoff under conditions of infiltration-excess (Hortonian overland flow). Where hydrologic response is heavily driven by other processes (e.g. saturation excess, variable source area) KINEROS2 should not be applied. Being an event-model, KINEROS2 is most successfully applied for discrete events in which rainfall variability is adequately captured. As such, rainfall is a major limiting factor in terms of the scale of application (size of the watershed) of KINEROS2 in AGWA. KINEROS2 uses the kinematic simplification of runoff for overland and channel flow and is not suitable for application in larger streams or rivers in which low slopes and associated backwater effects are significant. The model is most effectively applied in overland-flow dominated areas such as semi-arid or urbanized watersheds where rainfall–runoff processes control hydrologic response and groundwater contributions are either negligible or well quantified (Miller et al, 2007).
Versions	KINEROS, KINEROS2
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Carl Unkrich Southwest Watershed Research Center USDA-ARS 2000 East Allen Road Tucson, AZ 85719 USA Phone: (520) 670-6380-178 Fax: (520) 670-5550 e-mail: unkrich@tucson.ars.ag.gov Website: http://www.tucson.ars.ag.gov/kineros/ Cost: Free of Charge

	Documentation: Documentation can be found online at the KINEROS2 web site, including PDF versions of the online documents. Copies of the user manual from the 1990 release of KINEROS are available upon request. Tutorial: Sample of input file available at website http://www.tucson.ars.ag.gov/kineros/

<u>Generalized Watershed loadings Function (GWLF)/ AVGWLF</u>

Model Type (lumped or distributed), event-based or continuous, Hydrological unit	GWLF is considered to be a combined distributed/lumped parameter watershed model. For surface loading, it is distributed in the sense that it allows multiple land use/cover scenarios, but each area is assumed to be homogenous in regard to various attributes considered by the model. Additionally, the model does not spatially distribute the source areas, but simply aggregates the loads from each area into a watershed total; in other words there is no spatial routing. For sub-surface loading, the model acts as a lumped parameter model using a water balance approach. It is a continuous simulation model which uses daily time steps for weather data and water balance calculations. Monthly calculations are made for sediment and nutrient loads, based on the daily water balance accumulated to monthly values.
Origin (development and maintenance)	Developed by Haith and Shoemaker at the Department of Agricultural and Biological Engineering Cornell University
Platform (PC?), Operating System, Open source?, GIS-based (what GIS?), Computer Language, Visualisation facilities	**Platform:** PC **Operating System :** PC-DOS, Windows **Computer Language:** BASIC, Visual BASIC **Visualisation facilities:** ArcGIS interface (Penn State AVGWLF; Tetra Tech ArcView for BasinSim) **Open Source:** no **GIS-Based:** ArcGIS interface
Pathways and processes modelled	The GWLF model provides the ability to simulate runoff, sediment, and nutrient (N and P) loadings from a watershed given variable-size source areas (e.g., agricultural, forested, and developed land). It also has algorithms

	for calculating septic system loads, and allows for the inclusion of point source discharge data. GWLF models surface runoff using the SCS-CN approach with daily weather (temperature and precipitation) inputs. Erosion and sediment yield are estimated using monthly erosion calculations based on the USLE algorithm (with monthly rainfall-runoff coefficients) and a monthly composite of KLSCP values for each source area (e.g., land cover/soil type combination). A sediment delivery ratio based on watershed size and a transport capacity based on average daily runoff are then applied to the calculated erosion to determine sediment yield for each source area. Surface nutrient losses are determined by applying dissolved N and P coefficients to surface runoff and a sediment coefficient to the yield portion for each agricultural source area. Point source discharges can also contribute to dissolved losses and are specified in terms of kilograms per month. Manured areas, as well as septic systems, can also be considered. Urban nutrient inputs are all assumed to be solid-phase, and the model uses an exponential accumulation and washoff function for these loadings. Sub-surface losses are calculated using dissolved N and P coefficients for shallow groundwater contributions to stream nutrient loads, and the sub-surface sub-model only considers a single, lumped-parameter contributing area. Evapo-transpiration is determined using daily weather data and a cover factor dependent upon land use/cover type. Finally, a water balance is performed daily using supplied or computed precipitation, snowmelt, initial unsaturated zone storage, maximum available zone storage, and evapotranspiration values.
Inputs (data requirements)	daily precipitation and temperature data and runoff source areas Point source discharge and concentration
Outputs	Monthly streamflow, monthly watershed erosion and sediment yield, monthly total nitrogen and phosphorus load in streamflow, annual erosion from each land use, and annual nitrogen and phosphorus loads from each land use.
Calibration Method	Manual
Parameters	Transport parameters: runoff curve numbers, soil loss factor, evapotranspiration cover coefficient, groundwater recession and seepage coefficients, and sediment delivery ratio Chemical parameters: urban nutrient accumulation rates, dissolved nutrient concentrations in runoff, and solid-phase nutrient concentrations in sediment

Water quality constituents	sediment, and total and dissolved nitrogen and phosphorus
Assumptions and Limitations	**Assumptions** It is a distributed model by land use but ignores the spatial location within a land use in a subwatershed A unit (watershed or subwatershed) is divided into surface, unsaturated zone, and saturated zone Pollutant parameters values are based on data of a particular study area **Limitations** Simplifications in stream transport and water quality simulation Simulation of peak nutrient fluxes is weak because a constant concentration is used Highly simplified flow routing Groundwater inflow represented using a user-defined recession coefficient Stormwater storage and treatment are not considered
Case Studies / Publications	Ning, S., Chang, N., Jeng, K., Tseng, Y. (2006). Soil erosion and non-point source pollution impacts assessment with the aid of multi-temporal remote sensing images, Journal of Environmental Management, Vol 79, Issue 1, pp. 88-101. Tournoud, M.-G., Payraudeau, S., Cernesson, F., Salles, C. Origins and quantification of nitrogen inputs into a coastal lagoon: Application to the Thau lagoon (France), Ecological Modelling, Volume 193, Issues 1-2, Special Issue on Southern European Coastal Lagoons - Selected Papers from the Conference on Southern European Coastal Lagoons: The Influence of River Basin--Coastal Zone Interactions, Ferrara, Italy, 10 - 12 November 2003, 5 March 2006, Pages 19-33. Yu-Pin Lin, Pei-Jung Wu, Nien-Ming Hong (2008), The effects of changing the resolution of land-use modeling on simulations of land-use patterns and hydrology for a watershed land-use planning assessment in Wu-Tu, Taiwan, Landscape and Urban Planning, Vol. 87, Issue 1, pp. 54-66

Versions	AVGWLF, GWLF
How to obtain Model (contacts, documentation), Cost, Easy to use (?) / training available	Cost: Free of charge Documentation: can be downloaded from: http://www.avgwlf.psu.edu/download.htm Training available: unknown Contacts: Dr. Barry M. Evans Penn State Institutes of the Environment The Pennsylvania State University 128 Land and Water Research Building University Park, PA 16802 (814) 865-3357 bme1@psu.edu